Experimental data analysis for mechanical modelling of existing brick masonry structures

F. Parisi & N. Augenti
Department of Structural Engineering, University of Naples Federico II, Naples, Italy

SUMMARY:
Mechanical properties are key parameters in capacity modelling of existing masonry structures. In-situ tests cannot often be performed, especially in the case of historical constructions. Therefore, some codes and guidelines emphasise that a literature review is needed to gather knowledge on material properties, suggesting some reference values as in the case of the Italian building code commentary (IBCC). According to IBCC rules, the authors selected and processed experimental data available in the literature for brick masonry, which is one of the most used building materials all around the world. Data processing was carried out accounting for both composition and conservation state of masonry. Experimental results on compressive strength, shear strength at zero confining stress, Young's modulus, and shear modulus suggest to increase their code values. Modification factors are proposed to consider the influence of good-quality mortar and transverse connections on mechanical properties. Such results could be implemented in future code revisions.

Keywords: brick masonry, code proposals, experimental data analysis, mechanical properties

1. INTRODUCTION

The knowledge of mechanical properties of existing masonry constructions is of primary interest for their seismic assessment, especially when visual inspections rather than in-situ or laboratory tests cannot be carried out. This is the typical case of historical buildings where destructive tests are generally not allowed by national offices for cultural heritage preservation. Engineering judgement is then needed to assume appropriate values for mechanical properties of masonry and, if any, to select experimental data from the literature. To this end, the Italian building code commentary (IBCC) (IMIT 2009) provides useful values on mechanical properties of typical masonry assemblages, whereas international codes such as FEMA 356 (ASCE 2000), Eurocode 6 (CEN 2005a) and Eurocode 8 (CEN 2005b) do not give indications on this topic. A few researchers have reviewed past studies (Augenti 2000, Augenti and Parisi 2009, Tassios 2010), but only in the last years the authors have performed a comprehensive literature review developing MADA (MAsonry DAtabase), an online database aimed at supporting researchers and practitioners in mechanical modelling of masonry (Augenti et al. 2012) [URL: http://www.reluis.it/index.php?option=com_mada&Itemid=156]. This paper focuses on the experimental data analysis of brick masonry, which is one of the most used building materials all around the world and was employed in ancient times to build up cultural heritage constructions in earthquake-prone regions. The authors selected experimental data by MADA and processed them in a way to propose typical ranges for future revisions of IBCC (IMIT 2009) and implementation in seismic codes. Changes in masonry properties induced by good-quality mortar and transverse connections between masonry leaves were also analysed and are discussed herein.

2. METHODOLOGY

Forty-eight electronic files related to twenty-nine experimental works on tuff masonry were selected by MADA (Augenti et al. 2012). Since they refer to experimental tests carried out under several conditions, different test procedures and characteristics of masonry specimens were detected. Due to the sample heterogeneity, some issues were found by data processing and a large scatter in data was observed. Therefore, data were suitably aggregated and compared each other to get some estimates of mechanical properties. Experimental data were collected for the following masonry properties: uniaxial compressive strength in the direction orthogonal to mortar bed joints (f_c); shear strength at zero confining stress (τ_0); Young's modulus (E); and shear modulus (G). Such properties were gathered from research papers and reports dealing with uniaxial compression tests on masonry prisms, in-plane shear tests, and diagonal compression tests. Ranges of mean values of the aforementioned properties are provided by IBCC (IMIT 2009) under the following assumptions (Table 2.1): bad-quality mortar; lack of lacing (i.e., bond masonry layers with a given vertical spacing); simply-approached or badly-connected leaves; as-built unreinforced masonry; and masonry bond according to rules of art. In the case of rough masonry, reference values should properly be reduced, but no criteria are given in IBCC. Conditions different from those listed above should be taken into account through modification factors given in Table 2.2, where some indications on the effects of mortar joints with thickness lower than 10 mm and strengthening systems (i.e., mixture injections and reinforced plaster) are reported. It is emphasised that brick masonry is here assumed to be composed by lime mortar. The modification factor associated with transverse connections should only be applied in the case of historical brick masonry assemblages, because ranges in Table 2.1 are assumed to be representative of modern multi-leaf brick masonry as well. Experimental data analysis of brick masonry assemblages with cementitious mortar is still ongoing, because large samples are available and data aggregation is affected by further issues. Nevertheless, existing brick masonry assemblages typically include lime mortar and this is the main motivation of this study. In some cases, cementitious mortar was assumed to be good-quality mortar if the associated masonry properties were consistent with old brick masonry assemblages. Given that no rules are provided by IBCC to distinguish good-quality mortars from their medium- and bad-quality counterparts, mortars with mean compressive strength equal to or greater than 15 MPa were assumed to be of good quality.

