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A MULTISCALE EXPERIMENTAL CHARACTERIZATION OF DUTCH UNREINFORCED MASONRY BUILDINGS

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ABSTRACT

In recent years, induced seismicity in the north of the Netherlands significantly increased. As a consequence, the seismic assessment of the built environment, which mainly consists of unreinforced masonry (URM) structures not designed for seismic loads, became of high relevance. Within this context, an extensive multiscale testing program has been performed at the laboratory of Delft University of Technology since 2014 to characterize the behavior of URM buildings from structural down to material level and provide benchmarks for the validation of numerical and analytical models.

The paper presents an overview on the experimental campaign, which was structured in three phases: characterization of existing buildings; study of the structural response up to near collapse on replicated specimens; study of light damage state, also on replicated URM walls. The experimental campaign was characterized by a multiscale approach, with tests at structural, component, connection, and material level. At structural level, the campaign comprehended two quasi-static cyclic tests on full-scale two-story high assembled structures and a large number of both in-plane and out-of-plane tests performed either on single piers or on walls with openings. The in-plane stiffness and capacity of as-built and retrofitted timber floors was also assessed. At material level, destructive and slightly-destructive laboratory tests were performed on both existing and replicated masonry and timber specimens. Existing and retrofitting connections between the leaves of cavity walls and between concrete slabs and masonry veneers were studied. To study the initiation and propagation of cracking in URM structures, Digital Image Correlation (DIC) was used during dedicated in-plane tests.

Keywords: Unreinforced masonry; Dutch masonry; Experimental tests; Induced seismicity; Damage assessment

1. INTRODUCTION

The seismic assessment of unreinforced masonry (URM) structures is a traditional theme in many countries all over the world. In recent years, it has become popular also in the Netherlands, due to the increasing number and intensity of induced earthquakes in the province of Groningen. The built environment, mainly consisting of URM structures, was not designed for seismic loads and has specific characteristics that influence the seismic performance. In this framework, an extensive multiscale testing program has been performed at Delft University of Technology since 2014, in the context of an integrated testing program, part of which was developed at the European Centre for Training and Research in Earthquake (EUCentre) (Graziotti et al 2016, Graziotti et al 2017). The campaign aimed to characterize the behavior of URM buildings from material up to structural level, and provide benchmarks for the validation of numerical and analytical models. The paper presents an overview on the different testing typologies performed for the considered testing campaign. The experimental campaign was structured in three phases. In the first phase, the tests focused on the

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characterization at material level of masonry and timber samples extracted from existing buildings. The obtained data allowed to select the properties of the replicated masonry that was tested in a second phase to investigate the response with specific focus on the structural behavior up to near collapse (NC). Finally, a third phase, focused on the serviceability limit state to identify the damage initiation and propagation, has been carried out. Figure 1 shows a concept map that represents the connection between the different performed tests.

The experimental campaign was characterized by a multiscale approach, with tests at structural, component, connection, and material level. At material level, destructive (DT) and slightly-destructive (SDT) laboratory tests were performed on masonry specimens. Compression, bending, and shear properties were investigated, and the derived properties categorized according to the type of masonry and the construction period. At component level, both quasi static in-plane and out-of-plane tests were performed either on single piers or on walls with openings. Different materials (solid and perforated clay bricks, calcium silicate (CS) bricks and elements), geometries, and boundary conditions were considered, and the influence of the different parameters evaluated. In addition, two quasi-static cyclic tests were carried out on full-scale two-story high assembled structures representative of different types of terraced houses, characterized by the use of either CS bricks or CS elements for the masonry walls and stiff concrete floors. Beside the identification of the material and structural properties of the masonry elements, also the determination of the in-plane stiffness of roofs and floors is an important factor for the assessment of masonry buildings, since the flexibility of timber diaphragms is of primary importance to create a structural box behavior and redistribute the forces between different piers. Besides, it affects also the out-of-plane capacity of the masonry walls. As-built and retrofitted connections between the leaves of the cavity walls and between the concrete slabs and the masonry veneers were studied. Along with safety, also light damage determined by the induced earthquakes is an essential topic, related to economic and serviceability losses. As a consequence, dedicated tests were focused on the initiation and propagation of cracking in URM structures. Different causes, among which dynamic loads (earthquake vibrations), imposed deformations and repeated loading, were investigated. The Digital Image Correlation (DIC) measuring system was used to accurately detect the crack formation and the evolution of the crack pattern.

2. IDENTIFICATION OF THE AS-BUILD CONDITIONS OF THE BUILDING STOCK

Residential URM buildings in the province of Groningen can be classified in four main typologies:

