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Esposito, Rita; Jafari, Samira; Ravenshorst, Geert; Schipper, Roel; Rots, Jan

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INFLUENCE OF THE BEHAVIOUR OF CALCIUM SILICATE BRICK AND ELEMENT MASONRY ON THE LATERAL CAPACITY OF STRUCTURES

R. Esposito[1], S. Jafari[2], G.J.P. Ravenshorst[3], H.R. Schipper[4] and J.G. Rots[5]

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

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

[3]Assistant professor, Delft University of Technology, Delft, The Netherlands, G.J.P.Ravenshorst@tudelft.nl

[4]Assistant professor, Delft University of Technology, Delft, The Netherlands, H.R.Schipper@tudelft.nl

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

In recent years induced seismicity in the Netherlands considerably increased. This phenomenon has a wide impact on the built environment, which is mainly composed by unreinforced masonry (URM) structures. These buildings were not designed for seismic loading, and present peculiar characteristics include very slender walls (100 mm thickness and 2.5m in height), limited connections between walls and floors, and use of cavity walls.

A large portion of the URM building stock consists of terraced houses in which the presence of calcium silicate (CS) masonry is often used. The CS masonry is used to build the loadbearing walls, which are part of the cavity wall system. The cavity walls are generally composed of two leaves of masonry separated by an empty cavity, having a thickness of 8-6 mm, and connected with steel anchors. On the basis of the construction year, different masonry unit were adopted to build the inner loadbearing leave: in the period 1960-1980 small CS brick and general purpose mortar were used, while after 1980, the presence of large CS elements and thin mortal layers is predominant. Although these materials are often used in the northern part of Europe, little information is available on their material and structural performance.

In this paper, a comparison between the behaviour of CS brick and element masonry is presented. The results of two experimental campaigns carried out at Delft University of Technology are reported. Both masonry types have been characterised at the material level by performing standardised destructive tests, such as compression, shear, and bending tests on wallets. The characterisation at the structural level is carried out by performing quasi-static cyclic tests on full-scale two-story high assembled structures.

Keywords: *Calcium silicate brick masonry, calcium silicate element masonry, quasi-static cyclic tests, full-scale assembled structure*

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INTRODUCTION

Due to the increase of the seismic activity in the northern part of the Netherlands, the assessment of the unreinforced masonry (URM) structures become a relevant topic. In this area, the majority of the structures are residential buildings among which the presence of terraced houses is substantial.

After the Second World War, the construction of terraced houses in URM became substantial in the Netherlands. Although many differences can be found from building to building, similar aspects characterise this typology. Terraced houses are usually composed of 5 to 10 housing units. Each of them is typically a two-story high masonry building. The units are characterised by a narrow floor plan being approximatively 5 m in width and 7-9 m in depth. The interstory height varies typically between 2.5 and 2.7 m. The construction is characterised by the presence of large daylight opening in the facades. Consequently, the loadbearing structure is composed of very slender piers and long transversal walls. The walls are mainly cavity walls, in which leaves are connected by steel ties. Different masonry types were used during the years including calcium silicate masonry for the inner leaf and clay brick masonry for the outer leaf. Generally the two leaves are separated by an empty cavity and they are connected with steel anchors. The majority of the buildings present concrete floors, which can be cast in-situ or prefabricated. The transversal walls are loadbearing and carry the floors, while the piers in the facades do not. The floors can span over a single house or be continuing for more than a housing unit. The timber roofs are usually adopted.

Despite the common characteristic illustrated in the previous paragraph, during the years differences can be found in the construction materials and thus the construction details; in particular the use of CS brick and element masonry is of importance. In the period 1960-1980 the mostly CS brick masonry was used to build the inner loadbearing part of the cavity wall, while in the period 1980-2000 the use of CS become popular due to the reduction and simplification in the construction process. Although calcium silicate masonry is diffused in the northern part of Europe, limited information can be found on the characterisation of brick and element masonry. In the past, Dutch researchers studied the behaviour of calcium silicate brick and element masonry (van der Pluijm, 1999; Vermeltfoort, 2007; Vermeltfoort, 2008); however they did not focus on seismic assessment of these structures. On the other hand, European researchers in the field of earthquake engineering (Salmanpour et al., 2015; Zilch et al., 2008) mainly studied the behaviour of CS block masonry having a thickness larger than 10 cm, which is not typically used in the Netherlands.

