NUMERICAL MODELLING AND SEISMIC ANALYSIS OF DUTCH MASONRY STRUCTURAL COMPONENTS AND BUILDINGS

V. Mariani[(1)], F. Messali[(2)], M.A.N. Hendriks[(3)], J.G. Rots[(4)]

[(1)] *Postdoc, Delft University of Technology, Department of Structural Engineering, Delft, Netherlands, V.Mariani@tudelft.nl*
[(2)] *Postdoc, Delft University of Technology, Department of Structural Engineering, Delft, Netherlands, F.Messali@tudelft.nl*
[(3)] *Prof. Dr. Ir., Delft University of Technology, Department of Structural Engineering, Delft, Netherlands, M.A.N.Hendriks@tudelft.nl*
Also Norwegian University of Science and Technology, Department of Structural Engineering, Trondheim, Norway
[(4)] *Prof. Dr. Ir., Delft University of Technology, Department of Structural Engineering, Delft, Netherlands, J.G.Rots@tudelft.nl*

Abstract

In recent years induced seismicity in the Netherlands considerably increased. This implied the need for a comprehensive study to assess the seismic vulnerability of the built environment exposed to this phenomenon. Currently, very limited data is available on the seismic response of construction typologies specific to Dutch practice. Moreover, most of these buildings are masonry structures and were not conceived to resist considerable lateral forces. Indeed, they were designed to withstand gravity and wind loads only. Most likely the design for wind loads could be not enough to provide for adequate lateral resistance and ductility against potential seismic loads.

In this framework, this paper presents part of the results of a numerical study that is currently in progress, aimed at the seismic assessment of most common Dutch buildings typologies. The study is based on an extensive experimental campaign at components and full-scale levels. The experimental tests are reproduced by nonlinear finite element analysis, validated and calibrated against data available from the experimental testing campaign. Some limitations of the application of an existing total strain based constitutive model under lateral cyclic loading are shown. Consequently, a recently developed new constitutive model is introduced and its potentials in terms of numerical stability and capability to capture different failure modes are presented with reference to some tests on components and full-scale building specimen.

These studies are of fundamental importance for the assessment of the seismic vulnerability of the build environment through the definition of fragility curves and consequently to define potential strengthening measures.

Keywords: seismic analysis, masonry constitutive model, model validation

1. Introduction

In the last years induced seismicity associated to gas depletion in the Netherlands has significantly increased in the area of Groningen. This phenomenon has a potential impact on the building stock of the area which is mainly made by unreinforced masonry (URM). Since the Netherlands is not historically affected by natural seismic hazard, these buildings have been designed for gravity and wind loads only and this could lead to a not sufficient capacity against potential seismic events.

This scenario was the reason for the activation of a wide research program financed by the Nederlandse Aardolie Maatschappij (NAM), a Dutch exploration and production company, to assess the vulnerability of the urban environment of the Groningen area to potential seismic events. Among other aspects, this project involves the characterization of the seismic behavior of URM buildings in Groningen through experimental and numerical activities, starting from the derivation of the mechanical properties at material and component levels, up to the investigation of full-scale building typologies.

The use of finite element analysis represents a powerful tool to characterize the seismic performance of different building typologies in order to identify the most vulnerable ones, define potential damage scenarios and possibly design preventive actions for seismic risk mitigation in the area. Within a wide range of different commercial and research oriented softwares, different modelling approaches are available to numerically reproduce the behavior of masonry material. Among those involving the modelling of masonry as a homogeneous material, the use of a smeared crack model based on a total strain formulation [1] included in the software Diana [2] is rather attractive, because of its unified approach providing for nonlinearity in both tension and compression, through simple total stress-total strain relationships. Nevertheless this model has been originally conceived for concrete and the possibility to extend its use to the analysis of masonry structures has been subsequently explored.

The reliability of the adopted numerical models is extremely important in order to obtain an accurate prediction. To this aim, there are several benchmarks studies in literature that allow the validation and calibration of numerical models against experimental tests [3-8]. Despite numerous validation studies using the total strain crack model for concrete on masonry structures are available in literature [9,10], some critical issues can be identified in the use of such model for cyclic loads: (i) possible instability of solution, especially for near collapse conditions evaluation when implicit solvers are used, (ii) impossibility to take into account for initial orthotropy and to distinguish different failure modes, due to the fact that a unique tensile/compressive strength is assumed in all directions, (iii) secant unloading/reloading law, reasonable for tensile failure not for shear and compression, leading to underestimation of energy dissipation and (iv) difficulties in the definition of reasonable values for the shear retention factor in the “fixed” version of the crack model ensuring stability of the solution without any shear locking phenomenon. All these points of attention led to the activation of a joint project between TNO DIANA and Delft University of Technology aimed at the development of a more stable and suitable constitutive masonry model, always within a total strain approach [11].