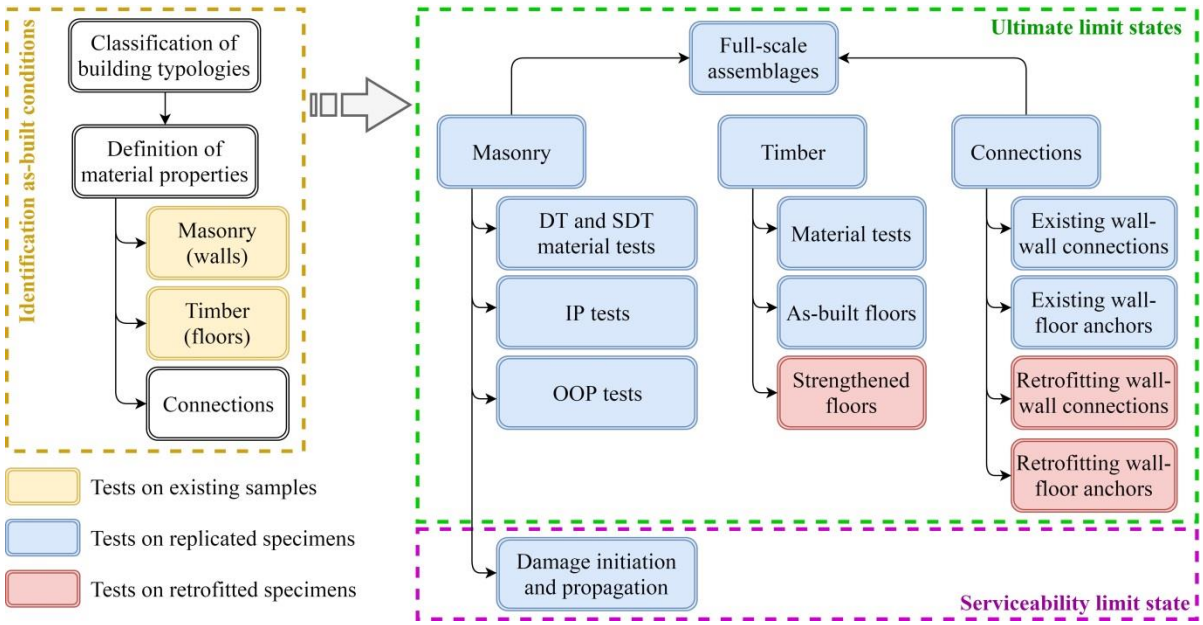


Figure 1. Conceptual diagram of the testing campaign performed at TU Delft laboratory in 2014/17

terraced houses, detached houses, semi-detached houses and apartments (NAM 2015). Detached houses (free standing buildings) represented the most diffuse dwelling typology built before the Second World War (WW2). They are low-rise buildings (one or two stories) with timber diaphragms and internal and perimeter loadbearing walls made of single and double wythe solid clay brick masonry, respectively. These buildings have relatively small openings and are often irregular in plan. After WW2, the construction of terraced houses became more and more common in the Netherlands. Terraced houses are usually composed of 5 to 10 horizontally connected two-story high units. Given the presence of large daylight opening in the facades, the loadbearing structure is composed of slender piers and long transversal walls. The loadbearing walls are mainly cavity walls, whose leaves are connected by steel ties. Different masonry types were used during the years including CS masonry for the inner leaf and clay brick masonry for the outer leaf. The majority of the buildings present concrete floors, which can be cast in-situ or prefabricated, and timber roofs.

An extensive experimental campaign was performed to determine the structural characteristics of the materials used in the Dutch masonry building typologies. The outcomes of this research were used to replicate the structures and components with new materials having similar material properties (replicated specimens).

2.1 Masonry

Despite of the widespread application of clay and CS brick masonry in the Netherlands, a refined characterization of masonry behavior is almost absent in the literature. Few pioneering research was carried out in the past years by Rots (1997) and Van der Pluijm (1999) to characterize Dutch URM, with particular attention to the material level. Material tests on masonry and its constituents were conducted on specimens extracted from existing buildings with a twofold aim: i) providing information on input parameters for assessment methods (Annex F NEN NPR 9998); ii) develop constitutive relationship for the masonry material to be used in numerical analysis (Jafari et al. 2017a, Jafari et al. 2018a). Masonry buildings built in the period between 1920 and 2010 were object of the research. The buildings were categorized according to the year of the construction (Figure 2). The masonry type tested were mainly brickwork made of general purpose mortar (joint thickness approximatively 10 mm). The clay brick masonry including solid, perforated and frogged unit was categorized as pre-war (until 1945) and post-war period (after 1945) masonry. For CS brick masonry, only the buildings constructed before 1985 were analyzed, when bricks and general purpose mortar were used. By using well designed displacement-control testing set-ups, the full non-linear compression behavior along the directions parallel and perpendicular to the mortar bed joint, the shear-sliding behavior at the masonry unit-mortar interface and the bending behavior in the two orthogonal direction were determined. The outcome of this study enhanced the insights into the strength, stiffness and softening post-peak behavior of different masonry types.

2.2 Timber

In the Netherlands, most masonry buildings built before WW2 have timber floors and timber roofs, while after WW2 only a timber roof and sometimes also a timber floor at the attic are usually present.

