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Characterizing the material properties of dutch unreinforced masonry

Samira Jafari[a,]*, Jan.G Rots[a], Rita Esposito[a], Francesco Messali[a]

[a]*TU Delft, Faculty of Civil Engineering & Geoscience, Delft, The Netherlands*

Abstract

In the northern part of the Netherlands, the recent seismic activities have raised concerns about the behavior of unreinforced masonry structures which were not designed and constructed to resist seismic loading. The first step towards assessment of seismic behavior of masonry structures is to characterize the material properties. This characterization is the matter of importance, since the findings serve as input parameters for analytical and numerical models. To do so, destructive laboratory tests (standard and non-standard tests) have been carried out on samples extracted from existing masonry buildings. The compression, bending and shear properties of masonry were investigated in this research. The obtained properties were categorized with respect to masonry typologies and time periods.

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Keywords: URM; Experimental tests; Destructive tests; Material properties

1. Introduction

Due to the gas extraction, the number of seismic activities has recently been increasing in the northern part of the Netherlands. In this region the majority of building stocks are unreinforced masonry (URM) and they have not been designed and constructed to resist seismic loading. Consequently, the use of numerical models as well as analytical

* Corresponding author. Tel.: +31 15 278 9597; fax: +31 15 278 5767.
E-mail address: S.Jafari@tudelft.nl

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design methods is required to assess the behavior of the existing URM buildings. Therefore, there is a need to characterize the masonry at material level. To do so, an extensive experimental testing campaign was conducted with the collaboration of Delft University of Technology (TU Delft) and Eindhoven University of Technology (TU/e).

A large variety of typologies in terms of used materials and the year of the construction is typical features of the Dutch URM. Regarding the mechanical properties of URM, although some studies were conducted in other parts of the word [1], limited information was provided on the Dutch URM in terms of time periods and masonry typologies [2-4]. Therefore, an objective of the current research is to develop a guideline and provide a database, in order to characterize the behavior of the Dutch URM.

Accordingly, thirteen buildings from the northern part of the Netherlands were investigated and selected as testing objects. Different masonry typologies were identified, even from the inspection of each individual building. A series of masonry samples were extracted from the objects and delivered to the laboratories of TU Delft and TU/e. The specimens were characterized considering compression, bending and shear properties of masonry. In this paper, a summary of all the obtained results is presented. Furthermore, a comparison between the average values of the experimental results and corresponding values proposed in the design standards is addressed. Further details on the testing campaign presented here can be found in the related technical reports [5-6].

2. Materials and methods

Destructive tests were performed on samples extracted from existing masonry buildings and they were delivered to the laboratories of TU Delft and TU/e. All the delivered samples were sawn-cut in the field and separately packed according to ASTM C1532 [7]. The delivered samples were composed of masonry units including clay and calcium silicate brick and general purpose mortar with the joint thickness of 10 mm. The masonry objects belonged to the period between 1920 and 2010. Since the evolution of the construction process may affect the mechanical properties of masonry, the objects were also categorized according to the year of the construction. The clay brick masonry including solid, perforated and frogged unit was categorized as the pre-war period (until1945) and post-war period (after 1945) masonry. For calcium silicate brick masonry only the buildings constructed before 1985 were analyzed, when bricks and general purpose mortar were used. Compression, tension and shear tests were conducted to characterize the mechanical properties of masonry specimens. In addition, a displacement-controlled testing procedure was used to perform all the tests except the bond wrench test.

The compression properties of masonry were investigated by conducting tests in agreement with EN1052-1 [8]. The compression tests were performed in two orthogonal directions, perpendicular and parallel to the bed joints, with the aim of investigating the orthotropic behavior of masonry. Both cyclic and monotonic compression tests were performed. Following the agreements of the standard the test was modified for the case of cyclic loading and horizontal compression tests. For both vertical and horizontal configurations, the masonry specimens had the same dimensions and the same loading rate was applied.