In order to provide benchmarks for the validation of assessment tools, experimental investigations have been carried out at Delft University of Technology to characterise from material to structural level the behaviour of typical Dutch terraced houses. Two experimental campaigns have been carried out with the focus on the two aforementioned construction periods. In this paper the quasi-static cyclic pushover tests on a CS brick masonry assemblage (Esposito et al. 2016, Esposito et al. 2017a) and on a CS element masonry assemblage (Esposito et al. 2017b) are presented and compared.

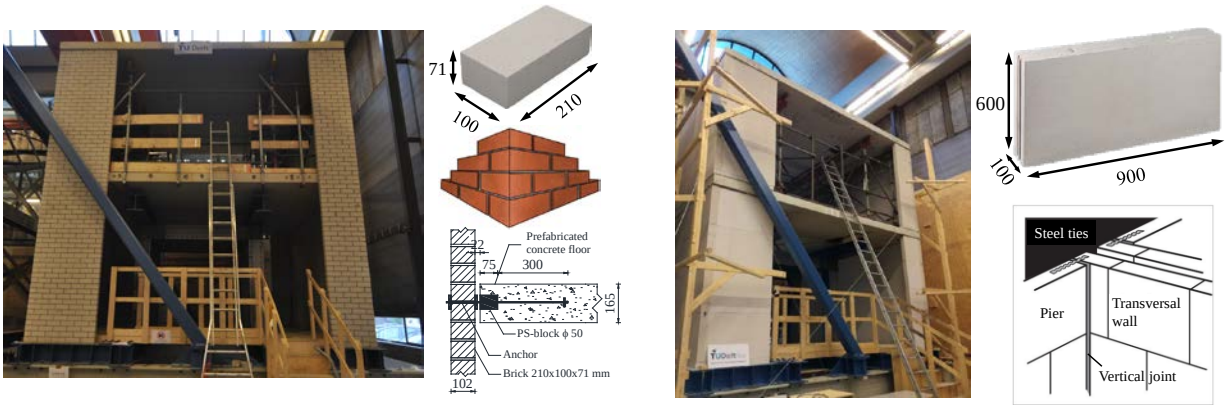
CASE STUDIES

Two specimens resembling typical Dutch terraced houses have been tested: a CS brick masonry assemblage and a CS element masonry assemblage. In both cases, the specimen represents only the loadbearing part of a single terraced house unit. As a consequence, only the inner leaf of the cavity wall was built and in the facades the masonry portion between the two piers was excluded.

The overall geometry of the two specimens was kept constant. The facades of the specimens have a length of 5.4 m. Due to limitation of the set-up; the depth of the specimen was restricted to 5 m. The total height of the specimen is 5.4 m. The south and north facades, which are identically, are represented only by the two piers connected to the transversal walls. Two sizes of the piers have been selected: on the western side the wide piers P1 and P3 have a width of 1.1 m, while on the eastern side the narrow piers P2 and P4 have a width of 0.6 m. In order to avoid sliding of the masonry at the bottom, the first course of brick masonry or the kicker layer was glued on the foundation beams. Each floor consisted of two separated prefabricated concrete slabs spanning between the loadbearing transversal walls. The floors were first laid up on the loadbearing walls in a mortar bed joint; subsequently the joints between the floor and the piers were filled by mortar. Consequently, the weight of the floor is not directly carried by the piers in the facades, but only by the transversal walls. The two separated concrete slabs per floor were then connected by cast-in-place reinforced concrete dowels, aiming to approach the behaviour of a monolithic floor.

