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Publication date
2018

Document Version
Final published version

Citation (APA)
Jafari, S., Ferretti, F., & Esposito, R. (2018). *Flatjack and shove tests: method validation and correlation*. Delft University of Technology.

Project number	C31B67
File reference	C31B67WP1-15
Date	February 28, 2018
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TU Delft Large-Scale Testing Campaign 2016

FLATJACK AND SHOVE TESTS: METHOD VALIDATION AND CORRELATION

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***Cite as**: Jafari, S.,* Ferretti, F., *Esposito, R. Flat-jack and shove tests: method validation and correlation. Report No. C31B67WP1-15, 28 February 2018. Delft University of Technology.*

This research work was funded by NAM Structural Upgrading stream.

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1 Introduction

Material characterisation of existing masonry can be pursued either by performing tests in laboratory on the samples extracted from masonry buildings or by performing in-situ tests. Although the laboratory tests have the advantage of directly providing properties; such as strength, stiffness and stress-strain relationship, technical challenges as well as devastating sampling method put severe constraints on this method. On the contrary, in-situ testing techniques have the advantage of being performed on undisturbed samples and requiring less time; however, the accuracy of the obtained results is a matter of uncertainty. As it was puzzled in the experimental campaign of 2015 ([1]-[2]), a clear correlation has not been established between the result of standardised in-situ test methods (double flatjack test [4] and shove test [5]) and standardised laboratory tests (compression tests [6] and shear-compression on wallets [7]). Therefore, an experimental study was conducted, within the "NAM Structural Upgrading Project" developed at TU Delft in 2016/2017. The aim is to validate the suitability of the in-situ methods to evaluate the properties of masonry as well as to investigate the correlations between the results of in-situ and laboratory testing methods. To this end, the experimental study was conducted on masonry samples replicated and tested in a controlled laboratory environment.

The majority of the existing unreinforced masonry structures in the seismic region of the Groningen was only built and designed to resist against gravity load. The safety level of these structures can be assessed using structural analysis. As a result, the mechanical properties of masonry are required to be implemented as an input for both numerical and analytical solutions. The mechanical properties of the existing masonry can be evaluated either by performing laboratory tests on reduced-scale samples or using in-situ testing techniques. In order to determine the characteristics of masonry structures in-situ, a new testing method was introduced by Rossi in 1982 [8]. Using this technique, in which different tests are performed, the stress-state of masonry, the compression properties and the shear-sliding properties of the brick-mortar interface are evaluated, while the integrity of the wall is being slightly altered. The control of the stress-state in the wall is essential, when repair and rehabilitation of structures are operated. The masonry properties that can be retrieved using the mentioned in-situ testing method are listed in Table 1.

In this report, the suitability of the in-situ slightly-destructive testing (SDT) methods for the characterisation of masonry material properties is investigated, as the obtained results were validated against the results of destructive test (DT) performed on companion samples. Following the prescriptions of the ASTM standards and the guidance of EUCentre [9], the SDTs were performed on three different locations of one calcium silicate (CS) brick masonry wall. It is worth noting that during the prequalification of the companies (WP1a), practical knowledge was transferred to TUDelft, which enabled to carefully design the testing set-ups. The designed testing set-ups allowed continuous measuring of the wall's deformations during each testing phase, aiming to provide more insight into the compressive-shear behaviour of the tested masonry.

The materials used for the constructions of the wall and of the companion samples subjected to destructive test (DT) are characterised in Section 3. Section 4 describes the testing procedure for the in-situ slightly-destructive testing (SDT) methods. The results of the single flatjack, the double flatjack and the shove test are provided in Section 5. Correlation between the results of the standardised DTs performed on the companion samples and the ones obtained from the in-situ SDTs is discussed in Section 6. Concluding remarks are presented in Section 7.

Table 1 – In-situ test for the characterisation of masonry properties.

Type of test	**Material property**
Single flatjack	Stress state in the masonry wall
Double flatjack	Stress-strain relationship in compression Young's modulus of masonry
Shove test	Initial and residual shear strength Shear stress vs. shear displacement relationship (pre- and post-peak)

2 Nomenclature

2.1 Symbols

This report adopts mainly the nomenclature used in Eurocode 6 [10] and the ones introduced by ASTM standards ([3]-[5]). In addition, symbols used in the codes for testing are adopted.

ν	Poisson ratio of masonry
l_m	Length of the mortar specimen
l_s	Length of the masonry specimen as built
l_p	Length of the loading plate for compression tests on mortar specimens
l_u	Length of the masonry unit as used in the construction of masonry
h_m	Height of the mortar specimen
h_u	Height of the masonry unit as used in the construction
t_m	Thickness of the mortar specimen
t_u	Thickness of the masonry unit as used in the construction of masonry
μ	Masonry (bed joint) coefficient of friction
μ_{res}	Masonry (bed joint) residual coefficient of friction
f_m	Compressive strength of masonry mortar
f_{mt}	Flexural strength of masonry mortar
$f_m^{'}$	Compressive strength of masonry in the direction perpendicular to the bed joints
A_s	Cross sectional area of the specimen parallel to the bed joints (shear test)
E_1	Secant elastic modulus of masonry subject to a compressive loading perpendicular to the bed joints, evaluated at 1/3 of the maximum stress
E_2	Secant elastic modulus of masonry subject to a compressive loading perpendicular to the bed joints, evaluated at 1/10 of the maximum stress
E_3	Chord elastic modulus of masonry subject to a compressive loading perpendicular to the bed joints, evaluated at between 1/10 and 1/3 of the maximum stress
$f_{m,SFJ}$	Compressive stress in the masonry measured during single flatjack test
K_m	Dimensionless contact that reflects the geometrical and stiffness properties of the flatjack
K_a	Ratio between the effective area of the flatjack and the average measured area of the slot
p	Flatjack pressure
$f_{m,DFJ}$	Compressive stress in the masonry measured during double flatjack test
E_{DFJ}	Chord modulus calculated from double flatjack test
E^*_{DFJ}	Fictitious chord modulus calculated from double flatjack test in the shove test configuration
$\delta f_{m,DFJ}$	Increment of stress during double flatjack test
$\delta \varepsilon_{m,DFJ}$	Increment of strain during double flatjack test
D	Horizontal displacement of test unit at each horizontal load step during shove test
d_{i-1}^{hor}	Horizontal displacement at the i-th load increment during shove test
τ	Average mortar joint shear strength

τ_0	Initial shear strength (cohesion)
F_{hor}	Shear force corresponds to the sliding of the test unit at i-th load increment during shove test
σ_j	Normal compressive stress applied by flatjack
σ_{bj}	Normal compressive stress on the test unit due to the flatjack pressure
σ_b	Normal compressive stress on the test unit due to the far-field effects
k_{bj}	Jack to brick correction factor
τ_{res}	Masonry (bed joint) residual shear strength
σ_b^*	Contribution to the normal compressive stress in the test unit due to the far field effect

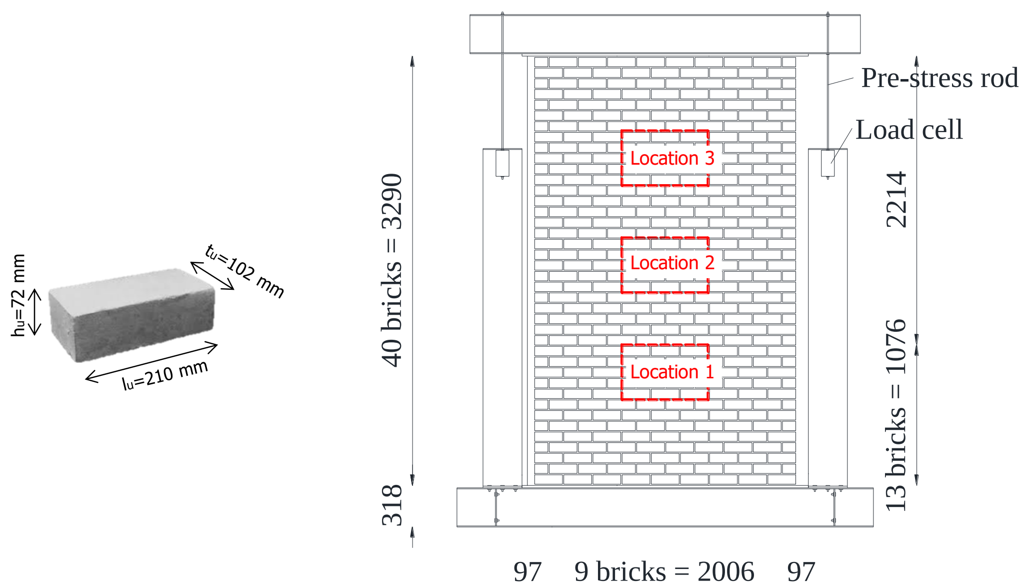
2.2 Abbreviations

Avg.	Average
C.o.V.	Coefficient of variation
St. dev.	Standard deviation
CS	Calcium silicate
LVDT	Linear variable differential transformer
DT	Destructive test
SDT	Slightly-destructive test

3 Materials and methods

The masonry walls to be used for the in-situ test as well as the companion samples to be subjected to standardised laboratory tests were constructed in the same period by employing the same materials. The specimens were built in the Stevin II laboratory at Delft University of Technology [11]. The samples were made of calcium silicate bricks and cement based mortar, with joint thickness of 10 mm. The declarations of performance of the materials are reported in Appendix A. The compression and bending properties of masonry constituents are summarised in Section 3.1 and 3.2.

Figure 1 shows the adopted masonry unit and the dimensions of the full-scale wall adopted for the in-situ tests. The in-situ tests were performed over three different locations of the replicated CS masonry wall (see Figure 1b). The tests were performed in the lowest location of the wall toward the highest one, in a sequence. In each location, the single flatjack, the double flatjack and the shove tests were performed sequentially. Before performing the test on the other locations, the masonry portion subjected to the tests was repaired using high-strength mortar.
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 actual stress state in the wall was calculated considering the overburden applied by the pre-stressed bars, weight of the masonry portion above the slot and the weight of the top beam. 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 single flatjack test was performed. 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. An overview of the overburden for each testing location is listed in Table 2.



(a) (b)

Figure 1 – Geometry of calcium silicate wall adopted for in-situ test technique and testing locations.

Table 2 – Overburden pressures at each testing location.

Location No.	Stress due to weight of steel beam	Stress due to self-weight of masonry	Stress due to pre-stressing of the rods	Stress-state in the top slot
	MPa	MPa	MPa	MPa
Location 01	0.016	0.038	0.546	0.60
Location 02	0.016	0.031	0.203	0.25
Location 03	0.016	0.010	0.124	0.15

3.1 Properties of mortar

During the masonry construction, mortar samples were collected and cast in moulds to be tested for the flexural and compressive strength in agreement with EN 1015-11:1999 [13]. At least three mortar specimens having a length of l_m = 160 mm, a height of h_m = 40 mm and thickness of t_m = 40 mm were collected. The samples were stored in controlled conditions. The first two days they were placed in a fog room (T = 20 ± 2 °C, RH = 95 ± 5%) with the moulds. After two days, they were unmoulded and kept for other five days in the fog room. Eventually, they were placed in a conditioning room with a temperature of 20 ± 2 °C and a relative humidity of 50 ± 5 % until testing. The test was performed after at least 28 days from construction.

The flexural strength was determined by three-point bending test. The test set-up is composed by two steel bearing rollers having a diameter of 10 ± 0.5 mm and spaced d_1 = 100 ± 0.5 mm. A third roller is centrally placed on top of the sample to apply the load. The compression test was performed on the broken pieces obtained from the flexural test, which have at least a length of 40 mm. The specimen is placed between two steel plates with a length of l_p = 40 mm. For the interpretation of the results the specimens were considered to be 40x40x40 mm. For both tests, the load was applied without shock at a uniform rate so that failure occurred within a period of 30 to 90 s. The maximum load was recorded. The flexural strength and compressive strength of the mortar used for the construction of calcium silicate brick masonry are listed in Table 3. More information regarding the test set-up and testing procedure can be found in Ref. [12].

Table 3 – Flexural and compressive strength of mortar.

Masonry type	Flexural tests				Compression test			
	No. test	f_{mt}	St. dev.	C.o.V.	No. test	f_m	St. dev.	C.o.V.
		MPa	MPa			MPa	MPa	
CS brick masonry	75	3.21	0.18	0.05	150	7.57	0.46	0.06

3.2 Properties of brick

The normalised compressive strength of a masonry unit (brick) is determined in agreement with EN 772-1:2000 [14]. To estimate the brick compressive strength a single masonry unit, having a length l_u = 210 mm, a height h_u = 72 mm and thickness t_u = 102 mm, was subjected to compression load.

The flexure strength of the masonry unit was determined with the three-point bending test following NEN 6790:2005 [15]. The single masonry units were tested with the bed joint plane parallel to the loading direction. The specimen was supported by two roller bearings, which were placed 10 mm away from the end of the specimen. A third roller was used to apply load to the specimen at mid-span.
A summary of the compression and of the bending properties of calcium silicate bricks are listed in Table 4. More information regarding the test set-up and testing procedure can be found in Ref. [12].

Table 4 – Flexural strength and normalised compressive strength of masonry unit.

Masonry type	Flexural tests				Compression test			
	No. test	f_{bt}	St. dev.	C.o.V.	No. test	f_b	St. dev.	C.o.V.
		MPa	MPa			MPa	MPa	
CS brick	6	2.74	0.16	0.06	6	13.26	1.71	0.13

4 Testing procedure

The in-situ tests were performed following the prescriptions of ASTM Standards ([3]-[5]) as well as using the testing protocol of EUCentre formulated in the previous campaigns [9]. For each location of the wall, first the single flatjack test was performed; then, the test was continued by performing of the double flatjack test; finally, the shove test was executed. In this testing campaign, rectangular flatjacks were adopted having dimensions of 400x100x4-mm. Note that the flatjacks were purchased from Italy and calibrated by University of Genoa (see Appendix B).

Prior to testing, the masonry wall was pre-compressed via pre-stressed rods placed between the top steel beam and the steel column. The overburden load was adopted in a way to investigate the applicability of this technique even for the case of masonry wall with a very low level of stress state (0.15 MPa) and a high level of stress state (0.6 MPa).

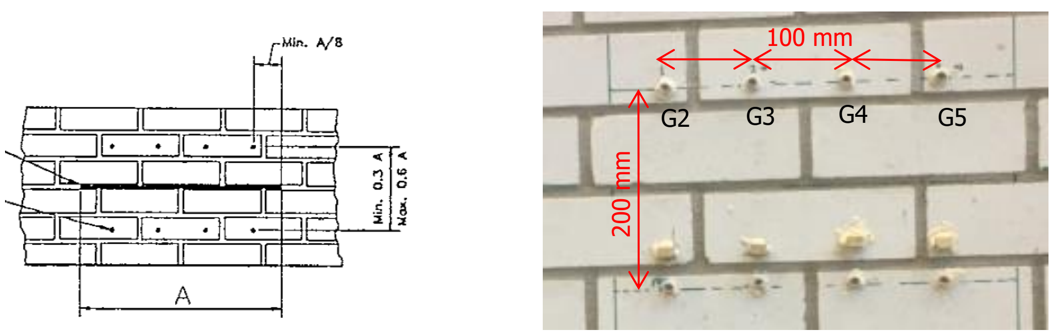
4.1 Single flatjack test

The average compressive stress in existing unreinforced *solid-unit* masonry is determined in agreement with ASTM C1196-14a [3]. When a slot is formed in a masonry bed joint, compressive stress at that point will cause the masonry portion above and below the slot to move together. If reference points are positioned above and below the slot, compressive stress in the masonry may be measured by inserting a flatjack into the slot and increasing its internal pressure until the original distance between these reference points is restored.

The testing procedure, according to ASTM C1196-14a [3], can be summarised as follows:

i. The location at which the compressive stress estimates are performed is dictated by engineering objectives. The basic arrangement, as suggested by ASTM C1196-14a, is illustrated in Figure 2.
ii. The location and length of slot to be formed should be selected and marked, prior to testing.
iii. Attach at least four pairs of equally spaced gauge points, aligned vertically above and below the slot (Figure 2). Each row of gauge points (above and below the slot to be formed) must have the same distance from the slot. The following requirements apply:
    (a) Minimum gauge length : 0.3·A (A: length of flatjack, Figure 2a),
    (b) Maximum gauge length: 0.6·A.
    (c) Position of the first and last gauge point: at least at 1/8 of the length A, inward toward the centre of the slot from each end (Figure 2a).

    The rectangular flatjack used in the current study has a length of 400 mm (A = 400 mm). To fulfil the testing requirements, the distance between the gauge points was chosen as 100 mm (see Figure 2b).



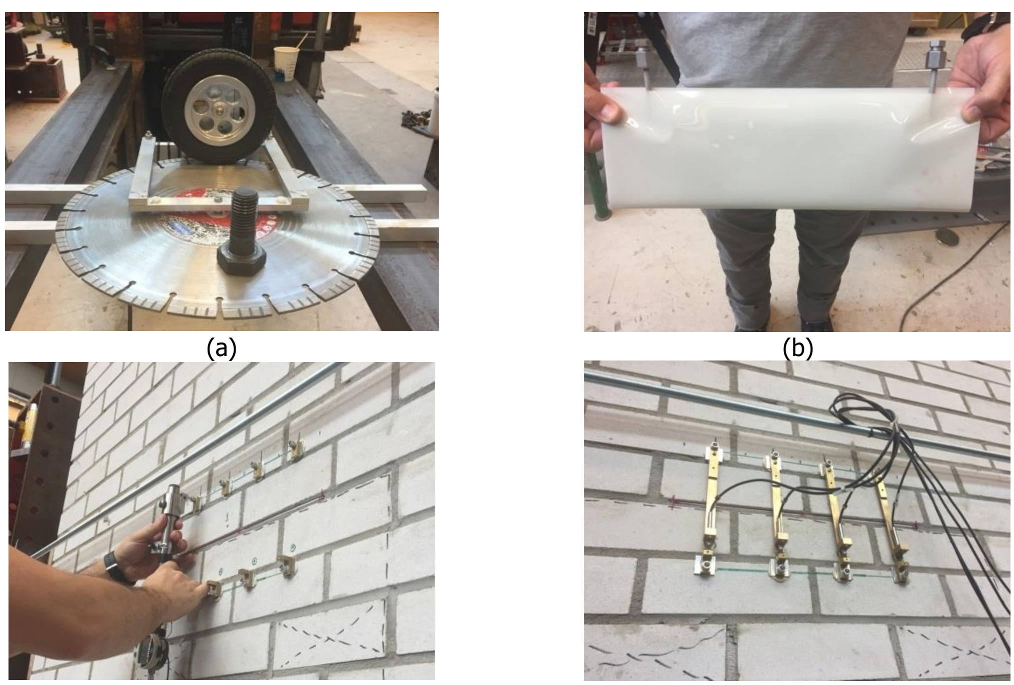
(a) (b)

Figure 2 – Flatjack test set-up (Fig.2 ASTM C1196-14).

iv. Measure the initial distance between each couple of gauge points, at the undamaged masonry condition.
v. Prepare the slot and record the measured slot dimensions. It should be noted that a circular sawing machine was designed and developed at TU Delft which allows cutting a slot as thin as possible (see Figure 3a).
vi. Clean the slot, now formed, from mortar particles.
vii. Measure again the gauge point distance, after the slot has been prepared, in order to obtain the initial deviation from the original gauge distance.

viii. Insert the flatjack into the slot. Shim is required to achieve a tight fit and bridge over any interior voids in the masonry.
ix. To identify the effective area of the flatjack, pressure measurements film was used. It was wrapped around the flatjack prior to inserting the flatjack (see Figure 3b).
x. Connect hydraulic hoses and fill the calibrated flatjack, until the pressure begins to increase, with the hydraulic fluid.
xi. Increase the pressure till about 50% of the estimated maximum flatjack pressure (which corresponds to the estimated compressive stress in the wall). Reduce the pressure in the flatjack to zero. This is done in order to "seat" better the flatjack and any shims in the slot.
xii. Increase pressure in the flatjack to 25%, 50%, 75% of the estimated maximum pressure, and hold the pressure constant at each level. Measure and record the distance between each pair of gauge points, at each load increment. It is necessary to repeat each measure three times. It is recommended to conduct the test as soon as possible, after formation of the slot: the time taken for the load application should be approximately equal to the time elapsed since formation of the slot to minimize the effect of creep deformation.
xiii. Continue increasing the flatjack pressure until the original gauge distances are restored.
The allowable average deviation from the original gauge length: greater of ± 0.013 mm, or 1/20 of the maximum initial deviation, with no single deviation exceeding: greater of± 0.025 mm or 1/10 of the maximum deviation. Tests in which these limits are exceeded shall be considered invalid. Record the final pressure in the flatjack.
xiv. Reduce the pressure in the flatjack to zero.
xv. It is recommended to repeat the points xi) and xii) in order to verify the final flatjack pressure.
xvi. Disconnect hoses and remove the flatjack. The slot must be filled with fastening mortar.

In the current study, the distance between the gauge points before making the slot and after that was measured using a manual instrument with precision of 0.0001 mm (see Figure 3c). However, the variation of deformation caused by the increase of pressure in the flatjack was monitored using LVDTs as well (Figure 3d). This was done following the procedure suggested by P&P/Eucentre: “Install 4 LVDTs (precision 0.001 mm) connecting each vertical couple of gauge points to monitor the vertical relative displacement of the couple of points. In this case a proper self-centring screw should be used. This system should be easily tested removing and attaching several times the LVDTs, while the error should be less than 0.005 mm”.



(a) (b)

(c) (d)

Figure 3 – Testing procedure of the single flatjack test: (a) circular sawing machine; (b) pressure measurements film; (c) manual measurements of the initial distance between gauge points; (d) LVDTs arrangement.

The state of compressive stress in the masonry is approximately equal to the flatjack pressure multiplied by factors which account for: (i) the physical characteristics of the flatjack and; (ii) the ratio of the bearing area of the jack in contact with the masonry to the area of the slot. The average compressive stress in masonry is calculated as follows:

$$f_{m,SFJ} = K_m K_a p \quad (1)$$

Where:
K_m = a dimensionless constant which reflects the geometrical and stiffness properties of the flatjack,
K_a = the ratio of measured area of the flatjack to the average measured area of the slot,
p = flatjack pressure required to restore the gauge points to the distance initially measured between them within the tolerance allowed (psi or MPa).

As reported by Binda et al. [16], the effective area of the flatjack was reported to be lower than the nominal area of the flatjack due to imperfections or unevenness of the surfaces inside the slot. To measure the effective area of the flatjack in the current study, sensitive pressure paper was used to enclose the flatjack prior to its installation in the slot. The effective area of the flatjack was retrieved calculating the area of the sensitive pressure paper marked in places of contact. It was observed that the effective area of the flatjack was lower than the nominal one.

4.2 Double flatjack test

The deformation properties of existing unreinforced solid-unit masonry, including stress and Young's modulus, can be determined in agreement with ASTM C1197-14a [4]. A portion of masonry wall is subjected to a compressive stress state by means of two flatjacks placed at the extremities of the masonry portion. By gradually increasing the flatjack pressure and continuous measuring of deformation of the masonry between the two flatjacks, load-deformation (stress-strain) properties could be obtained. This test allows evaluating the elastic modulus of masonry.
The test procedure is summarised as follows:

i. Define the location and mark the length of the slots. The slots should be located at least 1.5 times the flatjack length with respect to wall opening or ends.
ii. Prepare the slots and record their dimensions and positions. The slots should be separated by at least five courses of masonry, but not more than 1.5 times the flatjack length. Clean the slots from mortar and bricks particles.
iii. Attach at least three LVDTs in vertical direction, equally spaced. The LVDTs must be perpendicular to the slots, and they must have at least a gauge length of 20 cm. The LVDTs must be attached to the unit blocks of masonry, and not on the mortar joints.
    The following requirements apply concerning the position of the first and last measurement points [4]: at least at 1/8 of the length A (A: length of flatjack) from the ends of the slot.
    In the experimental campaign, 4 LVDTs were adopted (Figure 4). An additional horizontal LVDT was placed within the tested masonry portion, equally distant to the two slots.
iv. Insert the flatjacks into the slots.
v. Connect hydraulic hoses and fill the calibrated flatjack, until the pressure begins to increase, with the hydraulic fluid.
vi. Increase the pressure till about 50% of the estimated maximum flatjack pressure (which corresponds to the estimated compressive stress in the wall). Reduce the pressure in the flatjacks to zero. This is done in order to "seat" better the flatjacks in the slots.
vii. Take initial measurements.
viii. Increase the pressure in the flatjacks slowly. Record the LVDT measurements at each increment of pressure. Monitor the flatjack pressure - masonry deformation ratio, at each increment of pressure. If failure of the masonry between the flatjacks is not desired, the test should stop when the ratio begins to notably decrease.
ix. Release pressure in the flatjack, after the final measurement has been taken.
x. Disconnect hoses and remove the flatjack. The slots should be filled with hard fastened mortar.

