# A Comparative study on the evaluation of different testing techniques
## Evaluating the mechanical properties of masonry

Jafari, Samira; Esposito, Rita; Rots, Jan

**Publication date**
2018

**Document Version**
Accepted author manuscript

**Published in**
Proceeding of the 10th international masonry conference

**Citation (APA)**
Jafari, S., Esposito, R., & Rots, J. (2018). A Comparative study on the evaluation of different testing techniques: Evaluating the mechanical properties of masonry. In G. Milani, A. Taliercio, & S. Garrity (Eds.), *Proceeding of the 10th international masonry conference : Milan, Italy, July 9-11, 2018*

10th IMC
10th International Masonry Conference
G. Milani, A. Taliercio and S. Garrity (eds.)
Milan, Italy, July 9-11, 2018

# A COMPARATIVE STUDY ON THE DIFFERENT TESTING METHODS: EVALUATING THE COMPRESSION PROPERTIES OF MASONRY

**Samira. Jafari[1], Rita. Esposito[2], and Jan.G. Rots[3]**

[1] PhD candidate
Delft University of Technology, Delft, The Netherlands
S.Jafari@tudelft.nl

[2] Postdoctoral researcher
Delft University of Technology, Delft, The Netherlands
R.Esposito@ tudelft.nl

[3] Full professor
Delft University of Technology, Delft, The Netherlands
J.G.Rots@ tudelft.nl

**Keywords:** Unreinforced Masonry, Compression properties, laboratory test, Double flatjack test, Cylindrical cores.

***Abstract.*** *To evaluate the compression properties of existing unreinforced masonry (URM) either destructive tests (DT) or slightly destructive tests (SDT) can be performed. DTs can be performed in laboratory on small-scale samples that their dimensions meet the requirements of Standard. In practice, these tests can be performed in few cases, due to technical challenges during sampling, packing and transportation. However, SDT can be performed in-situ as proposed by ASTM standard using flatjack methods. Although, flatjack method has the advantage of being less destructive and less time-consuming; reliability of the results obtained from this method is still a matter of concern in particular for masonry wall with a limited thickness and thus, low stress acting on it. As an alternative to the standardized DT and SDT methods, splitting tests on cylindrical cores have been recently introduced as a promising SDT method to characterize the compression properties of masonry. To date, there is a paucity of information concerning the suitability of the double flatjack as well as core testing method to evaluate the compression properties of masonry with a limited thickness. To bridge this gap, this research investigates the suitability of the double flatjack test and the core testing methods to characterize the compression properties of calcium silicate brick masonry walls with a thickness of 100 mm. The results obtained by these SDT methods are correlated with the results of DT performed on the companion samples, aiming to suggest a quick and slightly destructive method for assessing the compression properties of masonry. Moreover, this paper addresses the effect of boundary conditions and geometry on the compression properties of masonry.*

## INTRODUCTION

To properly assess the performance of unreinforced masonry (URM) buildings, numerical and analytical methods require a complete description of the material behavior under compression and bending loading and shear-sliding behavior of the unit-joint interface. In particular, the characterization of masonry under compression is of importance, being URM structures mainly designed to withstand gravity loads. The characterization of the compression properties of masonry is discussed in this paper.

Characterization of mechanical properties of masonry subjected to compressive loading can be pursued, either by performing destructive tests (DT) in laboratory on the samples extracted from existing masonry buildings [1], or by slightly destructive tests (SDT) using in-situ investigations [2]. More information can be retrieved from DTs with respect to SDTs. From DT, the full non-linear compression behavior of masonry can be derived, providing insights into the strength, stiffness and softening post-peak behavior of masonry. Although the destructive tests have the advantage of directly providing properties, technical challenges as well as devastating sampling method puts severe constraints on this method. On the contrary, in-situ double flatjack tests standardized by ASTM C1197-14a [2] have the advantage of being slightly destructive and requiring less time. However, reliability and accuracy over testing results are always a matter of concern due to difficult application of this method. As an alternative method to laboratory destructive tests and in-situ double flatjack tests, splitting tests on the masonry cores have be recently introduced as a novel investigation method to identify the compression properties of brick masonry. This method seems promising, because the adopted methodology causes minor damage to structures and it allows a direct estimation of the mechanical properties ([3]-[4]). The core testing method incorporates the positive features of both DT and SDT methods as well as avoids their limitations.