The CS brick masonry assemblage (Figure 1a) was tested as representative of terraced houses built in 1960-1980 in the northern part of the Netherlands. Small masonry unit having dimensions 210x71x100-mm were used. A running bond pattern was adopted allowing for the interlocking of the bricks at the corners of the transversal walls and the piers. At the first floor level, the floor was connected horizontally to the piers by anchors of 6 mm diameter, cast in the floor and masoned in the piers. The narrow piers were connected by three anchors, while the wide piers by five anchors. These anchors are commonly used as horizontal buckling or wind load support of the pier, and they are not designed to withstand any vertical load. At the second floor level, the floor was laid on both the loadbearing transversal walls and the piers.

The CS element masonry assemblage (Figure 1b) was tested as representative of terraced houses built in 1980-2000 in the northern part of the Netherlands. Large masonry unit having dimensions 897x643x100-mm were used for the facade piers, while unit having dimensions 897x643x120-mm were used for the transversal wall. The masonry was made in stretcher bond. In order to ensure verticality of the wall, a kicker layer made of small masonry unit was adopted at the bottom of the masonry walls both at the ground and first floor. The connection between the façade piers and the transversal wall consisted of a vertical joint; additionally steel ties were placed in the bed joint in correspondence of the vertical joint. Both at the first and second floor level, the floor slabs were laid on both the loadbearing transversal walls and the piers.



(a) **(b)**

Figure 1: Specimens and main construction details: (a) CS brick masonry assemblage; (b) CS element masonry assemblage.

MATERIAL CHARACTERISATION

The material properties of calcium silicate masonry were selected to represent Dutch masonry used in the construction of terraced house before and after 1980. The compression, bending and shear properties of both masonry specimens were investigated in dedicated experimental campaigns (Esposito et al. 2016, Jafari et al. 2017). The test were mainly performed by following the European standard EN 1052, however a displacement controlled procedure was adopted to obtain an indication of the post-peak behaviour. Table 1 lists the mean material properties for the CS brick and element masonry and their constituents. The CS element masonry showed a higher compressive strength and Young's modulus with respect to the CS brick masonry. In both cases, the pre-peak stage was characterised by linear-elastic followed by a hardening behaviour until the peak. After the maximum stress was reached, a softening behaviour was observed for the calcium silicate brick masonry, while a brittle failure was reported for the element masonry. Both the out-of-plane masonry flexural strength parallel to the bed joint and the initial shear strength resulted higher for the CS element masonry with respect to the CS brick masonry. Consequently the bond between masonry unit and mortar can be considered stronger in the case of CS element masonry.

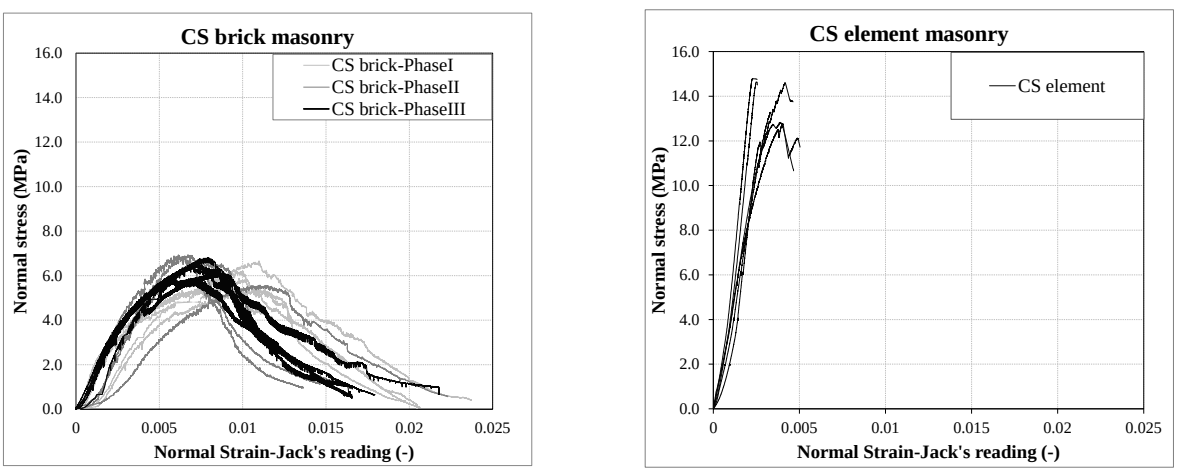
In both specimens the concrete floor was laid on the masonry wall by using a 10 mm thick joint made of general purpose mortar; the mortar adopted was the same of the one used for the CS brick masonry. To characterise the friction behaviour of the wall-to-floor connection, a shear-compression test was performed, similarly to the one for masonry, for the concrete to CS brick masonry interface. Table 2 lists the properties of the floor-to-wall connection. By comparing these properties with the shear properties of masonry specimens (Table 1), it is possible to conclude that the floor-to-wall connection present the same characteristics of any other bed joint in the case of the CS brick assemblage. On the contrary, in the case of the CS element masonry the floor-to-wall connection results weaker than the other mortar joints.