The bending properties of the masonry were studied by performing four-point bending tests, both out-of-plane and in-plane, and bond wrench tests. Horizontal out-of-plane bending tests, where the plane of failure was perpendicular to the bed joints, were performed according to EN1052-2 [9] to characterize the flexural strength of masonry. It should be mentioned that the vertical out-of-plane bending tests were not performed in this research, since the extraction of intact samples based on the requirements defined in the standard [9] was not feasible. In addition, a four-point in-plane bending test was adopted where the moment vector was orthogonal to the plane of the specimen. Dimensions of the specimens and the test set-up adopted for both the in-plane and out-of-plane bending tests were identical and based on EN1052-2 [9]. The flexural bond strength of masonry was studied through carrying out bond wrench tests, in conformity with EN1052-5 [10], on stack bonded specimens, sawn-cut from the remaining parts of the specimens tested beforehand in the bending tests.

The shear properties of masonry were obtained by performing shear tests on triplets in accordance with EN1052-3 [11]. By adopting a displacement-controlled procedure, the initial shear parameters, including initial shear strength and coefficient of friction was studied and the residual strength properties, where a plateau was reached, was investigated. The initial and residual shear properties were found by applying the Coulomb friction criterion.

Table 1 gives an overview about the types of the tests carried out, the standards used for the testing, the laboratories where these tests were performed and the numbers of the specimens adopted in this research.

Table 1. Summary of the tests and number of the samples tested in the present research.

Type of test	Number of the tested specimens					
	Compression test		Four- point bending test		Bond wrench test	Shear triplets tests
	Vertical	Horizontal*	Horizontal out-of-plane	Vertical in-plane*		
According to/inspired to	EN1052-1	EN1052-1	EN1052-2	EN1052-2	EN1052-5	EN1052-3
Laboratory	TU/e	TU Delft	TU Delft	TU Delft	TU Delft	TU/e
Masonry type						
Clay-solid < 1945	20	2	3	9	18	64
Clay-solid > 1945	23	6	12	15	30	65
Clay perforated > 1945	8	-	3	3	6	10
Clay-frogged > 1945	5	-	-	3	3	46
Calcium silicate < 1985	12	8	-	7	5	37

* Non-standard test.

- For these parts, no specimens were available due to poor quality during the extraction or damage during transportation.

3. Experimental results

3.1. Compression properties

Masonry is an orthotropic material due to its special stacking arrangement with head and bed joints. Consequently, the properties depend on the direction of loading with respect to the joints. To investigate the orthotropic behavior of masonry, vertical and horizontal configurations were adopted. The load direction in the vertical and horizontal configurations was either perpendicular or parallel to the bed joints, respectively. In addition, to acquire data for the stiffness degradation, cyclic tests (loading-unloading) were performed.

Table 2 lists the average values of the compressive strength and Young's modulus for both the vertical and horizontal configurations. The Young's modulus was defined as the slope of the most linear part of the stress-strain curve. Comparing the results obtained from the tests performed on the masonry objects constructed in different periods, it can be concluded that in the case of clay-solid masonry, a higher value of the compressive strength was obtained, confirming that by time passing either the quality of the materials used or the construction techniques was improved.

Table 2. Compression properties of masonry (coefficient of variation between brackets).

Masonry type	Vertical compression test		Horizontal compression test		Orthogonality ratio	
	Compressive strength	Young's modulus	Compressive strength	Young's modulus	Compressive strength	Young's modulus
	Mean: (MPa)	Mean: (MPa)	Mean: (MPa)	Mean: (MPa)		
Clay-solid<1945	12.7 (0.15)	9347 (0.27)	10.9 (0.11)	8983 (0.26)	1.3	1.5
Clay-solid>1945	17.7 (0.38)	9348 (0.35)	11.0 (0.23)	5470 (0.10)	1.9	2.3
Clay-perforated>1945	20.7 (0.13)	8688 (0.21)	-	-	-	-
Clay-frogged>1945	8.0 (0.05)	2575 (0.43)	-	-	-	-
Calcium silicate<1985	12.4 (0.20)	8241 (0.21)	7.3 (0.05)	3918 (0.19)	1.7	2.1

- For these parts, no tests were carried out.