Table 2.1. Reference ranges of mechanical properties according to IBCC

Masonry type	f_m [MPa]		τ_0 [MPa]		E [MPa]		G [MPa]	
	min	max	min	max	min	max	min	max
Old brick masonry with lime mortar	2.40	4.00	0.060	0.092	1200	1800	400	600

Table 2.2. Modification factors of brick masonry properties provided by IBCC

Characteristic	Modification factor
Good-quality mortar	1.5
Thin joints	1.5*
Transverse connections	1.3
Bad-quality and/or wide inner core	0.7
Mixture injections	1.5
Reinforced plaster	1.5

* 1.25 for shear strength at zero confining stress

Experimental data selected by MADA were associated with brick masonry having bond according to rules of art. Any masonry assemblage was assumed to have effective transverse connections, because all data were associated with single-leaf masonry specimens. No data are presently available in MADA for strengthened and rubble brick masonries. Therefore, the first three variants in Table 2.2 were considered. Four brick masonry classes were identified as shown in Table 2.3, where class 1 is associated with the presence of transverse connections (reference values in Table 2.1 multiplied by 1.3) and characteristic variants are in bold and capital letters. Aggregation/disaggregation procedures allowed to obtain data subsets and to identify their outliers which were excluded. Experimental data subsets associated with each mechanical property of interest are plotted along with IBCC ranges in the following sections. In many cases experimental data provided by single researchers were mean values of a series of in-situ or laboratory tests, instead of single realizations of mechanical parameters.

Table 2.3. Brick masonry classes and modified ranges of mechanical properties according to IBCC

Class	Characteristic	Judgment	f_m [MPa]		τ_0 [MPa]		E [MPa]		G [MPa]	
			min	max	min	max	min	max	min	max
1	Mortar quality	Bad								
	Transverse connections	**YES**								
	Strengthening	No	3.12	5.20	0.078	0.120	1560	2340	520	780
	Bond according to rules of art	Yes								
	Bad -quality and/or wide inner core	No								
2	Mortar quality	**GOOD**								
	Transverse connections	**YES**								
	Strengthening	No	4.68	7.80	0.117	0.179	2340	3510	780	1170
	Bond according to rules of art	Yes								
	Bad -quality and/or wide inner core	No								
3	Mortar quality	bad								
	Transverse connections	**YES**								
	Strengthening	No	4.68	7.80	0.097	0.149	2340	3510	780	1170
	Bond according to rules of art	Yes								
	Bad -quality and/or wide inner core	**YES**								
4	Mortar quality	**GOOD**								
	Transverse connections	**YES**								
	Strengthening	No	7.02	11.70	0.146	0.224	3510	5265	1170	1755
	Bond according to rules of art	Yes								
	Bad -quality and/or wide inner core	**YES**								

3. UNIAXIAL COMPRESSIVE STRENGTH

A large sample size was detected for brick masonry class 1 based on fourteen experimental studies (Annamalai et al. 1982, Mattone et al. 1982, Andreaus and Maroder 1991, Calvi and Magenes 1991, Pistone and Roccati 1991, Vermeltfoort 1992, Arduini et al. 1994, Tomisima and Udagawa 1996, Zhuge et al. 1998, Modena et al. 2002, Yuksel et al. 2002, Borri et al. 2004a,b, Kawahara et al. 2004). Some data were excluded because they were obtained from compression tests on masonry columns which experience a different behaviour with respect to masonry prisms, resulting in greater average values. Other data were not taken into account because they were related to masonry specimens of thickness 30 mm whose compressive strength was too high compared to the remaining data set (see, for instance, Daou and Hobbs 1991). As shown in Figure 1, a mean compressive strength equal to 7.97 MPa with a coefficient of variation (*CoV*) equal to 62.53% were found for brick masonry class 1. Even though a large scatter affects such data, *CoV* of single data sets ranged from 7% on 13 data (Zhuge et al. 1998) to 34% on 4 data (Pistone and Roccati 1991, Vermeltfoort 1992). A large scatter affected experimental results by Arduini et al. (1994) only because *CoV* was equal to 65%. The experimental-to-code ratio (ECR) in terms of average compressive strength was 1.92, suggesting that the code range should be shifted upward. The experimental data set analysed in this study for class 1 is characterised by a compressive strength ranging from 0.4 MPa (Borri et al. 2004b) to 17.8 MPa (Kawahara et al. 2004). This highligths that statistical analysis should be carried out on regional experimental data reflecting typical brick masonry assemblages of each country or region. Figures 2a, 2b and 2c show experimental data sets collected for brick masonry classes 2, 3 and 4, respectively.