The stress in the masonry between the flatjacks at any point in the pressurization process is calculated as:

$$f_{m,DFJ} = K_m K_a p \tag{2}$$

where:
K_m = a dimensionless constant which reflects the geometrical and stiffness properties of the flatjack,
K_a = the ratio of measured area of the flatjack to the average measured area of the slot,
p = flatjack pressure required to restore the gauge points to the distance initially measured between them within the tolerance allowed, psi or MPa.

The chord modulus at any stress interval is calculated by:

$$E_{DFJ} = \frac{\delta f_{m,DFJ}}{\delta \varepsilon_{m,DFJ}} \tag{3}$$

$\delta f_{m,DFJ}$ = an increment of stress,
$\delta \varepsilon_{m,DFJ}$= the corresponding increment of strain.

In the current campaign, apart from the measurements obtained during the testing phase, the deformation of the masonry portion during the preparation phase was measured. This was done to gain a better understanding regarding the distribution of the pressure, when the bottom slot was made. Note that the top slot was made during the single flatjack test to measure the stress state in the wall.

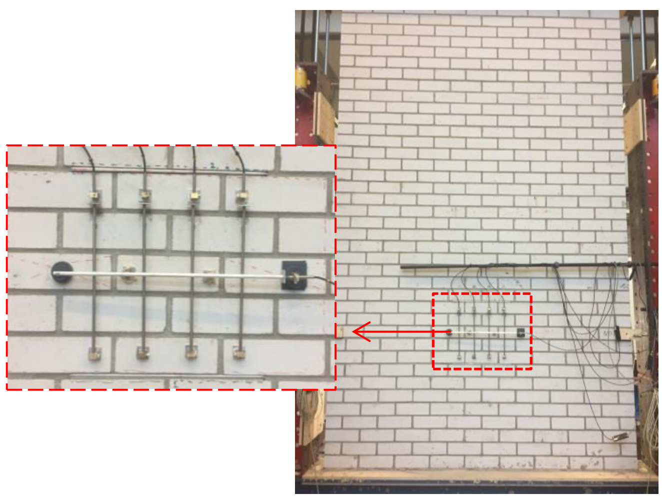


Figure 4 – Double flatjack test set-up.

4.3 Shove test

The average in-situ horizontal mortar joint shear strength in existing unreinforced solid-unit masonry is determined in agreement with ASTM C1531-15 [5]. The test allows the definition of the bed joint shear strength parameters according to the Coulomb strength criterion, i.e. cohesion τ_0 and friction coefficient μ.

Different test methods are proposed in the Standard [5]. In the present experimental campaign, the shove test is performed after execution of the single and double flatjack test; the shove test set-up is presented in Figure 5. The flatjacks used during the single and double flatjack tests are kept into place and, within the tested masonry portion between the two flatjacks, a masonry unit in the stretcher orientation is selected as reference (test unit). Then, the two adjacent units and head joints are removed. At this point, a horizontal jack is inserted on one side of the test unit and horizontal LVDTs are installed to record the shear sliding of the reference unit as well as the sliding of the contrast portion. By using the Coulomb strength criterion the residual properties as well as initial properties can be found.

Although shove test seems straightforward, there is always uncertainty regarding the distribution of the normal stress on the test unit. Indeed, it can be strongly influenced by the fact that two bricks are removed from the opposite ends of the test unit. Therefore, the contribution of both the flatjack pressure and of the overburden pressure (far field effect) on the test unit should be carefully evaluated. To resolve the mentioned uncertainty, a testing procedure was introduced by EUCentre [9] aiming to have a better understanding of the testing results.

A summary of the testing procedure introduced by EUCentre is as follows:

i. Execute the first slot in the masonry bed joint and perform the single flatjack test.
ii. Execute the second slot, at a distance of at least five courses below the upper flatjack, and perform the double flatjack test. The aim is to establish the Young's modulus.
iii. Remove the two masonry units adjacent (left and right) to the reference unit (Figure 5). The bed joints on the side of the masonry unit to be tested must be "cleaned" to avoid the presence of any leftover mortar that could prevent the masonry unit from sliding.
iv. Perform the double flatjack test in the "shove test configuration" to determine the fictitious elastic modulus *E**. At the end of the test keep the flatjacks in place.
v. Insert the horizontal load jack (spherical seat) and the metallic plates for the diffusion of the load (minimum thickness: 3 mm).

Evaluation of cohesion:

vi. Set the pressure in the two flatjacks to 0.07 MPa or less and maintain it constant.
vii. Increase the pressure in the horizontal loading jack gradually, such that failure of the bed joint occurs between 30 sec and 2 min after initial loading. Record all the measurements of both displacements and pressures, till the post peak phase (relative to horizontal direction). This gives information on the first rupture of the interface, taking in account cohesion as well as friction effects.

Evaluation of residual shear properties:

viii. Increase the pressure in the flatjacks to induce the next desired level of normal compressive stress and maintain it constant.
ix. Increase the pressure in the horizontal loading jack and record the measurements until the post peak phase. As suggested by EUCentre [9], if the brick displaces more than 0.5 cm, reverse the horizontal load.
x. As suggested by EUCentre [9], repeat the procedure at least 4 times increasing the pressure in the flatjacks up to a level considered "elastic" taking as a reference the results of double flatjack test.
xi. Release the pressure in the horizontal loading jack and take it apart, and eventually dismount also the instrumentation.
xii. The test could be performed also in the opposite direction, just by transferring the loading jack in the opposite opening, to investigate the effect of shear force reversal.

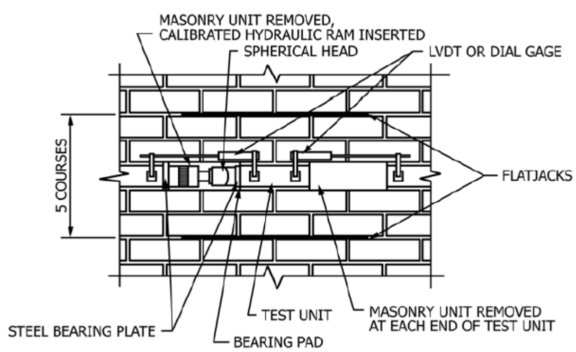


Figure 5 – Test set-up (Fig.1 ASTM C1531-15)

At each level of normal compressive stress the following information is required [5]:

- Flatjacks pressure,
- Relative sliding deformation of the test unit.

The horizontal displacement, *D*, of the test unit at each horizontal load step, *i*, is:

$$D_i^{hor} = d_i^{hor} - d_{i-1}^{hor} \quad (4)$$

d_{i-1}^{hor}= horizontal LVDT record at the *i*-th load increment

For a specific normal compressive stress σ_j, it is possible to plot the horizontal load versus the relative horizontal displacement of the test unit. Therefore, the point corresponding to the failure point can be identified.

For each level of vertical compression, two data are then recorded:
τ= average mortar joint shear strength
σ_j = normal compressive stress

The average mortar joint shear strength τ_i for each level of normal compressive stress σ_j, is calculated as:

$$\tau = \frac{F_h}{2A_s} \quad (5)$$

where F_h is the horizontal force corresponding to the failure point resisted by the test unit at the *i*- th level of normal compressive stress and A_s is the cross sectional area of the brick parallel to the bed joint.

The residual shear properties of the brick-mortar interface, i.e. residual shear strength τ_{res} and residual coefficient of friction μ_{res}, can be determined considering the Coulomb strength criterion, which is suitable to describe a sliding failure mode of the test unit. Accordingly, the shear strength τ and the corresponding normal compressive stress σ_j are plotted against each other for each level of compression applied by the flatjacks, except the first. Indeed, the first failure point is not associated to a pure frictional behaviour. By using a linear regression, the residual shear strength and the residual coefficient of friction can be found as intercept on y-axis and as a slope of the line, respectively. The set-up adopted for the shove test is shown in Figure 6.

$$\tau_{res} = \tau_{0,res} + \mu_{res}\sigma_j \quad (6)$$

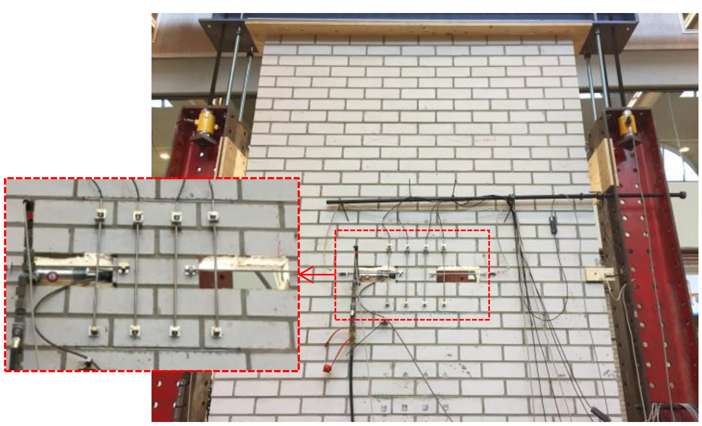


Figure 6 – Shove test set-up. Note the double flatjack test is performed in the “Shove Test configuration” (left and right brick have been removed).

Calculations:
According to the testing procedure of the shove test reported in the ASTM C1531 standard, the shear strength is related to the normal compressive stress acting on the test unit. A particular attention must be paid for normal stress distribution. Recent analyses [9] have shown that the distribution of normal stress on the test unit is non uniform, and the contribution of the flatjack pressure and the overburden pressure (far field effect) should be carefully evaluated. Subsequently, the following transformation is suggested by EUCentre [9]:

$$\tau(\sigma_j) \rightarrow \tau(\sigma_{bj}) \rightarrow \tau(\sigma_b)$$

Where
σ_j is the normal compressive stress applied by the flatjacks,
σ_{bj} is the normal compressive stress on the test unit, due to the flatjacks pressure and
σ_b is the normal compressive stress on the test unit, after correction for far field effects.

The steps, by which the actual compressive stress on the test unit is evaluated, after the corrections for both flatjack pressure and far field effects, can be summarised as follows:
Step 1
By plotting the values of the shear strength versus the associated normal compressive stress applied by the flatjacks (σ_j) the residual properties can be found, as shown in Figure 7.

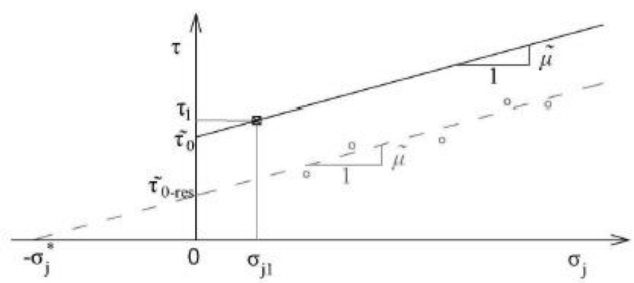


Figure 7 – Shear strength as a function of the normal compressive stress applied by the flatajcks (denoted as Step 1).

Step 2
This step includes the modification of the stress in the test unit due to the flatjack pressure. The "flatjack to brick correction factor" can be defined as follows [9]:

$$K_{bj} = \frac{E_{DFJ}}{E^{*}_{DFJ}} \tag{7}$$

where:
E_{DFJ} is the elastic modulus of masonry evaluated from the double flatjack test and
E_{DFJ}^* is the elastic modulus of masonry evaluated from the double flatjack test performed in the "shove test configuration".

The values of compressive stress applied by the flatjacks are then corrected using the above mentioned correction factor to obtain the equivalent values of compressive stress in the brick unit due to the flatjack pressure:

$$\sigma_{bj} = E_{DFJ} / E^{*}_{DFJ} . \sigma_j = K_{bj} . \sigma_j \tag{8}$$

By plotting the values of the shear strength and normal compressive stress on the test unit due to the flatjacks pressure (σ_{bj}) the residual properties can be found, as shown in Figure 8

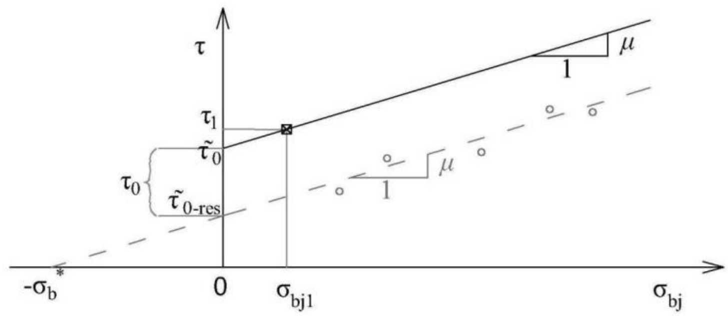


Figure 8 – Shear strength as a function of the normal stress in the test unit due to the flatjack pressure (denoted as Step 2).

Step 3

As it was observed in Figure 8, the residual failure criterion does not lead to zero value of residual cohesion. Therefore, the residual failure criterion should be translated to account for overburden pressure. Thus, the compressive stress in the test unit can be considered as the sum of two factors as follows:

$$\sigma_b = \sigma_{bj} + \sigma_b^* \quad (9)$$

where:

σ_{bj} is the normal compressive stress on the test unit due to the flatjacks pressure and

σ^*_b is contribution to the normal compressive stress in the test unit due to the far field effect (e.g. the weight of the wall and the load applied at the top of the wall).

Finally, the residual values of shear strength versus the compressive stress in the test unit can be plotted as shown in Figure 9. Moreover, the initial shear strength (cohesion) can be found assuming the same values of coefficient of friction for the initial and residual failure criterion. To this end, the shear stress corresponding to the first failure point should be plotted against the modified values of normal stress, taking into account both the jack to brick correction factor and the correction due to overburden load.

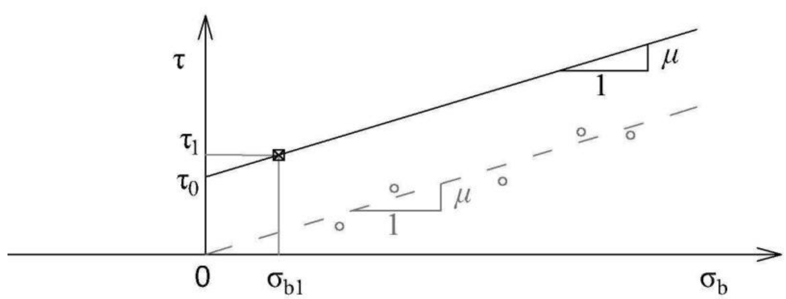


Figure 9 – Shear strength as a function of the normal stress in the tested unit after correctin for the flatjack pressure and far field effect (denoted as Step 3).

4.4 Summary of the in-situ testing procedure

The testing procedure for each location of the wall can be summarised as shown in Figure 10. Note, that the Phase 00 is regarded as a testing phase where the displacements of the undisturbed wall were measured at the first location. In each location, the single flatjack (Phase 01 and Phase 02), the double flatjack (Phase 03 and Phase 04) and the shove tests (Phase 05 to Phase 07) were performed sequentially. Then, the overburden load was adjusted to account for the subsequent location of the wall (Phase 08). Afterwards, the shove test was repeated at the same location of the wall (Phase 09). The aim was to investigate the effect of the overburden on the residual failure criterion.

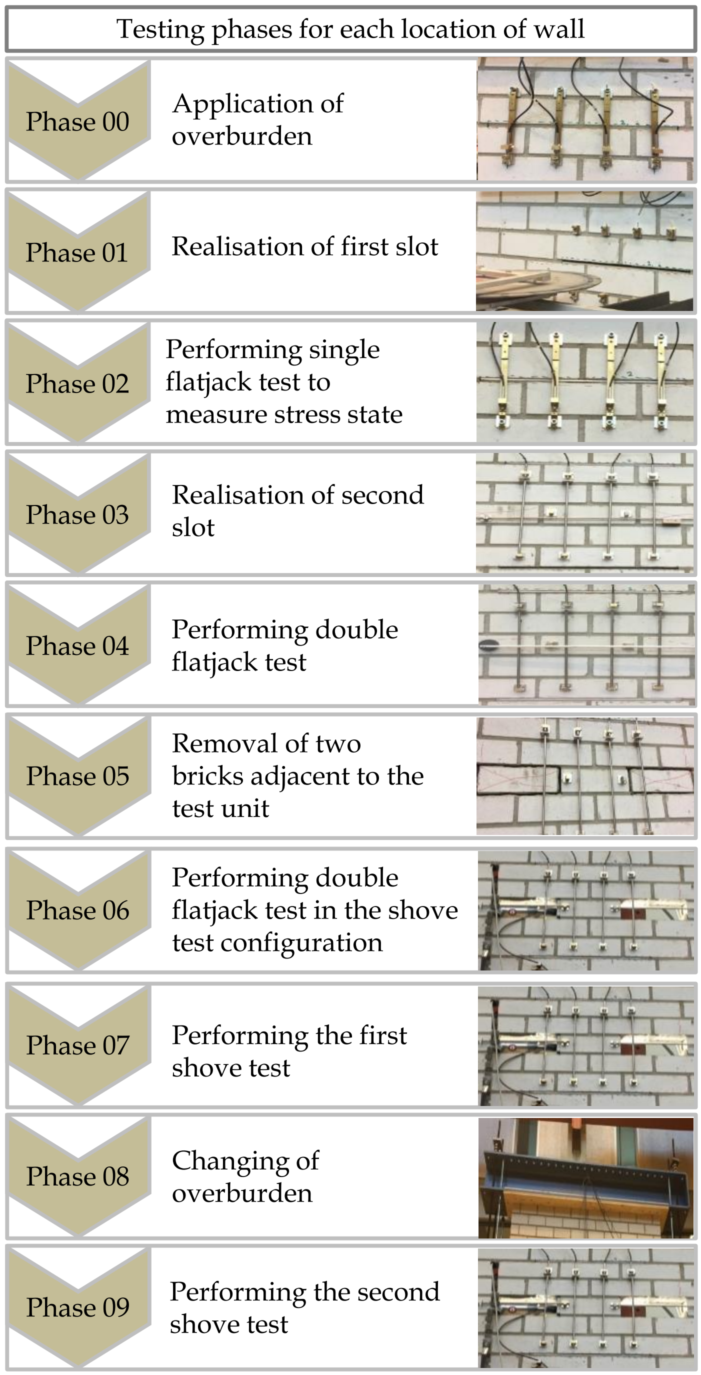


Figure 10 – Testing phases during the in-situ tests.

5 Experimental results

The results of the in-situ tests obtained from performing of the single flatjack, double flatjack and the shove tests are presented in this section. The results for each location of the wall are explained in more details.

5.1 Application of the overburden pressure

During the application of the overburden load on top of the wall (Phase 0), the deformation of the wall was measured using four vertical LVDTs, positioned in correspondence of the masonry portion tested in Location 01 and later used for the purpose of the single flatjack test (see Figure 11). The variation of the applied load (overburden) as well as the LVDTs' measurements versus time is shown in Figure 12. Taking into account the variations of the applied pre-compression load and the corresponding deformation, the elastic modulus can be evaluated, as listed in Table 5. The Young's modulus is evaluated considering the measurements of all the four vertical LVDTs. Note that these results are relevant only to the first location of the wall.

Table 5 – Calculation of the Young's modulus during application of overburden load.

	Stress	**Strain**	**Young's modulus**
	MPa	-	MPa
Point 01	0.054	0.0000	6258
Point 02	0.596	0.0001	

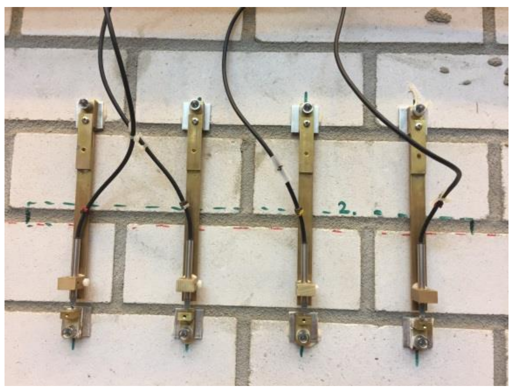


Figure 11 – Measurements of LVDTs during Phase 0.

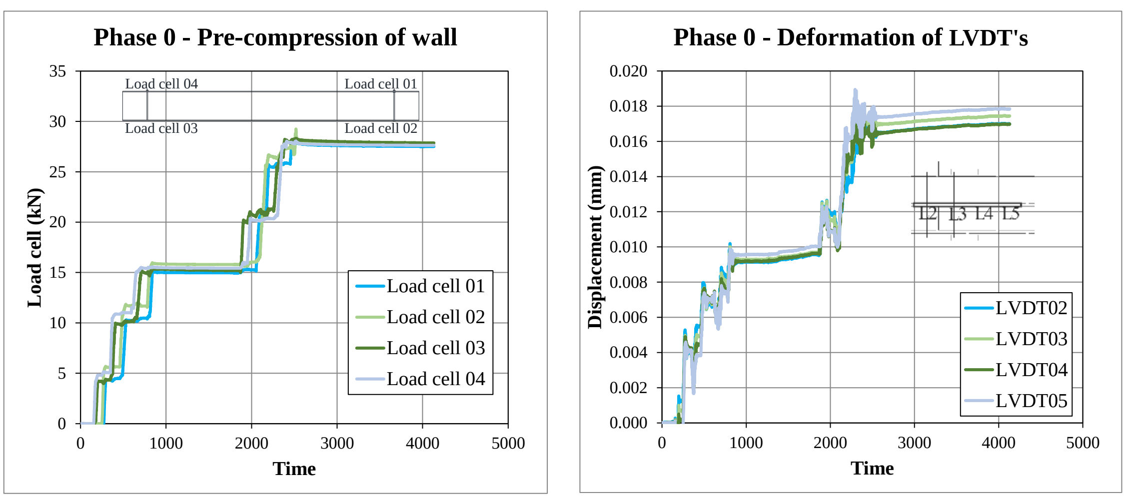


Figure 12 – Measurements during Phase 0: (a) load cell measurements versus time; (b) deformation of LVDTs versus time.

5.2 Single flatjack test

Location 01

The set-up of the single flatjack test at location 01 is presented in Figure 13. After the installation of the gauge points, reference measurements were taken before the realization of the slot. The variation of overburden during the cutting phase (Phase 01) is shown in Figure 14. No significant variation of the overburden is observed. It should be pointed out that the distance between the gauge points before and after the realisation of the slot as well as at the end of the test was measured using the manual instrument. While during the test, the increase in the distance between the gauge points, due to the pressure of the flatjack, was measured using the LVDTs, see Figure 15a. The variations of the applied overburden as well as the pressure in the flatjack versus time are shown in Figure 15b. It can be seen that by increasing the flatjack pressure, the overburden load was increased; however, these variations are not considerable. As mentioned earlier, the pressure in the flatjack is calculated as:

$$f_{m,SFJ} = K_m K_a p \quad (1)$$

where, K_m is a dimensionless constant which reflects the geometrical and stiffness properties of the flatjack. By calibrating the flatjack, a constant equal to 0.794 was found (see Appendix B). K_a is a dimensionless constant measured as a ratio of the effective area of the flatjack to the average measured area of the slot. This ratio is found as 0.7010. The effective area of the flatjack was retrieved calculating the area of the sensitive pressure paper marked in places of contact. It was observed that the effective area of the flatjack was lower than the nominal one.

The variation of the stress due to the application of pressure in the flatjack versus LVDT's displacements are shown in Figure 16a. The opening of the slot versus the applied pressure is shown in Figure 16b. The allowable average deviation and the allowable single deviation are also presented, as suggested by ASTM C1196-14a. It can be observed, both single deviations and the average deviations vary in the allowable ranges. Taking into account the obtained results, a linear relationship between the applied pressure and the displacements can be assumed. Thus, the pressure by which the initial position of the gauge points would be restored (i.e. opening = 0.0 mm) can be evaluated as 0.55 MPa. An acceptable agreement is found between the stress state measured from the single flatjack test (0.55 MPa) and the actual stress state in the wall (0.60 MPa).

To confirm the degree of accuracy of the LVDTs' measurements, the manual measurement was also conducted when the pressure in the flatjack reached 8.8 bar (0.5 MPa). These measurements are listed in Table 6. A good correspondence was found between the results obtained with the manual measurement and those obtained with the LVDTs.