Moreover, since there is a lack of knowledge on the performance of typical Dutch masonry components and building typologies to substantial horizontal loads, an experimental campaign including tests at material, component and full-assemblage levels have been performed in order to characterize the seismic behavior of typical Dutch masonry structures [12-14]. The results of such tests have been extremely important, since they have been assumed as reference data to validate and calibrate the new constitutive masonry model.

This paper summarizes the main features of the new Total Strain Masonry Model and its material parameters. Next, results from ongoing validation studies are presented for walls tested in-plane and out-of-plane and for a full-scale masonry house tested cyclically. The concluding section discusses the current state of the Total Strain Masonry Model.

2. Main features of the new total strain based masonry model

The recently developed Total Strain Masonry Model (TSMM) [11] is a total-strain based model that has been conceived to better reproduce the behavior of masonry material, still within a continuum approach, and to overcome the critical issues related to the use of the classical Total Strain Concrete Model (TSCM). The model is currently under improvement, but a first version is available in the latest development release of Diana [2].

The new TSMM has an orthotropic nature with three pre-defined crack directions (Fig. 1a). Two of them are oriented in the directions of head and bed mortar joints, since they represent the weak surfaces where cracks usually develop; a third one is introduced with the aim of capturing the typical step-wise cracking pattern often occurring in masonry components, and therefore it is normal to the diagonal direction determined by the pattern of the bed and head mortar joints. The orthotropy of the model is assured in both the linear and nonlinear range, since different properties are assigned for the stiffness, strength and softening laws for the two principal x and y directions. The model assumes that there is no coupling between the stiffness of the normal components in the x and y directions and that of the in–plane shear component. Therefore, the TSMM behaves as an orthotropic material with Poisson's ratio set equal to zero. The constitutive model can be applied in combination with regular plane stress (membrane) and curved shell elements for modelling either the in-plane or the out-of-plane failure of masonry structures. In shell elements, the out–of–plane shear stiffness components are assumed to be linear elastic.

The TSMM considers different failure mechanisms: tensile cracking, compressive crushing and shear sliding. Tensile cracking is assessed in the three directions normal to the crack planes (i.e. local x, y and n directions); a secant nonlinear unloading and reloading behavior (similar to that adopted in the traditional TSCM) is assumed (Fig. 1b). Compressive crushing is assessed in the directions normal to the local x and y directions only (i.e. normal to head and bed joints, respectively); a nonlinear non-secant unloading and reloading behavior is assumed in this case (Fig. 1c). The in–plane shear stresses are limited by a standard Coulomb friction failure criterion, based on the stress normal to the bed-joints (Fig. 1d).

3. Overview of the performed tests on replicated masonry and related numerical analyses

Within the research program financed by NAM, a comprehensive experimental campaign on replicated masonry has been performed at the testing laboratory of Delft University of Technology in 2015 [12-14]. The campaign investigated the behavior of Dutch masonry at material, component and assemblage level. The focus was on typical masonry house typologies from the period 1960-1980, often characterized by the presence of cavity walls composed of an inner leaf in calcium silicate (CS) masonry and an outer leaf in clay (CL) masonry connected by steel ties, and solid pre-fabricated concrete floors having a dry connection with the load bearing masonry walls.

For what concerns the material characterization, compressive and bending tests on bricks and mortar have been executed [12]. Several small specimens of replicated masonry have been set up and subjected to compressive, bending and bond-wrench tests, to determine the values of the main mechanical parameters of replicated Dutch masonry, subsequently used in the numerical analyses. Afterwards, the in-plane (IP) and out-of-plane (OOP) behavior of masonry piers have been investigated through quasi-static cyclic tests with different geometries, overburden levels and boundary conditions [13]. Seven panels have been tested IP and five panels OOP. Main attention has been paid to the CS walls, usually representing the load bearing walls, whereas the CL walls are mainly used as external revetment. Lastly, a full-scale building specimen, representing the scheme of a typical 2-storeys terraced house, has been built and subjected to a quasi-static cyclic pushover test [14].