According to Eurocode 6 [12], the relationship between masonry compressive strength and the modulus of elasticity can be expressed as:

$$E_m = K_E \times f_k \tag{1}$$

where f_k is the characteristic compressive strength and K_E is a constant defined in the National annex, which for all types of Dutch masonry typologies were defined as 700. Fig. 1 shows the relationship between the vertical Young's modulus and the characteristic value of the vertical compressive strength for both the clay and calcium silicate brick masonry. For the clay masonry, a coefficient K_E approximatively of 600 is found; however, a great dispersion of the data is observed. For the calcium silicate masonry a coefficient K_E approximatively of 750 is found with a high correlation coefficient. It should be mentioned that in the case of the calcium silicate brick masonry limited objects were tested. Therefore, the obtained ratio can be considered as an indicative value.

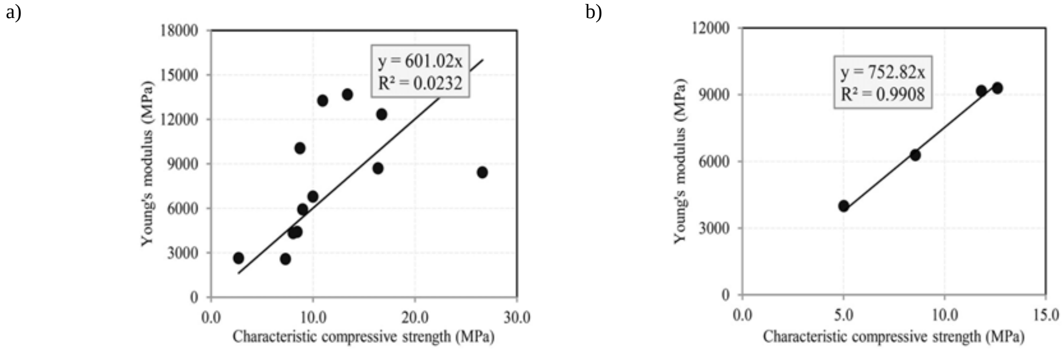

Fig. 1. Relationships of the Young's modulus-characteristic compressive strength for the: (a) clay brick masonry; (b) calcium silicate brick masonry.

The orthogonality ratio, defined as the ratio of the vertical to the horizontal properties, is also presented in Table 2. For both the compressive strength and the Young's modulus an orthogonality ratio higher than 1 is observed. The lower strength and stiffness observed in the horizontal compression test can be caused by: (i) the head joints, which are usually not completely filled due to the poor quality and workmanship, are being compressed rather than bed joints (ii) bricks easily buckled off because the lateral confinement was zero. Due to the limited number of the tested specimens in the horizontal direction and the limited boundary conditions, the obtained results must be considered as indicative values. In addition, since sufficient information on the orthotropic behavior of masonry under compression load is lacking in the literature, further study should be carried out to clarify this aspect.

An example of the stress-strain curves and the crack patterns in the vertical and horizontal compression tests for the samples extracted from one object is presented in Fig. 2. In both configurations, by increasing the deformation, vertical cracks parallel to the load direction occurred and extended over the height of the specimens. For the vertical configuration, once the maximum stress was reached, the spalling and delamination of the bricks was observed (Fig. 2(b)). Due to the mismatch between elastic properties of mortar and brick, the horizontal compressive stress originates in the mortar, while the horizontal tensile stress originates in the brick. Consequently, vertical cracks began to appear at the brick/mortar interfaces [13]. On the contrary, for the horizontal configuration, the specimen was divided into different "columns", separated by the bed joints (Fig. 2(d)).