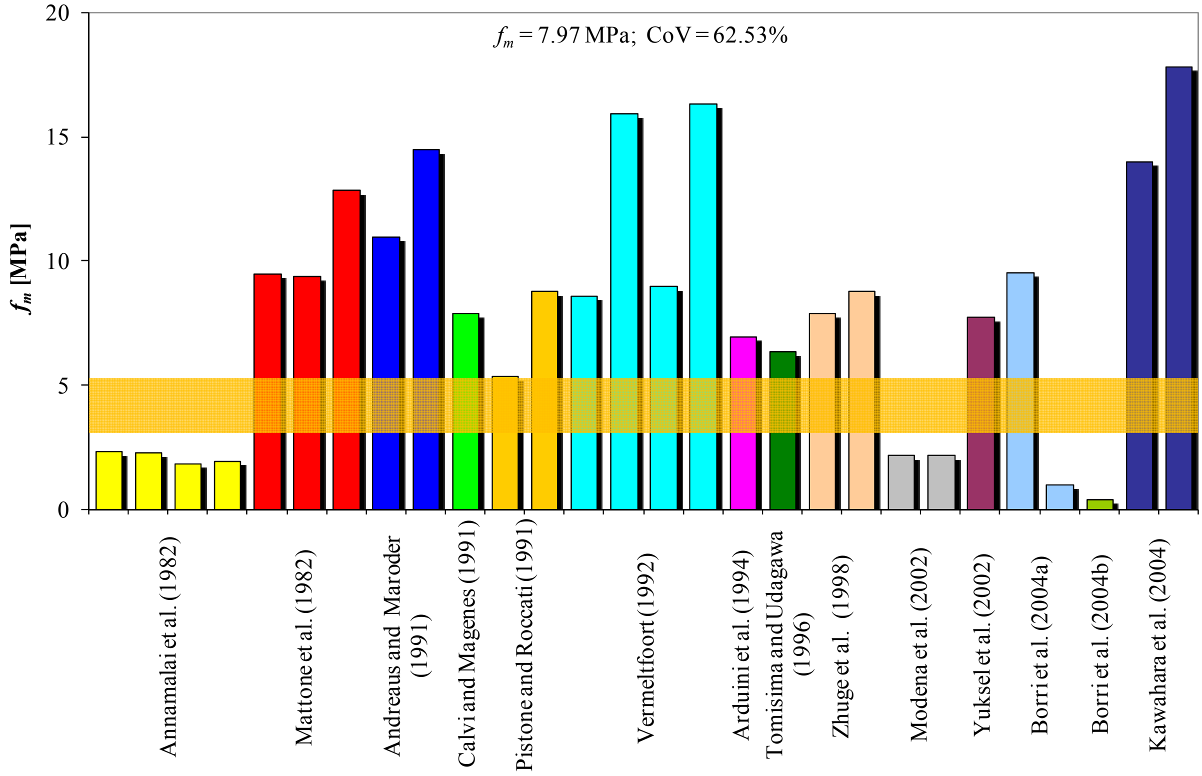

Figure 1. Experimental data on uniaxial compressive strength of brick masonry class 1

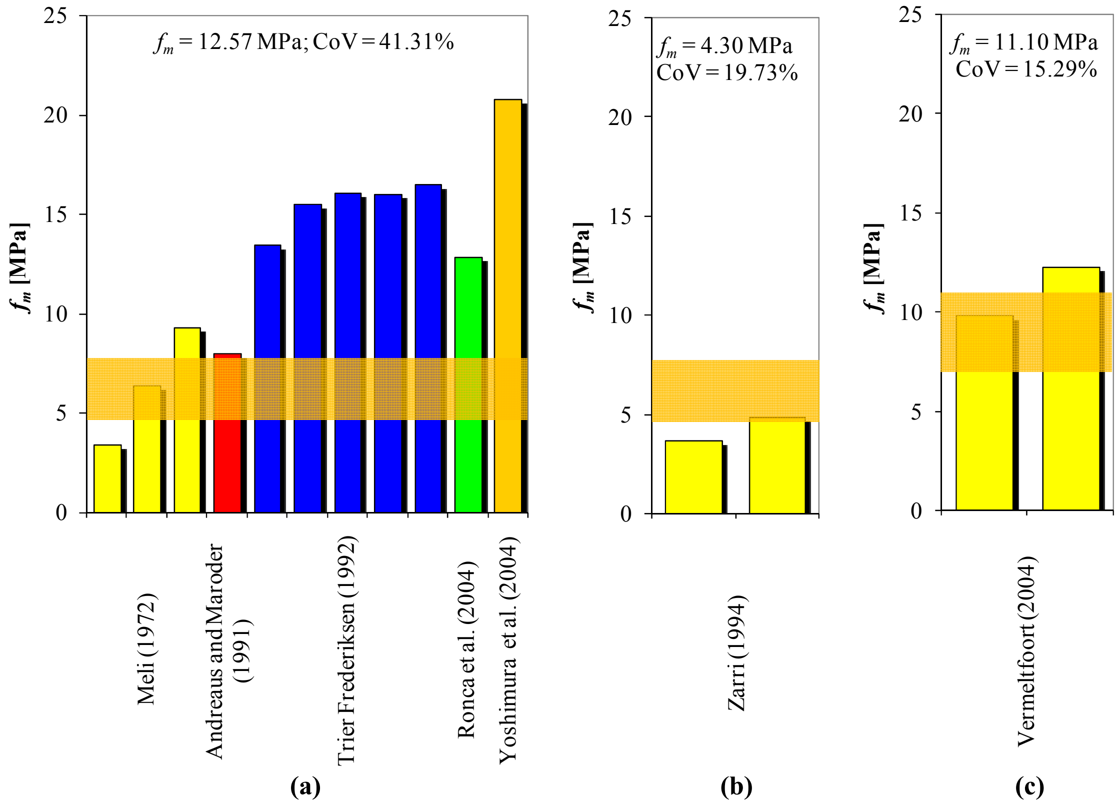

Figure 2. Experimental data on uniaxial compressive strength of brick masonry classes (a) 2, (b) 3 and (c) 4