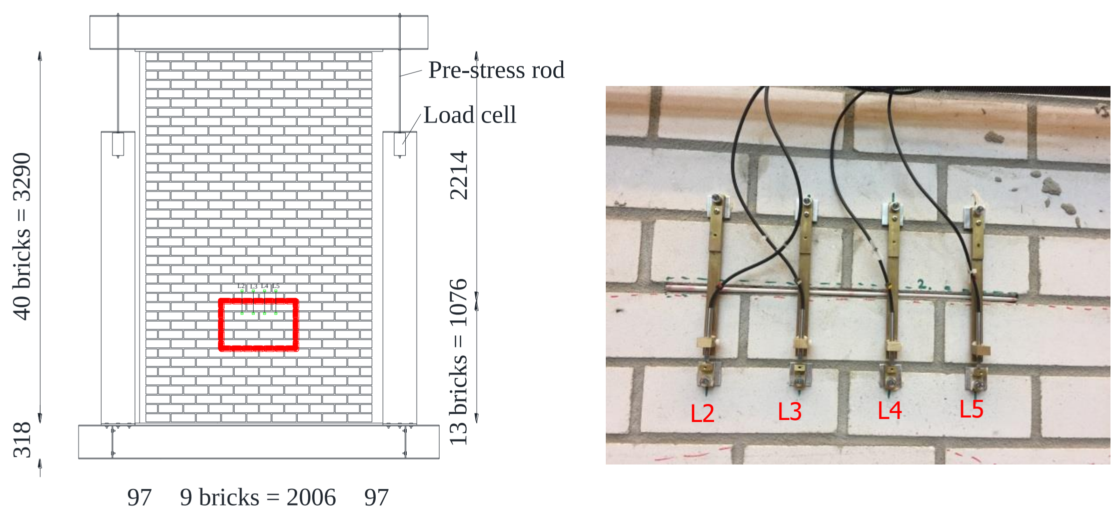


Figure 13 – Test set-up for single flatjack test at location 01. The dimensions are in mm.

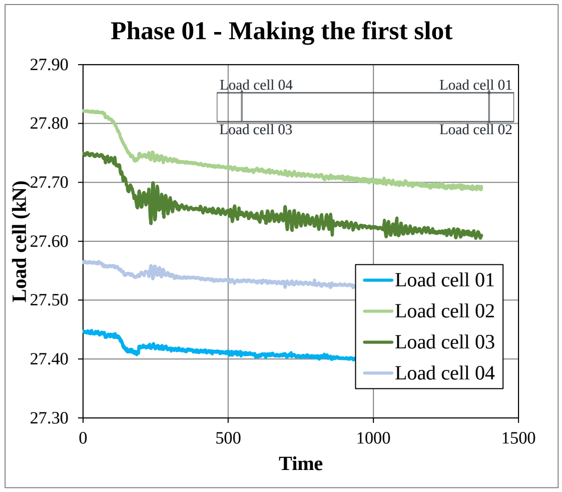
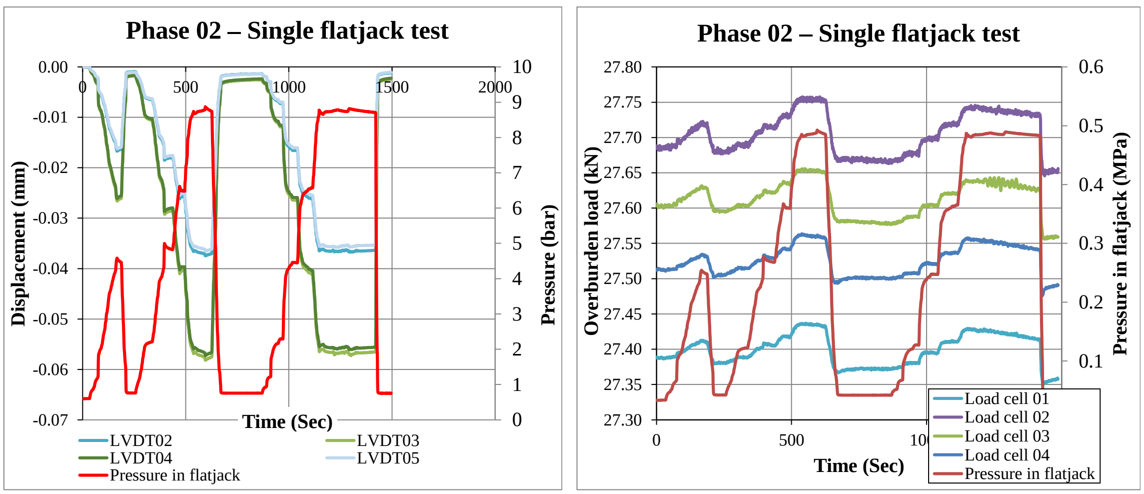
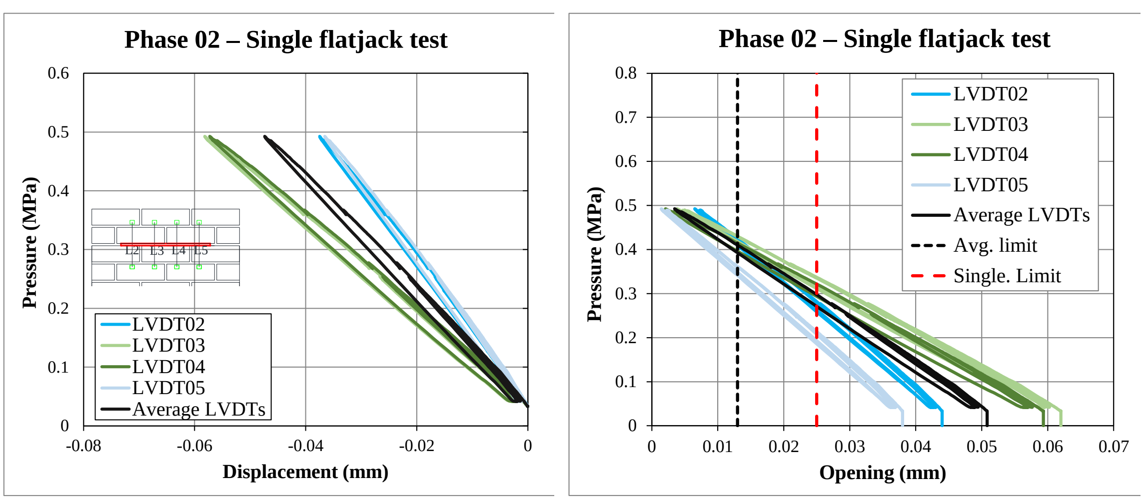


Figure 14 – Variation of overburden during the realisation of the first slot in the mortar joint.



(a) (b)

Figure 15 – Measurements during the single flatjack test at location 01: (a) LVDTs' deformation versus time; (b) overburden as well as flatjack pressure versus time.



(a) (b)

Figure 16 – Measurements during the single flatjack test at location 01: (a) LVDTs' reading versus flatjack pressure; (b) opening of the slot from the LVDTs' reading versus applied pressure by flatjack.

Table 6 – Comparison between the manual and LVDTs' measurements at location 01.

Status		Point 02	Point 03	Point 04	Point 05
Manual measurement	Before cut	0.542	0.546	-0.792	-0.325
	After cut at pressure 0 bar	0.498	0.484	-0.851	-0.363
	After cut at pressure 8.78 bar	0.534	0.540	-0.798	-0.329
	Opening of the slot due to pressure of flatjack at 8.78 bar	-0.036	-0.056	-0.054	-0.034
LVDTs'	Opening of the slot due to pressure of flatjack at 8.78 bar	-0.036	-0.057	-0.056	-0.035

Location 02

The set-up of the single flatjack test at location 02 is presented in Figure 17. After the installation of the gauge points, reference measurements were taken before the realization of the slot. The variation of overburden during the cutting phase (Phase 01) is shown in Figure 18; no significant variation of the overburden is observed. It should be pointed out that the distance between the gauge points before and after the realisation of the slot as well as at the end of the test was measured using the manual instrument. While during the test, the increase in the distance between the gauge points, due to the pressure of the flatjack, was measured using the LVDTs, see Figure 19a. The variations of the applied overburden as well as the pressure in the flatjack versus time are shown in Figure 19b. It can be seen that by increasing the flatjack pressure, the overburden load was increased; however, no significant variation is observed. As mentioned earlier, the pressure in the flatjack is calculated as:

$$f_{m,SFJ} = K_m K_a p \qquad (1)$$

where, K_m is a dimensionless constant which reflects the geometrical and stiffness properties of the flatjack. By calibrating the flatjack, a constant equal to 0.794 was found (see Appendix B). K_a is a dimensionless constant measured as a ratio of the effective area of the flatjack to the average measured area of the slot. This ratio is found as 0.875. The effective area of the flatjack was retrieved calculating the area of the sensitive pressure paper marked in places of contact. It was observed that the effective area of the flatjack was lower than the nominal one.

The variation of the stress due to the application of pressure in the flatjack versus LVDT's displacements are shown in Figure 20a. The opening of the slot versus the applied pressure is shown in Figure 20b. The allowable average deviation and the allowable single deviation are also presented, as suggested by ASTM C1196-14a. It can be observed, both single deviations and the average deviations vary in the allowable ranges. Taking into account the obtained results, a linear relationship between the applied pressure and the displacements can be assumed. Thus, the pressure by which the initial position of the gauge points would be restored (i.e. opening = 0.0 mm) can be evaluated as 0.22 MPa. An acceptable agreement is found between the stress state measured from the single flatjack test (0.22 MPa) and the actual stress state in the wall (0.25 MPa).

To confirm the degree of accuracy of the LVDTs' measurements, the manual measurement was also conducted when the pressure in the flatjack reached 3.9 bar (0.25 MPa). These measurements are listed in Table 7. A good correspondence was found between the results obtained with the manual measurement and those obtained with the LVDTs, with the exception of the measurements taken from the gauge point 3 and 5. Note that the differences between the two adopted measuring systems are acceptable, since their variations are still lower than the limit ranges prescribed by the ASTM Standard.

Table 7 – Comparison between the manual and LVDTs' measurements at location 02.

Status		Point 02	Point 03	Point 04	Point 05
Manual measurement	Before cut	0.123	-1.250	0.431	0.593
	After cut at pressure 0 bar	0.115	-1.258	0.419	0.587
	After cut at pressure 3.9 bar	0.127	-1.242	0.436	0.595
	Opening of the slot due to pressure of flatjack at 3.6 bar	-0.012	-0.024	-0.017	-0.008
LVDTs'	Opening of the slot due to pressure of flatjack at 3.6 bar	-0.011	-0.017	-0.017	-0.011

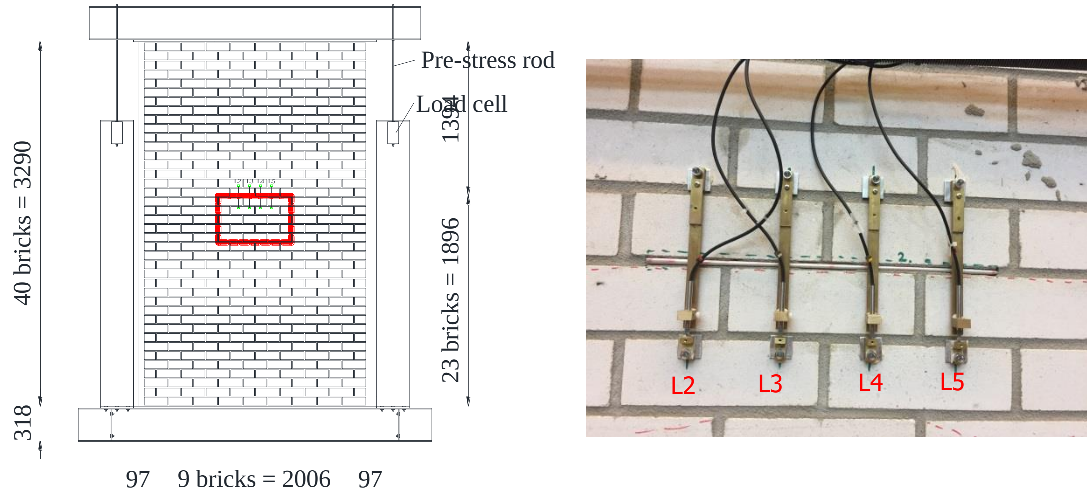


Figure 17 – Test set-up for single flatjack test at location 02. The dimensions are in mm.

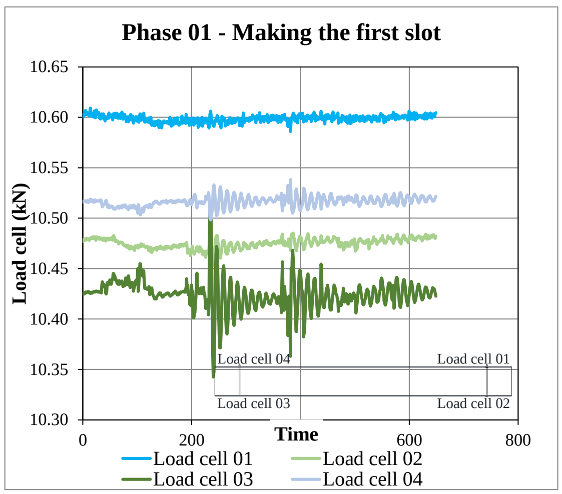
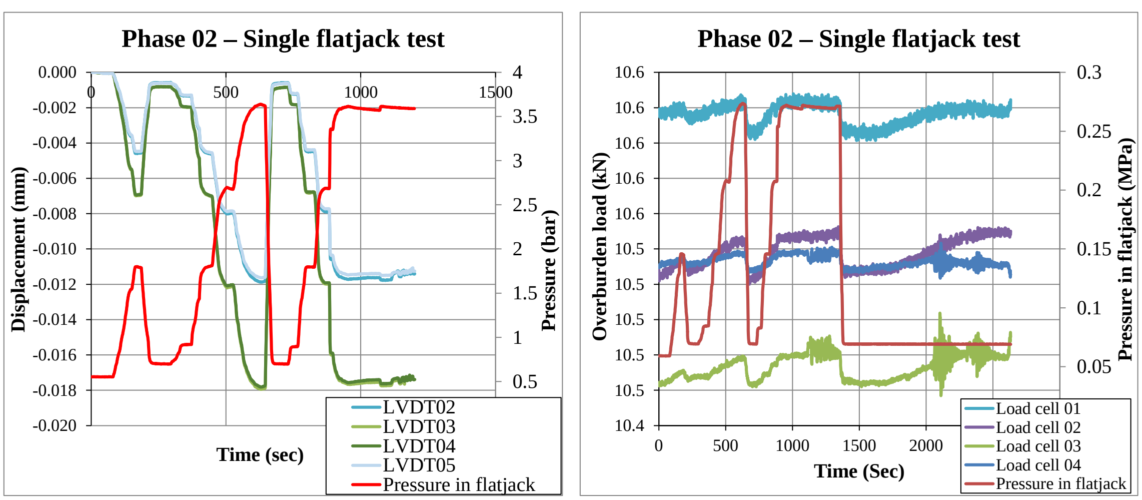
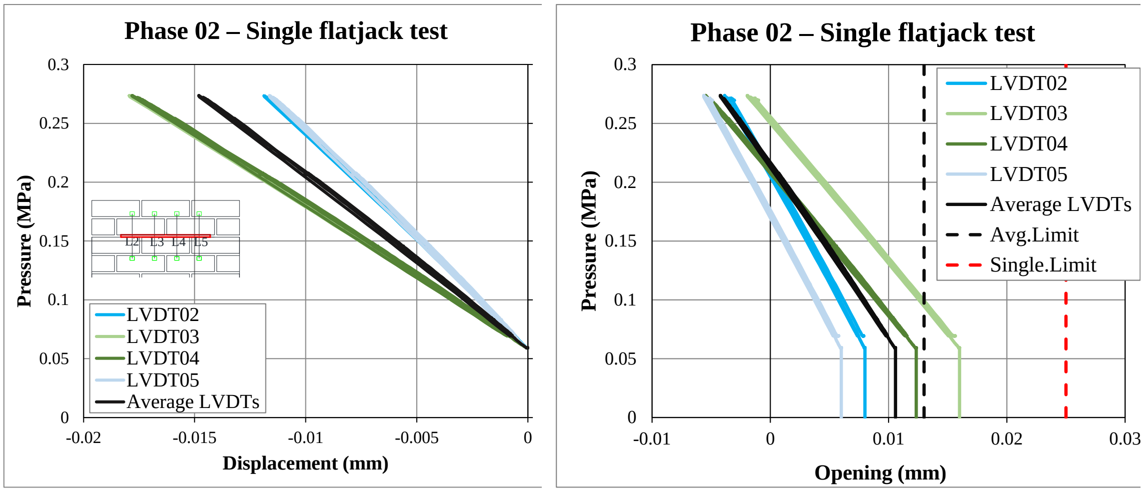


Figure 18 – Variation of overburden during the realisation of the first slot in the mortar joint.



(a) (b)

Figure 19 – Measurements during the single flatjack test at location 02: (a) LVDTs' deformation versus time; (b) overburden as well as flatjack pressure versus time.



(a) (b)

Figure 20 – Measurements during the single flatjack test at location 02: (a) LVDTs' reading versus flatjack pressure; (b) opening of the slot from the LVDTs' reading versus applied pressure by flatjack.

Location 03

The set-up of the single flatjack test at location 03 is presented in Figure 21. After the installation of the gauge points, reference measurements were taken before the realization of the slot. The variation of overburden during the cutting phase (Phase 01) is shown in Figure 22. No significant variation of the overburden is observed. It should be pointed out that the distance between the gauge points before and after the realisation of the slot as well as at the end of the test was measured using the manual instrument. While during the test, the increase in the distance between the gauge points, due to the pressure of the flatjack, was measured using the LVDTs, see Figure 23a. The variations of the applied overburden as well as the pressure in the flatjack versus time are shown in Figure 23b. It can be seen that by increasing the flatjack pressure, the overburden load was increased; however, these variations in the overburden load are not considerable. As mentioned earlier, the pressure in the flatjack is calculated as:

$$f_{m,SFJ} = K_m K_a p \quad (1)$$

where, K_m is a dimensionless constant which reflects the geometrical and stiffness properties of the flatjack. By calibrating the flatjack, a constant equal to 0.794 was found (see Appendix B). K_a is a dimensionless constant measured as a ratio of the effective area of the flatjack to the average measured area of the slot. This ratio is found as 0.8261. The effective area of the flatjack was retrieved calculating the area of the sensitive pressure paper marked in places of contact. It was observed that the effective area of the flatjack was lower than the nominal one.

The variation of the stress due to the application of pressure in the flatjack versus LVDT's displacements are shown in Figure 24a. The opening of the slot versus the applied pressure is shown in Figure 24b. The allowable average deviation and the allowable single deviation are also presented, as suggested by ASTM C1196-14a. As it can be observed, both single deviations and the average deviations vary in the allowable ranges. Considering the LVDT's reading, the pressure by which the initial position of the gauge points would be restored, can be evaluated as 0.063 MPa. Thus, an acceptable agreement is not found between the stress state measured from the single flatjack test (0.063 MPa) and the actual stress state in the wall (0.15 MPa). It should be noted that such a difference can be partially attributed to the fact that no perfect contact between the top steel beam and the wall was observed during the test.

To confirm the degree of accuracy of the LVDTs' measurements, the manual measurement was also conducted when the pressure in the flatjack reached 1.0 bar (0.066 MPa). These measurements are listed in Table 8. The differences between the manual measurements and the LVDT's measurements stand for less than 0.003 mm; which is due to the differences between the precisions of the two adopted measuring system. These differences are acceptable, since still they are lower than the limit ranges.

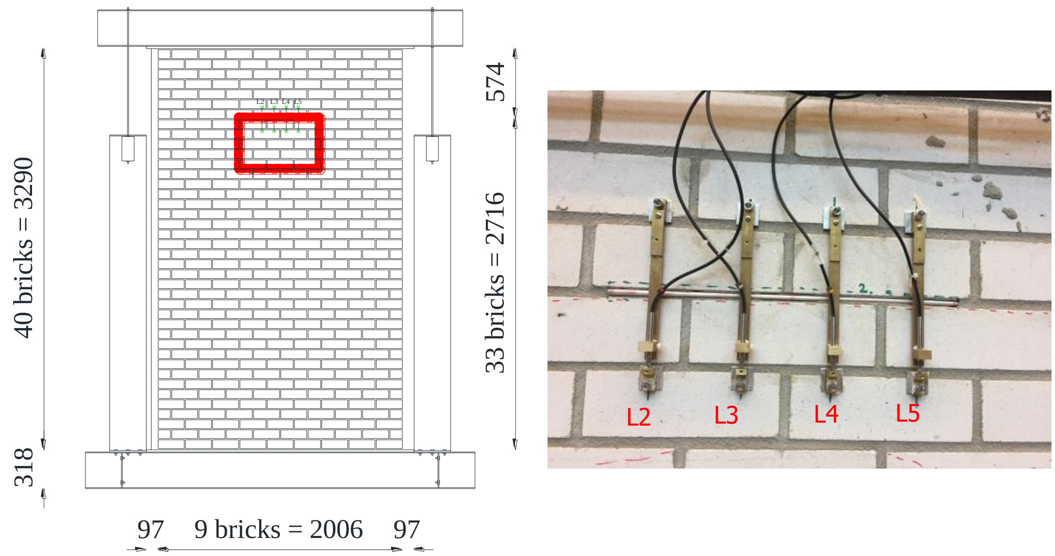


Figure 21 – Test set-up for single flatjack test at location 03. The dimensions are in mm.

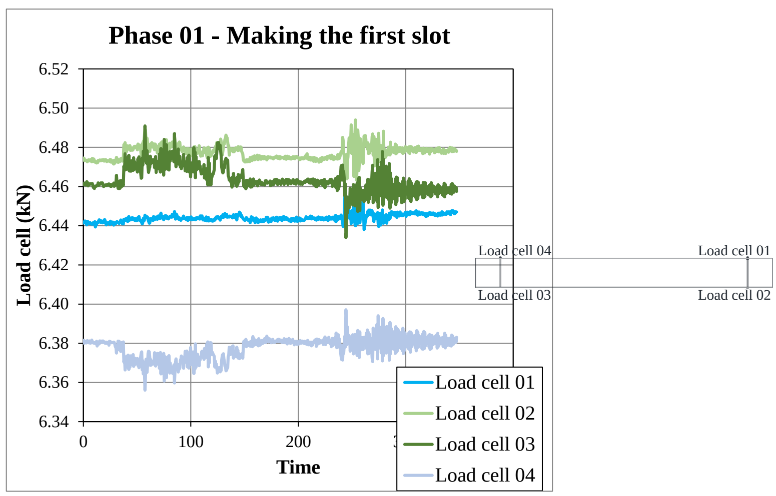
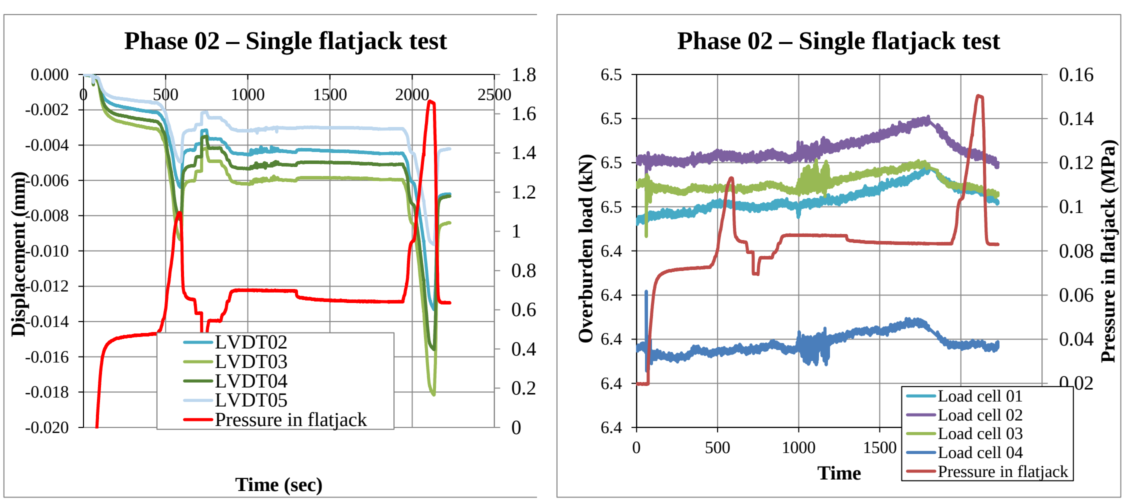


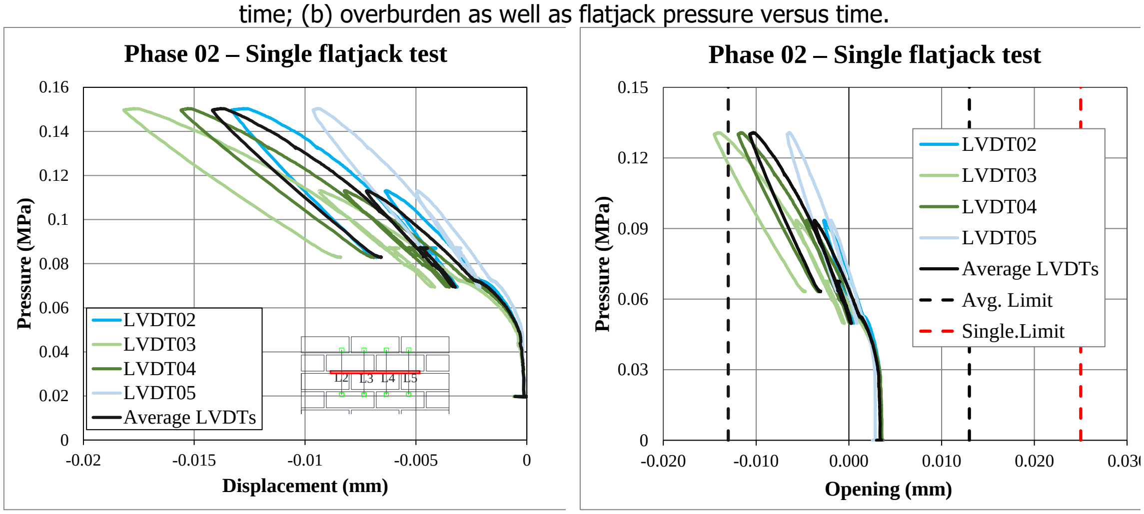
Figure 22 – Variation of overburden during the realisation of the first slot in the mortar joint.