All the IP, OOP and full-scale building tests have been numerically reproduced through finite element modeling in Diana, with the use of the new TSMM. Some comparison with results obtained through classical TSCM will be also presented in the following sections to show the improvements given by the TSMM. The material properties used for the TSMM have been assumed according to the test results at material level [12] and are reported in Table 1. Any parameter not available from the experimental campaign has been assumed with reference to typical values suggested in literature. The material parameters are clarified in Fig 1b-d. Parameter h is the crack band width, which represents the element size and is assumed to be independent of load orientation (x, y, n) and direction (tension, compression).

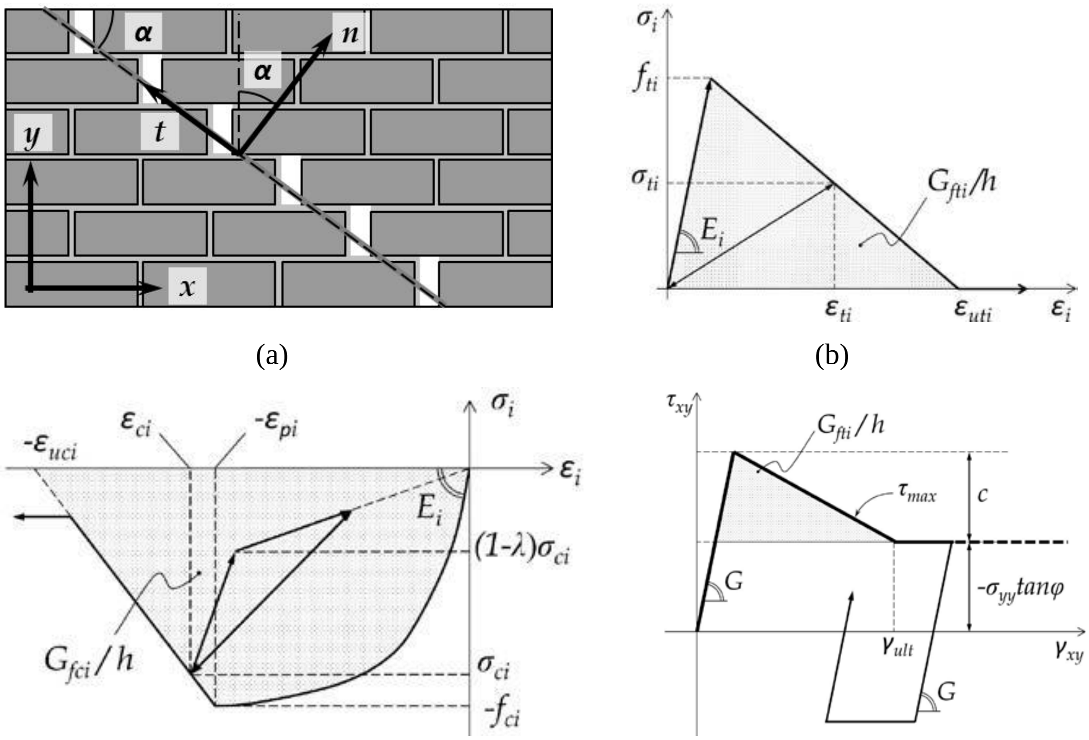


Fig. 1 – (a) Identification of the pre-defined crack directions included in the TSMM; (b) Uniaxial tensile stress-strain relationship; (c) Uniaxial compressive stress-strain relationship; (d) Uniaxial in-plane shear stress-strain relationship.

Table 1 –Material properties for CS masonry used for the numerical analysis with TSMM

Young modulus y-dir	E_y	5091	MPa
Young modulus x-dir	E_x	3583	MPa
Shear modulus	G_{xy}	1500	MPa
Tensile strength of bed joints	f_{ty}	0.14	MPa
Tensile strength of head joints	f_{tx}	0.51	MPa
Fracture energy in tension y-dir	G_{fty}	0.015	N/mm
Fracture energy in tension x-dir	G_{ftx}	0.055	N/mm
Compressive strength of bed joints	f_{cy}	5.93	MPa
Compressive strength of head joints	f_{cx}	7.55	MPa
Fracture energy in compression y-dir	G_{fcy}	31.3	N/mm
Fracture energy in compression x-dir	G_{fcx}	43.4	N/mm
Cohesion	c	0.14	MPa
Friction angle	$tg\varphi$	0.43	-

In the following sections, the numerical results of some of the aforementioned tests will be presented. Two IP tests will be reported, namely COMP-3, and COMP-6, that cover the two geometry typologies (short and long walls) and the two different boundary conditions (cantilever and double clamped). The improvements of the new TSMM with respect to the classical TSCM will be also presented. For what concerns the OOP tests, a 1-way bending test (COMP-7) and a 2-ways bending test (COMP-11) will be reported. Moreover, some preliminary results of the numerical analyses of the pushover test on the full-scale building specimen will be presented and compared to the experimental results, to show the potentials of the new TSMM applied to the seismic assessment of masonry structures.