Due to induced seismicity in the northern part of the Netherlands, characterizing the compression properties of existing Dutch URM has been received a great deal of attention. The Dutch building stocks are often characterized by very thin walls (i.e. 100 mm thickness) and low stress acting on the walls. Consequently, the reliability of the compression properties obtained from double flatjack tests is arguable, due to possibility of uplifting the masonry wall [5]. To date, there is a paucity of information concerning the suitability of the double flatjack tests as well as core testing methods to evaluate the compression properties of masonry with a limited thickness. The suitability of these methods can be confirmed as their results were validated against the results of the reference samples.

In view of the gaps in the literature and necessity to characterize the compression properties of existing masonry, the current paper discusses the different testing methods for evaluating the compression properties of masonry. To pursue this purpose, the double flatjack tests and splitting tests on the cores with 150 mm in diameter were performed on calcium silicate (CS) brick masonry samples replicated and tested in a controlled laboratory environment. This study was conducted within the framework of an extensive experimental campaign developed at Delft University of Technology. Apart from these tests, standardized destructive compression tests on companion samples were performed. The masonry walls and the companion samples were constructed in the same period by employing the same materials. By comparing the results obtained by the destructive and slightly destructive testing methods, this paper has a twofold aim: to suggest a slightly destructive method to assess the compression properties of masonry through in-situ investigations, and to study the effect of boundary conditions and geometry on the compression properties of masonry.

## MATERIALS AND METHODS

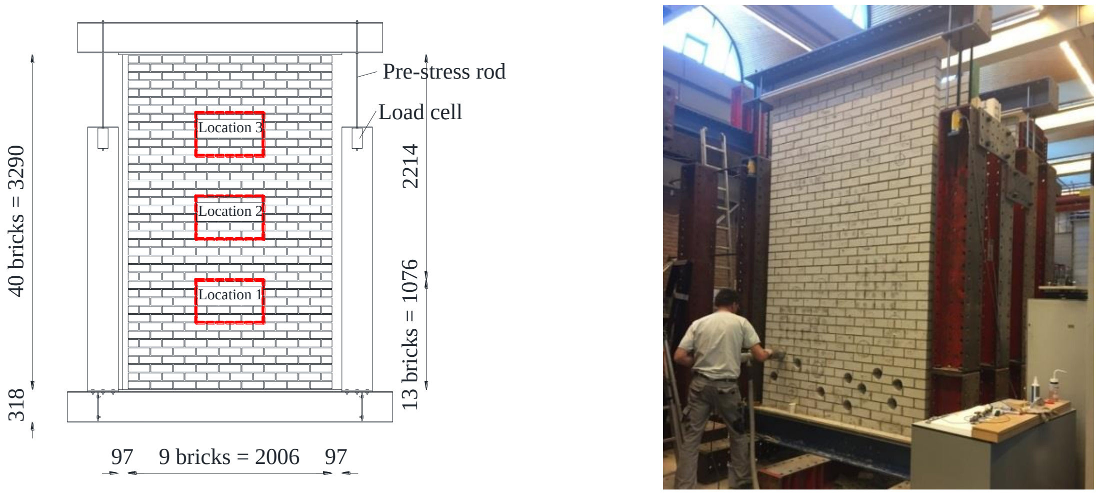
The experimental campaign was carried out on replicated masonry specimens built and tested in controlled laboratory conditions. The CS brick masonry specimens were built using premixed cement-based mortar and traditional bricks with nominal dimensions of 210x70x100-mm; joint thickness of 10 mm was used. To pursue the research aim, the following specimens were adopted:

(i) One full-scale wall was built to be used for the *double flatjack tests*. The tests were performed, in accordance with ASTM C1197-14a [2], over three different locations of the wall.
(ii) One full-scale wall was built for extraction of *cylindrical cores* with 150 mm in diameter. The results of six samples are reported herein.
(iii) Six *companion samples* (wallets) to be subjected to standardized destructive compression loading, in accordance with EN1052-1:1998 [1].