More data were selected for class 2 (Meli 1972, Andreaus and Maroder 1991, Trier Frederiksen 1992, Ronca et al 2004, Yoshimura et al. 2004) showing a mean compressive strength equal to 12.57 MPa with *CoV* = 41.31%, which is lower than that globally found for class 1. Data subsets obtained by individual experimental programs were characterised by mean compressive strength falling in the interval [3.4 MPa, 20.8 MPa] with *CoV* ranging from 8% on 5 data (Trier Frederiksen 1992) to 46% on 3 data (Meli 1972). Experimental data by Vermeltfoort (1992) were not included because high-strength cementitious mortar (f_{mm} = 45.60 MPa) was used. Some data by Yoshimura et al. (2004) were also excluded because either a high-stregth mortar was used (f_{mm} = 51.70–5360 MPa) or compressive stregths were significantly different from those included in the final data set. Two mean values of compressive strength were provided by Zarri (1994) and were associated with class 3, as follows: 3.7 and 4.9 MPa, each of them resulting from 5 tests. Therefore, mean compressive strength of class 3 was found to be f_m = 4.30 MPa with *CoV* = 19.73%. Regarding class 4, experimental data by Vermeltfoort (2004) with mean compressive strength between 9.9 MPa (3 data) and 12.3 MPa (2 data) were selected, resulting in f_m = 11.10 MPa with *CoV* = 15.29%.

4. SHEAR STRENGTH AT ZERO CONFINING STRESS

The sample selected for class 1 to investigate shear strength at zero confining stress is associated with 103 experimental data (Andreaus and Maroder 1991, Calvi and Magenes 1991, Braga et al. 1993, Filardi et al. 1996, Valluzzi et al. 2002, Corradi et al. 2003, Borri et al. 2004a, Malyszko 2004). The mean shear strength found by Mayorca and Meguro (2004) on 4 specimens was considered as outlier with respect to the remaining data, so it was not included in the final data set. Mean shear strength at zero confining stress was found to be τ_0 = 0.488 MPa with *CoV* = 57.05%. ECR in terms of average shear strength was 4.93, suggesting that the code range should be shifted upward also for this mechanical parameter. Scatter in experimental data related to individual programs was lower, as follows: *CoV* = 14% on 3 data (Braga et al. 1993); *CoV* = 17% on 2 data (Borri et al. 2004a); and *CoV* = 47% on 53 data (Filardi et al. 1996).

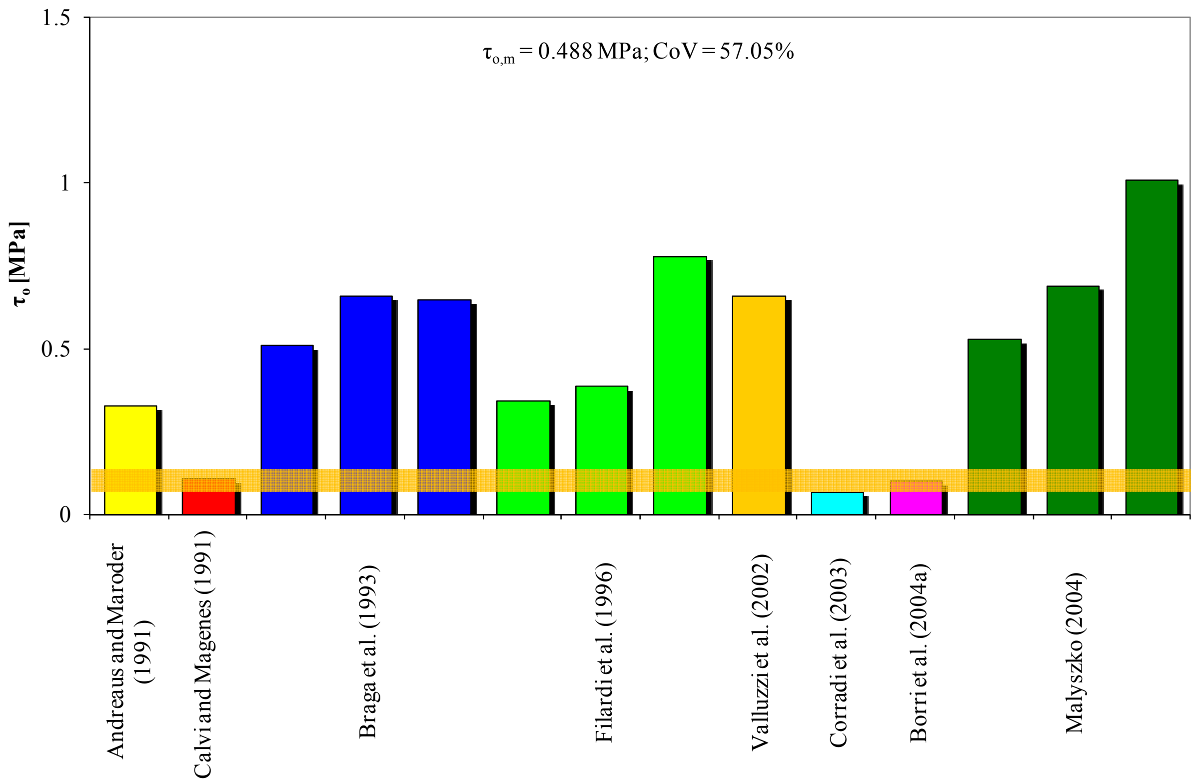

Figure 3. Experimental data on shear strength at zero confining stress of brick masonry class 1