(a) (b)

Figure 23 – Measurements during the single flatjack test at location 03: (a) LVDTs' deformation versus

time; (b) overburden as well as flatjack pressure versus time.



(a) (b)

Figure 24 – Measurements during the single flatjack test at location 03: (a) LVDTs' reading versus flatjack pressure; (b) opening of the slot from the LVDTs' reading.

Table 8 – Comparison between the manual and LVDTs' measurements at location 03.

Status		Point 02	Point 03	Point 04	Point 05
Manual measurement	Before cut	0.527	-0.768	-1.032	0.797
	After cut at pressure 0 bar	0.523	-0.772	-1.036	0.794
	After cut at pressure 1.0 bar	0.532	-0.763	-1.027	0.793
	Opening of the slot due to pressure of flatjack at 1.0 bar	0.009	0.009	0.008	-0.001
LVDTs'	Opening of the slot due to pressure of flatjack at 1.0 bar	0.005	0.006	0.005	0.002

Summary of the results of the single flatjack tests

A summary of the compressive stress state in the wall, in the three different locations where the slot was made is presented in Table 9. The actual stress state in the wall was calculated considering the overburden applied by the pre-stressed bars, weight of the masonry portion above the slot and the weight of the top beam. The stress-state in the wall is reported considering both LVDTs' measurements and manual measurements.

Considering LVDT's measurements, an acceptable correspondence is found between the actual stress state in the wall and the one measured during the test, in particular for the first and the second locations of the wall with the overburden of 0.60 and 0.25 MPa, respectively. For the last testing location with the minimum values of overburden (0.15 MPa), the difference between the stress-state in the wall and the stress calculated using LVDT's readings stands by 53%. Such a significant difference can be attributed to the fact that no perfect contact between the wall and the top steel plate was reported for this location. Moreover, as reported in the previous studies [16] the accuracy of the results of the flatjack method in the wall with low stress state is always a matter of concern.

Comparing the results of the single flatjack tests in the different locations of the wall having different stress states, the following conclusions can be drawn:

- The stress state in the wall can be reasonably estimated by using the single flatjack test for the high and the medium level of overburden.
- More research is crucial to investigate the accuracy of the results of the single flatjack method, in the case of wall with low stress state.
- The stress-state in the wall is evaluated more accurately using the LVDT's measurements, rather than using the manual measurements, since the LVDTs allowed a continuous measurements of the deformations.

Table 9 – Overview of the results of the single flatjack method.

Testing location	Actual stress state in the wall	Stress state in the wall measured using readings of	
		LVDTs	Manual measurements
	MPa	MPa	MPa
Location1	0.60	0.55	0.56
Location2	0.25	0.22	0.17
Location3	0.15	0.06	0.04

5.3 Double flatjack test

Location 01

The set-up of the double flatjack test at location 01 is presented in Figure 25. The second slot was realised at a distance of five courses below the top slot, which was made during the single flatjack test. LVDTs were positioned within the tested masonry portion, as described in Section 4.2. To gain a better understanding regarding the distribution of the pressure, the vertical deformations between the two slots were continuously recorded during the execution of the second slot. The vertical displacement of the LVDTs versus time is shown in Figure 26. The elongation of the LVDTs can be attributed to the fact that, by executing the second slot, the tested masonry portion is subjected to a relaxation with the consequent elongation of the LVDTs. As expected, the LVDTs on the sides deformed less than those located near to the centre of the slots.

After realisation of the second slot, it was regularised and cleaned from any dust. Subsequently, the second flatjack was inserted into the formed slot. As it was explained previously, the pressure sensitive paper was used aiming to find the effective area of the flatjack. The LVDT's displacement versus time is shown in Figure 27a. The stress-strain relationship during the double flatjack test is shown in Figure 27b. More displacements were measured from the LVDT's placed in the centre rather than the ones positioned on lateral side. This observation is consistent with the results of the previous studies reported by Binda et al. [16].

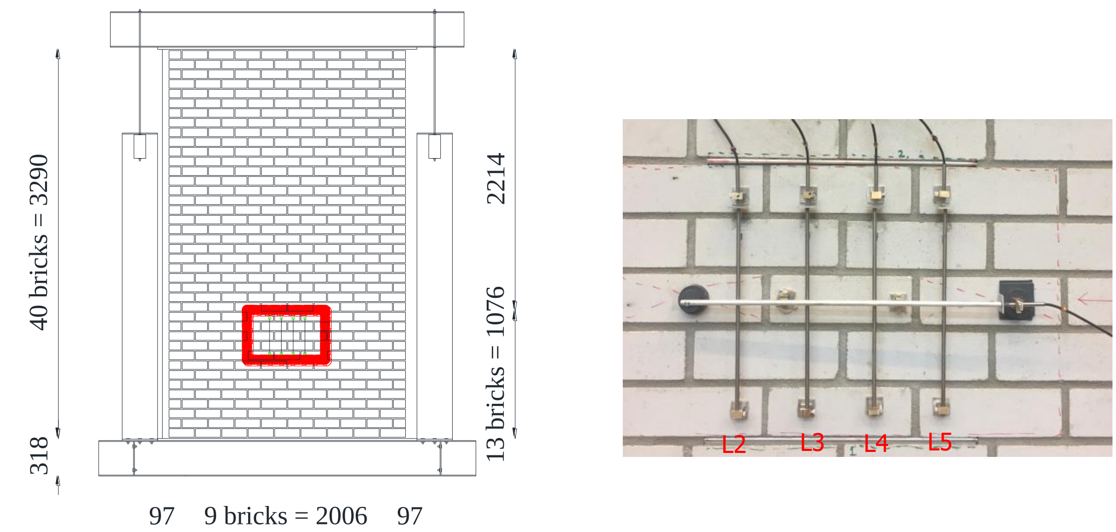


Figure 25 – Test set-up for double flatjack test at location 01. The dimensions are in mm.

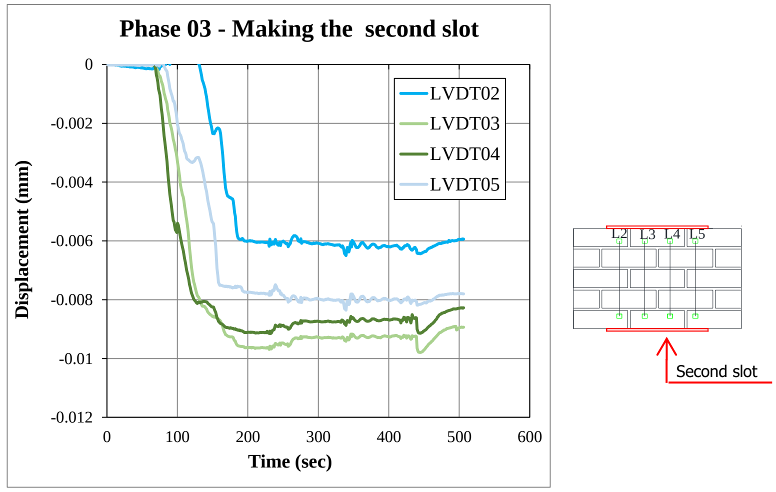
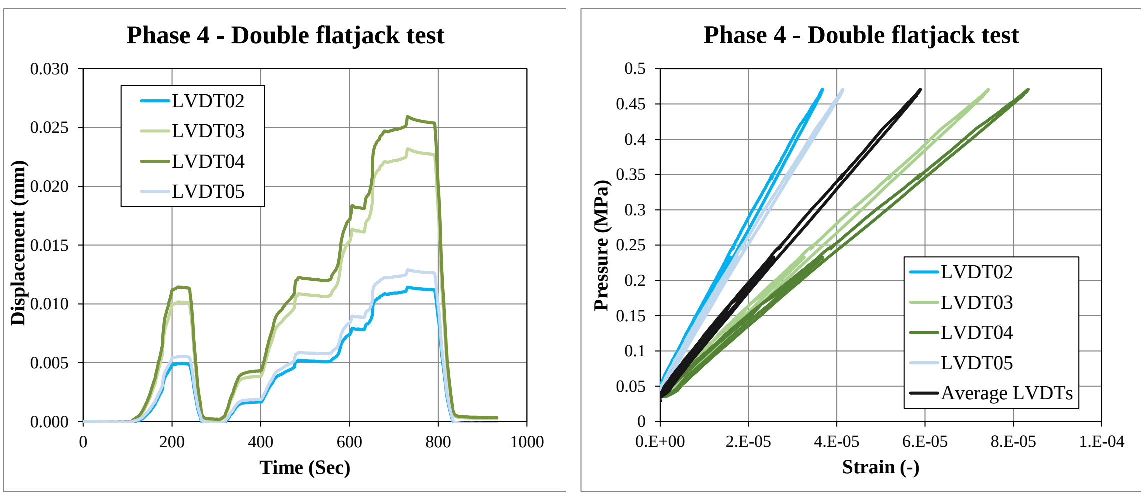


Figure 26 – Elongation of the LVDTs versus time during the execution of the second slot at location 01.



(a) (b)

Figure 27 – Double flatjack test at location 01: (a) LVDTs' readings versus time; (b) stress-strain relationship.

Location 02

The set-up of the double flatjack test at location 02 is presented in Figure 28. During the execution of the second slot, the deformations of the LVDTs placed between the two slots were continuously measured. The vertical displacement of the LVDTs versus time is shown in Figure 29. The elongation of the LVDTs might be attributed to the fact that by executing the second cut, less overburden pressure from the bottom beam was transferred to the portion of the masonry located between the two flatjacks. As expected, the LVDTs on the sides deformed less than those located near to the centre of the slots.

After realisation of the second cut, the slot was regularised and cleaned from any dust. Subsequently, the second flatjack was inserted into the slot. As it was explained previously, the pressure sensitive paper was used aiming to find the effective (net) area of the flatjack. The LVDT's displacement versus time is shown in Figure 30a. The stress-strain relationship during the double flatjack test is shown in Figure 30b. More displacements were measured from the LVDT's placed in the centre of the flatjack rather than the ones positioned on lateral side. This observation is consistent with the results of the previous studies reported by Binda et al. [16].

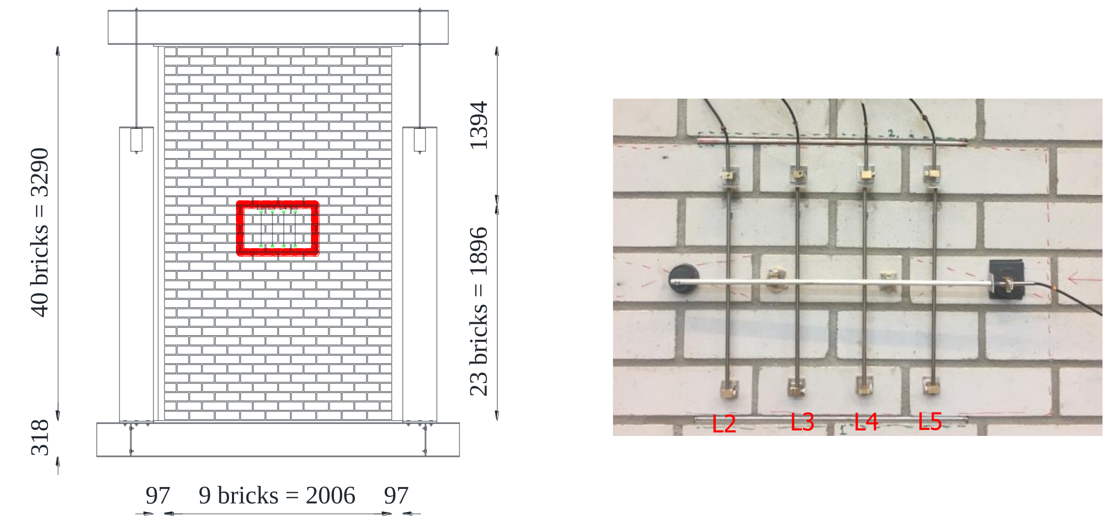


Figure 28 – Test set-up for double flatjack test at location 02. The dimensions are in mm.

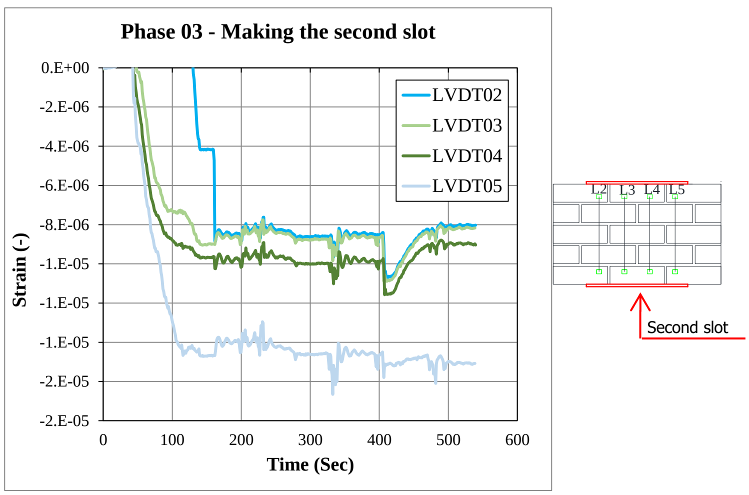
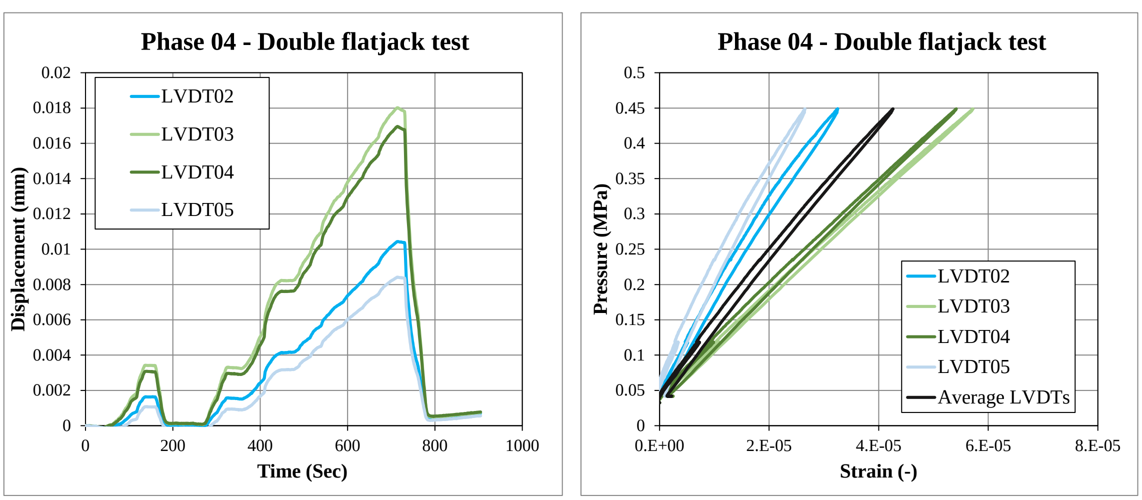


Figure 29 – Elongation of the LVDTs versus time during the execution of the second slot at location 02.



(a) (b)

Figure 30 – Double flatjack test at location 02: (a) LVDTs' readings versus time; (b) stress-strain relationship.

Location 03

The set-up of the double flatjack test at location 03 is presented in Figure 31. During the execution of the second slot, the deformations of the LVDTs placed between the two slots were continuously measured. The vertical displacement of the LVDTs versus time is shown in Figure 32. The elongation of the two central LVDTs might be attributed to the fact that by executing the second cut, less overburden pressure from the bottom beam was transferred to the portion of the masonry located between the two flatjacks. On the contrary, the two LVDT's placed on the lateral side shortened. This observation confirms that for the wall with the lowest value of overburden there was not enough contact between the steel beam and the wall.

After realisation of the second cut, the slot was regularised and cleaned from any dust. Subsequently, the second flatjack was inserted. As it was explained previously, the pressure sensitive paper was used aiming to find the effective (net) area of the flatjack. The LVDT's displacement versus time is shown in Figure 33a. The stress-strain relationship during the double flatjack test is shown in Figure 33b. As expected more displacements were measured from the LVDT's placed in the centre rather than the ones positioned on lateral side.

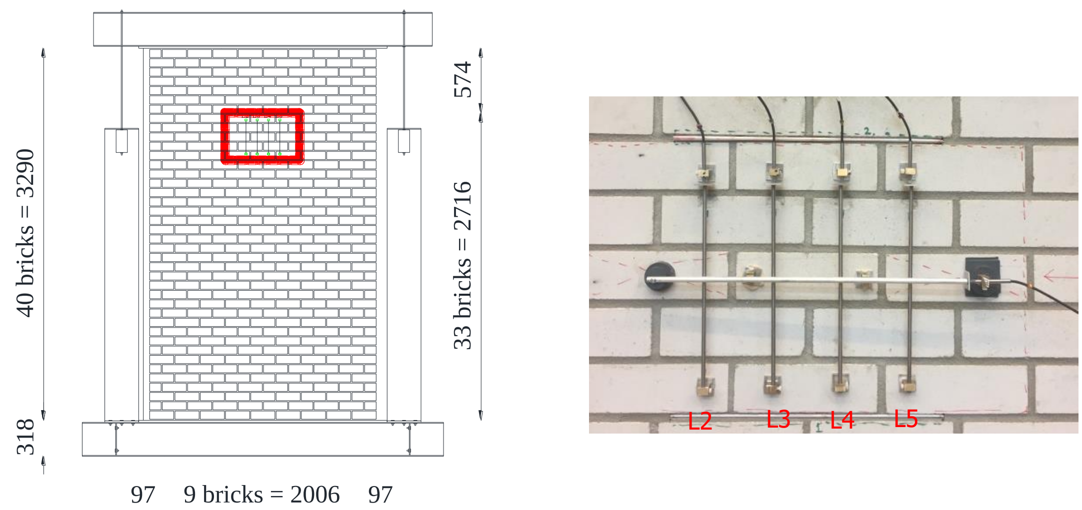


Figure 31 – Test set-up for double flatjack test at location 03. The dimensions are in mm.

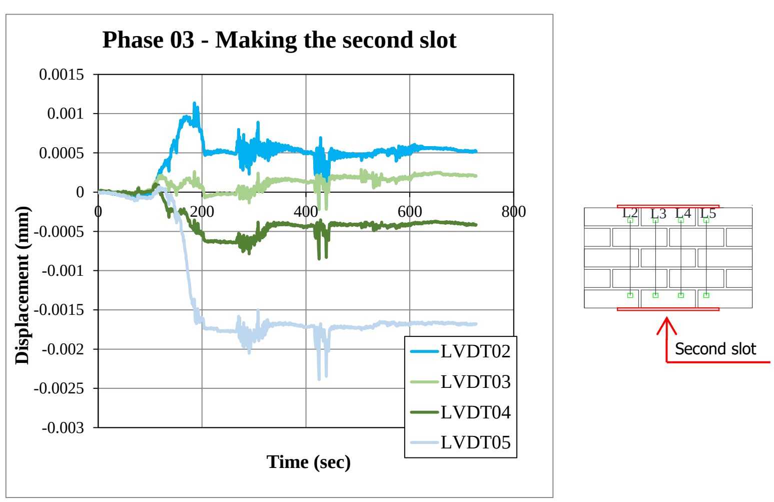
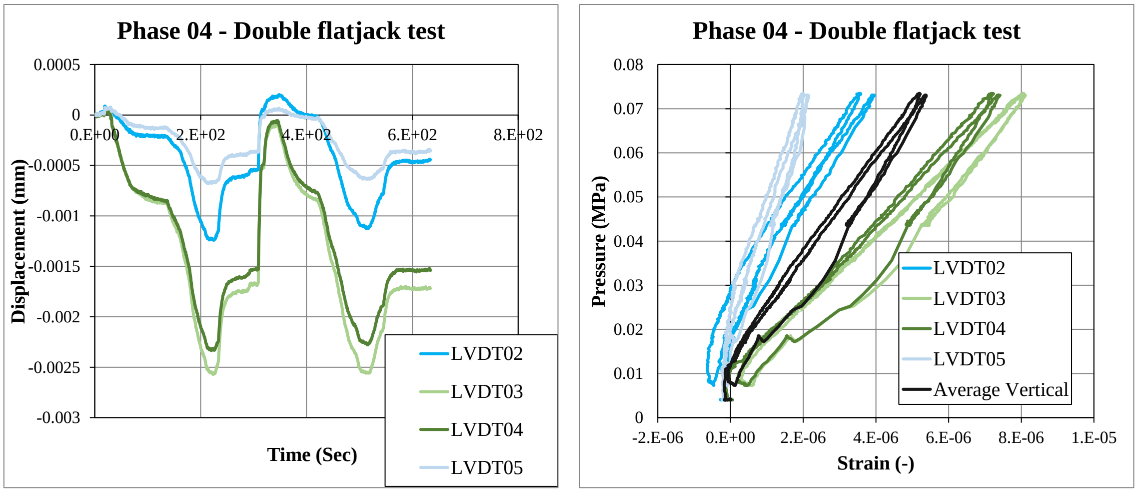


Figure 32 – LVDTs displacement versus time during the execution of the second slot at location 03.



(a) (b)

Figure 33 – Double flatjack test at location 03: (a) LVDTs' readings versus time; (b) stress-strain relationship.

Summary of the results of the double flatjack tests

A summary of the results of the double flatjack tests in the three different locations of the CS brick masonry wall, in terms of the chord elastic modulus is presented in Table 10. The chord Young's modulus is calculated as the most linear part of the ascending branch of the stress-strain relationship. The chord modulus is here calculated between the maximum registered stress and 1/2 of the maximum registered stress.

Three values of the chord modulus are evaluated by taking into consideration the readings of the LVDTs as follows:

- Readings of all the four vertical LVDTs
- Readings of the two vertical LVDTs placed in the middle of the flatjack
- Readings of the two vertical LVDTs placed on the edges of the flatjacak.

It can be concluded that the values of the deformations measured at different reference points are not constant. The deformations tend to be higher in the middle and to be lower in correspondence of the edges of the flatjack.

Considering the chord elastic modulus established from the double flatjack tests (Phase 04) as well as the relaxation displacements recorded during the realisation of the second slot (Phase 03), the stress relaxation of masonry portion can be evaluated as reported in Table 10.

Table 10 – Overview of the elastic modulus calculated from the double flatjack tests and the decrease of stress state in the tested masonry portion due to realisation of the second slot.

Testing phase		Unit	Overburden (MPa)		
			Location01	Location02	Location03
			0.60	0.25	0.15
Phase 04 – Evaluation of chord modulus (*E*)	Readings of all the four LVDT's	MPa	7078	8789	11974
	Readings of the two middle LVDT's		5320	7012	8620
	Readings of the two lateral LVDT's		13980	12215	19602
Phase 03 – Stress relaxation due to formation of slot	Readings of all the four LVDT's	MPa	0.18	0.10	0.04
	Readings of the two middle LVDT's		0.15	0.07	0.01
	Readings of the two lateral LVDT's		0.35	0.14	0.10

5.4 Shove test

Location 01

Before the execution of the shove test, the two bricks adjacent to the test unit have to be removed (Phase 05). The vertical LVDTs, used for the double flatjack tests, are kept in place. Throughout this phase, the vertical deformations were recorded. The deformations of the LVDTs' versus time are presented in Figure 34. It should be pointed out that prior to the removal of the bricks the pressure in the flatjacks was released. The shortening of all the LVDTs is reported. However, a lower deformation is registered for the ones placed in the middle (LVDT03 and LVDT04).