The double flatjack test was performed over three different locations of the replicated CS masonry wall; see Figure 1(a). To simulate the in-situ state of stress, an overburden load was applied at top of the wall, by pre-stressing four steel rods linked to a transverse beam. The tests were performed in the lowest location of the wall toward the highest one, in a sequence. In the first identified location, the overburden load was applied such as to obtain a nominal vertical compressive stress equal to 0.60 MPa at the height where the top slot was made to insert the flatjack. Afterwards, the joints where the flatjacks being inserted were repaired using high-strength mortar. The test was repeated in the other two locations of the wall; imposing an overburden of 0.25 MPa and 0.15 MPa in the second and third location, respectively. The testing procedure on the identified masonry portion can be summarized as follows: (i) two slots on the masonry bed joints were made, where the two flatjacks were inserted; (ii) the masonry portion between the two flatjacks was compressed as the pressure in the flatjack was increased. The masonry portion was equipped with four vertical and one horizontal Linear Voltage Displacement Transducers (LVDT) allowed continuous measuring of deformations along and perpendicular to the loading direction, respectively. The measuring range of LVDTs' was 10 mm with an accuracy of 0.1%. It should be pointed out that at each location of the wall, the "shove test" or "push test" was performed following the double flatjack test aiming to investigate the shear-sliding behavior of the brick-joint interface. Therefore, the failure of the masonry portion between the two flatjacks as well as undesired uplifting of the upper portion of the wall with respect to the top flatjack was not desired. To this end, the pressure in the flatjacks was almost kept lower than the overburden pressure; thus, the stress-strain relationship was estimated only in the elastic phase. To calculate the stress in the masonry portion between the flatjacks, the pressure in the flatjack should be corrected taking into account both geometrical characteristic of the flatjack ($k_m$) and the ratio between the area of the flatjack and the area of the cut ($k_a$). In previous studies [5]-[6], the effective area of the flatjack was reported to be lower than the nominal area of the flatjack. To measure the effective area of the flatjack in the current study, sensitive pressure paper was used to enclose the flatjack prior to their installation in the slot. The effective area of the flatjack was retrieved calculating the area of the sensitive pressure paper marked in place of contacts. It was observed that the effective area of the flatjacks was lower than the nominal one. This ratio ranged between 0.69 and 0.85.

A dedicated wall made of replicated CS brick masonry was built for extraction of the cores. The masonry cores were extracted perpendicular to the surface of wall. A dry extraction process was adopted. To preserve the integrity of the wall during the core drilling, the wall was pre-compressed via pre-stressed rods connecting the bottom and top steel profiles placed on the wall; see Figure 1(b). The applicability of 150 mm diameter core with two bed joints and one central head joint to evaluate the compression properties of masonry was investigated within this study. This method is proposed by International Union of Railway (UIC) [6]. In the current study, the extracted samples were completed with high-strength mortar in order to ensure that the loaded faces of the specimen were levelled to each other, as suggested by Pelà et al. [3], instead of using steel cradles as proposed by the UIC. The masonry cores were subjected to the compressive load using a hydraulic jack operated in displacement-control; using the displacement of the jack as control variable. The sample was instrumented by LVDTs, allowed measuring deformations along the vertical axis of symmetry and horizontal axis of symmetry and measuring the transversal expansion. To evaluate the compression properties of masonry cores, the applied compression stress can be evaluated either referring to the horizontal cross-section of the specimen or to the cross-section of the regularization cap, as suggested by Pelà et al. [3].

The destructive compression tests were performed according to EN 1052-1:1998 [1] on the companion samples. To ensure that the loaded faces of the specimens were levelled and parallel to one another, a 10-mm thick layer of gypsum was applied to faces in contact with the loading plates. This was done to prevent additional stresses in the specimens. By using well-designed displacement-control testing set-up, the full non-linear compression behavior was measured. Totally, six specimens were tested. Four LVDTs (two for each side) were attached to the specimen to register vertical relative displacements over the height of the specimen. They were installed as closely as possible to the surface of the specimen to reduce possible errors caused by rotation of the contact points to which they were attached. Additionally, the horizontal relative displacement over the length of the specimen was registered using two horizontal LVDTs (one for each side). The measuring range of the LVDTs was 10 mm with an accuracy of 0.1%.




(a) (b)

Figure 1: Calcium silicate walls adopted for the testing: (a) double flatjack tests, (b) core drilling.