Table 1: Material properties of calcium silicate brick and element masonry.

Material property	Symbol	Unit	CS brick		CS element	
			Average	C.o.V.	Average	C.o.V.
Compressive strength of mortar	f_m	MPa	7.27	0.14	16.10	0.09
Compressive strength of masonry unit	f_b	MPa	13.26	0.13	19.50	0.06
Compressive strength of masonry perpendicular to the bed joints	f'_m	MPa	6.01	0.09	13.93	0.07
Compressive strength of masonry parallel to the bed joints	$f'_{m,h}$	MPa	7.55	0.02	9.42	0.17
Elastic modulus of masonry in the direction perpendicular to bed joints	E	MPa	3339	0.25	8001	0.12
Elastic modulus of masonry in the direction parallel to the bed joints	E_h	MPa	2081	0.42	7400	0.13
Out-of-plane masonry flexural strength parallel to the bed joint	$f_{x,1}$	MPa	0.21	0.25	0.58	0.14
Out-of-plane masonry flexural strength perpendicular to the bed joint	$f_{x,2}$	MPa	0.76	0.47	0.73	0.04
Masonry initial shear strength of calcium silicate masonry	f_{v0}	MPa	0.12	-	0.83	-
Masonry shear friction coefficient of calcium silicate masonry	μ	-	0.49	-	1.49	-

Table 2: Material properties of concrete and floor-to-wall connection.

Material property	Symbol	Unit	Average	C.o.V.
Cubic compressive strength of concrete	f_{cc}	MPa	74.7	0.02
Initial shear strength of bed joint between concrete floor and calcium silicate masonry	$f_{v0,cm}$	MPa	0.09	-
Shear friction coefficient of bed joint between concrete floor and calcium silicate masonry	μ_{cm}	-	0.52	-



(a) **(b)**

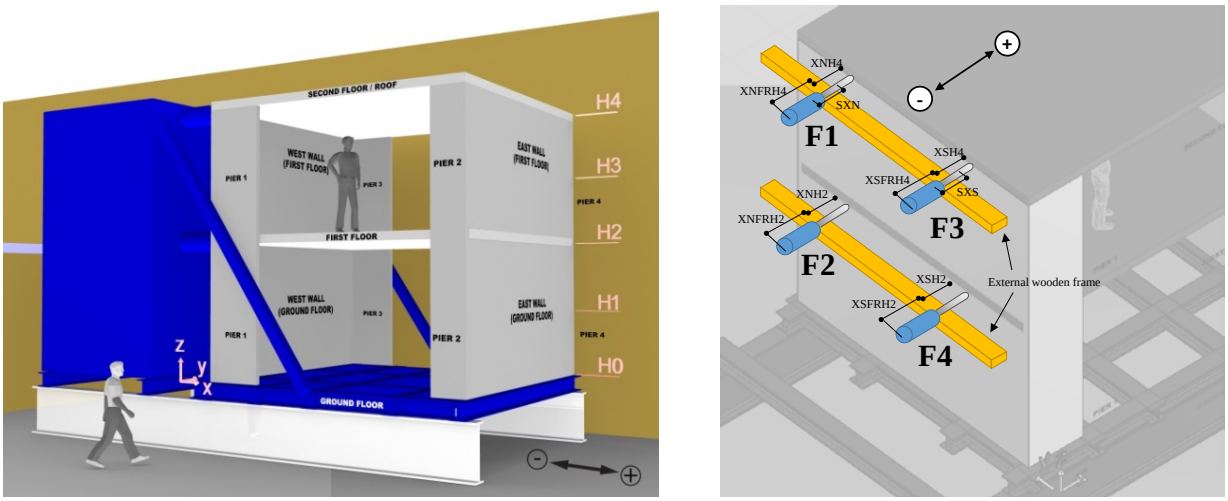
Figure 2: Stress-strain relationship in compression: (a) CS brick masonry; (b) CS element masonry.