The double flatjack test was repeated after removal of the two bricks ("shove test configuration") aiming to find the jack to brick correction factor (Phase 06). The vertical deformations were measured during the tests, which enabled to evaluate the fictitious Young's modulus of masonry (E_{DFJ}*), see Figure 35. The fictitious Young's modulus was calculated considering the measurements of the two middle LVDTs only. The chord modulus was evaluated in the ascending branch of the stress-strain relationship between the maximum registered load and 1/2 of the maximum stress. The calculation of the flatjack to brick correction factor is summarised in Table 11.

Table 11 – Calculation of the flatjack to brick correction factor at location 01.

***Location 01** of CS brick masonry wall*	Unit	
Pressure on top of the slot due to the weight of masonry and overburden load	MPa	0.60
Young's modulus (readings of middle LVDTs) – double flatjack test	MPa	5320
Young's modulus (readings of middle LVDTs) – modified double flatjack test	MPa	4063
Flatjack to brick correction factor $K_{bj} = \frac{E_{DFJ}}{E^{*}_{DFJ}}$	-	1.31

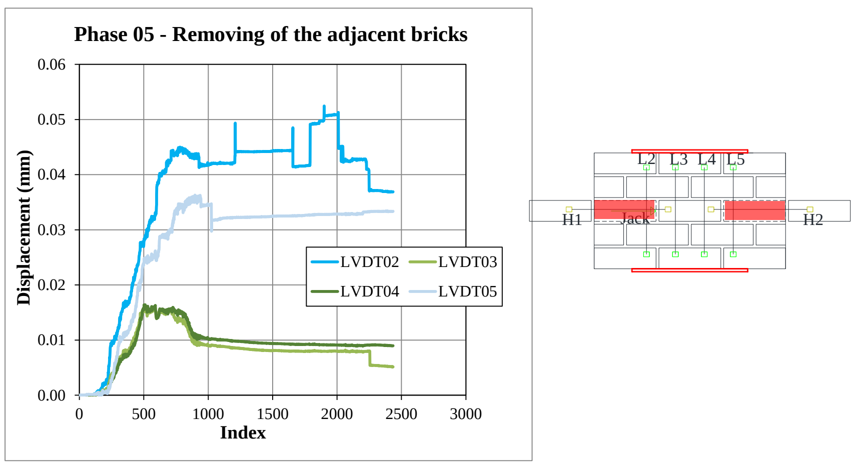
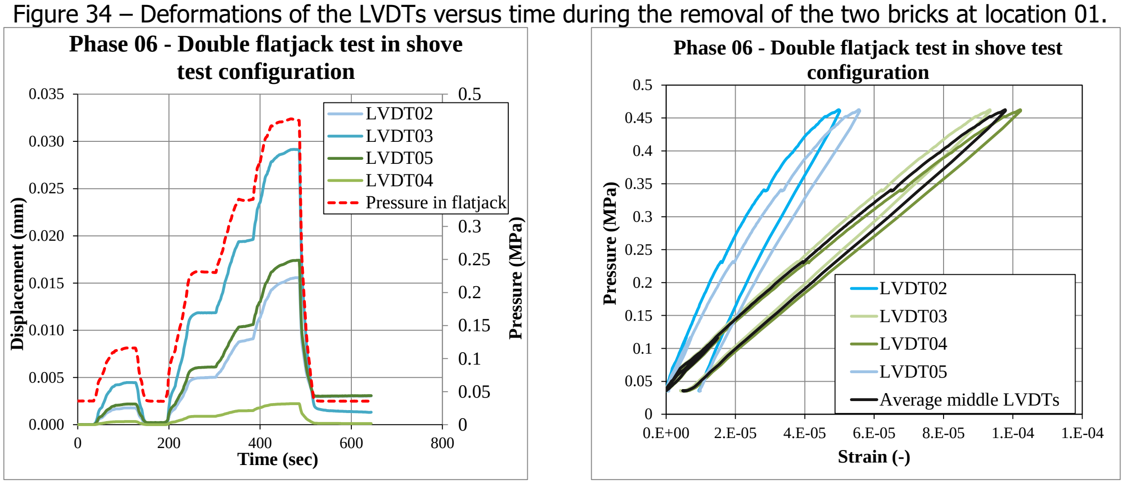


Figure 34 – Deformations of the LVDTs versus time during the removal of the two bricks at location 01.



(a) (b)

Figure 35 – Double flatjack test in the shove test configuration at location 01: (a) strain versus time; (b) deformations versus flatjack pressure.

After performing of the double flatjack test in the “shove test configuration”, a horizontal jack was inserted and the shove test was conducted (Phase 07). The test set-up is presented in Figure 36. The variation of the shear stress as well as overburden load versus time is shown in Figure 37a. The vertical LVDT’s deformations versus time are shown in Figure 37b. The shear stress versus sliding of the masonry unit is shown in Figure 37c.

The testing phases can be classified as follows: (i) the initial phase, in which the shear load can be associated with both cohesion and friction (marked in red); and (ii) the residual phase, where failure at the brick-mortar interface has already occurred, thus the shear load can be associated only with a frictional behaviour (marked in blue).

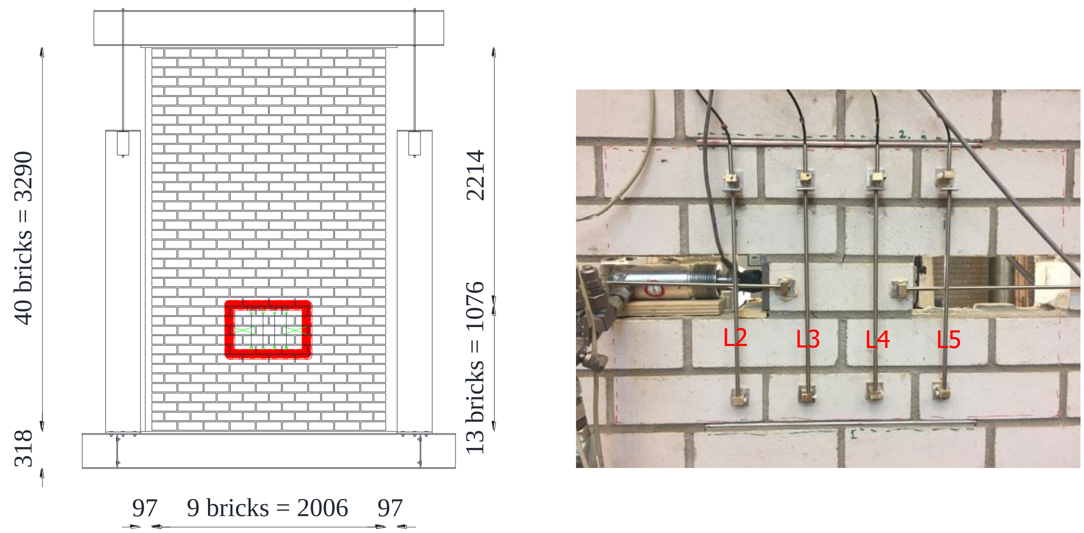


Figure 36 – Test set-up for shove test at location 01. The dimensions are in mm.

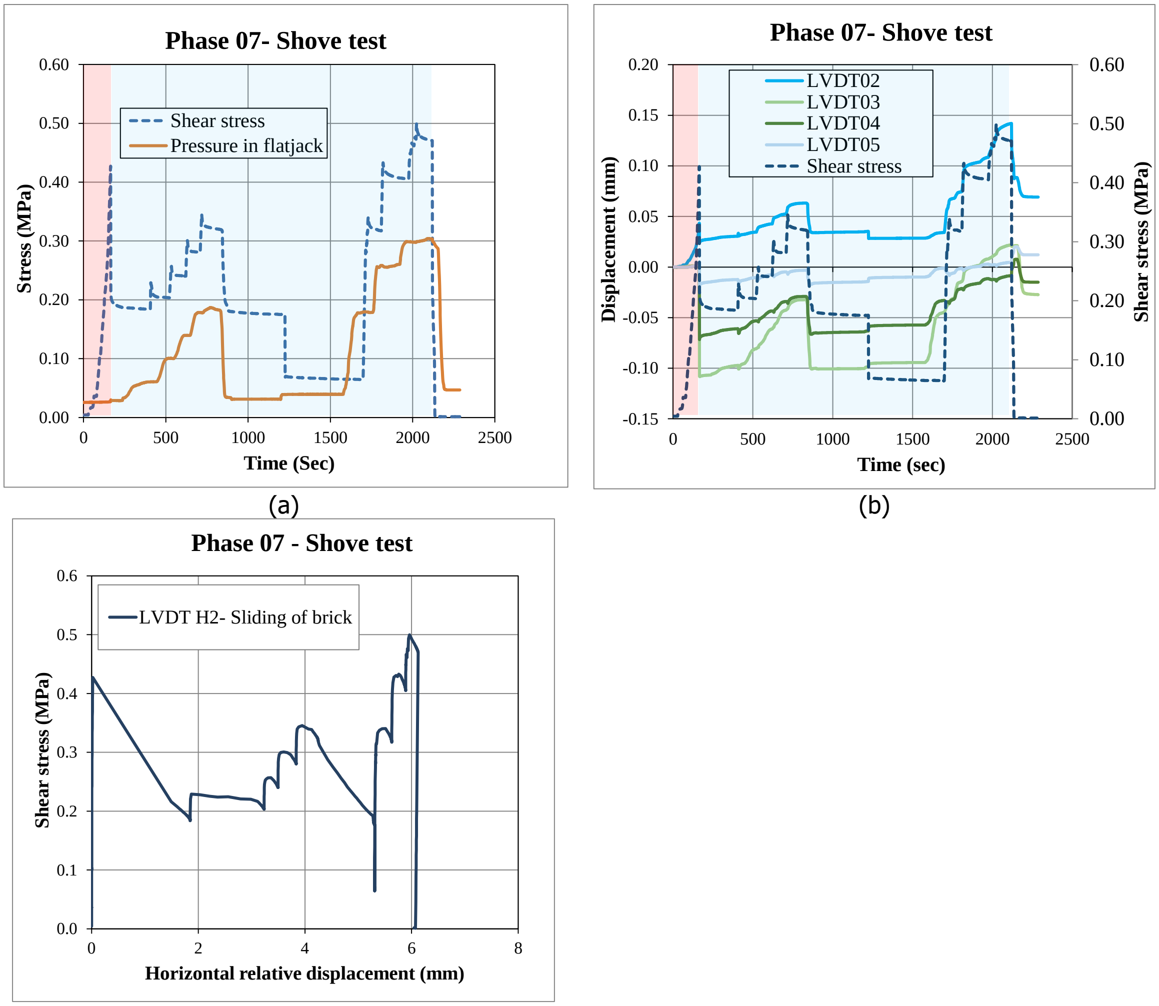


Figure 37 – First shove test at location 01: (a) shear stress and pressure in the flatjack versus time; (b) displacements of the vertical LVDTs and shear stress versus time; (c) shear stress versus absolute values of brick sliding.

The steps taken into account to interpret the results of the shove tests are shown in Figure 38. A summary of these steps is as follows:

- *First step* in which the values of the shear strength versus the corresponding pre-compression stress are plotted without any modification (see Figure 38a),
- *Second step* in which the values of the pre-compression stress is modified to account for the flatjack to brick correction factor (see Figure 38b),
- *Third step* in which the pre-compression stress is corrected to account for the overburden pressure (see Figure 38c).

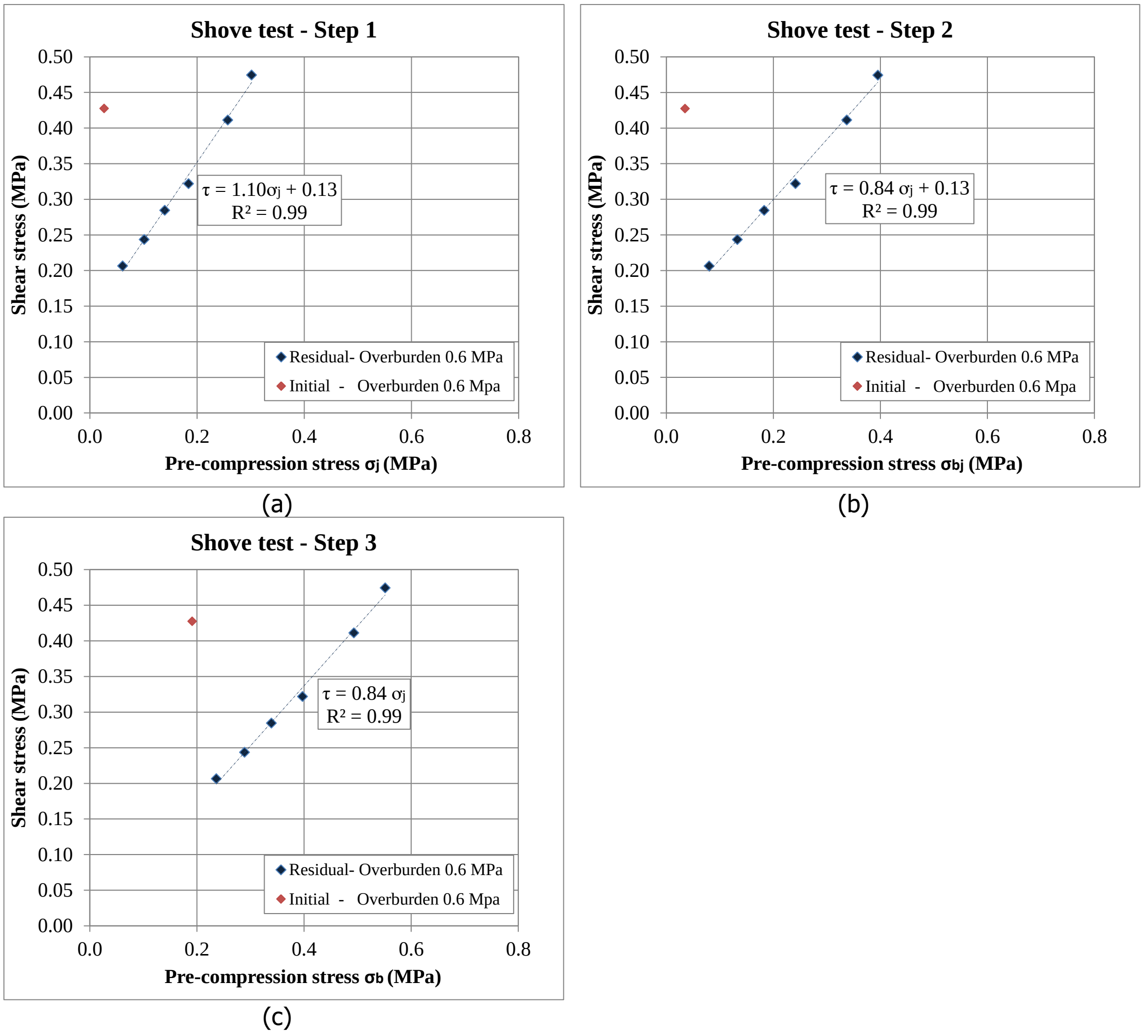


Figure 38 – Shear properties obtained from shove test at location 01: (a) shear stress versus corresponding values of pre-compression stress; (b) shear stress versus corresponding values of pre-compression stress to account for the jack to brick correction factor; (c) shear stress versus corresponding values of pre-compression stress to account for both the jack to brick correction factor and overburden.

After performing the shove test, the overburden on the top of the wall was reduced (Phase 08) from 0.60 MPa to 0.25 MPa, aiming to investigate the effect of the overburden on the testing results. The variations of the LVDTs' deformation during the release of pressure versus time are presented in Figure 39. Then, the shove test was repeated (Phase 09). The outputs of the second shove test on the first location of the wall are shown in Figure 40. Note that only the residual properties can be measured at this phase of test, since the bond between the brick-mortar interface was already broken.

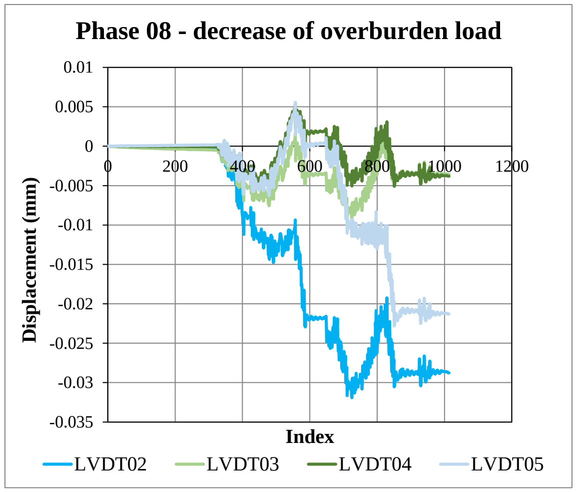
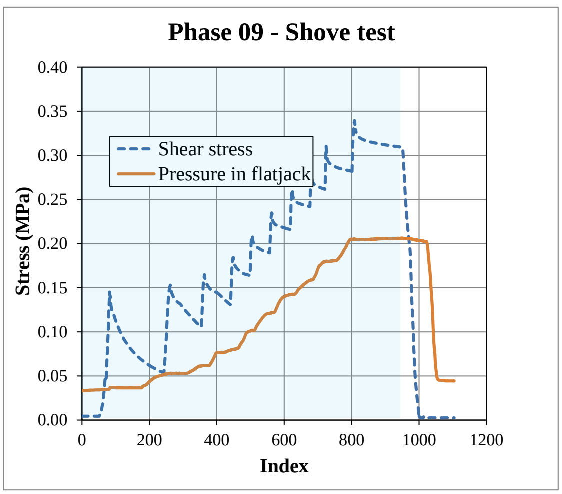
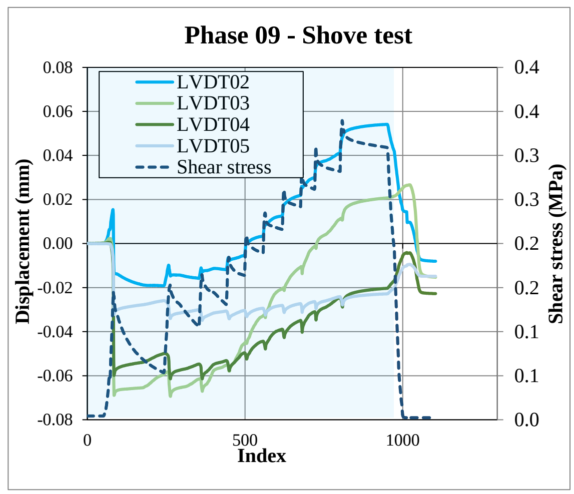


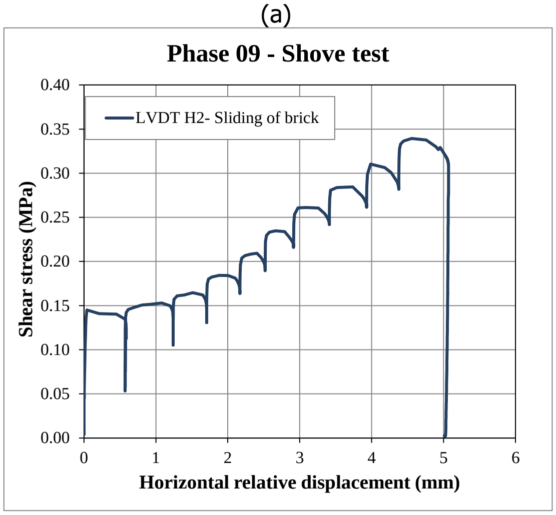
Figure 39 – The LVDTs' deformation during the reduction of overburden pressure from 0.60 MPa to 0.25MPa at location 01.



(a)



(b)



(c)

Figure 40 – Second shove test at location 01: (a) shear stress and pressure in the flatjack versus time; (b) displacements of the vertical LVDTs and shear stress versus time; (c) shear stress versus absolute values of brick sliding.

The steps taken into account to interpret the results of the second shove tests are shown in Figure 41. A summary of these steps is as follows:

- *First step* in which the values of the shear strength versus the corresponding pre-compression stress are plotted without any modification (see Figure 41a),
- *Second step* in which the values of the pre-compression stress is modified to account for the flatjack to brick correction factor (see Figure 41b),
- *Third step* in which the pre-compression stress is corrected to account for the overburden pressure (see Figure 41c).

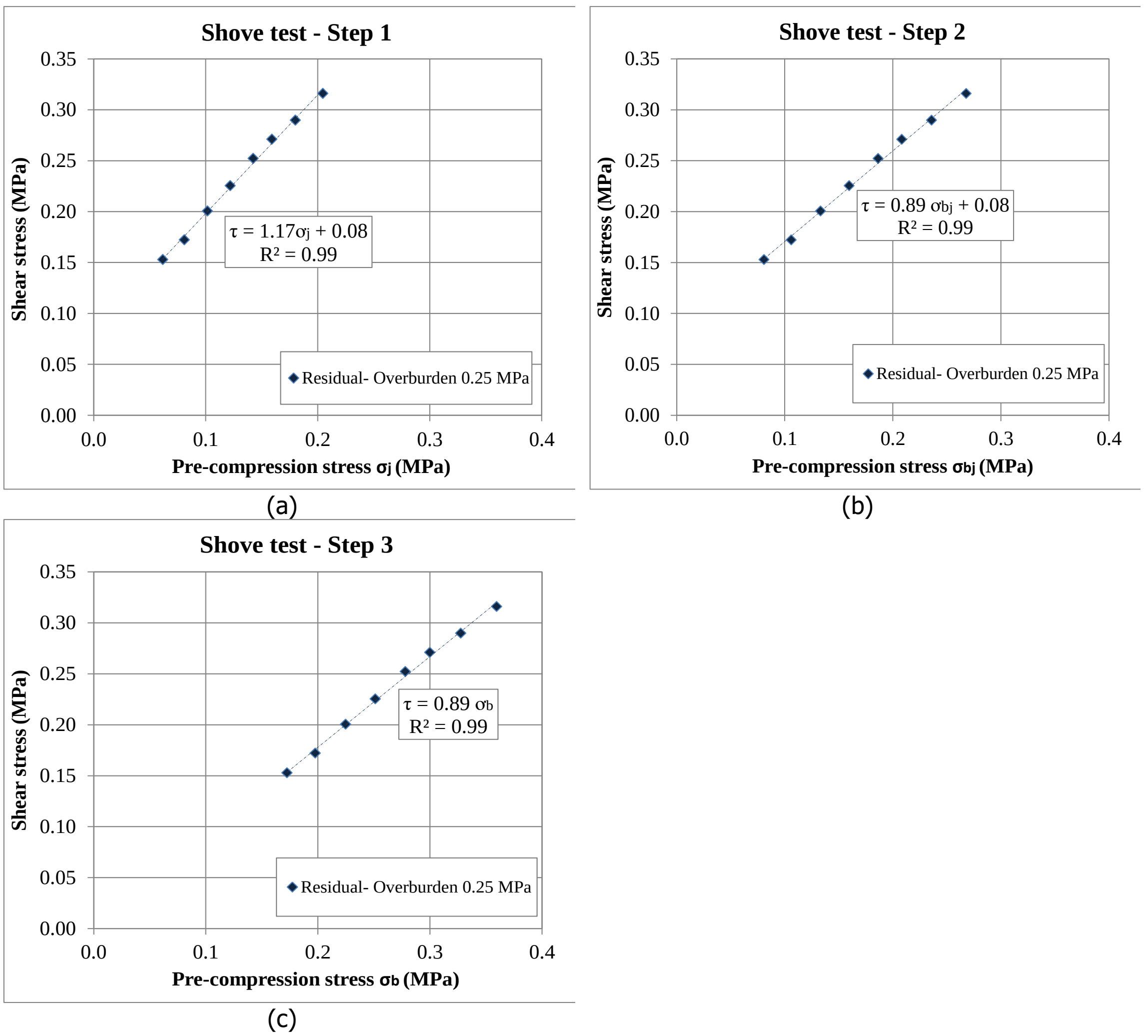


Figure 41 – Shear properties obtained from second shove test at location 01: (a) shear stress versus corresponding values of pre-compression stress; (b) shear stress versus corresponding values of pre-compression stress to account for the jack to brick correction factor; (c) shear stress versus corresponding values of pre-compression stress to account for both the jack to brick correction factor and overburden.

Location 02

Before the execution of the shove test, the two bricks adjacent to the test unit have to be removed. The vertical LVDTs, used for the double flatjack tests, are kept in place. Throughout this phase (Phase 05), the vertical deformations were recorded. The deformations of the LVDTs' versus time are presented in Figure 42. It should be pointed out that prior to the removal of the bricks the pressure in the flatjacks was released. The shortening of all the LVDTs is reported. However, a lower deformation is registered for the ones placed in the middle (LVDT03 and LVDT04).