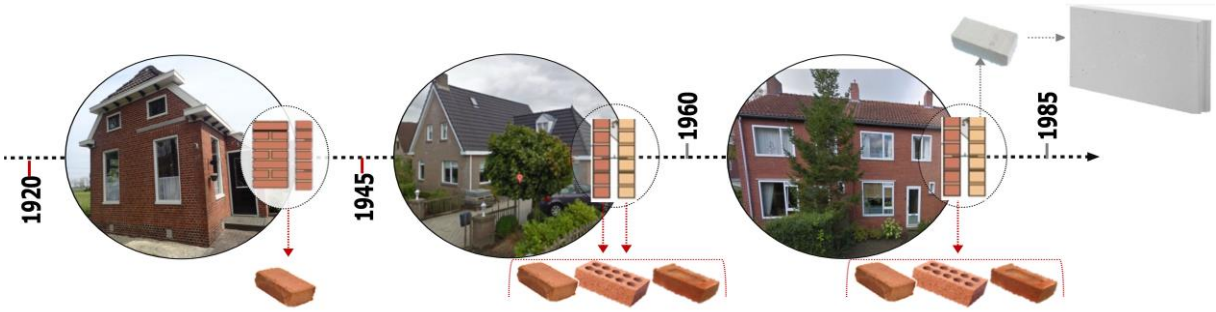


Figure 2. Correlation between different building typologies and construction materials

For timber floors some formulas for basic joists-planks configurations are reported by e.g. Brignola et al. (2008). In Giongo et al. (2011) the influence of different strengthening techniques on timber floors are presented. The stiffness of timber roofs and floors strongly depends on the specific characteristics (sizes of joists and plank, number and diameter of nails and screws) that are traditional in each single region. Due to lack of input data for typical Dutch roofs and floors, samples were extracted from dwellings that were intended to be demolished. Since it was not possible to extract entire roofs it was chosen to cut out squared samples of approximately 1.5m side. The configuration of the samples were then identified and then cut to specimens to be tested at the laboratory of the Delft University of Technology to determine the stiffness and strength of the inner connections. The samples were extracted from two houses representing two typologies: roof and floor samples from a pre-WW2 clay brick detached house, and roof and attic floor samples from a post-WW2 CS brick terraced house. The floors in the detached house consisted of traditional joists and planks, while in the terraced house the floor joists were made with chipboard panels and the roof with roof boxes on purlins. illustrates the procedure followed for a floor sample of a detached house: from the sample extraction to the construction of the replicated full size specimen.

3. CHARACTERIZATION OF SINGLE COMPONENTS OF MASONRY STRUCTURES

3.1 Tests on masonry walls

3.1.1 Material tests

The extraction of masonry samples from existing buildings is not always possible due to challenges, such as the preservation of the sample from any possible damage, that put severe constraints. As a result, different masonry types were replicated and tested to provide a complete description of the behavior of masonry under compression, bending, and shear loading. The following materials were considered: clay perforated brick masonry, solid clay masonry (both single and double wythe), CS brick and CS element masonry. An overview of the destructive tests to characterize the compression, bending and shear behavior of masonry at material level is shown in **Figure 4**. The compression properties of the masonry specimens were investigated by conducting tests according to EN1052-1 (1998). The tests were performed in two orthogonal directions, perpendicular and parallel to the bed joints (vertical and horizontal compression test, respectively), with the aim of investigating the orthotropic behavior of masonry. The compressive strength, the elastic modulus, the Poisson's ratio, the strain corresponding to the peak stress, the fracture energy, and the complete stress-strain relationship were identified.

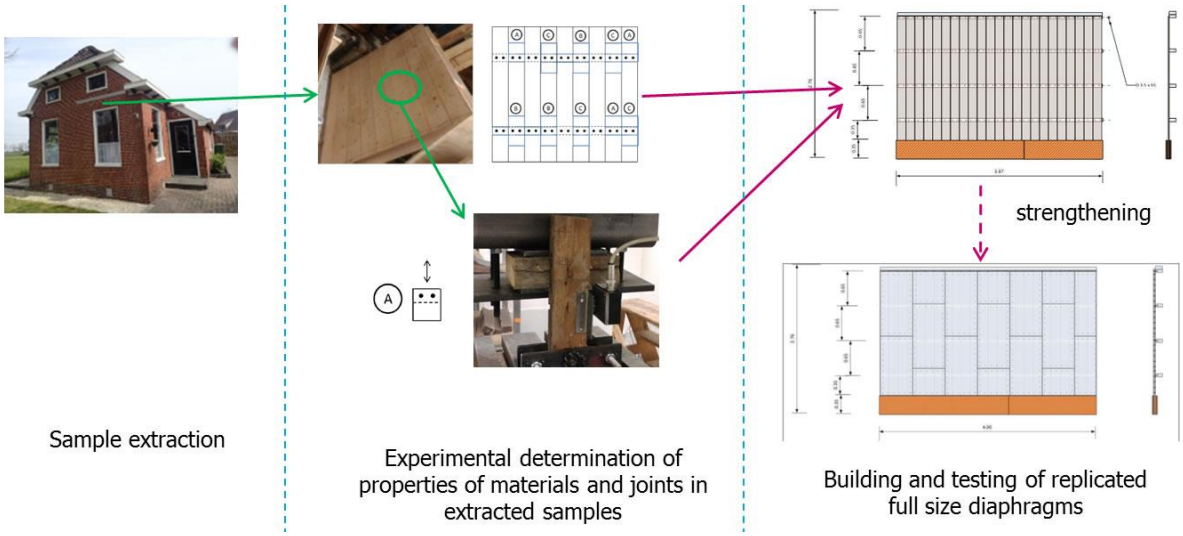


Figure 3. Principle of the procedure from sample extraction to replicated full size timber diaphragms for testing

The masonry bending properties were studied by performing four-point bending tests (both out-of-plane and in-plane tests), and bond wrench tests. Different typologies of out-of-plane bending tests, having the plane of failure either parallel or perpendicular to the bed joints, were performed in agreement with EN1052-2 (1999). In addition, four-point in-plane bending tests with the moment vector orthogonal to the plane of the specimen were executed. The flexural strength, the elastic modulus in bending, and the mode-I fracture energy were determined for each type of bending test. The flexural bond strength of masonry was studied also throughout bond wrench tests on stack bonded specimens, in conformity with EN1052-5 (2005). The masonry shear properties were obtained by performing shear tests on triplets/couplets in accordance with EN1052-3 (2002). The initial shear parameters, including initial shear strength and coefficient of friction, and the residual strength properties were investigated in the frame of the Coulomb friction model. The Mode-II fracture energy was computed from tests on triplets.