## EXPERIMENTAL RESULTS

The *double flatjack tests* were performed in the three different locations of the wall. To avoid undesired failure or causing damage to the contrast portion of the masonry, the pressure in the flatjacks were chosen carefully. This was applied in particular for the last location placed in the highest portion of the wall having the lowest overburden (0.15 MPa). The chord modulus and the ratio between the effective area of the flatjack and the nominal area of the flatjack are reported in Table 1. Although the horizontal expansion of the tested masonry portions was measured, no reliable values of Poisson ratio were found. This can be caused by the confinement of the tested masonry portion in the adopted testing configuration, which does not allow the lateral expansion of the wall. The stress-strain relationships stablished from the double flatjack tests are shown in Figure 2. For all the three locations, the stress-strain relationship in the normal direction shows approximately a similar trend; with 27% coefficient of variations.

The *splitting tests on masonry cores* with 150 mm in diameter were performed. Totally, six specimens were tested. The compression properties of masonry was obtained in terms of compressive strength ($f'_{m,core}$), elastic modulus ($E_{core}$), strain corresponding to the peak stress ($\varepsilon_{p,core}$) and Poisson ratio ($\nu_{core}$), as listed in Table 2. For the Young's modulus, three different estimates are adopted:

- $E_{1,core}$ is the secant elastic modulus evaluated at 1/3 of the maximum stress;
- $E_{2,core}$ is the secant elastic modulus evaluated at 1/10 of the maximum stress;
- $E_{3,core}$ is the chord Young's modulus evaluated between 1/10 and 1/3 of the maximum stress.

The typical crack pattern observed during the test is shown for one specimen; see Figure 3. The crack pattern in the pre-peak phase was characterized by vertical cracks starting at the extremities of the regularization cap. In the post-peak phase, the cracks were spreading through the height of the specimen. Consequently, it can be assumed that it is more appropriate to evaluate the compressive properties of masonry cores with respect to the cross-sectional area of the cap. It should be noted that during the test, damage in the cap was observed, which could affect the estimation of the fracture energy. Consequently, this value is not reported and further research is currently ongoing on this topic.

Performing *destructive compression tests on the masonry wallets* allowed establishing a comprehensive overview of the compression properties of masonry in terms of compressive strength ($f'_m$), Young's modulus both tangent ($E_1$, $E_2$) and chord modulus ($E_3$), Poisson's ratio ($\nu$), strain corresponding to the peak stress ($\varepsilon_p$) and the fracture energy ($G_{f\text{-}c}$); as provided in Table 3. The fracture energy is evaluated as the area underneath the stress-strain curve taking into account the height of the specimen. Figure 4(a) shows the stress-strain diagram of the CS masonry wallets under vertical compression tests. The graphs refer to the normal direction that is defined as the one parallel to the loading direction. The pre-peak stage was characterized by linear-elastic followed by a hardening behaviour until the peak. In this stage, nonlinearity occurred at a stress level approximatively 1/10 of the maximum stress. After the maximum stress was reached, a softening behaviour was observed. The softening branch was approximatively linear. Figure 4(b) shows the typical crack patterns observed under vertical compression test. The cracks started at the mortar-brick interface for the joints orthogonal to the loading direction. When the maximum stress was reached, vertical cracks developed in the bricks. The cracks mainly occurred in the central part of the specimens. In the post-peak phase, the vertical cracks mainly occurred in the bricks and developed uniformly through the length of the specimen, by splitting it in two parts. The cracking was observed to occur in a distributed manner over the height of the specimen; no localisation of the cracking at the boundary was observed.

| *Double flatjack test* | Over burden MPa | $E_{DFJ}$ MPa | $A_{Effective}/A_{Nominal}$ - |
|---|---|---|---|
| First location | 0.60 | 7078 | 0.69 |
| Second location | 0.25 | 8789 | 0.85 |
| Third location | 0.15 | 11974 | 0.85 |
| Average | | **9280** | |
| Coefficient of variation | | 0.27 | |

