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Publication date
2017

Document Version
Final published version

Published in
Proceedings of the 4th WTA International PhD Symposium

Citation (APA)
Jafari, S., Esposito, R., & Rots, J. (2017). Literature review on the assessment of masonry properties by tests on core samples. In W. J. Quist, S. J. C. Granneman, & R. P. J. van Hees (Eds.), *Proceedings of the 4th WTA International PhD Symposium* (pp. 173-180). WTA Nederland - Vlaanderen.

NEDERLAND-VLAANDEREN

Wetenschappelijk-technische groep voor aanbevelingen inzake bouwrenovatie en monumentenzorg

Proceedings of the 4th WTA International PhD Symposium

13-16 September 2017
Delft, The Netherlands

W.J. Quist, S.J.C. Granneman & R.P.J. van Hees (eds.)

TU Delft

LITERATURE REVIEW ON THE ASSESSMENT OF MASONRY PROPERTIES BY TESTS ON CORE SAMPLES

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KEYWORDS

Core, Unreinforced masonry (URM), Mechanical properties, Slightly-destructive tests, In-situ tests

ABSTRACT

Starting point in this research is to find a quick and non-destructive method to characterize the mechanical properties of existing masonry. Tests on cylindrical cores have been recently introduced as a novel in-situ testing method to identify the properties of existing clay brick masonry. Currently, some researchers reported promising results, showing that the adopted methodology causes minor damage to the structures and it allows a direct estimation of the mechanical properties.

To evaluate the mechanical properties of masonry, cores extracted perpendicular to the surface of a wall are subjected to the splitting tests, by which the compressive and shear properties of the masonry can be estimated. In the first case, previous studies adopted different core configurations (i.e. size and joint pattern) subjected to compressive load. In the second case, cores with only a single bed joint were used. In the literature, the cores were tested in a way that the bed joint was rotated with respect to its original position. Consequently, a mixed compression–shear stress state is induced at the centre of the mortar joint.

As far as the research methodology is concerned, a review of the literature is required. In the first part of this paper, the authors give an overview of available literature regarding compression tests and splitting tests on masonry cores. The correlation established in the literature between the mechanical properties obtained from tests on masonry cores and those standard tests on the companion samples are outlined in this paper. Afterwards, a summary of the adopted methods and drown conclusions are presented. Eventually, on the basis of these literature findings, a research project has been set-up at Delft University of Technology, aiming to establish a quick and non-destructive method to assess the masonry properties. The applicability of the core testing method is investigated for the brick masonry consisting of clay solid brick and general purpose mortar. The preliminary results of the tests on the clay brick masonry replicated in laboratory are reported in this paper.

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INTRODUCTION

Material characterization of existing unreinforced masonry (URM) can be pursued either by performing destructive tests (DT) in laboratory on the extracted samples or by performing slightly-destructive tests (SDT) in-situ. Although the laboratory tests have the advantage of directly providing properties, such as strength, stiffness and stress-strain relationship, these tests are invasive, costly and present technical challenges, when applied for in-situ assessment of mechanical properties. Consequently they can be performed in limited cases. On the contrary, in-situ tests have the advantage of being slightly-destructive and require less time. However, reliability of these test methods is still under investigation.

In alternative to the standardized in-situ techniques, such as double-flat jack [1] and shove tests [2], new slightly-destructive tests on masonry cores are currently under investigation by various researchers [3-9]. These methods aim to determine the compressive and shear properties of the masonry through splitting tests on cores. Similar to other SDT, this methodology seems promising because it allows a direct evaluation of mechanical properties and sampling induces limited damage to the structure. The test allows evaluating the compression and shear properties of masonry.

With the aim of establishing a quickly and slightly-destructively method for the material characterization of masonry, a literature review is presented in this paper concerning the tests on masonry cores. A comparative study of previous research findings is performed with attention to the correlation between the mechanical properties obtained by the tests on the cores and companion destructive tests. As a result, a testing procedure is defined that is being adopted by the authors.