TESTING PROCEDURE

A quasi-static cyclic pushover test was performed on both assembled structures. The masonry structure was loaded by four actuators (Figure 3b), two per each floor, positioned at approximatively 1.1 m inwards from the facades. A displacement was imposed at the second floor level, while a ratio 1:1 was maintained between the forces at the two floor levels ($F_1 + F_3 = F_2 + F_4$). To impose a constant ratio between the forces at the two floor levels, the forces in the actuators No. 1 and 3 at the second floor level were mechanically coupled to the forces at the first floor level ($F_1 = F_3$, $F_2 = F_4$).

The load was applied by mean of reversed cycles composed by 3 identical runs. A run is defined as the time needed to apply the maximum positive and negative target displacement starting and ending at zero. The speed of the imposed horizontal deformations was chosen for every cycle such that the cycle lasted 15 minutes. As a result of the increasing amplitude, the constant cycle time resulted in a deformation velocity increasing per cycle.

The deformation of the specimen was measured in absolute sense from a stiff wooden frame, which was connected neither to the steel reaction frame nor to the foundation beams (Figure 3b). The displacements along the X-axis, at the point of application of the loading, have been measured with draw wires with length of 150 mm.



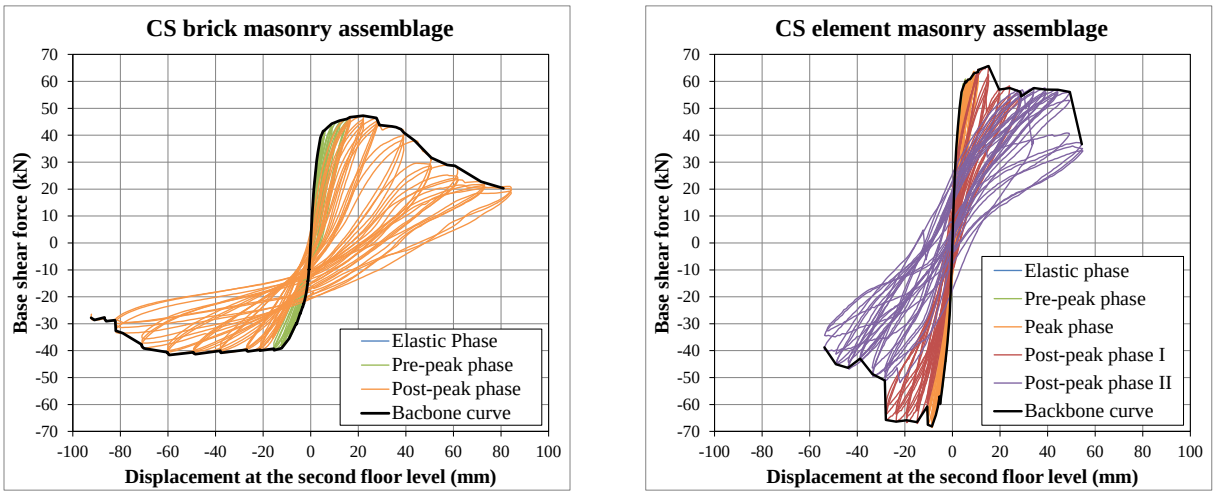
(a) **(b)**

Figure 3: Test set-up

EXPERIMENTAL RESULTS