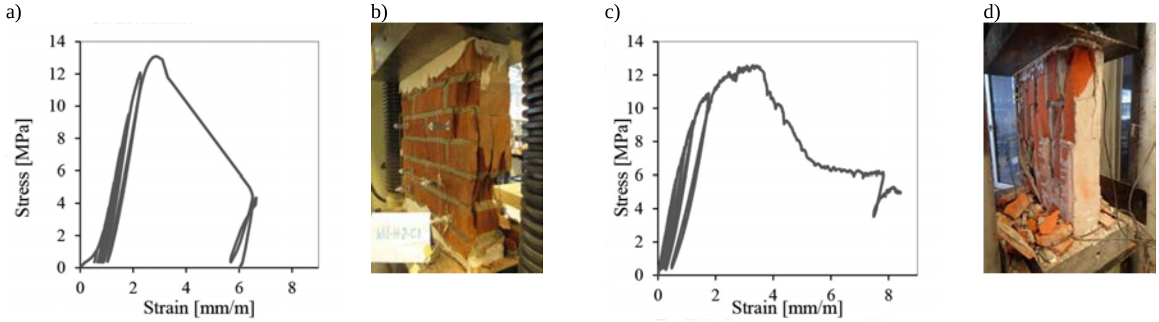

Fig. 2. Stress-strain curve: (a) vertical compression test, (c) horizontal compression test; crack pattern of specimen under: (b) vertical compression test; (d) horizontal compression test.

Apart from the initial slope, the shape of the stress-strain diagram is also needed to be used as an input property for hardening/softening constitutive models. Hendry [14] proposed the following approximation for the stress-strain relationship of masonry:

$$\frac{\sigma}{\sigma_{\max}} = 2\left(\frac{\varepsilon}{\varepsilon_{\max}}\right) - \left(\frac{\varepsilon}{\varepsilon_{\max}}\right)^2 \tag{2}$$

Fig. 3(b) and Fig. 3(c) show the normalized stress-strain curve obtained from the Hendry's model and those obtained from the test on one clay and one calcium silicate brick masonry specimen, respectively. As it can be seen in the Fig. 3(c), in the case of the calcium silicate brick masonry the stiffness is underestimated by Hendry's model. The agreement of the current test interpretation with the parabolic formula presented by Hendry was not remarkable in the existing Dutch masonry, especially in the case of calcium silicate brick masonry. Consequently, the authors propose the multi-polynomial law [15] to determine the stress-strain relationship under compressive loading, as shown in Fig. 3(a). The proposed constitutive law can be expressed as:

$$\sigma(\varepsilon)=\begin{cases} E_m\varepsilon & if \quad \varepsilon\langle\varepsilon_{el} \\ A\varepsilon^3+B\varepsilon^2+C\varepsilon+D & if \quad \varepsilon_{el}\le\varepsilon\le\varepsilon^* \\ E\varepsilon^2+F\varepsilon+G & if \quad \varepsilon^*\le\varepsilon\le\varepsilon_p \end{cases} \tag{3}$$

where E_m is the Young's modulus, f'_m is the compressive strength, ε_p is the strain at peak resistance, ε^* is the strain corresponding to a stress equal to f'_m/α, n is defined as the chord modulus versus the secant modulus at peak and α is defined as:

$$\alpha=\sqrt[3]{n} \tag{4}$$

The parameters A, B, C, D, E, F and G are constants depending on the strain ε_p , ε^* and the parameters n and α. The current model proposes a stess-strain relationship for the pre-peak phase. Further studied are ongoing to study the softening behavior.