LITERATURE REVIEW

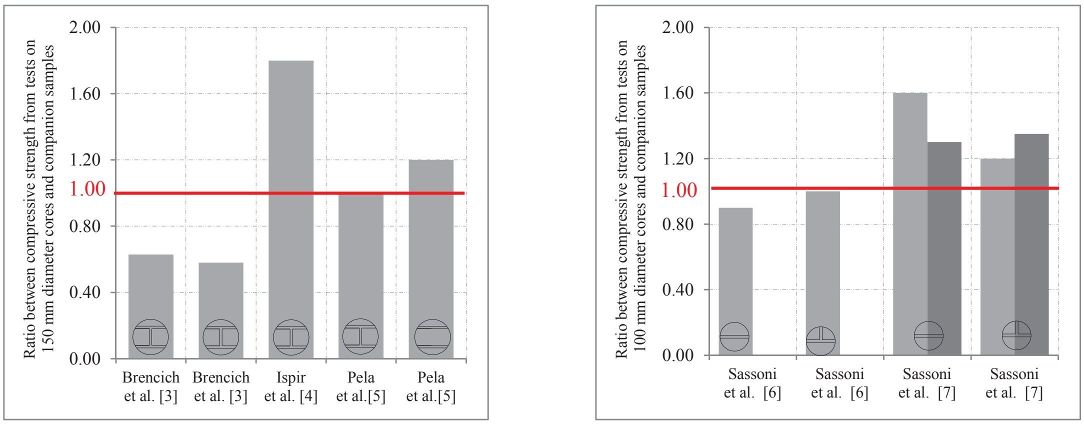
Compression tests on cores

The great potential of using small diameter cores for assessing the compression properties of clay brick masonry has recently been shown by some researchers [3-7]. These researchers adopted companion compression tests on the masonry wallets or stacked-bonded prism to validate the testing method. The correlation between the results of tests on cores and companion samples for the compressive strength and the Young's modulus were investigated.

The International Union of Railway (UIC) [10] proposed a method to perform compression tests on cores with 150 mm in diameter, including two mortar bed joints and a head joint in the centre of the section. The UIC standard suggests conducting a minimum number of three compression tests on each kind of masonry, and preferably six tests if possible. The applicability of using 150 mm and 100 mm diameter cores were investigated for the clay brick masonry in the previous studies [3-7], even though further investigations are still essential in this field.

Brencich et al. [3], Ispir et al. [4] and Pelà et al. [5] adopted the same core geometry as proposed by the UIC. Moreover, Pelà et al. introduced another type of 150 mm in diameter core consisting of only two bed joints. Sassoni et al. [6-7] studied the suitability of using 100 mm diameter cores, which were easier to extract from walls than the ones with 150 mm in diameter. They adopted two types of cores in their studies. The first type included a central bed joint, and the second type included one central bed joint and one head joint.

Figure 1 shows the ratio between the compressive strength obtained from performing tests on the masonry cores and those of companion destructive tests reported in the literature [3-7]. This ratio varies between 0.6 and 1.8 in different studies.



(a) (b)

Figure 1: Ratio between the compressive strength of cores and those of companion samples: (a) tests on cores with150 mm in diameter; (b) tests on cores with100 mm in diameter.

A ratio between results of tests on masonry cores and those of the companion samples was reported less than 1 by Brencich et al. [3]. This ratio deviates from the values reported in other studies. As reported by Brencich et al. [3] a concave metal was used during loading as recommended by the UIC. One reason for this outlier ratio might be explained by the stress concentration produced by imperfect contact between the steel cradles and the specimen. Instead of using steel cradles, Pelà et al. [5] and Sassoni et al. [6-7] suggested performing tests on the cores with casted high-strength mortar on their top and bottom. An acceptable correspondence between the results of core samples and companion samples were reported by them. The masonry cores completed with high-strength mortar to resemble the situation in a real wall, where the confinement effect is experienced. In addition, an optimum bond between the specimen and the high-strength mortar can be expected. Consequently, performing test on the masonry cores with casted high-strength mortar on their top and bottom is suggested.

A very high ratio of 1.8 was reported by Ispir et al. [4] between the compressive strength of core samples and those of companion samples. Since limited information was provided by them, no conclusions can be drawn. Accordingly, the results of the studies carried out by Brencich et al. [3] and Ispir et al. [4] are excluded from the current study, since the authors of the current study are uncertain about the reliability of those testing procedure.