Besides destructive tests, standardized slightly-destructive tests (single and double flat-jack test, and shove test) as well as of non-standardized slightly-destructive tests (tests on masonry cores with small diameter) were investigated. These tests were performed on replicated masonry specimens in a controlled laboratory environment. By comparing the results obtained from the different destructive and slightly-destructive testing techniques, the suitability of the in-situ tests for the case of Dutch masonry can be investigated (Jafari et al 2018b). Using the standardized slightly-destructive techniques, the stress-state, and the compression and the shear properties of the brick-mortar interface can be assessed without altering the structural integrity of the walls, while non-standardized testing of masonry core allows more direct estimation of the mechanical properties (Jafari et al 2017b). The compression and the shear properties of the brick-mortar interface can be evaluated using the core testing technique. The compressive strength of the masonry cores, and the corresponding values obtained by destructive tests on wallets are shown in Figure 5 (Jafari et al 2018b); a good correspondence can be observed.

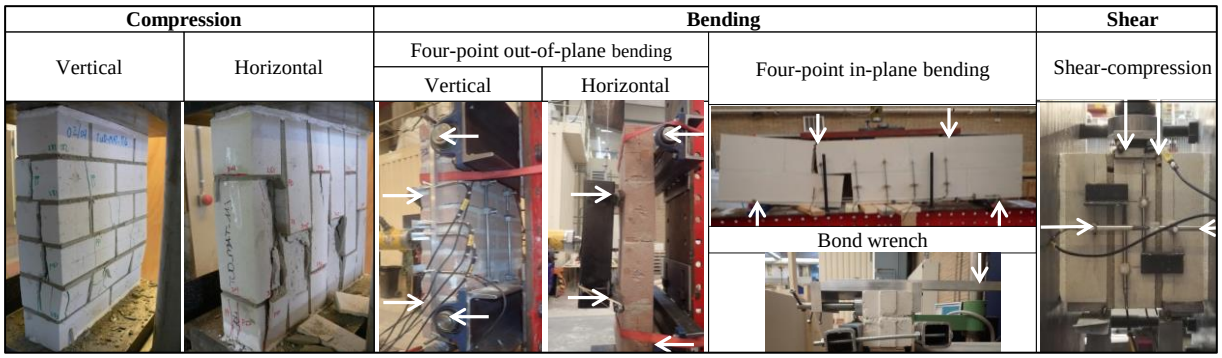
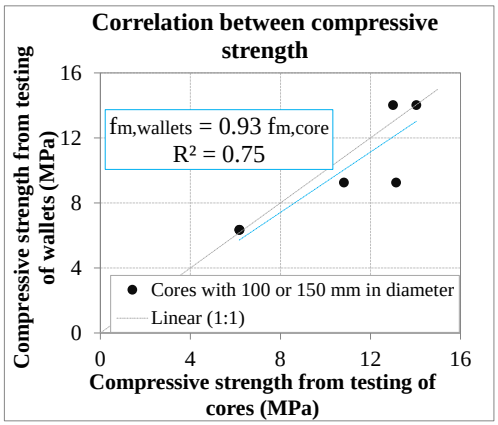


Figure 4. Overview of the destructive tests performed at material level



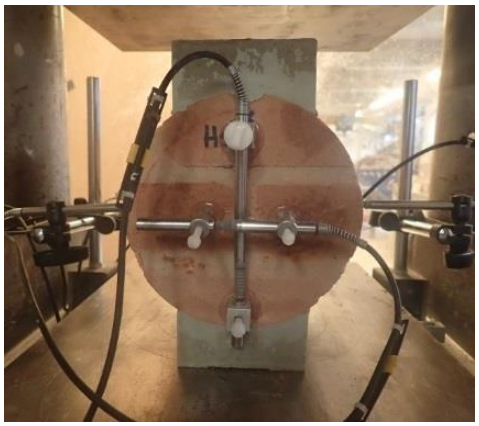


Figure 5. Correlation between the compressive strength derived by core tests and destructive tests on wallets