Figure 4 shows the response of the CS brick and element masonry assemblages in terms of base shear force versus displacement at the second floor level d_2. By comparing the two curves, it is possible to note that the CS brick masonry assemblage shows an higher displacement capacity, while the CS element masonry assemblage shows an higher maximum base shear force. In both cases a reduction of 20% in base shear force was achieved during the post-peak phase, but the test was continued until major damage (or even collapse) in the wide piers was observed. For the

CS brick masonry assemblage the 20% reduction in base shear force was obtained at a displacement of d_2 = +43 mm and d_2 =-80 mm, while for the CS element masonry assemblage it was reached at a displacement of d_2 = -28 mm and d_2 =+50 mm.



(a) **(b)**

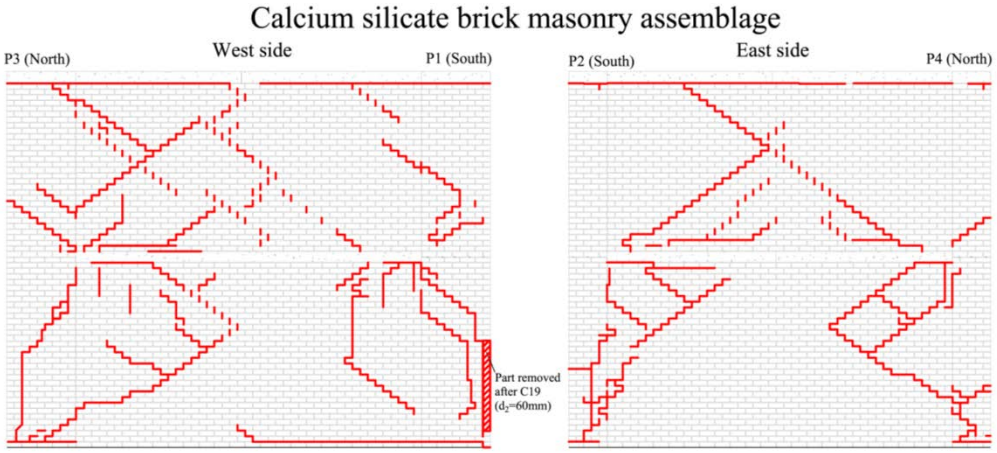
Figure 4: Capacity curve: (a) CS brick masonry; (b) CS element masonry.

In both cases, the failure mechanism was mainly governed by the in-plane damage of the facades piers at the ground floor (Figure 5, Figure 6). First, cracks occurred at the joint between the concrete floor and the masonry walls. Subsequently, diagonal/vertical cracks occurred in the wide pier P1 and P3 at the ground floor, while the rest of the structure was only slightly damaged. During the post-peak phase and prior to major damage in the narrow piers, the wide piers were subject also to a reduction in cross section that led to a further reduction in capacity. Both for the brick and element masonry the diagonal/vertical cracking occurred first in the head and bed joints. However, in the case of the CS element masonry assemblage, large out-of-plane deformation up to collapse of the piers occurred; this is caused by the large size of the masonry units.