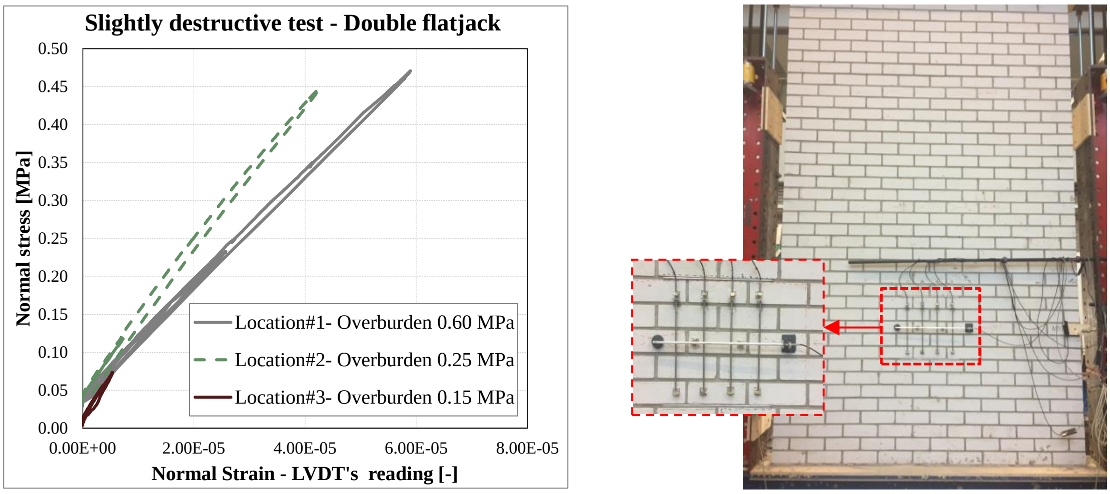
Table 1: Compression properties of CS brick masonry obtained from double flatjack tests.

| *Splitting tests on cores* | Cross-sectional area of the core | | | | Cross-sectional area of the cap | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $f'_{m,core}$ MPa | $E_{1,core}$ MPa | $E_{2,core}$ MPa | $E_{3,core}$ MPa | $f'_{m,cap}$ MPa | $E_{1,cap}$ MPa | $E_{2,core}$ MPa | $E_{3,core}$ MPa | $\varepsilon_{p,core}$ ‰ | $\nu_{core}$ - |
| **Average** | **3.85** | **823** | **2261** | **730** | **6.18** | **1321** | **3607** | **1172** | **13.0** | **0.18** |
| Standard deviation | 0.29 | 412 | 1957 | 474 | 0.44 | 667 | 3075 | 767 | 2.76 | 0.03 |
| Coefficient of variation | 0.07 | 0.50 | 0.85 | 0.65 | 0.07 | 0.50 | 0.85 | 0.65 | 0.21 | 0.15 |

Table 2: Compression properties of CS brick masonry obtained from splitting tests on masonry cores.

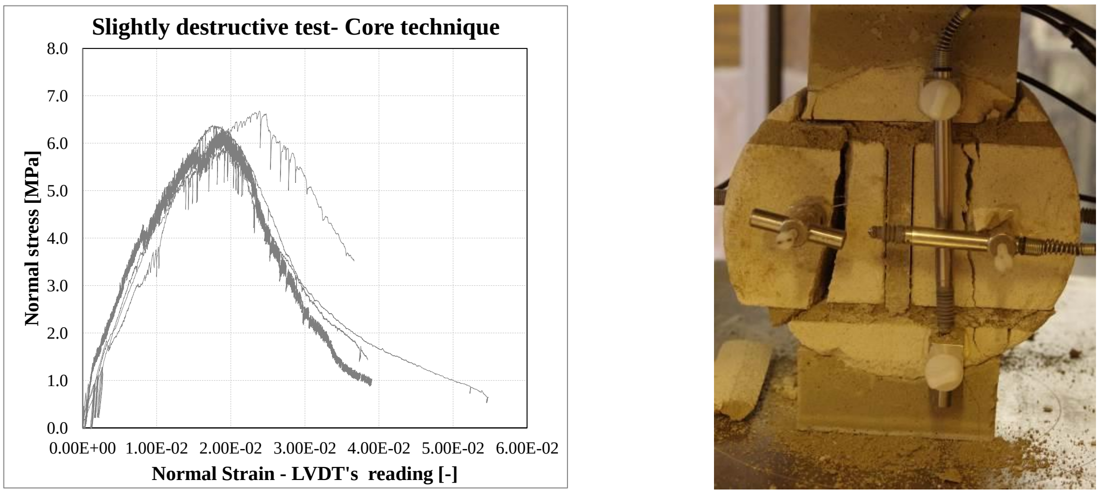
| *Standard test on masonry wallets* | $f'_m$ MPa | $E_1$ MPa | $E_2$ MPa | $E_3$ MPa | $G_{f-c}$ N/mm | $\varepsilon_p$ ‰ | $\nu$ - |
|---|---|---|---|---|---|---|---|
| **Average** | **6.35** | **4972** | **8206** | **4265** | **20.0** | **5.9** | **0.16** |
| Standard deviation | 0.32 | 568 | 1008 | 527 | 3.43 | 1.21 | 0.03 |
| Coefficient of variation | 0.05 | 0.11 | 0.12 | 0.12 | 0.17 | 0.2 | 0.19 |

Table 3: Compression properties of CS brick masonry obtained from DTs on masonry wallets.