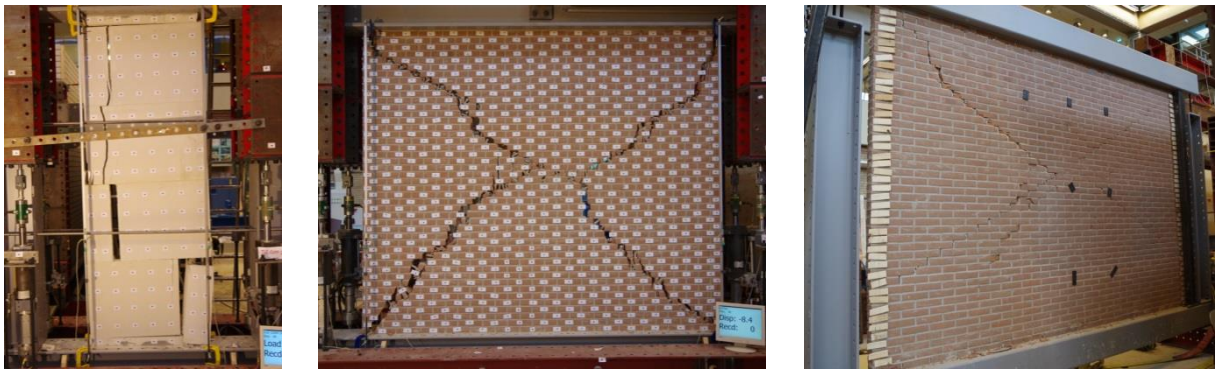
3.1.2 Component tests

The structural behavior of Dutch masonry walls was investigated with tests performed on single structural elements (components), loaded either in the in-plane or in the out-of-plane direction.
Thirteen URM walls were tested to study the in-plane behavior of piers under quasi-static loading conditions. The impact of several factors was investigated: aspect ratios (slender and squat walls), boundary conditions (cantilever and fixed-fixed walls), overburden loads (from 0.3 MPa to 0.7 MPa), materials (CS brick masonry, CS element masonry, solid clay brick masonry), type of mortar layers (regular joints and thin mortar layers), thickness of the wall (single and double wythe walls), and openings. The performed tests allow assessing the accuracy of predictions based on simple analytical procedures, included in international standards and guidelines, and provide a suitable dataset of benchmarks to validate numerical models. On the basis of the outcomes of both these tests and of the tests at material level, a new constitutive model for brick masonry has been recently proposed and validated (Rots et al 2016). Figure 6a,b show two examples of the outcomes of in-plane tests performed on a CS element masonry wall and a clay brick masonry wall.

Other nine full-scale URM walls were tested in the out-of-plane direction. Similar to in-plane tests, the tested walls were characterized by different properties, since boundary conditions (one-way and two-way spanning walls), overburden loads (from 0.05 MPa to 0.25 MPa) and materials (CS brick and element masonry, solid and perforated clay brick masonry) were varied. Besides, also the impact of openings was evaluated, and a windowed wall with concrete lintel was tested in a two-way spanning configuration. The tests were performed in displacement control. The quasi-static cyclic loads were applied using a system of airbags, to allow specifically the investigation of the post-peak behavior of the wall. Special attention was devoted to the impact of the boundary conditions on the wall strength, providing useful benchmarks to assess reliability and accuracy of analytical models included in the international standards (Damiola et al 2017). Figure 6c shows the crack pattern of a wall tested in a two-way spanning configuration. Detailed descriptions of the tests are included in Messali et al (2017), Esposito and Ravenshorst (2017), and Damiola et al (2018).

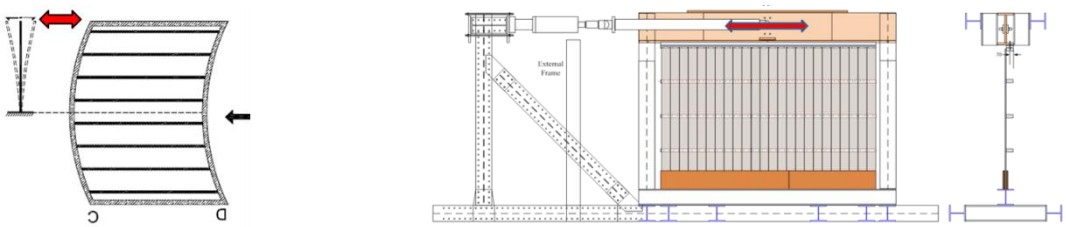
3.2 Tests on timber floors

Based on the tests described in section 2.2, replicated timber floor and roof specimens were built and tested. For both the building typologies (detached and terraced house), floor samples loaded in the two different directions and a roof sample are investigated. At the end of 2017 only the tests on the floor specimens of a detached house loaded parallel to the joists have been performed, while the remaining tests are planned for 2018. The tested timber diaphragm represents a floor loaded parallel to the joists as shown in Figure 8a. A cantilever set up was used (Figure 8b), so that the floor could be halved and the existing in-plane set-up at the TU Delft laboratory could be used. The test was displacement controlled, with a cyclic loading scheme according to ISO 21581 (2010). At the end of the test, a strip of the specimen was sawn-cut to test the connection between joists and planks of the replicated specimens; comparison with the results obtained by tests on samples extracted from existing buildings



(a) (b) (c)

Figure 6. Example of outcomes of in-plane (a,b) and out-of-plane (c) tests performed on URM walls



(a) (b)

Figure 8. Principle of the mechanical loading of a timber floor based on the displacement in practice (a) and the timber floor in the test set-up (b)

was made. The floor was not tested up to failure, and it was subsequently strengthened by screwing plywood panels on the planks, and tested up to failure. Figure 8 shows the hysteresis plots of the unstrenghtened and strengthened floor. The unstrengthened floor show a limited stiffness and a non-dissipative behavior. The strengthened floor shows a larger capacity, stiffness, and energy dissipation; the pinching effect is clearly visible. The strengthened floor failed at the connection of the plywood panels with the top joist. In most cases in practice the unstrengthened floor will not be stiff enough to take up seismic loads, whereas with a relative simple strengthening technique this is possible.