The double flatjack test was repeated after removal of the two bricks ("shove test configuration") aiming to find the jack to brick correction factor (Phase 06). The vertical deformations were measured during the tests, which enabled to evaluate the fictitious Young's modulus of masonry (E_{DFJ}*), see Figure 43. The fictitious Young's modulus was calculated considering the measurements of the two middle LVDTs only. The chord modulus was evaluated in the ascending branch of the stress-strain relationship between the maximum registered load and 1/2 of the maximum stress. The calculation of the flatjack to brick correction factor is summarised in Table 12.

Table 12 – Calculation of the flatjack to brick correction factor at location 02.

***Location 2** of CS brick masonry wall*	Unit	
Pressure on top of the slot due to the weight of masonry and overburden load	MPa	0.25
Young's modulus (readings of middle LVDTs) – double flatjack test	MPa	7012
Young's modulus (readings of middle LVDTs) – modified double flatjack test	MPa	6079
Flatjack to brick correction factor $K_{bj} = \frac{E_{DFJ}}{E^*_{DFJ}}$	-	1.15

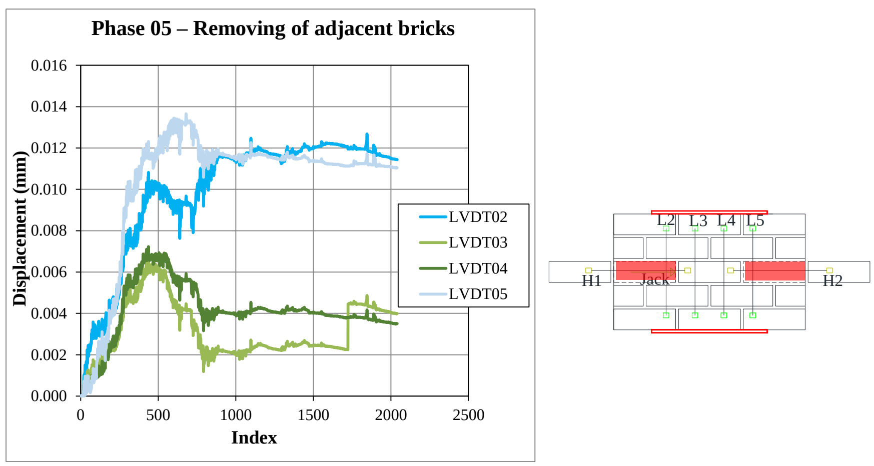
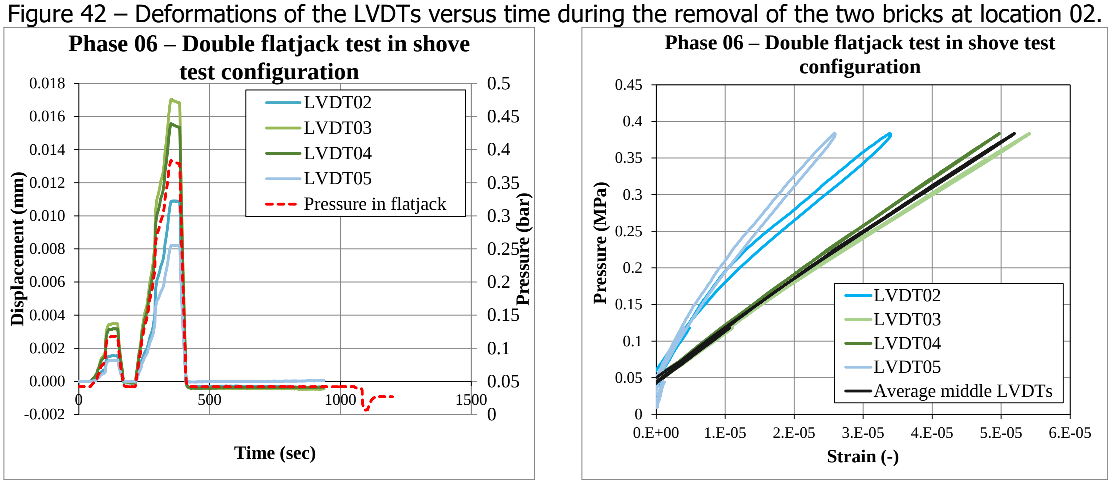


Figure 42 – Deformations of the LVDTs versus time during the removal of the two bricks at location 02.



(a) (b)

Figure 43 – Double flatjack test in the shove test configuration at location 02: (a) deformation versus time; (b) deformations versus flatjack pressure.

After performing of the double flatjack test in the “shove test configuration”, a horizontal jack was inserted and the shove test was conducted (Phase 07). The test set-up is presented in Figure 44. The variation of the shear stress as well as overburden load versus time is shown in Figure 45a. The vertical LVDT’s deformations versus time are shown in Figure 45b. The shear stress versus sliding of the masonry unit is shown in Figure 45c.

The testing phases can be classified as follows: (i) the initial phase, in which the shear load can be associated with both cohesion and friction (marked in red); and (ii) the residual phase, where failure at the brick-mortar interface has already occurred, thus the shear load can be associated only with a frictional behaviour (marked in blue).

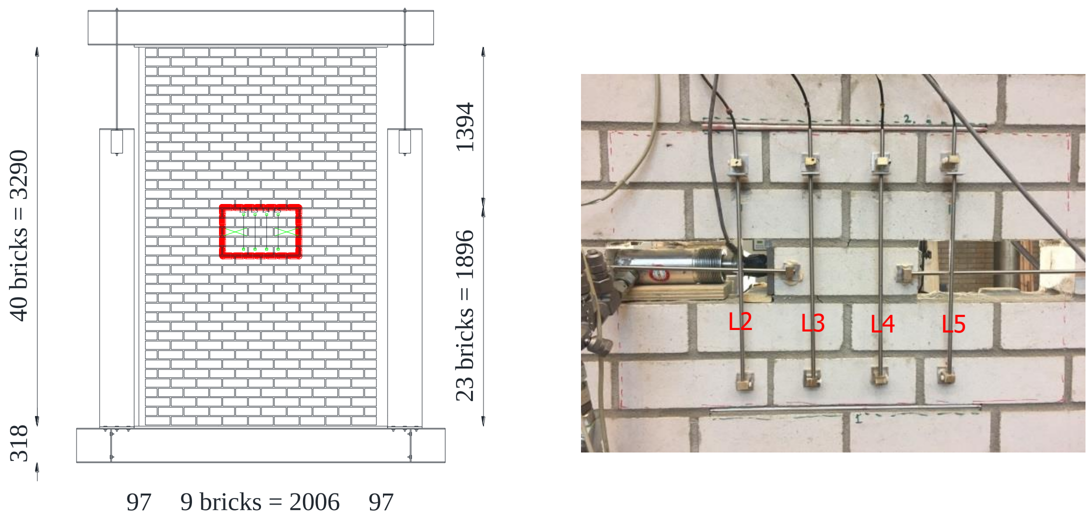


Figure 44 – Test set-up for shove test at location 02. The dimensions are in mm.

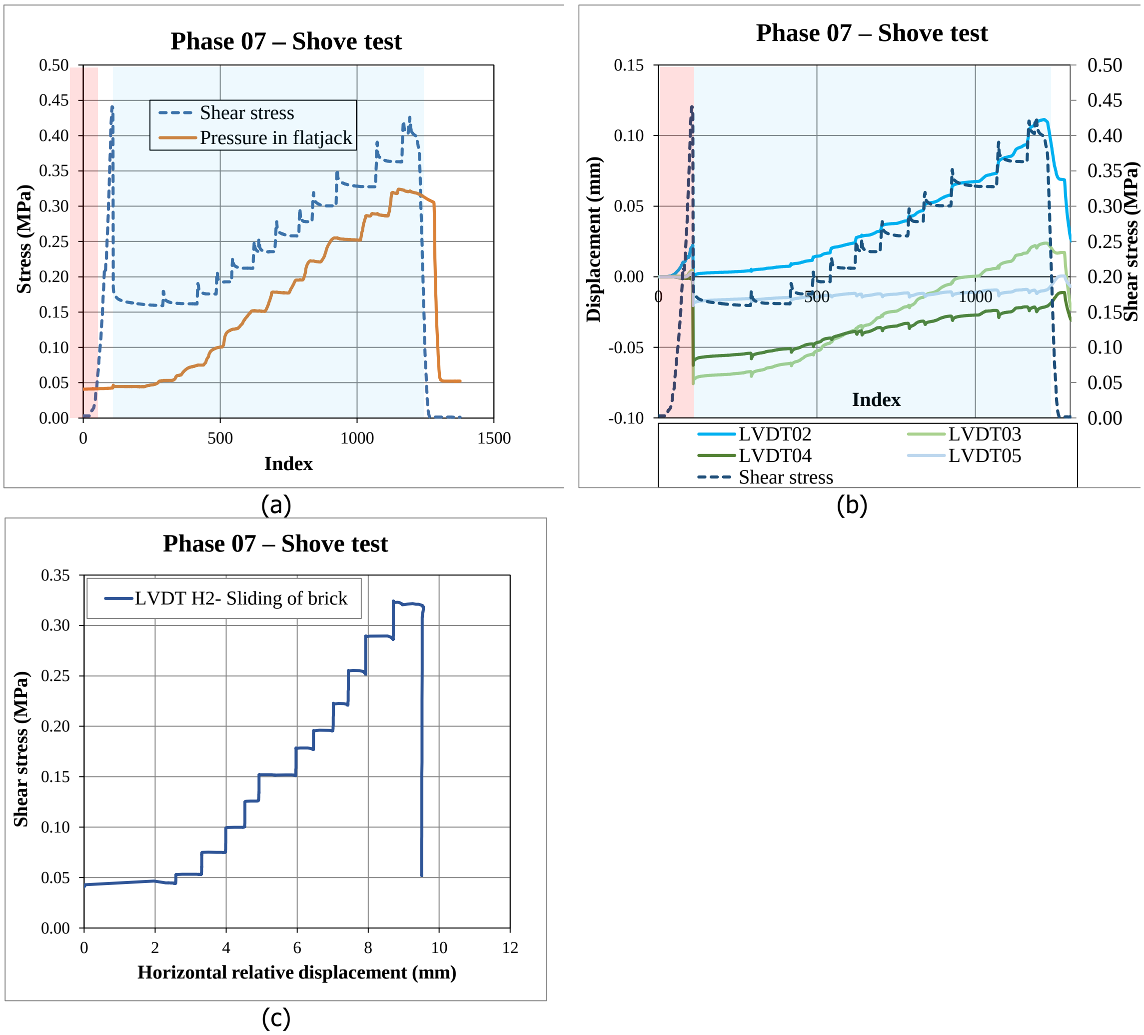
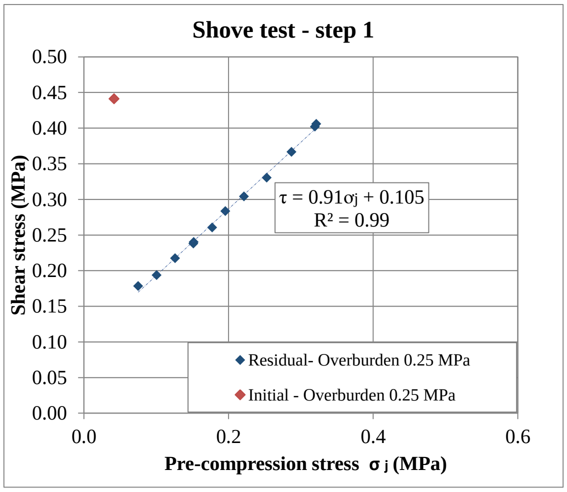


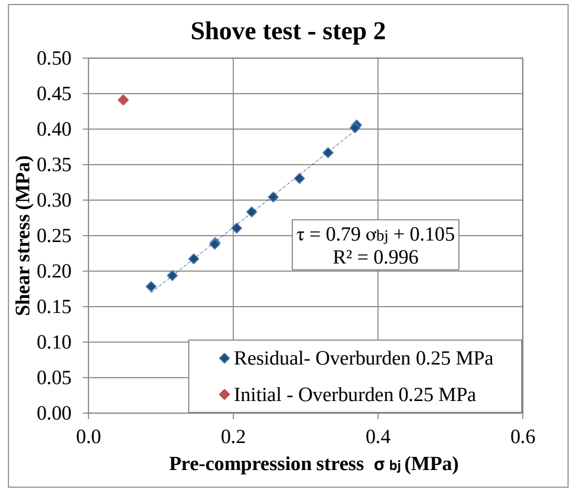
Figure 45 – First shove test at location 02: (a) shear stress and pressure in the flatjack versus time; (b) displacements of the vertical LVDTs and shear stress versus time; (c) shear stress versus absolute values of brick sliding.

The steps taken into account to interpret the results of the shove tests are shown in Figure 46. A summary of these steps is as follows:

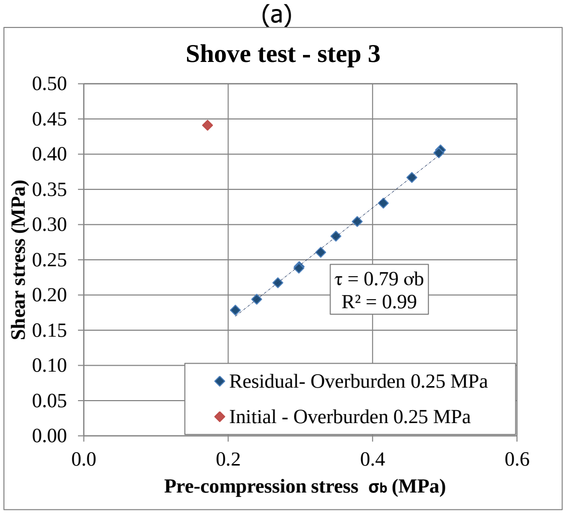
- *First step* in which the values of the shear strength versus the corresponding pre-compression stress are plotted without any modification (see Figure 46a),
- *Second step* in which the values of the pre-compression stress is modified to account for the flatjack to brick correction factor (see Figure 46b),
- *Third step* in which the pre-compression stress is corrected to account for the overburden pressure (see Figure 46c).



(a)



(b)



(c)

Figure 46 – Shear properties obtained from first shove test at location 02: (a) shear stress versus corresponding values of pre-compression stress; (b) shear stress versus corresponding values of pre-compression stress to account for the jack to brick correction factor; (c) shear stress versus corresponding values of pre-compression stress to account for both the jack to brick correction factor and overburden.

After performing the shove test, the overburden on the top of the wall was reduced from 0.25 MPa to 0.15 MPa (Phase 08). The variations of the LVDTs' deformation during the release of pressure versus time are presented in Figure 47. Then, the shove test was repeated (Phase 09). The outputs of the second shove test on the second location of the wall are shown in Figure 48. Note that only the residual properties can be measured at this phase of test, since the bond between the brick-mortar interface was already broken.

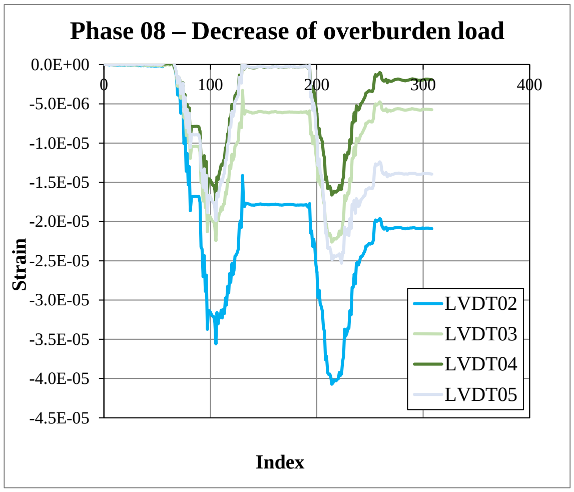
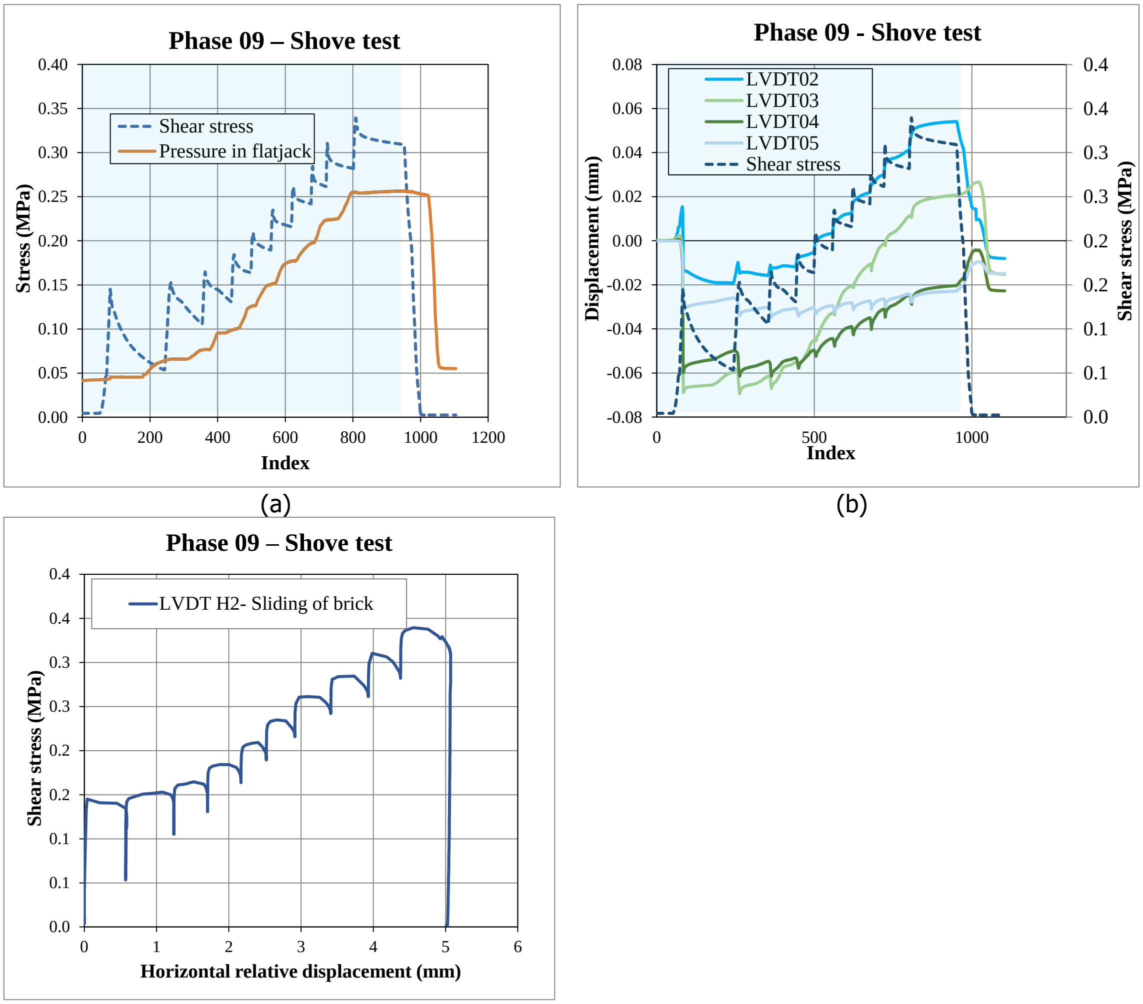


Figure 47 – The LVDTs' deformation during the reduction of overburden pressure from 0.25 MPa to 0.15 MPa at location 02.



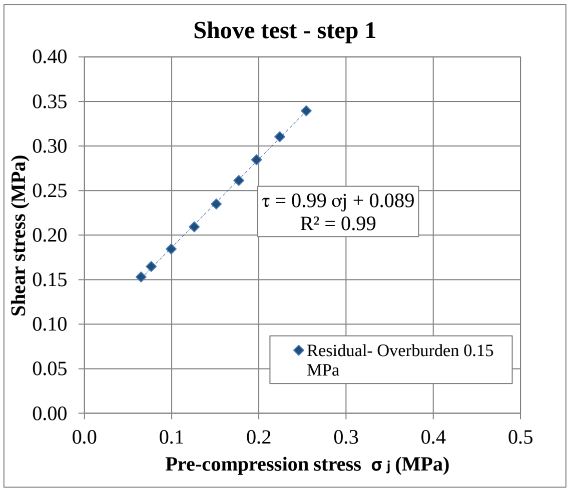
(a) (b)

(c)

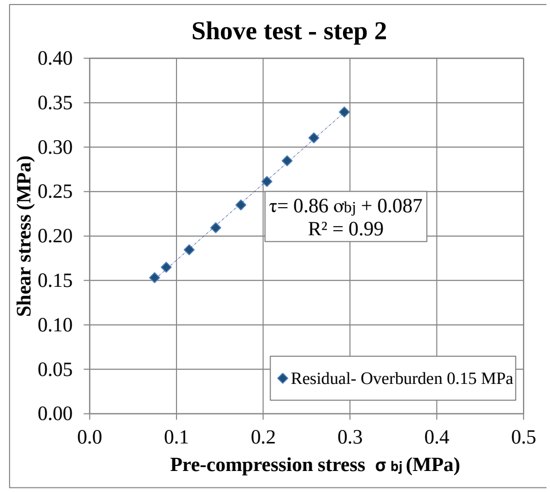
Figure 48 – Second shove test at location 02: (a) shear stress and pressure in the flatjack versus time; (b) displacements of the vertical LVDTs and shear stress versus time; (c) shear stress versus absolute values of brick sliding.

The steps taken into account to interpret the results of the second shove tests are shown in Figure 49. A summary of these steps is as follows:

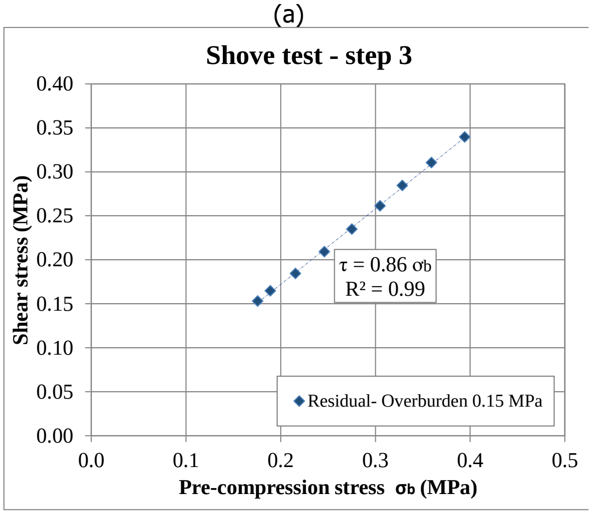
- *First step* in which the values of the shear strength versus the corresponding pre-compression stress are plotted without any modification (see Figure 49a),
- *Second step* in which the values of the pre-compression stress is modified to account for the flatjack to brick correction factor (see Figure 49b),
- *Third step* in which the pre-compression stress is corrected to account for the overburden pressure (see Figure 49c).



(a)



(b)



(c)

Figure 49 – Shear properties obtained from second shove test at location 02: (a) shear stress versus corresponding values of pre-compression stress; (b) shear stress versus corresponding values of pre-compression stress to account for the jack to brick correction factor; (c) shear stress versus corresponding values of pre-compression stress to account for both the jack to brick correction factor and overburden.

Location 03

Before the execution of the shove test, the two bricks adjacent to the test unit have to be removed. The vertical LVDTs, used for the double flatjack tests, are kept in place. Throughout this phase (Phase 05), the vertical deformations were recorded. The deformations of the LVDTs' versus time are presented in Figure 50. It should be pointed out that prior to the removal of the bricks the pressure in the flatjacks was released. The shortening of all the LVDTs is reported. However, a lower deformation is registered for the ones placed in the middle (LVDT03 and LVDT04).

The double flatjack test was repeated after removal of the two bricks ("shove test configuration") aiming to find the jack to brick correction factor. The vertical deformations were measured during the tests, which enabled to evaluate the fictitious Young's modulus of masonry (E_{DFJ}*), see Figure 51. The fictitious Young's modulus was calculated considering the measurements of the two middle LVDTs only. The chord modulus was evaluated in the ascending branch of the stress-strain relationship between the maximum registered load and 1/2 of the maximum stress. The calculation of the flatjack to brick correction factor is summarised in Table 13. A value less than 1 was found for the jack to brick correction factor. This result is not consistent with the results found in the first two locations of the wall, where a factor higher than 1 was obtained. This can be attributed that no perfect contact between the top steel beam and the wall was reported. Moreover, the limitations of the flatjack testing methods are accounted for masonry with low stress and objective elaboration of the testing results [16].

Table 13 – Calculation of the flatjack to brick correction factor at location 03.