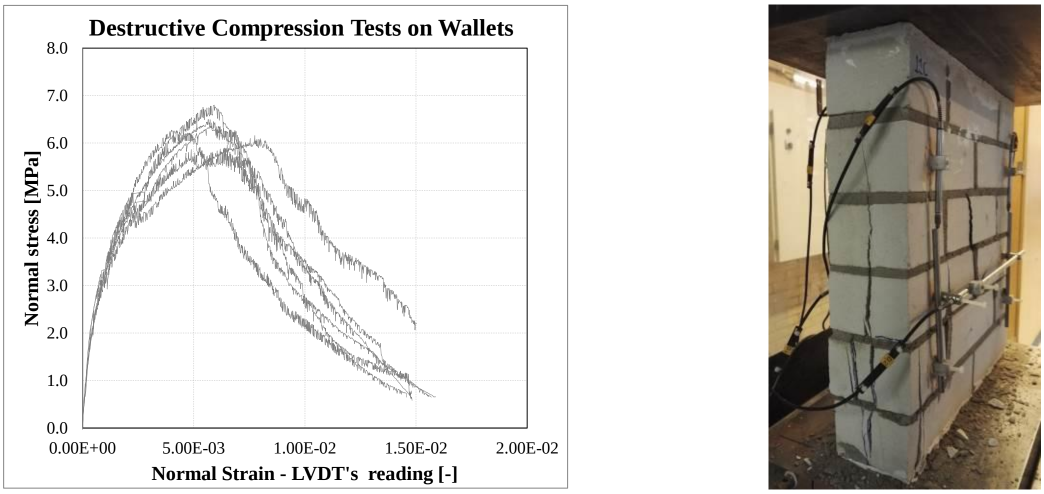

(a) (b)

Figure 2: Double flatjack on the portion of masonry wall: (a) stress-strain curve; (b) testing set-up.




(a) (b)

Figure 3: Splitting tests on *masonry cores*: (a) stress-strain curve; (b) typical observed crack pattern.




(a) (b)

Figure 4: Compression tests on the companion masonry wallets: (a) stress-strain curve; (b) typical observed crack pattern.

To validate the double flatjack test as well as tests on cores as a suitable in-situ investigation test methods, their results were correlated with the results obtained by standardized destructive tests. A ratio between the compression properties obtained by the double flatjack tests and tests on the companion wallets is listed in Table 4. The values of the chord modulus obtained from the double flatjack tests are in agreement with the elastic modulus of masonry obtained by test on wallets evaluated at 10% of the maximum stress ($E_2$). This comparison is made by considering that the maximum pressure in the flatjack was always kept lower than 0.61 MPa, which corresponds approximatively to 10% of the compressive strength of masonry.

| Ratio between the compression properties obtained from double flatjack tests and from testing of companion samples | $E_{DFJ}/E_1$ | $E_{DFJ}/E_2$ | $E_{DFJ}/E_3$ |
|---|---|---|---|
| | 1.9 | 1.1 | 2.2 |

Table 4: Ratio between the compression properties obtained by double flatjack tests and test on companion samples.

| Ratio between the compression properties obtained from cores testing and from testing of companion samples | Cross-sectional area of the core | | | | Cross-sectional area of the cap | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $f'_{m,core}$ / $f'_m$ | $E_{1,core}$ / $E_1$ | $E_{2,core}$ / $E_2$ | $E_{3,core}$ / $E_3$ | $f'_{m,cap}$ / $f'_m$ | $E_{1,core}$ / $E_1$ | $E_{2,core}$ / $E_2$ | $E_{3,core}$ / $E_3$ | $\varepsilon_{p,core}$ / $\varepsilon_p$ | $\nu_{core}$ / $\nu$ |
| | 0.61 | 0.17 | 0.27 | 0.17 | 0.97 | 0.27 | 0.44 | 0.28 | 2.2 | 1.1 |