3.3 Tests on connections and anchors

Load bearing cavity walls are a widely used system in URM Dutch terraced houses. The inner and outer walls (also called leaves) are usually connected by steel anchors that should provide the system a monolithic behavior in the out-of-plane direction. Connectors can be placed either between the leaves (wall-wall anchors) or, at the floor level, between one of the two leaves and the structural floor (wall-floor anchors). The presence and efficiency of the wall-wall anchors is essential to limit the vulnerability of the outer leaf which is usually bearing small gravity loads, while the wall-floor should be able to transfer the inertia forces acting on the wall to the adjacent floor.

Previous experimental campaign investigated the connections in cavity walls throughout tests at component level (Mertens et al 2014) or on full scale structures (Walsh et al 2015), for both existing and retrofitting ties (Giaretton et al, 2016). In the current campaign, both existing replicated and retrofitted wall-wall and wall-floor connections were tested. A detailed description of the tests on existing wall-wall connections is presented in Skroumpelou et al (2018). As for the wall-wall anchors, both axial and shear capacity of the connection was studied. The specimens representing the existing connections consisted of brick couplets including a wall tie embedded in the mortar joint (Figure 9a),

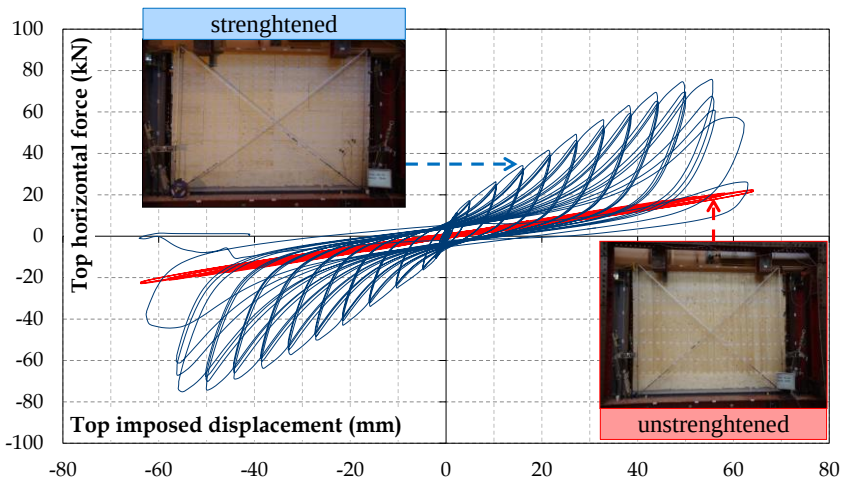


Figure 7. Hysteresis behavior of the unstrengthened and the strengthened timber floor

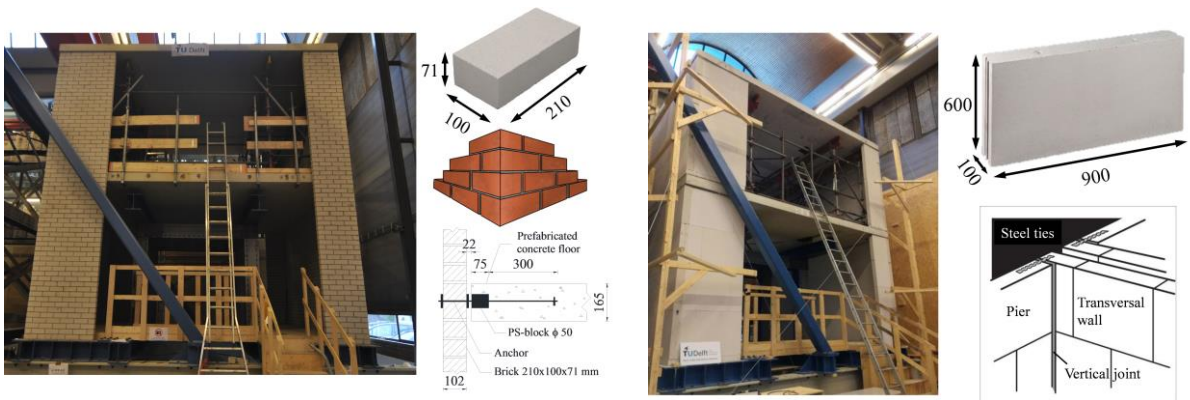
whereas the retrofitted ties (Helifix bars) were drilled directly in the bricks (such as in the common engineering practice, Figure 9b). These tests allowed for a complete mechanical characterization of the connections in static conditions, providing benchmarks to calibrate and validate specific numerical models. As regards the wall-floor anchors, only connections to concrete floors were investigated. For the existing connections, the anchorages consisted of steel threaded rods, and reproduce the connection between the masonry piers and the concrete floors, that typically span directly between the long transversal walls of a terraced house and are hence not supported by the piers. This anchoring typology (an example is shown in Figure 9c) is extremely efficient against the out-of-plane failure of the piers, but negligible shear forces can be transferred for small deformations. As for the retrofitting connections, a tailored system was tested for tensile axial loads only (Figure 9d). The system was composed of a threaded bar connected to two Helifix bars embedded in a mortar bed joint, and in real buildings may be coupled to a dissipative system that is able to withstand the compressive actions. The performed tests allowed to assess whether this type of connections is able to retain efficiently the out-of-plane failure of walls by transferring the reaction forces at the floor level. For every test typology, various levels of axial precompression were considered, in order to assess the component behavior in different locations in the building.