Figure 4 shows the experimental data set selected for class 2, highlighting again that a distance of the experimental mean from the average value of IBCC range (IMIT 2009). Twelve data were provided by Meli (1972), Andreaus and Maroder (1991), and Braga et al. (1993) with mean shear strength $\tau_{0,m}$ = 0.780 MPa and high scatter (*CoV* = 89.95%). A single data was found for class 3, namely, mean shear strength τ_0 = 0.4 MPa derived by Zarri (1994) on 20 specimens (*CoV* not available). Finally, three values were detected for class 4, as follows: 0.213 and 0.811 MPa (Andreaus and Maroder 1991); and 0.835 MPa (Vermeltfoort 2004). The mean shear strength value for class 4 was then found to be 0.620 MPa with *CoV* = 56.87%.

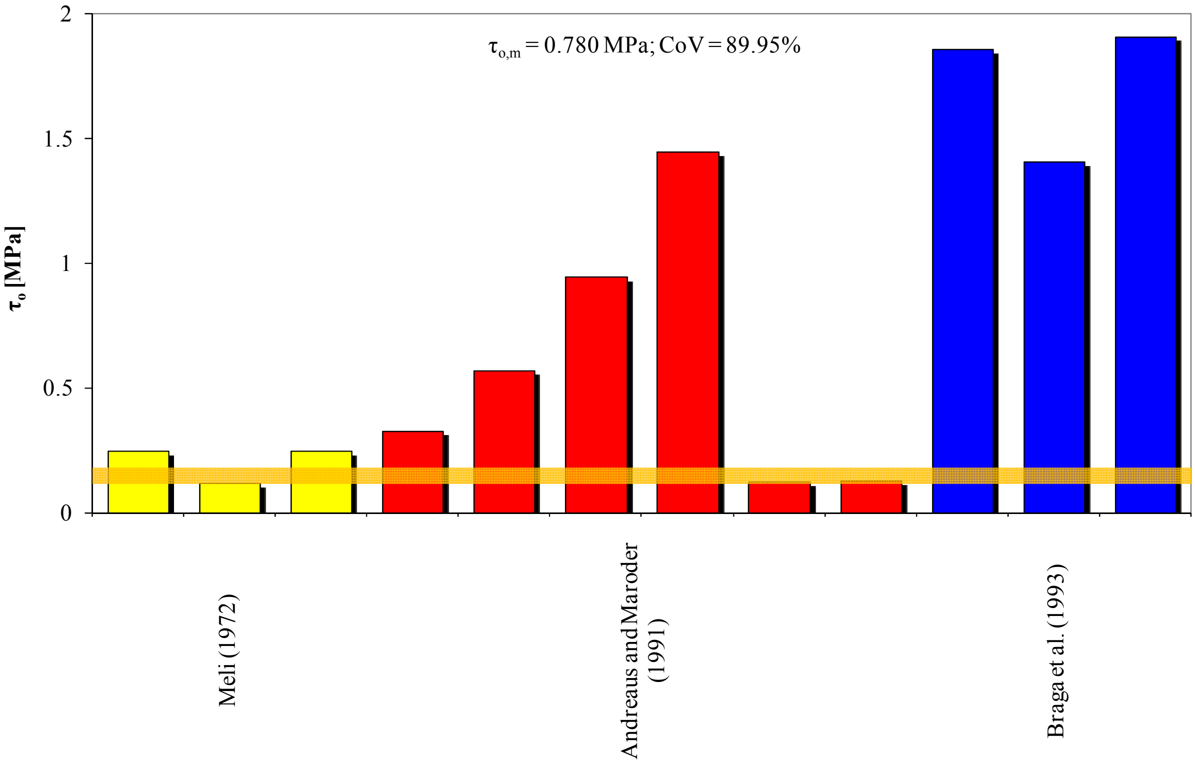

Figure 4. Experimental data on shear strength at zero confining stress of brick masonry class 2

5. YOUNG'S AND SHEAR MODULI

A significant number of tests have been performed in the past to characterise Young's modulus of brick masonry. Only the work by Adriani et al. (1991) was not included in the analysis because it provides experimental data significantly different from others. Figure 5 shows the data set selected for class 1 on the basis of 11 research studies related to 68 experimental results (Andreaus and Maroder 1991, Calvi and Magenes 1991, Pistone and Roccati 1991, Filardi et al. 1996, Tomisima and Udagawa 1996, Zhuge et al. 1998, Modena et al. 2002, Valluzzi et al. 2002, Yuksel et al. 2002, Borri et al. 2004a, Kawahara et al. 2004). They provided a mean Young's modulus E_m = 2699 MPa with *CoV* = 59.84%, resulting in ECR = 1.38. Experimental data subsets provided by individual researchers were characterised by *CoV* between 2% (Kawahara et al. 2004) and 56% (Andreaus and Maroder 1991).