***Location 03** of CS brick masonry wall*	Unit	
Pressure on top of the slot due to the weight of masonry and overburden load	MPa	0.15
Young's modulus (readings of middle LVDTs) – double flatjack test	MPa	8620
Young's modulus (readings of middle LVDTs) – modified double flatjack test	MPa	10457
Flatjack to brick correction factor $K_{bj} = \frac{E_{DFJ}}{E^{*}_{DFJ}}$	-	**0.82**

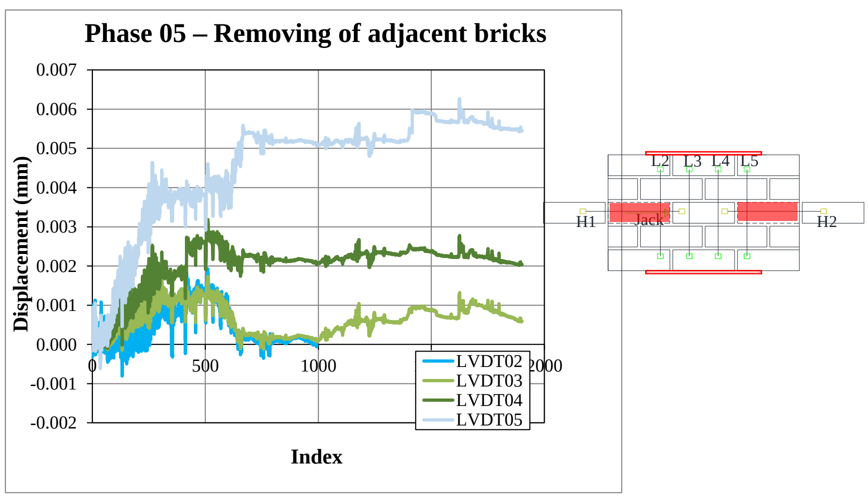
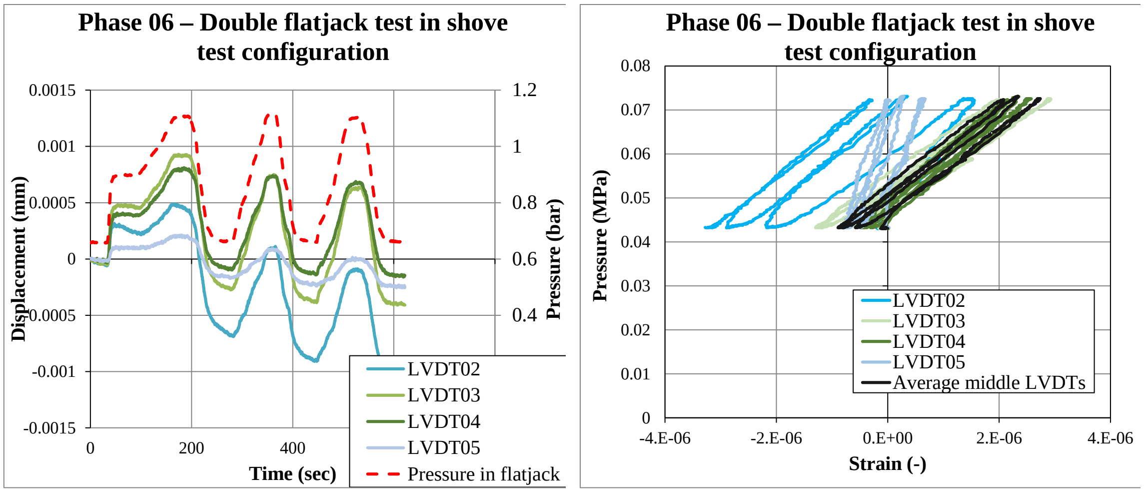


Figure 50 – Deformations of the LVDTs versus time during the removal of the two bricks at location 03.



(a) (b)

Figure 51 – Double flatjack test in the shove test configuration at location 03: (a) deformation versus time; (b) deformations versus flatjack pressure.

After performing of the double flatjack test in the "shove test configuration", a horizontal jack was inserted and the shove test was conducted (Phase 07). The test set-up is presented in Figure 52. The variation of the shear stress as well as overburden load versus time is shown in Figure 53a. The vertical LVDT's deformations versus time are shown in Figure 53b. The shear stress versus sliding of the masonry unit is shown in Figure 53c.

The testing phases can be classified as follows: (i) the initial phase, in which the shear load can be associated with both cohesion and friction (marked in red); and (ii) the residual phase, where failure at the brick-mortar interface has already occurred, thus the shear load can be associated only with a frictional behaviour (marked in blue).

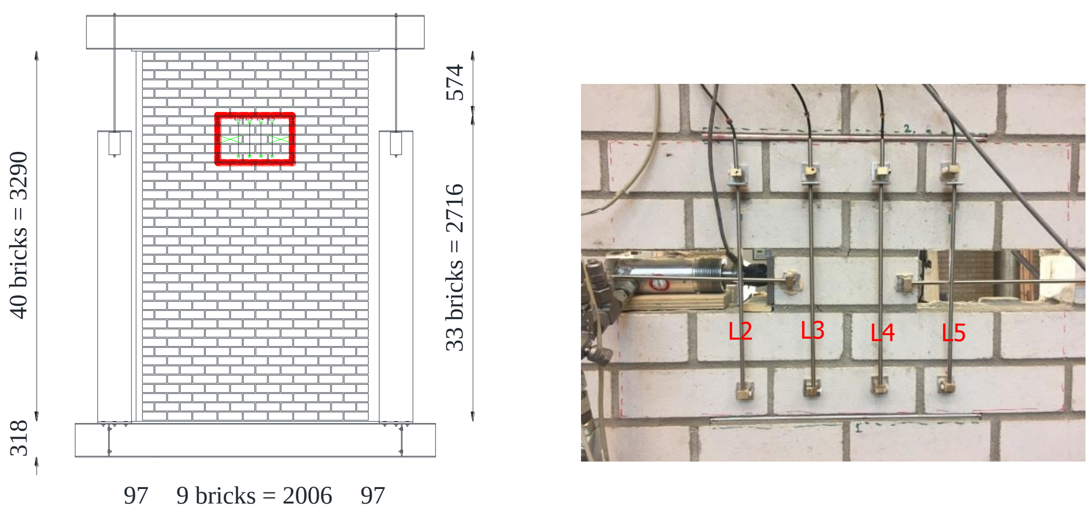
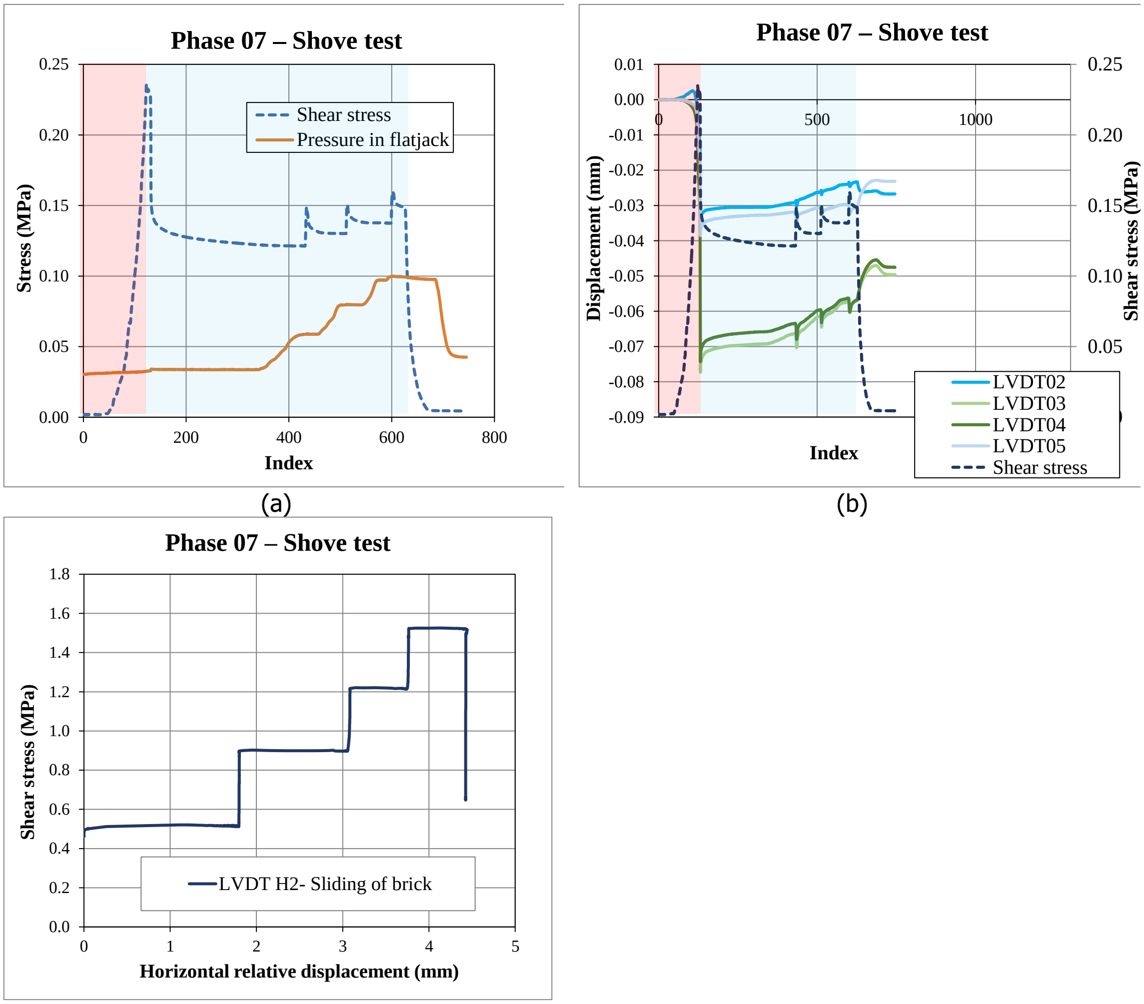


Figure 52 – Test set-up for shove test at location 03. The dimensions are in mm.

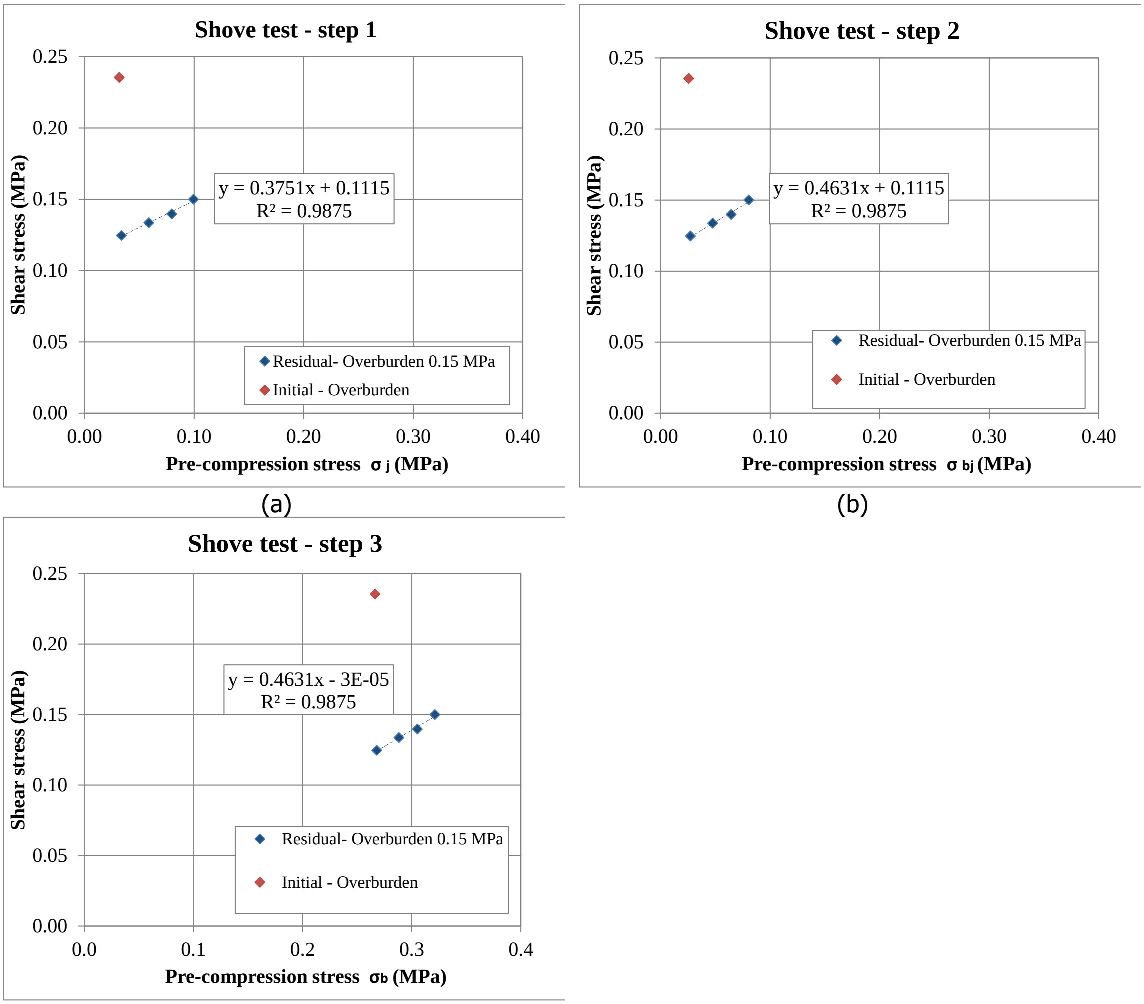


(a) (b) (c)

Figure 53 – First shove test at location 03: (a) shear stress and pressure in the flatjack versus time; (b) displacements of the vertical LVDTs and shear stress versus time; (c) shear stress versus absolute values of brick sliding.

The steps taken into account to interpret the results of the shove tests are shown in Figure 54. A summary of these steps is as follows:

- _First step_ in which the values of the shear strength versus the corresponding pre-compression stress are plotted without any modification (see Figure 54a),
- _Second step_ in which the values of the pre-compression stress is modified to account for the flatjack to brick correction factor (see Figure 54b),
- _Third step_ in which the pre-compression stress is corrected to account for the overburden pressure (see Figure 54c).



(c)

Figure 54 - Shear properties obtained from the first shove test at location 03: (a) shear stress versus corresponding values of pre-compression stress; (b) shear stress versus corresponding values of pre-compression stress to account for the jack to brick correction factor; (c) shear stress versus corresponding values of pre-compression stress to account for both the jack to brick correction factor and overburden.

After performing the shove test, the overburden on the top of the wall was increased from 0.15 MPa to 0.60 MPa (Phase 08). The variations of the LVDTs' deformation during the release of pressure versus time are presented in Figure 55. Then, the shove test was repeated (Phase 09). The outputs of the second shove test on the third location of the wall are shown in Figure 56. Note that only the residual properties can be measured at this phase of test, since the bond between the brick-mortar interface was already broken.

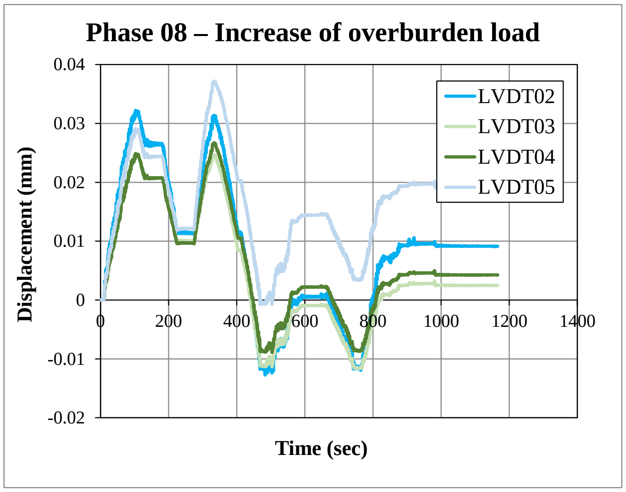
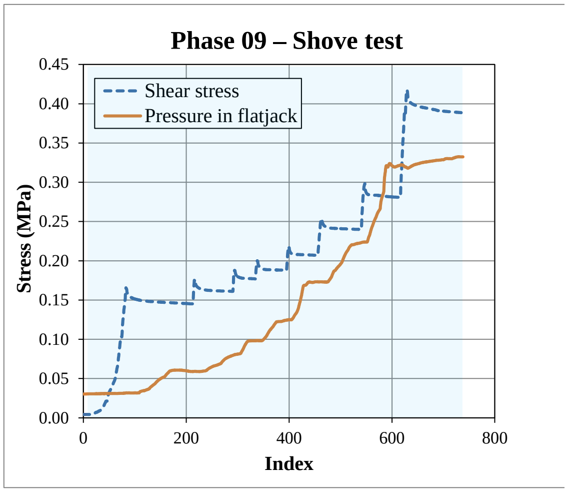
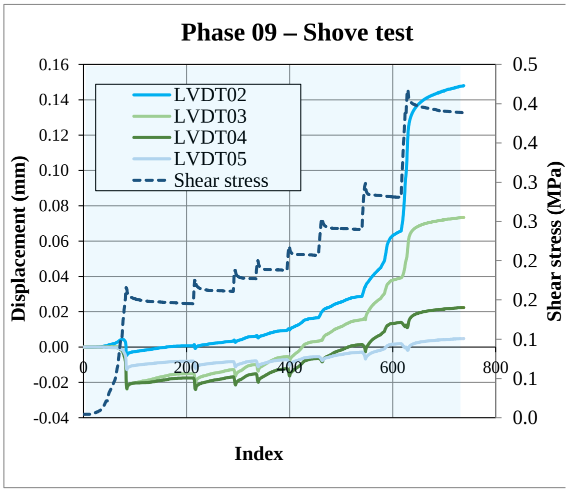


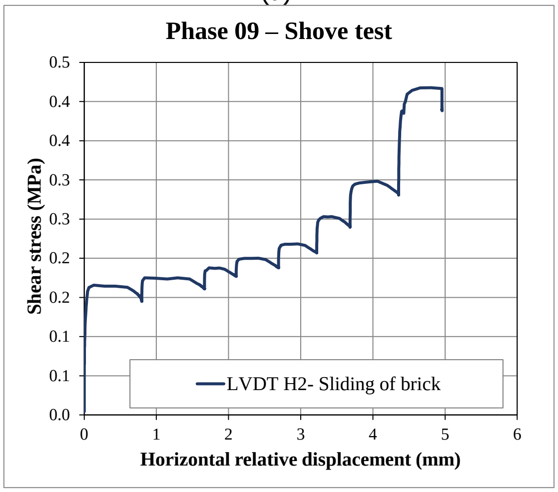
Figure 55 – The LVDTs' deformation during the increase of overburden pressure from 0.15 MPa to 0.60 MPa at location 03.



(a)



(b)

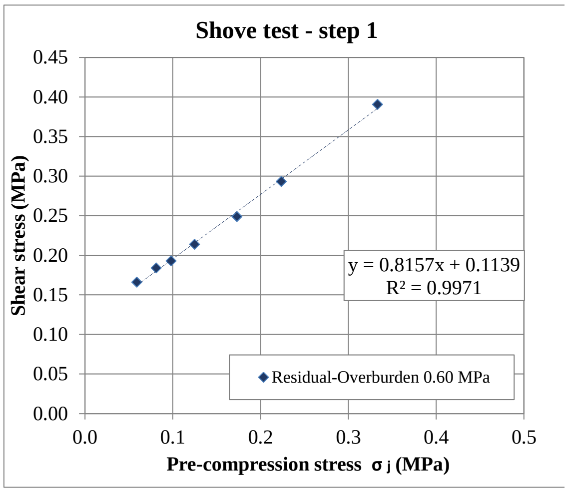


(c)

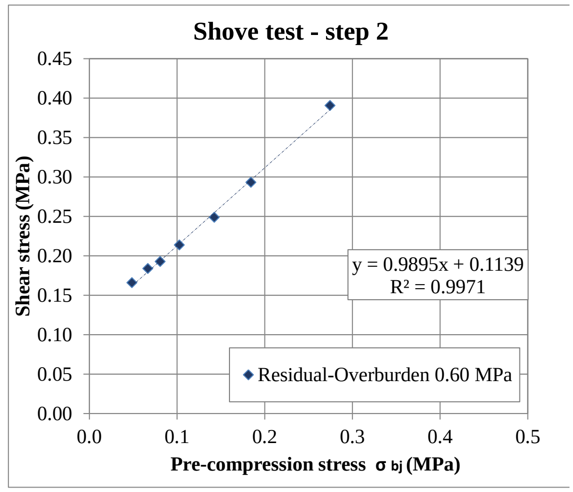
Figure 56 – Second shove test at location 03: (a) shear stress and pressure in the flatjack versus time; (b) displacements of the vertical LVDTs and shear stress versus time; (c) shear stress versus absolute values of brick sliding.

The steps taken into account to interpret the results of the second shove tests are shown in Figure 57. A summary of these steps is as follows:

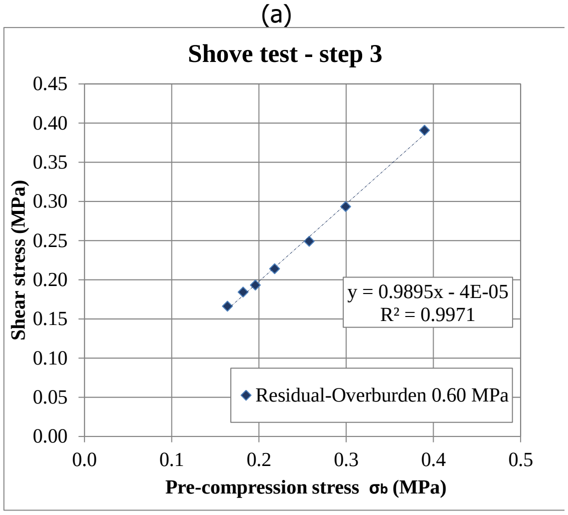
- *First step* in which the values of the shear strength versus the corresponding pre-compression stress are plotted without any modification (see Figure 57a),
- *Second step* in which the values of the pre-compression stress is modified to account for the flatjack to brick correction factor (see Figure 57b),
- *Third step* in which the pre-compression stress is corrected to account for the overburden pressure (see Figure 57c).



(a)



(b)



(c)

Figure 57 – Shear properties obtained from second shove test at location 03: (a) shear stress versus corresponding values of pre-compression stress; (b) shear stress versus corresponding values of pre-compression stress to account for the jack to brick correction factor; (c) shear stress versus corresponding values of pre-compression stress to account for both the jack to brick correction factor and overburden.

Summary of the results of the shove tests

A summary of the results of the shove tests for the three different locations of the CS brick masonry wall is presented in this section. The testing phases as well as the testing outputs for each location are listed in Table 14. The presented information is as follows:

- *Phase 05* – The increase in the stress state of the test unit due to removal of the two adjacent bricks. The increase of stress is calculated taking into account the displacements of the LVDT's attached in correspondence of the test unit (later being slide during the shove test) as well the chord modulus evaluated through the double flatjack test.
- *Phase 06* – Evaluation of the jack to brick correction factor. This factor is evaluated as the ratio of the chord elastic modulus, calculated from the double flatjack test, to the fictitious elastic modulus, evaluated from performing double flatjack test in the shove test configuration.
- *Phase 07* – Performing the shove tests and find the shear properties of the brick-mortar interface. In this phase the actual value of the normal compressive stress on the test unit should be evaluated, accounting for the contribution of the flatjack pressure (through the jack to brick correction factor found in phase 06) and of the overburden (far-field effect). To account for the far-field effect, the residual failure criterion is translated to result in zero cohesion.
- *Phase 08* – Changing the overburden with the aim to investigate the far-field effect on the residual shear properties. The increase/decrease in the stress state on the test unit due to the change of overburden is also evaluated. This stress is evaluated taking into account the measured displacements as well as the fictitious chord modulus calculated at *Phase 06*.
- *Phase 09* – Repeating the shove test with the changed overburden load. The stress in the brick due to the far-field effect and the residual properties under the new defined circumstances are evaluated.

The overburden contribution can be also evaluated considering the increase of stress state of the test unit measured at Phase 05. Thus, it can be expected that these values are comparable with the values obtained due to the translation of the residual failure criterion found at Phase 07; these values are marked with yellow in Table 14. For the three locations of the wall no acceptable correspondence is found between the values calculated at Phase 05 and Phase 07. It should be pointed out that in the last location of the wall with 0.15 MPa overburden load, the evaluation of the overburden contribution at Phase 07 resulted in a value equal to 0.24 MPa. Therefore, it can be concluded that due to the insufficient contact between the top steel beam and the wall, these results should be excluded from the evaluation of the shear properties. Considering the increase of the stress state calculated due to the removal of the bricks (Phase 05) and the variation of the stress measured due to the change in the overburden load (Phase 08), the stress state presents at the test unit can be evaluated. Thus, it can be expected that these values are comparable with the values obtained due to the translation of the residual failure criterion found at Phase 09; these values are marked with purple in Table 14. An acceptable correspondence between the evaluations of the overburden pressure at Phase 08 and Phase 09 is found, with an exception of the second location with 0.15 MPa overburden. As reported by Binda et al. [16], the reliability of the results of the flatjack method for a wall with low stress acting is always a matter of concern.