Core geometries, both with head joint and without head joint, were investigated by Pelà et al. [5] and Sassoni et al. [6-7] to study influence of the vertical joint on the test results. From their studies, it was concluded that the collapse mechanisms in the masonry cores without head joint deviates from those of masonry companion samples subjected to compressive tests. However, numerical modelling is essential to further study the influence of head joint. It might be expected that in the absence of head joint, the compressive strength of masonry can be overestimated, particularly, in the case of masonry with weak mortar and strong brick. Therefore, to gain deeper insight into the behaviour of masonry, cores with head joint are preferable to cores without head joint.

It is worth noting that a stack-bonded prism without head joint was adopted as companion sample by Pelà et al. [5]. Thus, it might be expected that the obtained results from companion samples are more comparable with those of cores without head joint. Consequently, it is suggested to adopt masonry wallets as a companion sample.

Comparing the results obtained by Pelà et al. [5] and Sassoni et al. [6-7] from tests on cores with different diameters, it can be concluded that both 100 mm and 150 mm diameter cores are able to adequately represent the compressive strength of masonry.

The ratio between the Young's modulus obtained from performing tests on the masonry cores and those of companion destructive tests reported in the literature is shown in Figure 2. The applicability of tests on core samples to evaluate the Young's modulus was investigated in the literature only for cores with 150 mm in diameter. This ratio varies between 0.3 and 1.3 in different studies. As mentioned earlier, the outlier results provided by Brencich et al. [3] and Ispir et al. [4] are excluded in this study. As shown in Figure 2, an acceptable correspondence was reported by Pelà et al. [5] for both types of cores (with and without head joint).

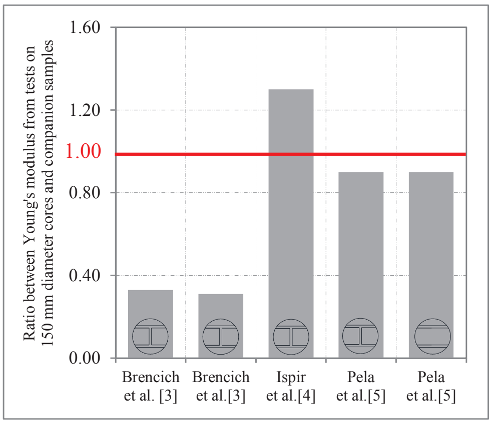


Figure 2: Ratios between the Yong's modulus of cores and those of companion samples for cores with 150 mm in diameter.

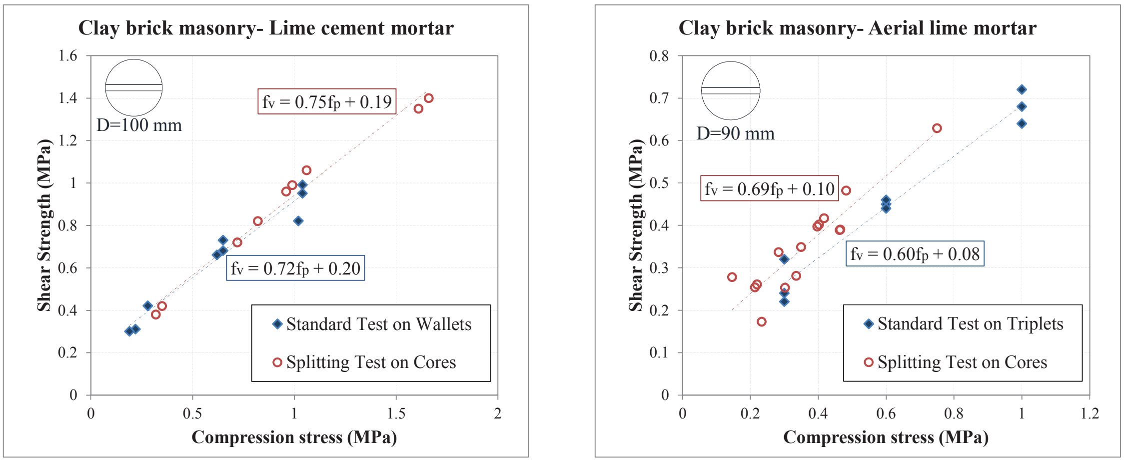
Splitting tests on cores for the determination of shear properties

Performing splitting tests on masonry cores was firstly introduced by Benedetti et al. [11], to investigate the properties of mortar. Subsequently, this type of test was improved as a technique to study the shear properties of mortar interface. However, very limited information was reported in the literature about the evaluation of shear properties of masonry by using this technique [8-9].