4. Numerical prediction of in-plane tests

The IP tests were numerically reproduced by modelling and analysis in Diana with the application of both TSCM and TSMM. Quadratic plane stress elements of average dimensions 0.1 m x 0.1 m were used to model the panels, tyings were applied on the top edge of COMP-3 to reproduce double fixed boundary conditions. Dead load and vertical overburden were preliminarily applied on the panel before the application of the cyclic load, consisting in an incrementally increasing top lateral displacement. Each value of lateral displacement has been cyclically applied for 3 times, before being increased again. More details about test-set up and loading protocol of the tests can be found in [13].

4.1 IP test on a double clamped slender CS masonry panel (COMP-3)

COMP-3 was a single-wythe URM wall constructed of CS units 102 mm thick. The geometry of the panel was 1.1 m long and 2.76 m high, with a height over length ratio equal to 2.5. The wall was tested with double clamped boundary conditions and 0.4 MPa of overburden on top. The experimental test initially showed horizontal cracks associated to rocking at the top and bottom boundaries followed by the development of diagonally oriented cracks for increasing displacement levels (0.9% drift). The failure mode was mainly governed by rocking behavior, associated with toe crushing and bed joint sliding. The test was stopped at a net drift of 1.3% at which severe damage was observed at the top portion of the wall.

The DIANA model of COMP-3 has been initially tested with the application of the classical TSCM. The analysis could not be run for the whole loading protocol, because numerical divergence occurred in correspondence of a drift value of 0.25%, much lower than the maximum drift experienced by the panel in the test. The prediction of the shear capacity was quite consistent with the experiment, but the energy dissipation was largely underestimated, as confirmed by the shear-displacement plot (Fig. 2a). Moreover, larger values of displacement could not be explored because of numerical issues.

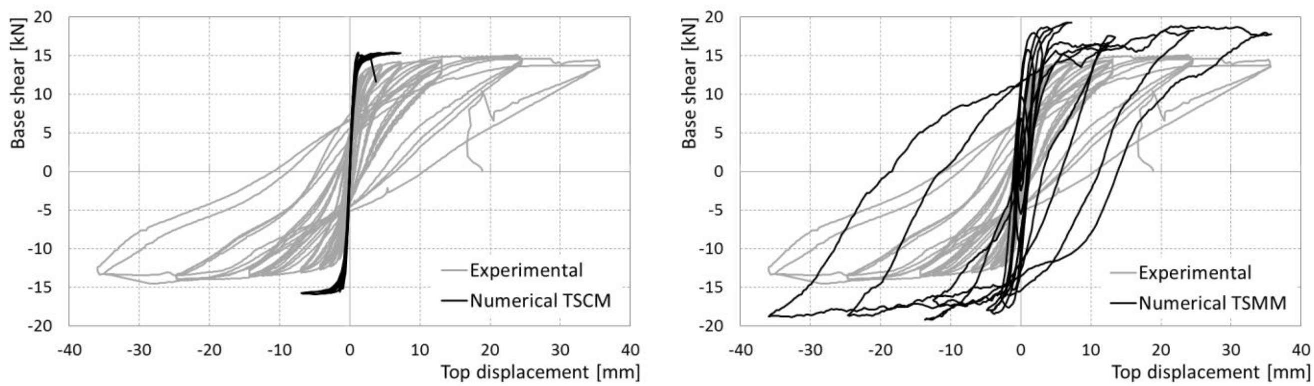
The numerical test was then re-executed with the application of the new TSMM. The prediction of the experimental behavior of the panel noticeably improved. The real loading protocol was applied with no convergence problems until large displacements. The shear-displacement history with the TSMM (Fig. 2b) resulted much more consistent with the experimental one with respect to the case of TSCM. The numerical loops are much closer to the test ones, with a remarkable amount of energy dissipation. The numerical damage pattern resulted more extensive with respect to the experiment (Fig. 3). A rocking behavior was detected with damage at the base and top of the panel, spreading also along the height in the last stages of the test.