(a) (b) (c) (d)

Figure 9. Existing (a) and retrofitting (b) wall-wall anchors. Tests on existing (c) and retrofitting (d) wall-floor connections

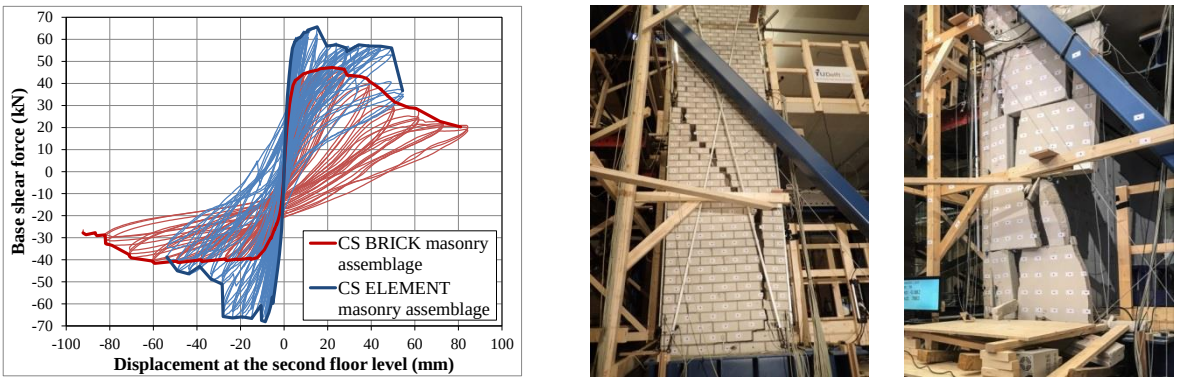
4. LATERAL CAPACITY OF FULL-SCALE ASSEMBLAGES

Quasi-static cyclic pushover tests on full-scale assembled structures resembling typical Dutch terraced houses have been performed. The specimens represent only the loadbearing part of a single terraced house unit (Esposito et al. 2017, Esposito et al. 2018), which is usually a two-story high building composed of rigid concrete floors and cavity walls. To represent both the construction period 1960-80 and the period 1980-2000 (Figure 2), CS brick masonry and CS element masonry were used, respectively (Figure 10a,b). As expected, the structural response was mainly linked to the in-plane damage of the wider piers, which showed extensive damage at the ground floor (Figure 11a,b,c).



(a) (b)

Figure 10. Full-scale assembled structures made of CS brick (a) and element (b) masonry



(a) (b) (c)

Figure 11. Test on full-scale assemblages: hysteretic behavior (a) and main failure mechanism (b,c)

5. DAMAGE INITIATION AND PROPAGATION IN MASONRY WALLS

The case of light damage is particularly relevant for induced earthquakes, since their magnitude is often lower than that of tectonic earthquakes, leading to a higher percentage of service-level damage. As such, the experimental campaign did not only focus on the near-collapse states, but also on the lower damage states related to mostly aesthetic damage and serviceability of the structures.

Since light damage corresponds predominantly to the appearance and growth of cracks in masonry, cracking was selected as the measure for damage. This is also relevant for the aesthetic nature of the light damage. Based on the work by Giardina (2013), where the traditional damage states are subdivided into finer categories qualitatively related to the width of the cracks, and which correspond to an "ease of repair" of the damage, a quantitative expression was formulated (equation 1).

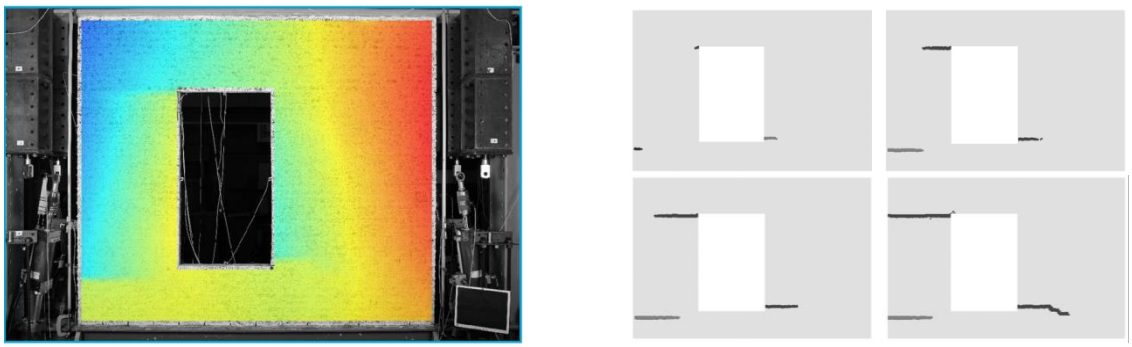
$$\Psi=2\cdot n^{0.15}\cdot \check{c}^{0.3} \quad (1)$$

where Ψ is the damage parameter, n is the number of cracks on the wall, and $\check{c}$ is the length-weighted average crack width computed with equation 2:

$$\check{c}=\Sigma c_i^2\cdot L_i/\Sigma c_i\cdot L_i \quad (2)$$

where c_i is the maximum crack width of each crack and L_i is the length of each crack. Equation 1 is tailored such that a value of 1 corresponds to cracks of around 0.1mm, that is considered the threshold at which cracks can be detectable by naked eye. Larger cracks up to 1mm receive a value of 2 and are easy to address, commonly requiring repainting of the walls. Cracks up to 5mm, which will require repointing and repainting, obtain a score around 3. Cracks larger than 5mm typically require additional repair work and were deemed to be outside of the scope of light damage and correspond to more severe and structurally-compromising damage. Not only the width, but also the number and length of the cracks influence the exact damage value computed with equation 1. The use of this strict definition allows for an objective and quantitative comparison between various laboratory samples and numerical models. Moreover, the progression of damage due to repeated or different loading cycles can be assessed directly. In the scope of service-level damage, also exploratory tests have been conducted with the goal of elaborating fragility curves for the initiation of damage for various types of masonry material and building typologies (see section 2). These tests aim to provide a first view into the initiation of (light) damage and its evolution. Five in-plane tests on windowed walls made of single wythe solid clay brick masonry were tested. To detect the initiation and propagation of cracks in the masonry walls, Digital Image Correlation (DIC) was used by painting a random pattern on the wall and capturing high-resolution images with a camera (Didier 2017). The images were later processed to obtain the displacement field of the wall (Jones, 2015) at different test cycles (Figure 12a). The

displacement field was further analyzed to identify and characterize the cracks (Figure 12b), the damage parameter Ψ was computed automatically and related to the top lateral displacement of the wall expressed as drift. Based on these results, drift values between 0.3‰ and 1.1‰ seem to correspond to aesthetic damage for the tested wall (Figure 13).



(a) (b)

Figure 12. Actual laboratory setup with an overlay of DIC vertical displacement for a lateral top displacement of 2mm (a), and Sequence of crack propagation for different cycles in the test (b)

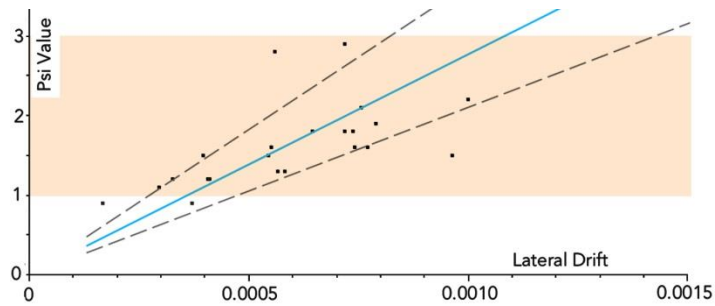


Figure 13. Linear regression of results for the damage parameter (Ψ) against lateral drift of masonry test walls, highlighting the zone corresponding to aesthetic damage. Dashed lines indicate one standard deviation

6. CONCLUDING REMARKS

In recent years, induced seismicity in the Netherlands has increased considerably, leading to the need of assessing the current building stock. In order to provide input parameters and validation benchmarks for the assessment tools, an extensive multiscale testing program has been performed at Delft University of Technology since 2014. The experimental campaign focused on the characterization of URM buildings from material up to structural level from the point of view of both the near collapse and the serviceability limit states.

In the first phase, masonry and timber samples were extracted from existing buildings and tested in the laboratory. The tests allowed to identify the masonry and timber properties at material level for different building typologies and construction periods. In the second phase, a multiscale testing campaign was conducted at both structural and material level on replicated specimens, whose properties were selected to match those derived by the aforementioned tests on existing materials. In general, the campaign was characterized by loading protocols based on the application of quasi-static cyclic loads that allowed investigating the hysteretic and the post-peak behavior of the specimens. At material level, different testing methodologies were considered: standard destructive tests, standardized slightly-destructive tests (flat-jack and shove tests), and non-standardized tests on cylindrical cores. Compression, bending, and shear properties were investigated and categorized according to the type of masonry and the construction period. Possible correlations between the results obtained with the different techniques are currently under investigation. At component level, both in-plane and out-of-plane tests were performed on URM walls. The influence of several parameters

(material, geometry, boundary conditions, overburden loads, and presence of openings) was analyzed. The outcomes of these tests were also used to derive and validate a recent constitutive model for brick masonry. The in-plane stiffness and strength of timber diaphragms, both as-built and strengthened floors were investigated. As-built diaphragms proved not to be stiff enough to create a structural box behavior in the buildings, whereas a relative simple strengthening technique provided sufficient stiffness. Similarly, existing and retrofitted connections between the leaves of cavity walls and between a floor concrete slab and the masonry veneer were studied. Retrofitting anchors are significantly more effective at providing adequate restraint against the out-of-plane failure of veneers. The behavior at structural level was investigated by two quasi-static cyclic tests on full-scale two-story high assembled structures representative of different types of terraced houses. The structural response was analyzed and the consequence of adopting different materials and connection details was investigated. In the third phase, additional tests were focused on the initiation and propagation of cracking to investigate the light damage conditions in URM structures. The tests, currently ongoing, employ a Digital Image Correlation (DIC) measurement system to identify cracking and so relate different intensities of light damage to drift values of approximately 0.1%.

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