In order to determine the shear properties of the brick-mortar interface, cores with only a single bed joint were subjected to splitting tests while they were inclined with respect to horizontal reference. A mixed compression–shear stress state was induced at the centre of the mortar joint. Then, the shear stress and compression stress states could be derived, respectively, by projecting the failure stress in the parallel and orthogonal directions with respect to the rotated mortar layer. By employing Coulomb friction criterion the initial shear strength and coefficient of friction was determined.

Apart from splitting tests on the masonry cores, Mazzotti et al. [8] and Pelà et al. [9] conducted shear-compression tests on the companion samples. The masonry wallets and masonry triplets were adopted as companion samples by Mazzotti et al. [8] and Pelà et al. [9], respectively. Tests on the companion samples were performed according to relevant standards [12-13]. As shown in Figure 3, an acceptable correspondence between the results obtained from splitting tests on cores and from standard shear tests on the companion samples was observed. The applicability of cores with 100 mm and 90 mm in diameter was investigated in their research.

Different modes of failure were reported in the previous studies. The inclination angle of the mortar layer was found as a decisive factor in formation of the mode of failure. The observed different modes of failure at different mortar layer inclinations were reported as follows: (a) splitting of the cores, (b) mix of splitting and sliding along the mortar-brick interface and (c) sliding along the mortar-brick interface. For the masonry cores tested according to an inclination of 40°, 45° and 50°, the predominant observed failure mode was sliding along the brick-mortar interface. While the masonry cores that were tested at mortar layer inclinations of less than 40° and higher than 60° showed splitting and brick wedge detachment, respectively. Therefore, those results obtained from performing tests on masonry cores at mortar layer inclination between 40° and 50° were used to determine the shear properties, since sliding along the brick-mortar interface was dominant failure mode.



(a) (b)

Figure 3: Comparison between the results obtained from standard shear tests on the companion samples and splitting tests on the masonry cores with: (a) 100 mm in diameter [8]; (b) 90 mm in diameter [9].

EXPERIMENTAL PROGRAM

Quick and less-destructive characterization of the mechanical properties of masonry is the ambitious target of the authors. Accordingly, a testing program was defined at Delft university of technology (TU Delft) aiming at investigating the applicability of new proposed slightly-destructive tests on the masonry cores and standardized in-situ techniques (i.e. double flat jack tests and shove tests) to obtain the mechanical properties of masonry. Moreover, the applicability of non-destructive tests such as Schmidt hammer test and ultrasonic tests are being investigated in the scope of the mentioned program. However, the current paper only deals with the testing program dedicated to perform tests on the masonry cores.

The lack of testing procedure to characterize the masonry properties by performing tests on the cores is evident in the literature. In order to pursue the correlation between the results of tests on masonry cores and companion samples, a summary of the adopted methods and drawn conclusions presented in the previous sections are compiled to define and develop a testing program.

Pursing the correlation objectives, experiments on masonry cores and companion samples are being performed on the clay brick masonry specimens replicated at TU Delft laboratory. If possible, adopting a dry-extraction procedure is recommended, which could not affect the integrity of the mortar. Tests on the masonry cores are being performed according to the testing program briefed in this section.

The accuracy of the obtained properties from tests on cores can be confirmed by comparing them with the properties obtained from performing standard tests on the companion samples. The compression tests on the masonry wallets are carried out according to the standard EN 1052-1 [14], and shear-compression tests on triplets are performed following the standard EN1052-3 [12] prescriptions.

Compression tests

The applicability of 100 mm diameter cores with one central bed joint and one head joint as well as 150 mm diameter cores with two bed joints and one central head joint are being investigated within this study. Two samples for each type of core were tested. 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. The compression load was applied by a hydraulic jack operated in displacement-control, using the displacement of the jack as control variable. The sample was instrumented by linear variable differential transformers (LVDT), allowed measuring deformations along the vertical axis of symmetry, horizontal axis of symmetry and 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. [5]. In Figure 4 , $f_{m,c1}$ and $E_{m,c1}$ refer to the compressive strength and the Young's modulus obtained considering the cross-section of the cores and $f_{m,c2}$ and $E_{m,c2}$ are calculated considering the cross-section of the regularization cap. The ratio between compression properties of core samples and masonry wallets (companion samples) in terms of compressive strength and Young's modulus is shown in Figure 4. As it can be seen, this ratio for the compressive strength varies between 0.69 and 1.00; and for the Young's modulus varies between 0.44 and 0.82. As mentioned earlier, to this point only four core specimens were tested, while more tests are being performed.