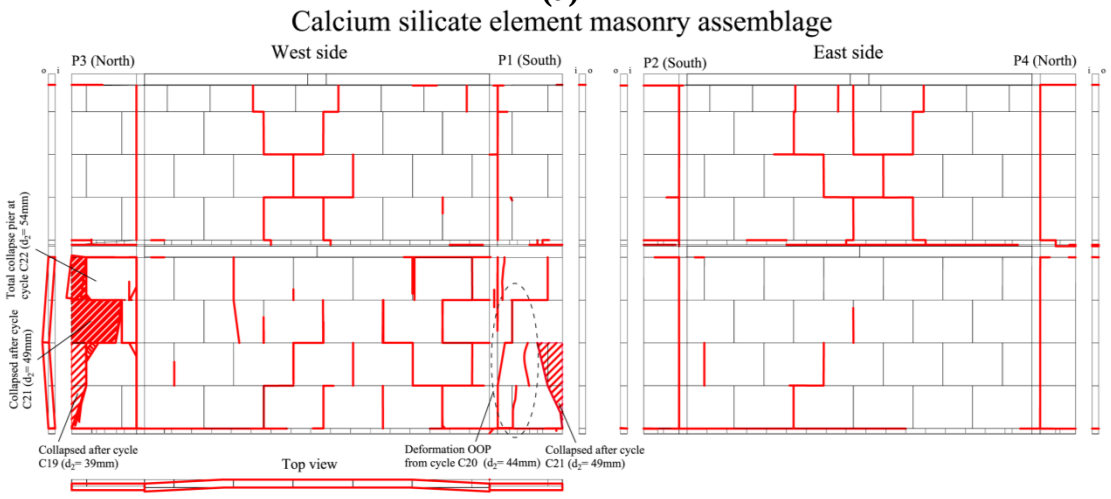
By accommodating the in-plane deformation of the piers, the transversal walls deformed out-of-plane showing the effectiveness wall-to-wall connection in both cases. In the case of the CS brick masonry assemblage the running bond allowed a strong connection between the piers and the transversal walls and promoted the flange effect, which is of importance for the base shear capacity (Esposito et al., 2017a). In the case of the CS element masonry assemblage, although cracking occurred in correspondence of the vertical joints at approximatively the peak load, the connection was still effective. This was caused by the presence of the steel ties and by the sliding friction mechanism at the vertical joint governed by the high friction coefficient of the CS element masonry. Additionally, the extensive damage of the pier and the detachment of masonry pieces that interlocked within the open cracked promoted local deformation at the end of the transversal wall for a length of approximatively 1 m from each wide pier (Figure 6b).

(a) **(b)**

Figure 5: Main damage in the wide piers at the ground floor: (a) CS brick masonry assemblage (d_2 = 82 mm); (b) CS element masonry assemblage (d_2 = 54 mm).



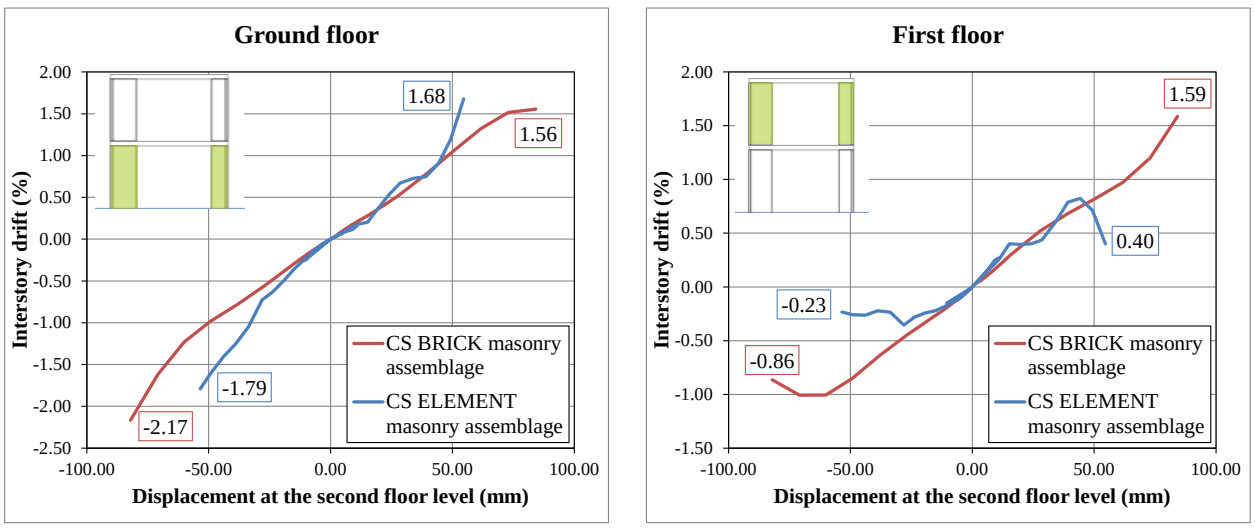
(a)



(b)

Figure 6: Crack pattern: (a) CS brick masonry; (b) CS element masonry.