4.2 IP test on a cantilever long CS masonry panel (COMP-6)

COMP-6 was a single-wythe URM wall constructed of CS units 102 mm thick. The geometry of the panel was 4.0 m long and 2.76 m high, with a height over length ratio almost equal to 1.5. The wall was tested with cantilever boundary conditions and 0.5 MPa of overburden on top. During the experiment, first cracks along the main diagonal of the wall appeared for very low displacement values (0.02% drift). Similar cracks along the opposite diagonal also formed. These cracks progressively increased during the duration of the test and passing through both bricks and mortar. In addition, bed-joint sliding near the bottom of the wall and significant brick crushing occurred at increasing displacements (around 0.4% drift). The test was stopped at 0.56% drift due to potential danger of collapse of part of the wall.

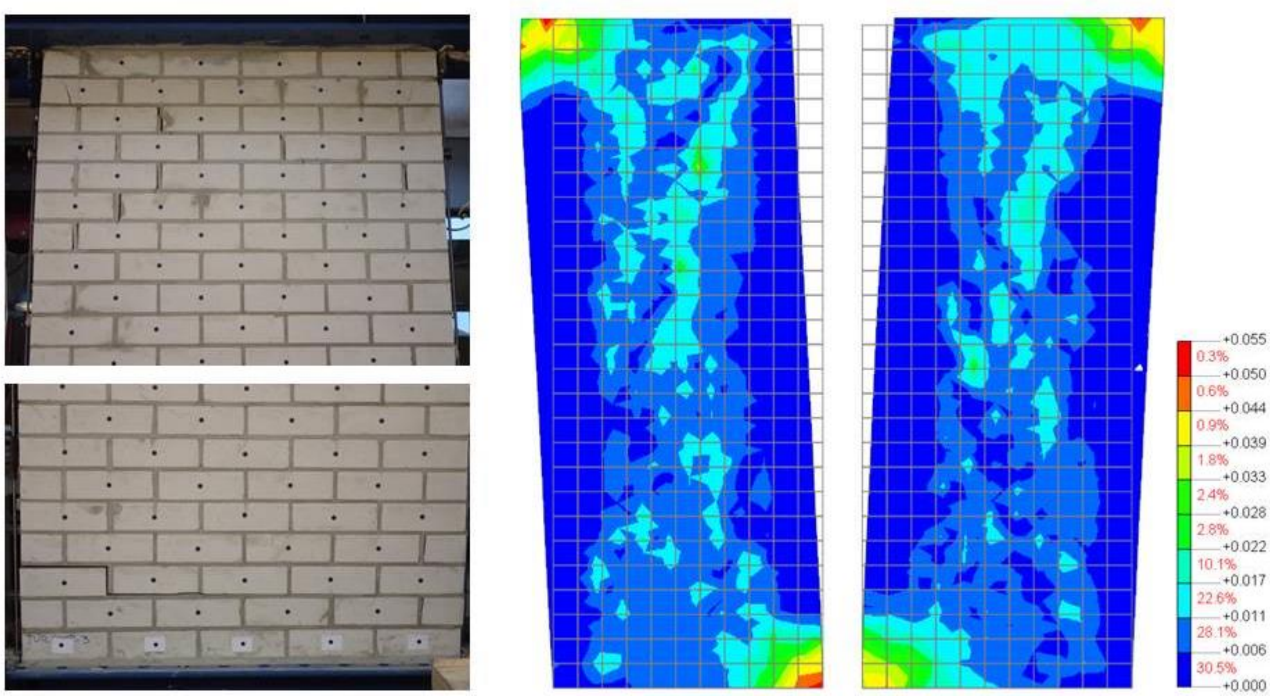
As for the previous slender panel, the DIANA model of COMP-6 has been initially tested with the application of the TSCM. The analysis with TSCM could not be performed to large displacement levels due to numerical instability. The dissipated energy was lower than that observed in the experiment (Fig. 4a). The application of the TSMM noticeably improved the prediction of the experimental behavior of the panel (Fig. 4b). A much larger energy dissipation, similar to what observed in the experiment was obtained. A slight hardening effect occurred in the numerical test, whereas a moderate decay of shear capacity was recorded during the experiment at the increasing of the drift level. The TSMM resulted numerically very stable during the entire loading protocol application.

The numerical damage pattern resulted more extensive with respect to the experiment (Fig. 5). Most of the damage is in the middle of the panel, but it was not possible to completely identify the typical X-shaped cracks observed in the experiment.