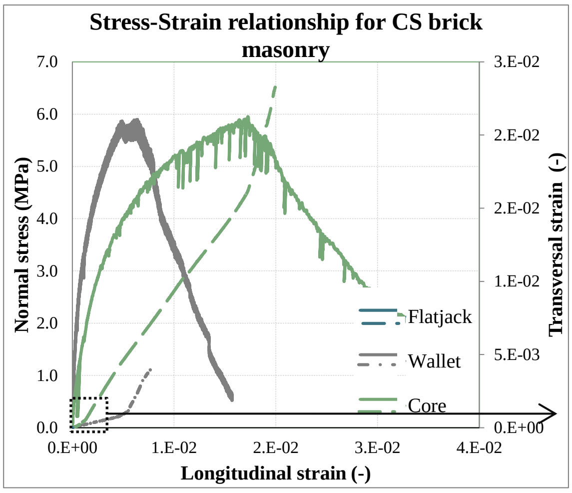
Table 5: Ratio between the compression properties obtained by test on cores and test on companion samples.

A ratio between the compression properties obtained by tests on cores and tests on companion specimens is shown in Table 5. The compression properties of masonry cores are given both considering the cross-sectional area of the core and the one of the cap. The comparison leads to the following conclusions:

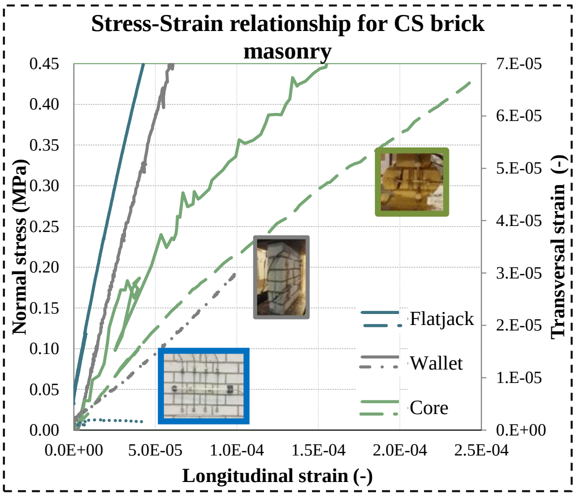
- The evaluation of the compressive strength depends on the considered cross-sectional area. In the case the cross-sectional area is defined in agreement with the failure mode (cross-sectional area of the cap), a good correlation is found between the compressive strength determined by the test on cores and the test on wallets.
- The ratio obtained by test on cores and test of wallets for the chord elastic modulus varies between 0.2 and 0.4 for different estimates of the Young's modulus. It can be concluded, that the evaluation of the chord modulus is underestimated using the core testing methods.
- The strain corresponding to the peak strength evaluated with test on cores is higher than the one evaluated with tests on wallets. A ratio equal to 2 is found.

In the present study, the compression properties of the masonry were investigated for the specimens having different geometries and boundary conditions. The translation of the properties of masonry obtained from testing of small-scale samples to the objective testing parameters is still a controversial issue. Independently of the specimen size, the same values of energy are released from the fracture growth [8]. Therefore, higher values of stress can be expected by reducing the sample size for the same imposed strain. However, in the current study, almost the same values of the compressive strength were obtained by testing wallets and cores. Consequently, assuming that the two testing methods provide both similar values of the fracture energy and of the compressive strength, lower values of the Young's modulus and higher values of the strain at peak can be expected by using the core testing method. This conclusion matches with the experimental results (see Table 5).

The stress-strain relationships established from testing of one core sample, a wallet and from testing of a portion of CS masonry wall using the double flatjack testing method are shown in Figure 5. The variation of the stress versus longitudinal strain is presented using the solid lines. The secondary axis allows monitoring the variation of the longitudinal strain versus transversal strain; the curves are indicated by the dashed lines. A more detailed view of the graph in the initial elastic phase is presented in Figure 5(b). Although this comparison is made for a limited number of samples, it can be concluded that as the size of the samples increased an upward trend in the initial stiffness is reported. However, the variation of the transversal strain over the longitudinal strain shows the opposite trend with respect to the specimen size. It can be assumed that, the larger samples are more confined, thus a restrain of the deformation in the transversal direction can be expected.




(a)




(b)

Figure 5: Stress-strain relationship obtained from testing of the samples with different geometries: (a) full curve; (b) detailed view in the elastic phase.