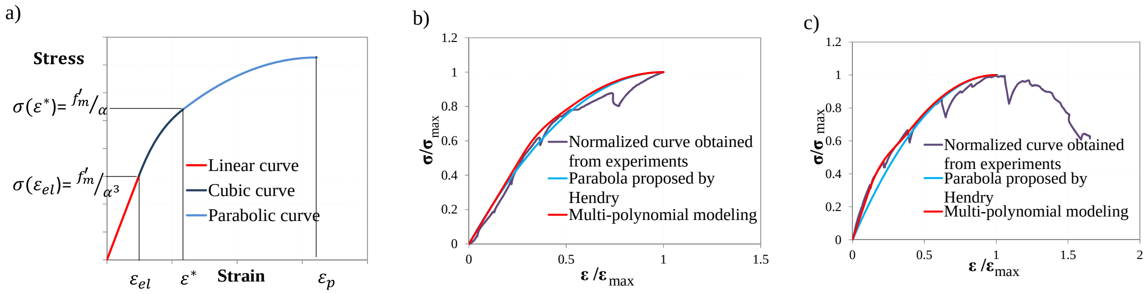

Fig. 3. (a) Multi-polynomial modeling of the experimental behavior of a masonry prism under compressive loading proposed in this study; Comparison between Hendry's model and adopted model in this research for the: (b) clay masonry; (c) calcium silicate brick masonry.

3.2. Bending properties

The bending properties of the masonry specimens were obtained from four-point bending tests, including in-plane and out-of-plane tests, and from bond wrench tests.

The average values of the horizontal out-of-plane bending test and in-plane bending test are summarized in Table3. The behavior of the samples under four-point bending tests was reported as quasi-brittle or brittle with the formation of the cracks in the constant moment zone and instantaneous failure. different types of the observed crack patterns in the in-plane bending test and horizontal out-of-plane bending test are as follows: (i) the oblique crack alternating through the head and bed joints, (ii) the straight crack passing through the head and bed joints and through any bricks in the crack path (Fig. 4).

Table 3. Bending properties of masonry (coefficient of variation between brackets).

Masonry type	Horizontal out-of-plane bending test f_{x2} Mean: (MPa)	In-plane bending test f_{x3} Mean: (MPa)	Bond wrench test f_w Mean: (MPa)	*Ratio between characteristic values of* f_{x2k}/f_{wk}
Clay-solid < 1945	0.83 (0.47)	0.61 (0.20)	0.33 (0.71)	3
Clay-solid > 1945	1.22 (0.09)	0.76 (0.28)	0.43 (0.38)	3
Clay-perforated > 1945	0.87 (0.09)	0.81 (0.43)	0.15 (0.20)	6
Clay-frogged > 1945	-	0.14 (0.30)	0.05 (0.92)	-
Calcium silicate < 1985	-	0.36 (0.59)	0.18 (0.33)	-

- For these parts, no tests were carried out.

By comparing the results of the flexural strength and failure pattern for the specimens of the same object, it can be concluded that the obtained value of the flexural strength when a straight crack passes through the head and bed joints and through any bricks in the crack path is higher than when an oblique cracks passes only through the head joints and bed joints (Fig. 4). In addition, it was observed that when the joints were poorly filled, the failure happened through debonding in the brick/mortar interfaces. This feature can attribute to this fact that mortar joint acts as a plan of weakness which is relevant in the case of weak mortar-strong brick joints combination [16].

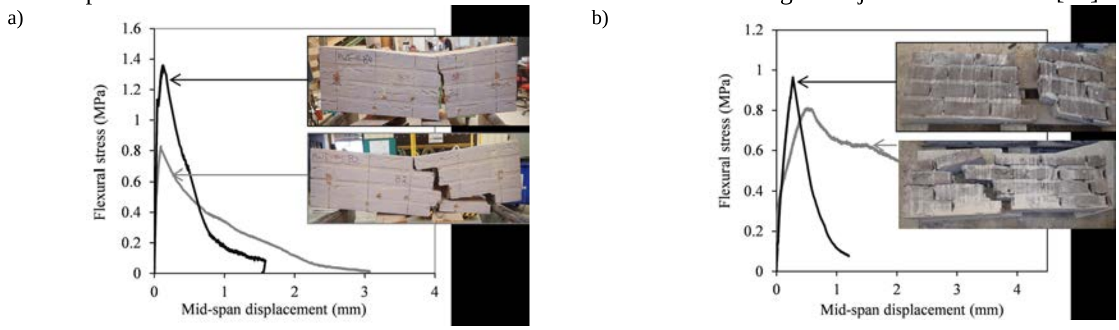

Fig. 4. (a) In-plane bending test: flexural stress-mid span displacement diagrams, (b) out-of-plane bending test flexural stress-mid span displacement diagrams.