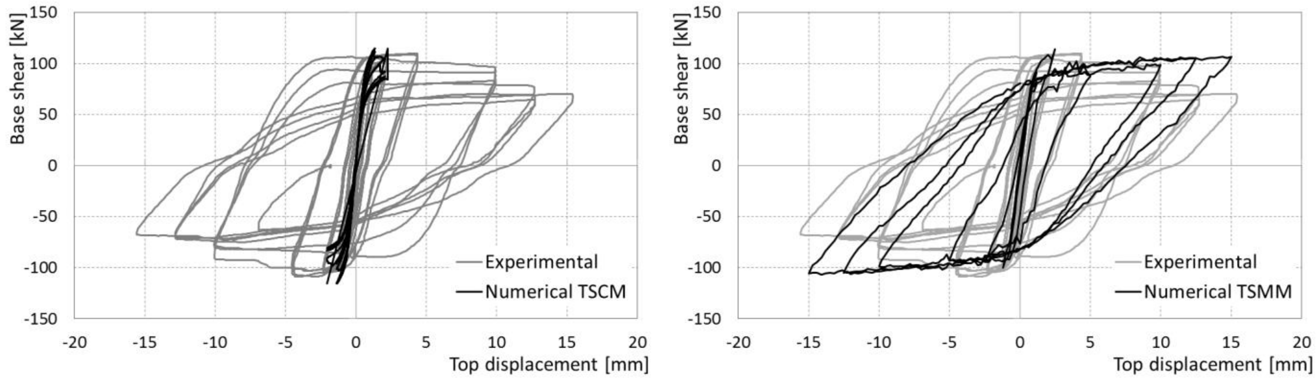
(a) (b)

Fig. 2 – COMP-3 IP test: Comparison of experimental and numerical base shear-top displacement curves for (a) TSCM and (b) TSMM.



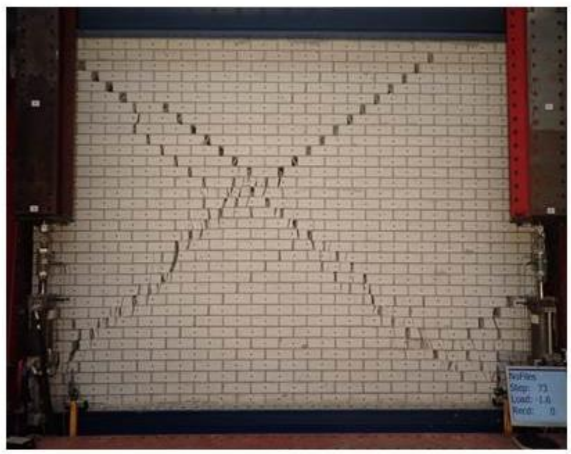
(a) (b)

Fig. 3 – COMP-3 IP test: (a) Observed damage at the end of the experimental test on top and bottom of the panel; (b) Numerical damage pattern obtained with TSMM, expressed by principal tensile strains for the maximum negative and positive top displacement.

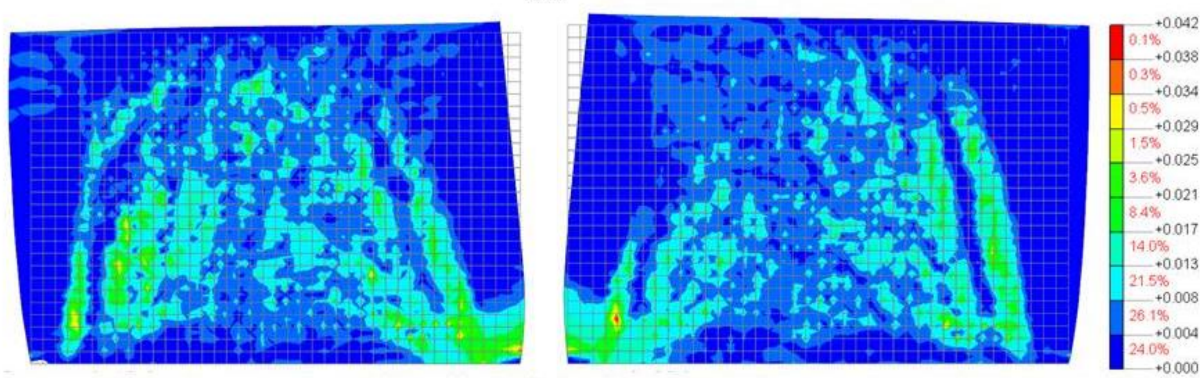


(a) (b)

Fig. 4 – COMP-6 IP test: Comparison of experimental and numerical base shear-top displacement curves for (a) TSCM and (b) TSMM.



(a)



(b)

Fig. 5 – COMP-6 IP test: (a) Observed damage at the end of the experimental test; (b) Numerical damage pattern obtained with TSMM, expressed by principal tensile strains for the maximum negative and positive top displacement.