## CONCLUSIONS

The current paper discusses the different testing methods for evaluating the compression properties of masonry. The aim is to suggest a quick and slightly destructive testing method to characterize the compression properties of masonry. To pursue this purpose, the double flatjack tests and the splitting tests on the cores with 150 mm in diameter were. Apart from the slightly destructive tests, standardized destructive compression tests on the companion samples were performed. The results of the compression tests on the companion samples were used as a reference to validate the applicability of the slightly destructive methods. The masonry samples replicated and tested in a controlled laboratory environment. As a case study, calcium silicate (CS) brick masonry wall with a thickness of 100 mm is selected. The CS brick masonry is frequently employed in the construction of the low-rise URM buildings in the Netherlands (i.e. maximum two-story).

Comparing the properties obtained from the double flatjack test and the companion samples, it can be concluded that the double flatjack test gives an overestimation of the elastic modulus evaluated at 13% of the maximum stress. The Young’s modulus differences between the two methods stand for 23%. In the current study, the applicability of the core method to evaluate the compression properties of masonry was validated by comparing the obtained results with the results of destructive standardized tests on the companion samples. In view of the results achieved in the present study, the following conclusions can be drawn: A good estimation of the compressive strength of masonry was found using the core testing method; as the properties were evaluated in accordance with the loaded cross-sectional area defined in agreement with the failure modes. Consequently, a ratio equal to unity between the compressive strength of masonry cores and compressive strength of companion samples was found. In contrast with the estimation of the compressive strength, the core testing methods gave an underestimation of the Young’s modulus. It should be pointed out that the results obtained in this study are based on a limited number of tests. To improve the correlation between the compression properties established from standard destructive tests and from double flatjack tests as well as core testing methods, additional studies are being conducted.

To conclude, analogies between the two SDT methods, double flatjack test and the core testing method are drawn. The comparisons are accounted for both the testing procedure itself and the suitability of the methods to assess the compression properties of masonry; as they were validated against the results of the companion samples. Being low the state of stress on the wall, more expertise is required to execute the double flatjack test without abrupt failure of the wall, which is not desired in the case of historical buildings. On the contrary, the core testing procedure seems more straightforward with respect to the double flatjack test. Calculation of the Young's modulus using the double flat jack tests resulted in relatively large values of the coefficient of variations (27%). Using the core testing method, a less dispersion of the compressive strength was found (7% coefficient of variation), while higher dispersion of the estimation of the Young's modulus was observed (65% coefficient of variation).

## ACKNOWLEDGMENT

This research was funded by Nederlandse Aardolie Maatschappij B.V. (NAM) under contract number UI53654 "Testing program 2016 for structural upgrading of URM structures" as part of the NAM Structural Upgrading program, which is gratefully acknowledged. Lucia Licciardello and Elena Casprini are gratefully acknowledged for carrying out the tests.

## REFERENCES

[1] EN 1052-1:1998: Methods of test for masonry – Part 1: Determination of compressive strength. European committee for standardization. Sept. 1998.

[2] ASTM C11974-14a: Standard test method for in situ measurements of masonry deformability properties using the flatjack method. ASTM International. West Conshohocken. PA 19428-2959. 2014.

[3] L. Pelà, E. Canella, A. Aprile, P. Roca, Compression test of masonry core samples extracted from existing brickwork. *Construction and Building Materials*, 230-240, 2016.

[4] S. Jafari, R. Esposito, J.G. Rots, Literature review on the assessment of masonry properties by tests on core samples. *Proc. 4th Int. WTA PhD Symposium,* W. J. Quist, S. J. C. Granneman, & R. P. J. van Hees eds., WTA Nederland – Vlaanderen, 2017, 173-180.

[5] E. Cescatti, M.D Benetta, C. Modena, F. Casarin, Analysis and evaluations of flatjack test on a wide existing masonry buildings sample, *Proc. 16th Int. Brick & Block Masonry Conference*, CRC Press London, UK, 2016, 1485-1491.

[6] L. Binda, C. Tiraboschi, A slightly destructive technique for the diagnosis of brick and stone masonry structures, *Restoration of Buildings and Monuments*, 449-472,1999.

[7] UIC 778-3R: Recommendations for the assessment of the load carrying capacity of the existing masonry and mass-concrete arch bridges. UIC – International Union of Railways. UIC. Paris. 1995.

[8] P.B Lourenço, Two aspects related to the analysis of masonry structures: Size effect and parameter sensibility, Technical report. Delft University of Technology, 1997.