Figure 7 shows the behaviour of the structure in terms of interstory drifts as a function of the displacement at the second floor level. They are calculated as the ratio between the relative floor displacement and the interstory height, which is 2.7 and 2.6 m for the first and second floor level, respectively. Although the CS brick masonry assemblage reached larger displacement at the second floor level (82 mm in comparison with the 54 mm of the CS element masonry assemblage), the two structures showed a similar interstory drift for the ground floor varying between 1.6% and 2.2%. A substantial different behaviour is observed at the first floor, where at the onset of damage of the wide pier the CS element masonry assemblage showed a nearly constant drift. This difference can be caused by the different load redistribution on the piers at the level of the first floor slab, which is consequence of the different construction detail. In the case of the CS brick masonry assemblage the piers are only horizontally connected to the floor by anchors, while for the CS element masonry assemblage the floor laid on top of the piers. Although in both cases the piers do not bear the floor in the undamaged configuration, for relative large displacement the load transferred by the first floor slab is directly redistributed to the piers in the case of the CS element masonry assemblage, while it is indirectly transferred via the transversal walls in the case of the CS brick masonry assemblage. Consequently, in the former case a concentration of displacement is observed at the ground floor leading to a soft-story mechanism.



(a) **(b)**

Figure 7: Comparison in terms of interstory drift: (a) Ground floor; (b) First floor.

CONCLUDING REMARKS

In the recent years the assessment of unreinforced masonry (URM) structures become of importance in the Netherlands due to the increase of seismic activity in a country in which earthquake resistant design criteria were not applied. The building stock in the area is mainly composed of low-rise URM structures among which terraced houses represent a large portion.

In order to study the behaviour of typical Dutch terraced houses and to provide benchmarks for the validation of models to be used in the assessment, quasi-static cyclic pushover tests on CS brick and CS element masonry assembled structures have been carried out and presented in this

paper. These tests are part of two large experimental campaigns carried out at Delft University of Technology between 2015 and 2017. The experimental investigation aimed at characterising the behaviour from material to structural level in the framework of the seismic assessment.

Despite the difference in unit size and construction details (e.g. wall-to-wall connection and floor-to-pier connection), similarity can be found in the behaviour of the CS brick masonry assemblage and CS element masonry assemblage. In both cases, the damage is localised at the ground floor and the structural response is mainly governed by the cracking in the wide piers. Although a different wall-to-wall connection is adopted, in both cases the transversal walls accommodate the deformation of the piers. If this can be easily predicted in the case of the CS brick masonry assemblage where the running bond is present, doubts could rise with respect to the vertical joint connection for the CS element masonry assemblage. In fact in this latter case, cracking at the vertical joint occurred approximatively at the peak load; however the transversal wall maintained its coupling with the pier thanks to the presence of the steel ties and the sliding friction mechanism.

A substantial difference can be noticed in the displacement capacity of the two structures. The maximum displacement reached at the second floor level was 82 mm and 54 mm for the CS brick masonry assemblage and the CS element masonry assemblage, respectively. Comparing the behaviour of the two structures in terms of the interstory drift, the difference in displacement capacity can be explained by the localisation of the deformation at the ground floor for the CS element masonry assemblage, which did not occurred for the CS brick masonry assemblage. This caused by the different load redistribution on the piers at the level of the first floor slab, which is consequence of the different construction detail. However, it should be mentioned that the difference in displacement capacity can also be influenced by the different material behaviour. In fact, the CS element masonry material has a more brittle behaviour with respect to the CS brick masonry.

ACKNOWLEDGEMENTS

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