5. Numerical prediction of out-of-plane tests

The OOP tests were also numerically reproduced by modelling and analysis in Diana. Quadratic shell elements of average dimensions 0.1 m x 0.1 m were used to model the panels. Dead load and vertical overburden were preliminarily applied on the panel before the application of the cyclic load, consisting in an incrementally increasing pressure, uniformly applied on the lateral surfaces of the specimens. More details about test-set up and loading protocol of the tests can be found in [13].

5.1 One-way OOP bending test on a slender CS masonry panel (COMP-7)

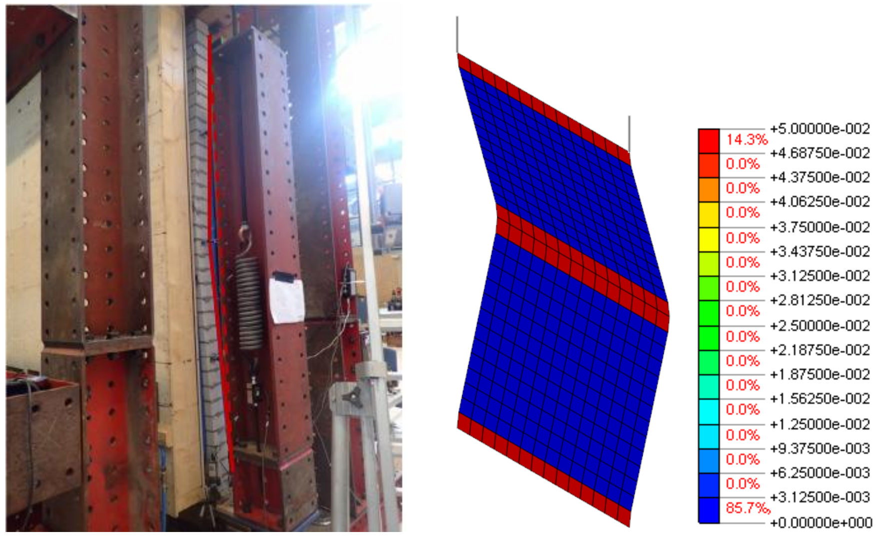
COMP-7 was a CS masonry specimen subjected to one-way bending test with double clamped top and bottom boundary conditions and 0.2 MPa of overburden. During the experiment, the specimen denoted an elastic behavior for the first four cycles, up to a displacement of 2 mm and a force of 8 kN. First cracks appeared at the top and bottom mortar layer and subsequently at mid-span, for displacements comprised between 2 and 5 mm. For displacements larger than 20 mm, a gradual reduction of resistance occurred. For a displacement of ±80 mm (80% of the thickness of the wall), the actual resistance of the wall was almost reduced to zero. At the final stage, the cracks at the supports and at mid-span were clearly visible and fully open, and also the deflected shape of the wall could be distinctly observed (Fig. 6a).

The DIANA model with the application of the TSMM correctly predicted a three-point out-of-plane rocking mechanism; cracks localized at the top, bottom and mid-span of the wall (Fig. 6b). Compared with the lab test results, the peak resistance is correctly predicted (Fig. 7a). The post-peak phase is characterized by a gradual reduction of resistance for larger displacements that is mainly caused by second order effects. The trend of the reduction is in line with the experiment. Nevertheless in the numerical model, the damage phenomenon is mainly characterized by cracking, that is why the energy dissipation is underestimated.