A single data on Young's modulus was found for class 2, namely, E = 5700 MPa (Andreaus and Maroder 1991), whereas no data are presently available for class 3. Finally, MADA (Augenti et al. 2012) provided the following mean values of Young's modulus for class 4 (Vermeltfoort 2004): 4000 MPa on 3 data and 4500 MPa on 2 data. Therefore, a global mean value E_m = 4250 MPa with *CoV* = 8.32% was obtained for class 4.

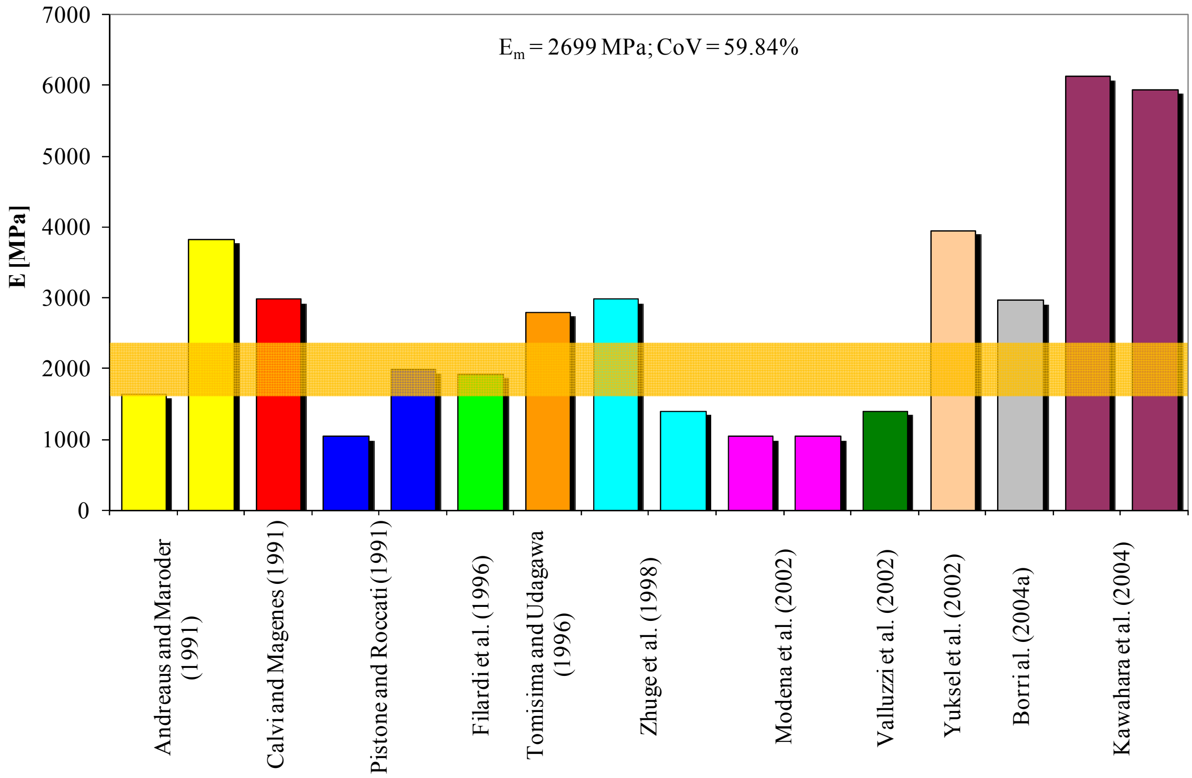

Figure 5. Experimental data on Young's modulus of brick masonry class 1

A few data are presently available in MADA (Augenti et al. 2012) for shear modulus of brick masonry. The following *G*-values were selected for class 1 only: 131 MPa (Corradi et al. 2003); 154 MPa (Borri et al. 2004a); 309 and 716 MPa (Borri et al. 2004b). Therefore, the mean value was G_m = 328 MPa, but it provides just an indication because a large scatter affects data (CoV = 82.71%).

6. CODE PROPOSALS

Based on the experimental data analysis presented above, some proposals can be identified for mechanical properties of old brick masonry with lime mortar, by dividing their average values by 1.3, i.e., the modification factor suggested by IBCC (IMIT 2009) to account for transverse connections within masonry. Future analysis based on further experimental data should assess the validity of such a modification factor. Proposed average values of ranges are provided in Table 6.1 where their respective average code values are also reported. No proposals can be made for shear modulus at present as a result of a small data sample, even if collected data seem to indicate an average value approximately half that suggested by IBCC.