The flexural bond tensile strength of masonry obtained from the bond wrench test is also presented in Table 3. In some cases of the clay brick masonry, no bond between the brick and mortar was observed and the bond strength was reported as zero, resulting a large scatter of the results. Due to the poor quality of the calcium silicate brick masonry samples, limited specimens could be sawn-cut only from one object. Therefore, the obtained result can be considered as an indicative value.

From a physical point of view, it may be expected that there is a correlation between the flexural bond tensile strength, f_w, and flexural masonry strength. This correlation depends on loading direction so that the crack plane occurs along the brick to mortar interface in the bed joint plane, f_{x1}. One reason might be the fact that these parameters depend on the adhesion between mortar and brick. Previous studies [2-4] reported a one to one correlation between these two mechanical properties. Assuming this correlation allows us to investigate the orthogonality ratio (the ratio of the perpendicular to the parallel plane of failure of flexural strength) and to compare the characteristic values of the obtained results with those values proposed in Eurocode 6 [12] and NPR 9096-1-1:2012 [17]. The characteristic value of the experimental results is determined by dividing the mean value to the factor 1.5. As proposed in Eurocode 6 and NPR 9096-1-1:2012, the orthogonality ratio of characteristic flexural strength for the clay and calcium silicate brick masonry is the same and equal to 4. This ratio for the current study is also reported in Table 3. The value proposed by the standards is in the range of the obtained experimental values for the clay brick masonry. Due to poor quality of the arrived calcium silicate masonry specimens, no horizontal bending test was conducted in this study.

3.3. Shear properties

The shear behavior of masonry joints and the governed failure mode were majorly influenced by the relation between the shear stress and compressive stress. The results of the shear triplet tests are summarized in Table 4, in terms of the initial and residual shear strength parameters. These parameters are obtained by using Coulomb criterion.

Adopting the Coulomb friction criterion, the initial shear strength and coefficient of friction can be determined. The initial shear strength is defined as the shear stress corresponding to zero compression stress and the coefficient of friction is obtained from the slope of the regression line. The residual parameters, shear strength and residual coefficient of friction, can be determined by applying a similar consideration when a plateau was reached.

Comparing the average values of the initial shear strength for different masonry typologies, it can be observed that the perforated clay masonry shows the highest initial shear strength. This can be caused by the effect of the mortar dowels present in the holes of the brick, which provide extra resistance.

Considering the residual parameters, it can be concluded that the residual shear strength and the residual coefficient of friction for all types of the masonry typologies are approximately on the same range.

A comparison between the characteristic values of the initial shear strength obtained from the experiments and the ones proposed in the standards is also presented in Table 4. From the experiments, the characteristic value of the initial shear strength is determined as the 80% of the mean measured value [11]. Eurocode 6 proposed different values of the characteristic shear strength for the clay and calcium silicate brick masonry, while there is no classification in the NPR 9096-1-1:2012 based on the brick typologies. Comparing the obtained results of the initial shear strength from the experiments and those values suggested in the design standards, it can be concluded that the initial shear strength for the perforated brick is underestimated by the standards, while for the case of frogged brick this value is overestimated. Therefore, a wider classification of the characteristic values of the initial shear strength based on the brick typologies might be needed for the clay masonry. However, for the calcium silicate brick masonry an acceptable agreement between the initial shear strength obtained from the experiments and those of standards is found.

Table 4. Shear properties of masonry.