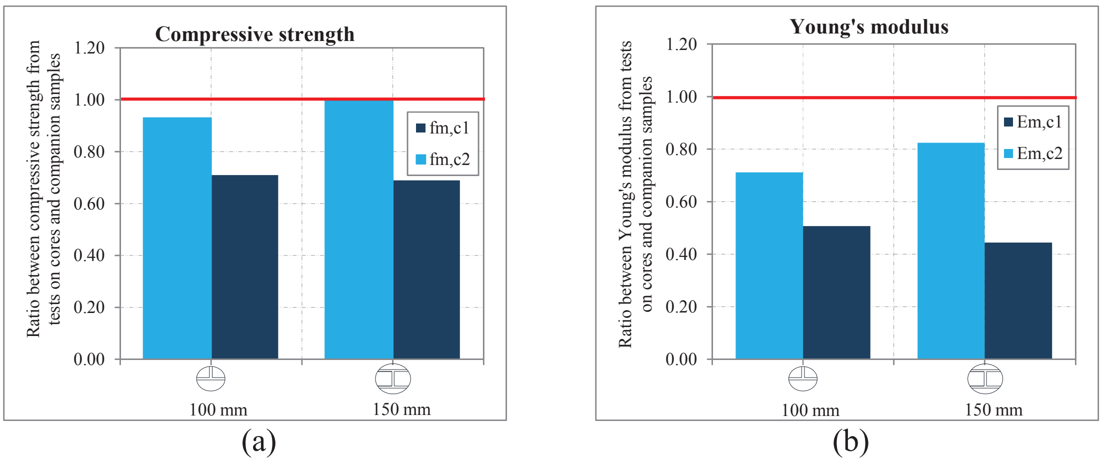
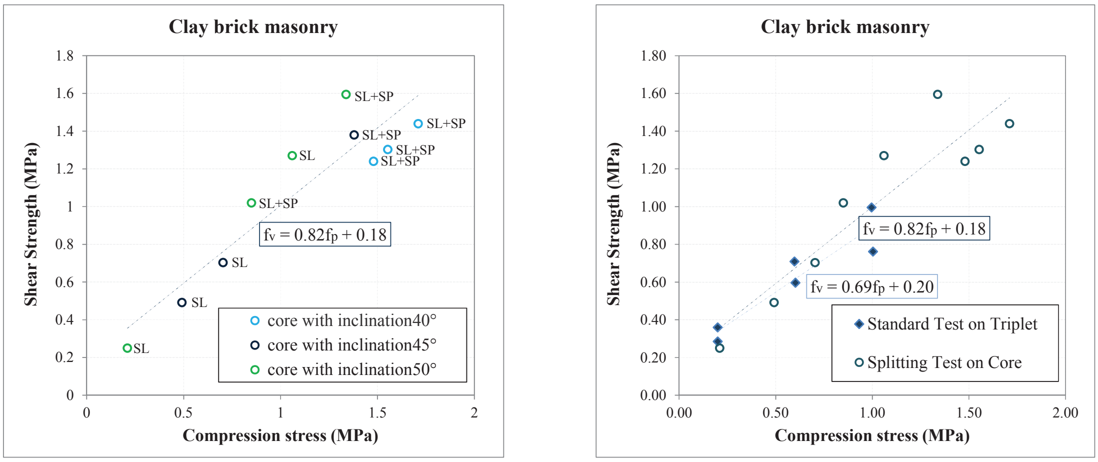


Figure 4: Ratio between the compressive strength of cores and those of companion samples: (a) compressive strength; (b) Young's modulus.