Table 14 – Summary of the results of the shove tests.

Testing phase		Unit	Overburden (MPa)		
			Location01	Location02	Location03
			0.60	0.25	0.15
Phase 05	Variation of the stress state due to removal of bricks	MPa	0.11 ↗	0.07 ↗	0.04 ↗
Phase 06	Evaluation of the jack to brick correction factor (K_{bj})	-	1.31	1.15	0.85
Phase 07	Evaluation of the overburden pressure (far-field effect)	MPa	0.16	0.13	0.24
	Initial shear strength (τ_0)	MPa	0.27	0.30	0.11
	Coefficient of friction (μ)	-	0.84	0.79	0.46
Phase 08	Changing the overburden load to investigate the effect of overburden on the results		Overburden (MPa)		
			Location01	Location02	Location03
			0.25	0.15	0.60
	Variation of stress due to applied overburden	MPa	0.04 ↘	0.023↘	0.10↗
	Stress state presents in the test unit	MPa	0.07	0.05	0.14
Phase 09	Evaluation of the overburden pressure (far-field effect)	MPa	0.09	0.10	0.12
	Coefficient of friction (μ)	-	0.89	0.86	0.99

The results of the shove tests, in terms of shear strength versus modified values of normal compressive stress in the test unit, obtained for the different locations of the CS brick masonry wall with different overburden loads, are presented together in Figure 58. The residual Coulomb strength criterion established from performing six tests at the three different locations of the wall are almost similar, with the exception of the results found at the third location of the wall, in particular for the one with the overburden of 0.15 MPa. As mentioned before, at overburden of 0.15 MPa an acceptable contact between the top steel beam and the wall was not observed. Thus, both the initial and the residual failure points found for the third location of the wall with overburden of 0.15 MPa are excluded from the calculation of the shear properties of the brick-mortar interface. Considering the results of the first and second location of the wall, the residual friction coefficient is obtained as 0.79. Assuming that the slope of the failure criterion for both the initial and residual properties is the same, the initial shear strength resulted in a value equal to 0.28 MPa.

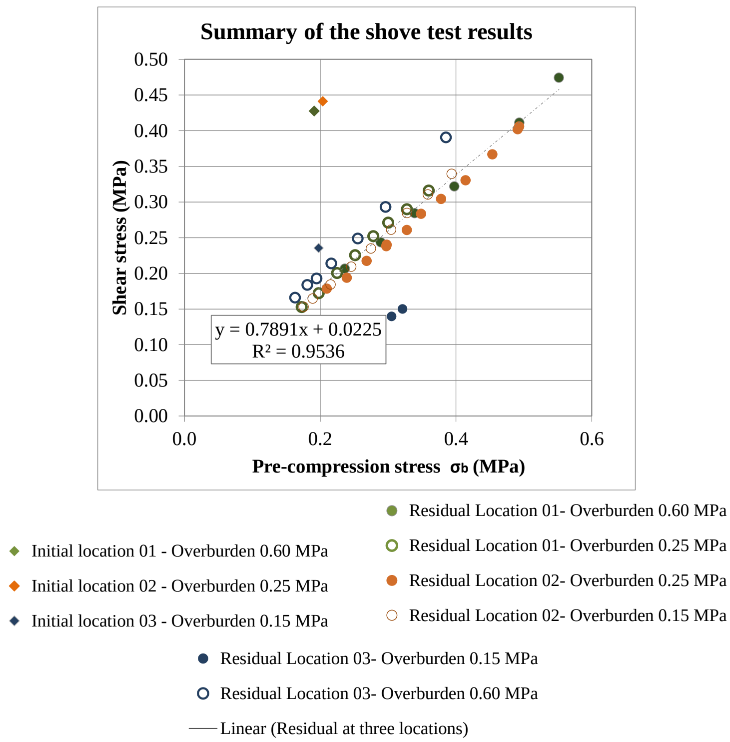


Figure 58 – Results of the shove tests on the three different locations of the CS brick masonry wall. The data are elaborated using the proposal of EUCentre.

6 Correlations between the results of SDT and DT

To validate the suitability of the in-situ slightly-destructive test (SDT) methods to evaluate the compression and shear properties of masonry, their results can be validated against the results of standardised destructive tests (DT) on the companion samples. In this section, a comparison is made between the results of: (i) the double flatjack tests and the results of compression tests on small scale wallets as suggested by EN1052-1:1998 [6] and; (ii) the shove tests and the results of the shear-compression tests on triplets as suggested by EN1052-3:2002 [7].

The applicability of the double flatjack test to evaluate the compression properties of masonry was validated by comparing the obtained results with the results of standardised tests on wallets. The double flatjack tests were performed on the three different locations of the wall. To avoid undesired failure and damages to the contrast portion of the masonry, the pressure values in the flatjacks were chosen carefully. In general, quite low values were adopted. This was applied in particular for the last location placed in the highest portion of the wall having the lowest overburden (0.15 MPa). 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 could not completely allow the lateral expansion of the wall. The stress-strain relationships established during the double flatjack tests are shown in Figure 59a. For all the three locations, the stress-strain relationship in the normal direction presents a similar trend, with an average chord modulus of 9280 MPa and 27% coefficient of variations.

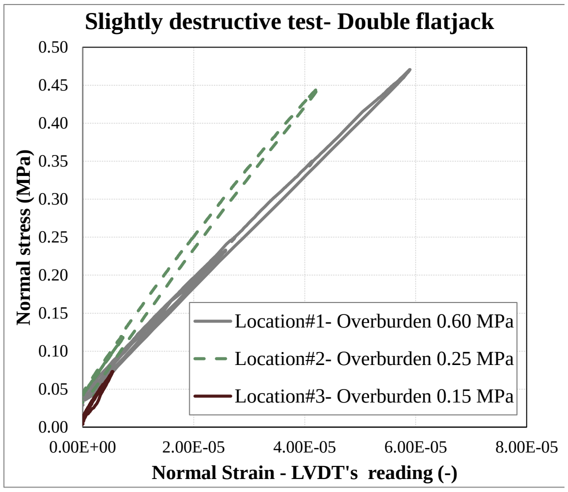
Performing destructive compression tests on the masonry wallets allowed establishing a comprehensive overview of the compression properties of masonry in terms of compressive strength and Young's modulus (both tangent and chord modulus), as provided in Table 15. More detailed information regarding the testing set-up, testing procedure and the outcome of these tests can be found on Ref. [12]. The stress-strain relationship established from destructive compression tests on the masonry wallets is presented in Figure 59b. For the Young's modulus, three different estimates are adopted [12]:

- E_1 is the secant elastic modulus evaluated at 1/3 of the maximum stress;
- E_2 is the secant elastic modulus evaluated at 1/10 of the maximum stress;
- E_3 is the chord Young's modulus evaluated between 1/10 and 1/3 of the maximum stress.

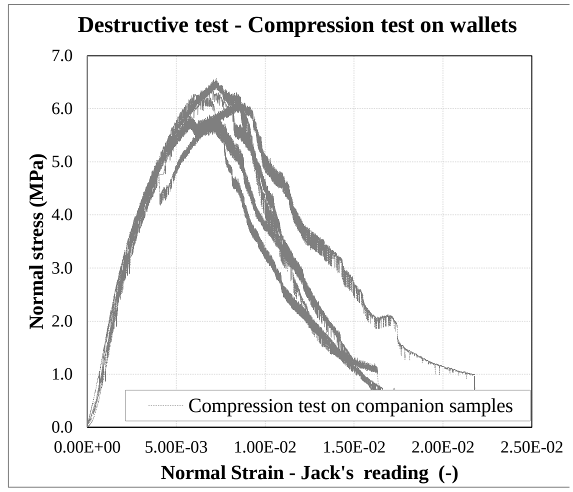
A ratio between the compression properties obtained by testing companion wallets and the double flatjack tests is listed in Table 15. The values of the chord modulus obtained from the double flatjack tests are almost in agreement with the elastic modulus of masonry obtained by test on wallets evaluated 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, see Figure 59c. It can be concluded that the Young's modulus established from the double flatjack test is overestimated by 13%.

Table 15 – Compression properties found from DT on the companion samples and from double flatjack tests.

DT on masonry wallets	***f'm*** MPa	***E_1*** MPa	***E_2*** MPa	***E_3*** MPa
Average	**6.35**	**4972**	**8206**	**4265**
Standard deviation	0.32	568	1008	527
Coefficient of variation	0.05	0.11	0.12	0.12
SDT double flatjack testing method	***f'm*** MPa	***E_{DFJ}*** MPa		
Average	-	**9280**		
Standard deviation	-	2485		
Coefficient of variation	-	0.27		
Ratio between DT/SDT		***E_1/E_{DFJ}***	***E_2/E_{DFJ}***	***E_3/E_{DFJ}***
		0.54	0.88	0.46



(a)



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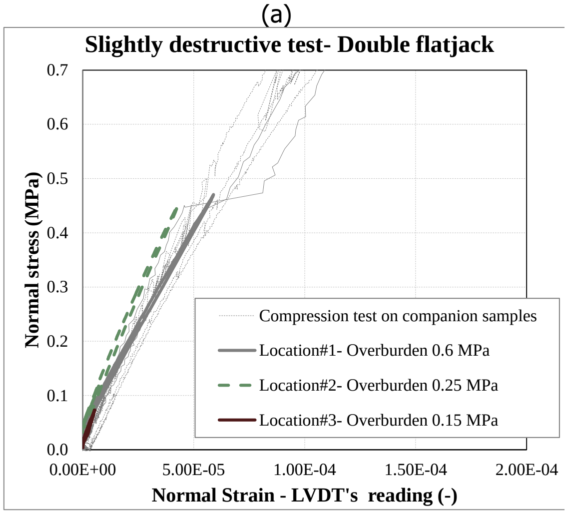

(c)

Figure 59 – Stress-strain relationship obtained from: (a) double flatjack tests on the portions of masonry CS wall; (b) compression tests on the companion samples; (c) detailed view of the elastic phase of both double flatjack test and compression test on companion samples.

The applicability of the shove test to evaluate the shear properties of the brick-mortar interface was validated by comparing the obtained results with the results of standardised compression-shear tests on triplets. The shove tests were performed in the three different locations of the wall. The observed crack patterns for each location can be described as sliding along the brick-mortar interface including cracking of the mortar joint, see Figure 60. The shear properties assessed from the shove test are listed in Table 16.

The nonlinear shear behaviour of the masonry unit-mortar interface was studied by performing shear tests on triplets subjected to three different levels of pre-compression; a minimum of three specimens for each pre-compression level were tested. In the frame of the Coulomb friction model, assuming a linear relationship between the shear strength and the pre-compression stress, the initial shear strength (cohesion) and frictional properties of the brick-mortar interface were characterised. More detailed information regarding the testing set-up, testing procedure and the outcome of these tests can be found on Ref. [12]. The failure of the CS triplets occurred along the brick-mortar interface, in correspondence of the maximum shear load, see Figure 61.

A ratio between the shear properties obtained by shear-compression tests on the companion samples and the shove test is listed in Table 16. Generally, the shear properties are overestimated by more than 60% using the shove test method. Such a significant difference can be primarily caused by the different conditions of the tested masonry portion in the two adopted testing configurations, i.e. different dimensions, boundary conditions, loading arrangement and confinement. It should be noted that since limited number of shove tests were performed, more research is suggested to incorporate both experimental studies and numerical simulation.

Table 16 – Shear properties found from DT on the companion samples and from shove tests.

Shear properties of the brick-mortar interface	Initial shear strength	Initial coefficient of friction	Residual shear strength	Residual coefficient of friction
	MPa	-	MPa	-
Shear-compression test on Triplets	0.18	0.46	0.03	0.48
Shove Test	0.28	0.79	0.02	0.79
Ratio between triplet and shove test	0.65	0.58	1.50	0.61

(a) (b) (c)

Figure 60 – Crack pattern observed during the shove test at: (a) first location; (b) second location; (c) third location.

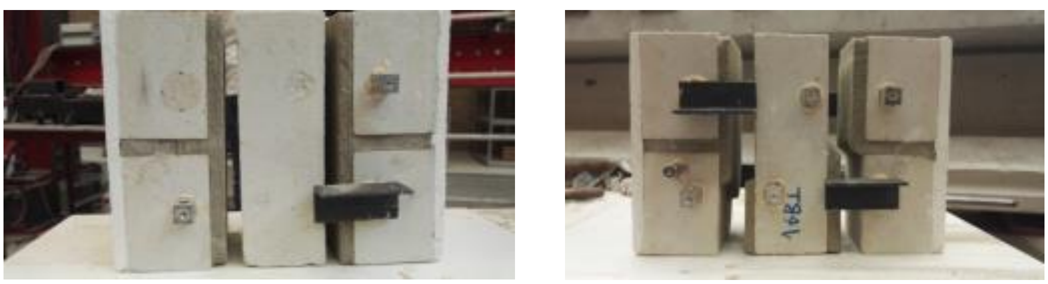

Figure 61 – Typical crack patterns observed during the shear-compression tests on triplets.

7 Concluding remarks

The use of flatjack testing methods to characterise the masonry properties in existing buildings is recommended by ASTM Standards ([3]-[5]). These methods allow assessing the stress state of masonry walls as well as evaluating the compression properties and the shear-sliding properties of the brick-mortar interface, while the integrity of the wall is slightly altered using few operations. Although the testing methods seem straightforward, the limitations of these methods are accounted for both challenging application in case of masonry with low stress and objective elaboration of the testing results [16].

The Dutch building stocks in the Groningen region are often well known for low-rise URM buildings (i.e. maximum two-story) and walls with limited thickness (i.e. 100 mm). Thus, they are characterised as buildings with low state of stress. Within the framework of an extensive experimental campaign developed at TUDelft, a replicated single-wythe calcium silicate brick masonry wall is adopted as a case study. The experimental study was conducted in the laboratory controlled environment using a well-designed acquisition system, which allows the continuous measurements of the applied load and the corresponding deformations. The aim is to gain a better insight into the behaviour of masonry during the testing procedures. It is worth noting that the equipment required to perform the in-situ tests can be hardly found in the Netherlands; the flatjacks were purchased from Italy and the sawing machine was designed and built by TUDelft. The in-situ test was performed over three different locations of the CS masonry wall. For each location, single flatjack test, double flatjack test and the shove tests were conducted, one after another. 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 other two locations of the wall; imposing an overburden of 0.25 MPa and 0.15 MPa in the second and third location, respectively. In the current study, the pressure in the flatjack was chosen carefully to avoid undesired failure of the contrast portion of masonry wall.

Comparing the results of the single flatjack tests in the different locations of the wall having different stress states, the following conclusions can be drawn: an acceptable correspondence between the stress state acting on the wall and the stress evaluated using the single flatjack test is obtained for the overburden of 0.60 MPa and 0.25 MPa. More research is crucial to investigate the accuracy of the results of the single flatjack method, in the case of wall with low stress state.

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 10% of the maximum stress. The Young's modulus differences between the two techniques stand for 13%.
The coefficient of variation associated with the estimation of the Young's modulus using the double flatjack test is 27%.

To correctly interpret the shove test results, the effective level of the normal compressive stress acting on the sliding brick should be determined, since it significantly differs from the assumed uniform one imposed by the flatjacks. Thus, the imposed stress by the flatjacks should be modified to account for both the flatjack to brick correction factor and for the overburden contribution. Assuming a linear relationship between the shear strength and the normal compressive stress acting on the sliding brick, the shear properties of the brick-mortar interface can be evaluated according to a Coulomb failure criterion. Comparing the properties obtained from the shove test and the companion samples, the shear properties are overestimated by more than 60% using the shove testing method. It should be noted that since limited number of the shove tests were performed, more research is suggested, where experimental studies and numerical simulation are integrated.

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Appendix A

This appendix reports the declaration of performance for the construction materials used during the experimental campaign.

Table A. 1 - Declaration of performance of calcium silicate bricks.

Wanddikte in mm	Type steen	Afmetingen (BxHxL) mm	Gewicht per stuk in kg	Druksterkte N/mm^2	Aantal per m^2 (incl. voeg)	Kg Metselfix per m^2 excl. morsverlies
55 (klamp)	Waalformaat	102x55x214	2	16	39,9	12,3
72 (klamp)	Amstelformaat	102x72x214	3	16	39,9	16,1
82 (klamp)	Maasformaat	102x82x214	3	16	39,9	18,4
102	Waalformaat	102x55x214	2	16	68,7	33,7
102	Amstelformaat	102x72x214	3	16	54,4	28,3
102	Maasformaat	102x82x214	3	16	48,5	26,1
150	Dubbel amstelformaat	150x72x214	4	16	54,4	42,5
150	Dubbel maasformaat	150x82x214	5	16	48,5	39,2

Table A. 2 - Declaration of performance for calcium silicate masonry mortar.

1. Unieke identificatie	**Sakrete Brickfix**	**Nr. RV001 – 2013-11-05**
2. Aanduiding	**M5 type G (voor algemene toepassing) conform NEN-EN 998-2: 2010**	
3. Toepassing	**Metselmortel voor binnen- en buitentoepassing**	
4. Naam en contactadres fabrikant	**Remix Droge Mortel BV** **Hoofdstraat 41 NL-9531 AB Borger** **Postbus 3 NL-9530 AA Borger**	
5. Naam en contactadres gemachtigde	geen	
6. Systeem voor de beoordeling en verificatie van de prestatiebestendigheid	systeem 2+	
7. Activiteit van de aangemelde certificatie-instantie zoals vereist in de geharmoniseerde norm	De aangemelde certificatie-instantie Kiwa BMC B.V. (identificatienummer 0620) heeft onder systeem 2+ de initiële inspectie van de productie-installatie en van de productiecontrole in de fabriek uitgevoerd en zal tevens de permanente bewaking, beoordeling en evaluatie van de productiecontrole op zich nemen. Op basis daarvan is het conformiteitscertificaat voor de productiecontrole in de fabriek verstrekt.	
8. Europese Technische beoordeling	niet van toepassing	
9. Aangegeven prestaties		
Essentiële kenmerken (NEN-EN 998-2)	**Prestaties**	**Europees beoordelingsdocument**
5.4.1 druksterkte	M5	NEN-EN 998-2:2010
5.4.2 Hechtsterkte (kruisproef)	≥ 0,3 N/mm² (tabelwaarde)	
5.2.2 chloridegehalte	< 0,1 M.-%	
5.6 brandklasse	A1	
5.3.3 waterabsorptie	≤ 0,40 kg/(m²*min0,5)	
5.4.4 waterdampdoorlaatbaarheid	15/35 (tabelwaarde)	
5.4.6 warmtegeleidbaarheid	≤ 0,82 W/(m*K) P = 50% ≤ 0,89 W/(m*K) P = 90% (tabelwaarden)	
5.4.7 duurzaamheid	NPD	
vrijkomende gevaarlijke bestanddelen	NPD	

10. De prestaties van het in de punten 1 en 2 omschreven product zijn conform de in punt 9 aangegeven prestaties. Deze prestatieverklaring wordt verstrekt onder de exclusieve verantwoordelijkheid van de in punt 4 vermelde fabrikant.

Borger, 5 November 2013

Getekend: AGAR Holding BV

Mr. R.M.P.P. Reef
Algemeen directeur

Remix Droge Mortel BV is een werkmaatschappij van Agar Holding BV.

Appendix B

UNIVERSITY OF GENOA
DICCA - Department of Civil, Chemical and Environmental Engineering
SISTEM OF THE DICCA LABORATORIES

Official Laboratory for Building Materials – Official Laboratory of Geotechnics
Structural and Geotechnical Engineering Laboratory

Certificate n. 7799

Calibration of the BOVIAR flat jack s.n. 16FJR42.0034-A/35 *according to ASTM C1197-2009.*

CUSTOMER: BOVIAR s.r.l., via Rho 56, 20020 Linate (Mi), C. F.: 00481810638 e P.IVA 06612870151

DELIVERY: 9th of November 2016 - **CALIBRATION:** 21st of November 2016

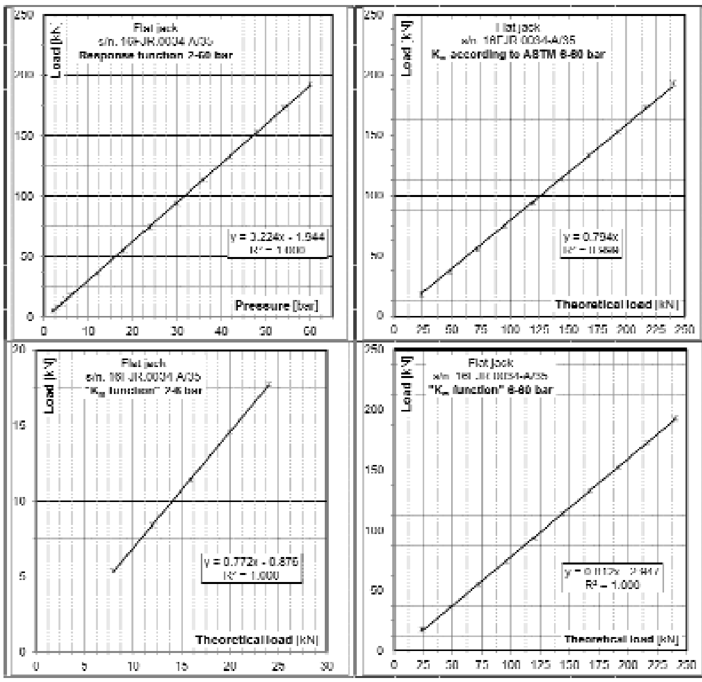
NAME: MP 8A – s.n. 16FJR42.0034– A/35, 400x100x4.1mm, $t_{plate\ thickness}$: 0.8mm – $A_{nominal}$: 40000 mm²

TEST STANDARD: ASTM C1197-2009. Distance between the plates kept constant equal to 1.33 times the thickness of the plates of the flat jack (5.4 mm). 3 load cycles up to the max service pressure. Calibration: i) 2 to 6 bar, Δp = 1bar; ii) 6 to 60 bar, Δp = 6bar.

COMPENSATION OF THE DISTANCE IN-BETWEEN THE PLATES: by means of hydraulic press GALDABINI model 3000 kN, s.n. 22449/1962, measured error <1% at 20°C, class 1, internal verification according to UNI EN 12390-4.

PRECISION AND TRACABILITY: distance in-between the loading plates constant with precision ± 1/100mm
Pressure gauge: AEP LabDMM.415.R5 – class 0.05, error ≤0.05%
on the flat jack: 100 bar – verified by *Accredia* n. 98613P - 14.6.2013
on the press: 250 bar – verified by *Accredia* n. 98513P - 13.6.2013

STEP	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$P_{FLAT\ JACK}$ [bar]	2	3	4	5	6	12	18	24	30	36	42	48	54	60
$F_{FLAT\ JACK}$ [kN]	5.36	8.37	11.38	14.55	17.72	36.41	55.10	74.31	93.75	113.35	132.95	152.88	172.64	192.88



FLAT JACK CONSTANT
ASTM 1197-2009

K_m = F_flat jack_measured / F_flat jack_calculated = **0.794**

NOTES

The flat jack response at pressures below 6 bar is quadratic and does not pass through the origin. The linearization of the response on the whole operating range, as implicitly suggested by ASTM 1197-2009 (K_m assumed constant on the whole operating range) may produce an error in-between 2-to-7%.

For higher precision, linear approximations not passing through the origin are preferred.

For Flat Jack s.n. 16FJR42.0034-A/35:

Unic global response function
y = 3.224x – 1.944
(R²=1.000 x: flat jack pressure in bar)

Flat Jack K_m function 2-to-6 bar
y = 0.772x – 0.876
(R²=1.000 x: theoretical load in kN)

Flat Jack K_m function 6-to-60 bar
y = 0.812x – 2.947
(R²=1.000 x: theoretical load in kN)

In all the three equations:
y = applied force by the flat jack [kN]

Genoa, 28th of November 2016

TECHNICIAN IN CHARGE OF THE TEST	TECHNICAL DIRECTOR OF THE LABS	DEAN OF THE DEPT. OR TECHNICAL SUPERVISOR OF THE LABS
DOTT. ING. GIANCARLO CASSINI PH.D.	PROF. ING. ANTONIO BRENCICH PH.D.	

CERTIFICATE N. 7799 CONSISTS OF 1 PAGE

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