Type of masonry	Initial parameters		Residual parameters		Characteristic values of the initial shear strength		
	f_{v0} (MPa)	μ -	$f_{v0,res}$ (MPa)	μ_{res} -	Experiment	EC6	NPR 9096-1
Clay-solid < 1945	0.30	0.80	0.06	0.71	0.24	0.20	0.20
Clay-solid > 1945	0.45	0.89	0.07	0.72	0.36	0.20	0.20
Clay-perforated > 1945	0.82	0.66	0.06	0.72	0.66	0.20	0.20
Clay-frogged > 1945	0.15	0.69	0.07	0.70	0.12	0.20	0.20
Calcium silicate < 1985	0.24	0.81	0.06	0.67	0.19	0.15	0.20

It might be expected that there is a correlation between bond shear strength and bond (uniaxial) tensile strength, since these parameters depend on the adhesion between mortar and brick. According to the fracture mechanism for crack propagation in softening material, the uniaxial bond tensile strength is lower than the flexural bond tensile strength. For masonry walls, previous studies have indicated this ratio as 2/3 [2]. Therefore, for this research, the uniaxial bond tensile strength can be obtained by multiplying the bond strength values by 2/3.

Fig. 5 shows the ratio between the initial shear strength and the derived uniaxial tensile bond strength of joint as a function of the uniaxial tensile bond strength for the clay masonry. The ratio between the initial shear strength and the tensile bond strength varies between 0.75 and 8.2, while Van Der Pluijm [2] obtained a range of ratios between 1.3 and 6.5. It can also be observed that high ratios are observed for low value of the tensile bond strength (e.g. f_w < 0.1 MPa).

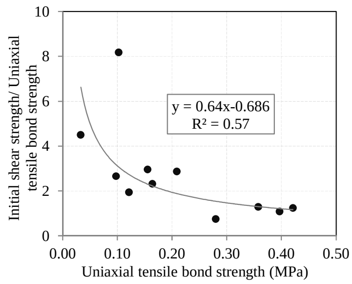

Fig. 5. Ratio between the initial shear strength and uniaxial tensile bond strength of joints as a function of the tensile bond strength for the clay masonry.

4. Conclusions

This paper aimed to establish a comprehensive database of material properties which can be used for the numerical models as well as analytical design methods. The accuracy of seismic assessment and computer modeling can be improved by using our proposed database. Valuable data was obtained in terms of compression, bending and shear properties of masonry. The compressive strength and Young's modulus of masonry specimens were obtained from performing compression tests both in the vertical and horizontal configurations. Flexural tensile strength was obtained through four-point bending tests, both horizontal out-of-plane and in-plane tests, while the bond tensile strength was obtained by performing the bond wrench test. The shear strength parameters, both initial and residual, were defined by conducting the shear tests on the triplets at three different levels of confinement. Finally, the obtained values from the experimental campaign were compared to the proposed values in design standards. Based on the results and observations, the following remarks can be concluded:

(a) A relationship between the characteristic values of the vertical compressive strength and vertical Young's modulus for the clay and calcium silicate masonry can be established. The ratio of the Young's modulus to the characteristic value of the compressive strength for the clay and calcium silicate masonry can be defined as 600 and 750, respectively.

(b) A multi-polynomial stress-strain relationship for the pre-peak behavior is proposed. Further studies are currently ongoing for the modeling of the softening behavior.

(c) From both the vertical and horizontal compression results on the masonry specimens, it can be seen that the orthotropic effect is significant (the orthogonality ratio ranged between 1.3 and 1.9 for the compressive strength and ranged between 1.5 and 2.3 for the Young's modulus).

(d) A higher value of the flexural strength was reported either on the in-plane or horizontal out-of-plane bending tests, when a straight crack passes through the head and bed joints and through any bricks in the crack path rather than when an oblique cracks passes only through the head joints and bed joints.

(e) A ratio between the characteristic values of the horizontal bending tests and bond wrench tests for the clay masonry was found. For case of the calcium silicate brick masonry no horizontal bending test was conducted, due to the poor quality of the samples.

(f) The initial shear strength of the perforated clay masonry is much higher than that of the other masonry typologies. This can be explained the fact that the mortar was entered into the holes and it creates a dowel action.

(g) It can be concluded that the values of the residual shear strength and residual coefficient of friction are independent from the masonry typologies here studied.

(h) The ratio between the initial shear strength and uniaxial tensile strength ranged between 1.3 and 6.5, for the clay masonry. This ratio was not established for the calcium silicate brick masonry, due to the limited tested specimens.

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