The experimental data analysis presented in this study points out average values significantly greater that those listed in Annex C8A.2 to IBCC. Modification factors proposed by the authors for mechanical properties of old brick masonry with lime mortar are outlined in Table 6.2 together with their relevant code values. As a result of the few data on shear modulus, no modification factors can be proposed for such a parameter at this time. It is emphasised that the presence of thin joints was found to be a deficiency for brick masonry, as it was found to be the cause of lower mechanical properties.

Table 6.1. IBCC and proposed average values of mechanical properties

Reference class	f_m [MPa]		τ_0 [MPa]		E [MPa]	
	IBCC	Proposal	IBCC	Proposal	IBCC	Proposal
Old brick masonry with lime mortar	3.20	6.13	0.076	0.375	1500	2076

Table 6.2. IBCC and proposed modification factors of mechanical properties

Mechanical parameter	Good-quality mortar		Thin joints	
	IBCC	Proposal	IBCC	Proposal
f_m	1.5	2.05	1.5	0.70
τ_0	1.5	2.08	1.25	0.80
E	1.5	2.74	1.5	0.75

On the other hand, IBCC (IMIT 2009) suggests to increase both compressive strength and Young's modulus by 50% and shear strength at zero confining stress by 25%, respectively, in the presence of thin joints. Therefore, the authors recommend further investigations on the influence of mortar joint thickness.

7. CONCLUSIONS

An experimental data analysis on mechanical properties of brick masonry has been presented with the aim of supporting researchers and practitioners in mechanical modelling of existing masonry structures. Brick masonry was investigated because it is one of the most used building materials all around the world and was employed in ancient times to build up cultural heritage constructions in earthquake-prone regions. Experimental data sets were selected by MADA, an online database developed by Augenti et al. (2012), and were processed to investigate mechanical properties for different brick masonry classes. Such classes were defined according to code criteria on the basis of both composition and conservation state of masonry specimens provided in research papers and reports on this topic. Typical ranges resulting from the experimental data analysis have been presented for compressive strength, shear strength at zero confining stress, Young's modulus, and shear modulus, together with their mean values and coefficient of variations. In all cases, experimental results have been found to be greater than those suggested by IBCC (IMIT 2009), that is the current Italian building code commentary. In the case of brick masonry with poor-quality mortar, typical joint thickness and no transverse connections, the following ratios between experimental mean and average code values were obtained: 1.92 for compressive strength; 4.93 for shear strength at zero confining stress; and 1.38 for Young's modulus. Therefore, the authors recommend to shift their average code values upward. Finally, modification factors have been also proposed in order to consider the effects of good-quality mortar and transverse connections on both strengths and elastic moduli of existing brick masonry assemblages. The outcome of the experimental data analysis presented in this study could be of interest for future IBCC revisions and possible implementation in other seismic codes. Further data on shear modulus of brick masonry are needed to revise coded ranges and their modification factors.

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REFERENCES

Adriani, L., Frunzio, G. and Pasquino, M. (1991). Use of rapid assembly components in restoration and renovation of buildings in seismic areas. *Ninth International Brick & Block Masonry Conference*, 1436-1448.

Andreaus, U. and Maroder, M., eds. (1991). Stato dell'arte sui legami costitutivi dei solidi murari, *Studies and Researches* **2**, 49-59 (in Italian).

Annamalai, G., Jayaraman, R. and Madhava Rao, A.G. (1982). Investigations on the compressive strength of walls built using local chamber burnt bricks. *Sixth International Brick & Block Masonry Conference*, 442-