Splitting test

As investigated in previous studies, masonry cores subjected to splitting load were able to reproduce the masonry shear properties in terms of initial shear strength and coefficient of friction. As a result, in the current research program masonry cores with one central bed joint are being subjected to the splitting tests with mortar layer inclinations of 40°, 45°and 50° with respect to its original position. The splitting load is applied by a hydraulic jack operated in displacement-control, using the displacement of the jack as control variable. Two wood strips are inserted between the loading platens and the sample. The relative sliding displacement between the two bricks is measured using one LVDT on each face. Figure 5(a) shows the results of splitting tests on the samples for the three different inclinations. During the tests on cores two failure mechanisms were observed: sliding at the interface and splitting of the brick near the constraints (SL+SP) or sliding along the mortar-brick interface (SL). Comparing the shear properties obtained from tests on the cores and standard test on triplet, see Figure 5(b), an acceptable agreement in terms of initial shear strength is established. However, the coefficient of friction evaluated with the core tests is 20% higher than the one estimated with the triplet tests. More tests are still being performed, therefore, the obtained results should be considered as preliminary.



(a) (b)

Figure 5: Splitting tests on the core samples: (a) indicating the observed failure mode; (b) comparison between results of cores and those results obtained from standard tests on triplets.

CONCLUDING REMARKS AND FUTURE WORK

The suitability of using cores to assess the compression and shear properties of masonry was investigated by few authors. It was concluded that tests on the masonry cores seem promising, since an acceptable correspondence between test results was reported in the literature.

The ambitious target set by the authors of this paper is to supersede the standard destructive tests with a quick and slightly-destructive method. Following the purpose of this research, a testing program was developed at TU Delft. The efficiency of tests on cores to evaluate the compression and shear properties of masonry is being investigated in this program. The compression and splitting tests on the masonry cores are conducted based on the procedure described in this paper; and standard tests are performed in agreement with relevant standards. Finally, a comparison between the compression properties (both compressive strength and the Young’s modulus) and the shear properties (both initial shear strength and coefficient of friction) is reported. The ratio between the results of cores and those of companion samples for the compressive strength varies between 0.69 and 1.00; and for the Young’s modulus varies between 0.44 and 0.82. By comparing the shear properties obtained from tests on the cores and those of standard tests on triplet, an acceptable agreement in terms of initial shear strength is established. However, the coefficient of friction evaluated with the core tests is 20% higher than the one estimated with the triplet tests. It is worth noting that the obtained results should be considered as preliminary, due to the limited number of the samples tested. To draw a final conclusion, more tests are still being performed on the masonry cores.

ACKNODWLEDGMENT

This research was funded by Nederlandse Aardolie Maatschappij B.V. (NAM) under contract number UI46268 "Physical testing and modelling – Masonry structures Groningen" as part of the NAM Hazard & Risk program, and 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.

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COMPUTATIONAL MODELING OF THE CYCLIC PUSHOVER TEST ON A CALCIUM SILICATE ELEMENT MASONRY ASSEMBLAGE

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KEYWORDS

Calcium Silicate Elements, Masonry, Finite Element Modelling

ABSTRACT

Induced seismicity in the Groningen region of the Netherlands has led to a large scale testing campaign on Calcium silicate element masonry structures at Delft University of Technology. An overview of the finite element analysis (FEA) using an implicit solver, on the full scale quasi-static cyclic pushover test performed on a two-storey calcium silicate element masonry assemblage is presented in this paper. Tests have been performed in the experimental campaign at material, component, and structural level, of which the material tests like bond wrench tests, compression tests and shear tests are also briefed in this paper.

The pushover case study has been modelled using a total strain based rotating crack modelling approach for the Calcium silicate masonry and a discrete cracking / coulomb friction model along the connections in the assemblage. The material parameters used in the FEA for the pushover case study are obtained from the aforementioned material level tests. In this study, monotonic analyses are performed along both directions of the cyclic loading and the loading protocol is simulated using a displacement controlled approach. Comparisons are made with the experiment in terms of force-displacement curve, crack pattern and drift ratios.

The use of an implicit solver for quasi-brittle materials comes with convergence issues, and these have been elucidated in this study. If material parameters calibrated on the basis of the material tests are used, a significant overestimation of the capacity in both loading direction of the test is found. Therefore, there is need for better correlation between material level tests and the behavior observed at the structural level to understand the true behavior of the masonry. The computed maximum displacements have been severely under predicted in both directions reiterating the need for most robust solution procedures to realize global softening behavior in masonry structures.

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