457.
Arduini, M., Di Leo, A., Di Tommaso, A. and Pascale, G. (1994). Experimental methods for on site evaluation of the mechanical properties of masonry. *Tenth International Brick & Block Masonry Conference*, 1269-1277.
ASCE (2000). FEMA 356: Prestandard and commentary for the seismic rehabilitation of buildings, American Society of Civil Engineers, Washington, DC.
Augenti, N. (2000). Il calcolo sismico degli edifici in muratura, UTET, Turin, Italy (in Italian).
Augenti, N. and Parisi, F. (2009). Experimental data analysis on mechanical parameters of tuff masonry. *Second Workshop on Design for Rehabilitation of Masonry Structures*.
Augenti, N., Parisi, F. and Acconcia, E. (2012). MADA: online experimental database for mechanical modelling of existing masonry assemblages. *Fifteenth World Conference on Earthquake Engineering*, CD-ROM.
Borri, A., Corradi, M., Galano, L. and Vignoli, A. (2004a). Analisi sperimentali e numeriche per la valutazione della resistenza a taglio delle murature. *Ingegneria Sismica* **21:3**, 50-68 (in Italian).
Borri, A., Corradi, M. and Vignoli, A. (2004b). Nuove sperimentazioni per la valutazione della resistenza a taglio delle murature prima e dopo rinforzo. *Eleventh Italian Conference on Earthquake Engineering*, CD-ROM (in Italian).
Braga, F., Dolce, M. and Masi, A. (1993). Interpretazione statistica di prove sperimentali per l'accertamento della resistenza a taglio della muratura di edifici esistenti. *Sixth Italian Conference on Earthquake Engineering*, 577-586 (in Italian).
Calvi, G.M. and Magenes, G. (1991). Experimental evaluation of seismic strength of old masonry structures. *Ninth International Brick & Block Masonry Conference*, 490-497.
CEN (2005a). Eurocode 6: Design of masonry structures – Part 1-1: General rules for reinforced and unreinforced masonry structures, Comité Européen de Normalisation, Brussels, Belgium.
CEN (2005b). Eurocode 8: Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings, Comité Européen de Normalisation, Brussels, Belgium.
Corradi, M., Borri, A. and Vignoli, A. (2003). Experimental study on the determination of strength of masonry walls. *Construction and Building Materials* **17:5**, 325-337.
Daou ,Y. and Hobbs, B. (1991). Strength of brickwork loaded in different orientations. *Ninth International Brick & Block Masonry Conference*, 157-163.
Filardi, B., Liberatore, D., Masi, A. and Nigro, D. (1996). Valutazione della resistenza a taglio di una tipologia muraria tramite prove su pannelli, carote e triplette. *Italian Conference "La meccanica delle murature tra teoria e progetto"*, 75-83 (in Italian).
Kawahara, R., Baba, A., Mori, A. and Dainobu, T. (2004). Axial compression behavior of burnt clay masonry units and improving load bearing capacity on brick assemblages with injection materials. *Thirteenth International Brick & Block Masonry Conference*, 17-26.
IMIT (2009). Circ. 02.02.2009, n. 617: Istruzioni per l'applicazione delle «Nuove Norme Tecniche per le Costruzioni» di cui al decreto ministeriale 14 gennaio 2008. Italian Ministry of Infrastructures and Transportation, Rome, Italy (in Italian).
Malyszko, L. (2004). In plane shear ad tensile strength tests of small brickwork specimens. *Fourth International Conference on Structural Analysis of Historical Constructions*, 291-298.
Mattone, R., Pasero, G., Pavano, M., Pistone, G. and Roccati, R. (1982). Experimental tests on samples of various sizes for determining the mechanical characteristics of old masonry. *Sixth International Brick & Block Masonry Conference*, 198-208.
Mayorca, P. and Meguro, K. (2004). Proposal of an efficient technique for retrofitting unreinforced masonry dwellings. *Thirteenth World Conference on Earthquake Engineering*, CD-ROM, Paper n. 2431.
Meli, R. (1972). Behaviour of masonry walls under horizontal loads. *Fifth World Conference on Earthquake Engineering*, 853-862.
Modena, C., Valluzzi, M.R., Tongini Folli, R. and Binda, L. (2002). Design choices and intervention techniques for repairing and strengthening of the Monza cathedral bell-tower. *Construction and Building materials* **16:7**, 385-395.
Pistone, G. and Roccati R. (1991). Mechanical characteristics of masonry rebuilt with ancient bricks and fresh mortars. *Ninth International Brick & Block Masonry Conference*, 1473-1480.
Ronca, P., Franchi, A. and Crespi, P. (2004). Structural failure of historic buildings: masonry fatigue tests for an interpretation model. *Fourth International Conference on Structural Analysis of Historical Constructions*, 273-279.
Tassios, T.P. (2010). Seismic engineering of monuments. In: Garevski, M. and Ansal, A. (eds.). Earthquake Engineering in Europe, Springer: 1-42.
Tomisima, S. and Udagawa, K. (1996). Investigation of a brick masonry building completed in 1895. *Eleventh World Conference on Earthquake Engineering*, CD-ROM, Paper n. 1399.
Trier Frederiksen, V. (1992). Membrane effect in laterally loaded masonry walls. A second order phenomenon.

Sixth Canadian Masonry Symposium, 537-547.
Valluzzi, M.R., Tinazzi, D. and Modena, C. (2002). Shear behavior of masonry panels strengthened by FRP laminates. *Construction and Building Materials* **16:7**, 409-416.
Vermeltfoort, A.T. (1992). Mechanical properties under compression of masonry and its components. *Sixth Canadian Masonry Symposium*, 657-662.
Vermeltfoort, A.T. (2004). Shear, bond and 2D compressive properties of thin bed mortar masonry. *Thirteenth International Brick & Block Masonry Conference*, 73-82.
Yoshimura, K., Kikuchi, K., Kuroki, M., Nonaka, H., Tae Kim, K., Wangdi, R. and Oshikata, A. (2004). Experimental study for developing higher seismic performance of brick masonry walls. *Thirteenth World Conference on Earthquake Engineering*, CD-ROM, Paper n. 1597.
Yuksel, E., Karadogan, F., Yildirim, H., Pala, S., Saruhan, H., Teymur, P. and Sagbas, G. (2002). Experiments carried out on a historical masonry building for retrofitting purposes. *Twelfth European Conference on Earthquake Engineering*, CD-ROM, Paper n. 317.
Zarri, F. (1994). Parametri di resistenza e deformabilità meccanica di murature di laterizio. *Costruire in Laterizio* **41**, 452-455 (in Italian).
Zhuge, Y., Thambiratnam, D. and Corderoy, J. (1998). Nonlinear dynamic analysis of unreinforced masonry. *Journal of Structural Engineering* **124:3**, 270-277.