5.2 Two-ways OOP bending test on a long CS masonry panel (COMP-11)

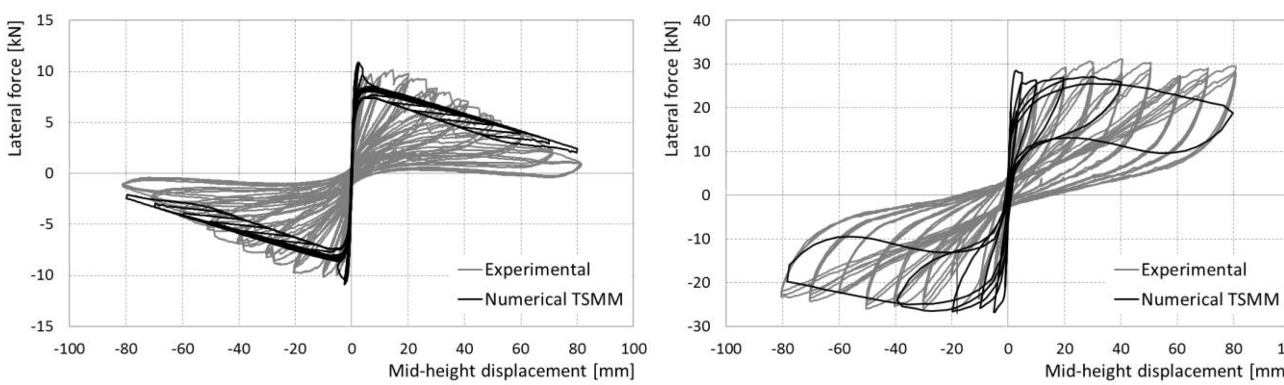
COMP-11 was a CS masonry specimen subjected to two-ways bending test; the top and bottom boundaries were clamped, whereas the lateral edges were hinged. The applied overburden is 0.05 MPa. During the experiment, the specimen denoted an elastic behavior up to a displacement of 2 mm and a force of 13 kN. The peak resistance was reached at a lateral displacement of 30 mm and it was equal to 30.7 kN for positive drifts; whereas in the opposite direction it was obtained at -20 mm and it was equal to -26.9kN. The resistance remained almost constant for the following cycles up to the largest displacement (80 mm) for positive drifts, whereas a slight decay (-15%) was observed for negative drifts. The final crack pattern was characterized by two horizontal cracks along the bed joints close to the supports, four diagonal cracks, mainly along the mortar joints, approximately starting from the corners and oriented towards the center of the wall and a horizontal crack along the bed joint at mid-height, connecting the diagonal cracks (Fig. 8a).

The DIANA model correctly predicted a two-ways out-of-plane bending mechanism. The top and bottom damaged lines are correctly reproduced. The crack pattern in the middle of the panel instead presents some differences, since the cracks tend to develop in the vertical and horizontal directions instead of spreading toward the panel corners (Fig. 8b). The predicted capacity is consistent with the experiment even if the model showed a slight higher strength decay at the increase of lateral displacement (Fig. 7b). The wider hysteresis cycles with respect to the case of COMP-7 (Fig. 7a) highlight a more substantial damage also associated to compressive failure.



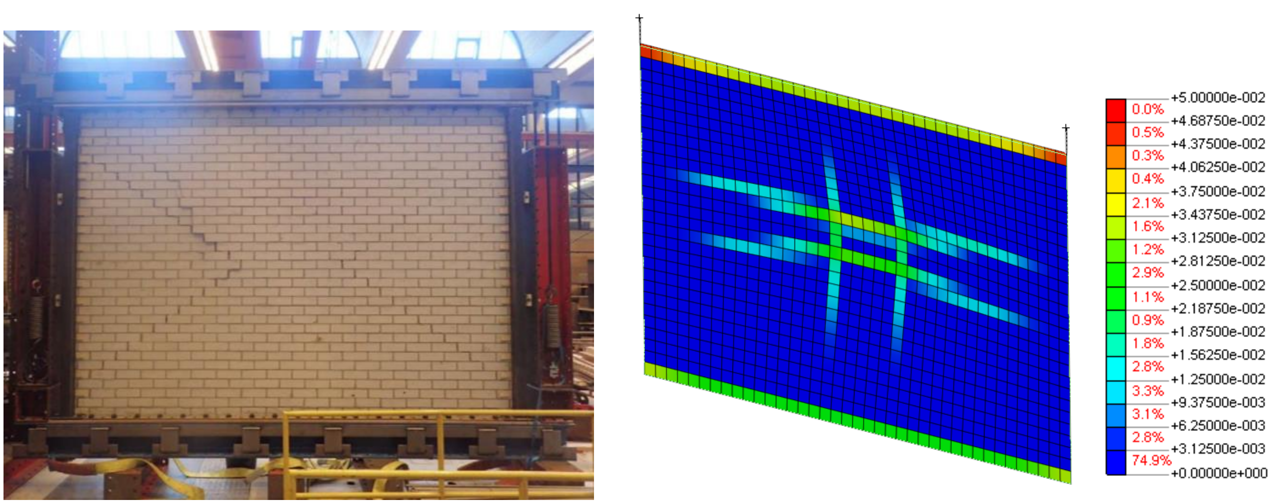
(a) (b)

Fig. 6 – COMP-7 OOP test: (a) Observed damage at the end of the experimental test; (b) Numerical damage pattern with TSMM, expressed by principal tensile strains for the maximum positive mid-height displacement.



(a) (b)

Fig. 7 – Comparison of experimental and numerical lateral force vs. mid-height displacement curves: (a) COMP-7 OOP test; (b) COMP-11 OOP test



(a) (b)

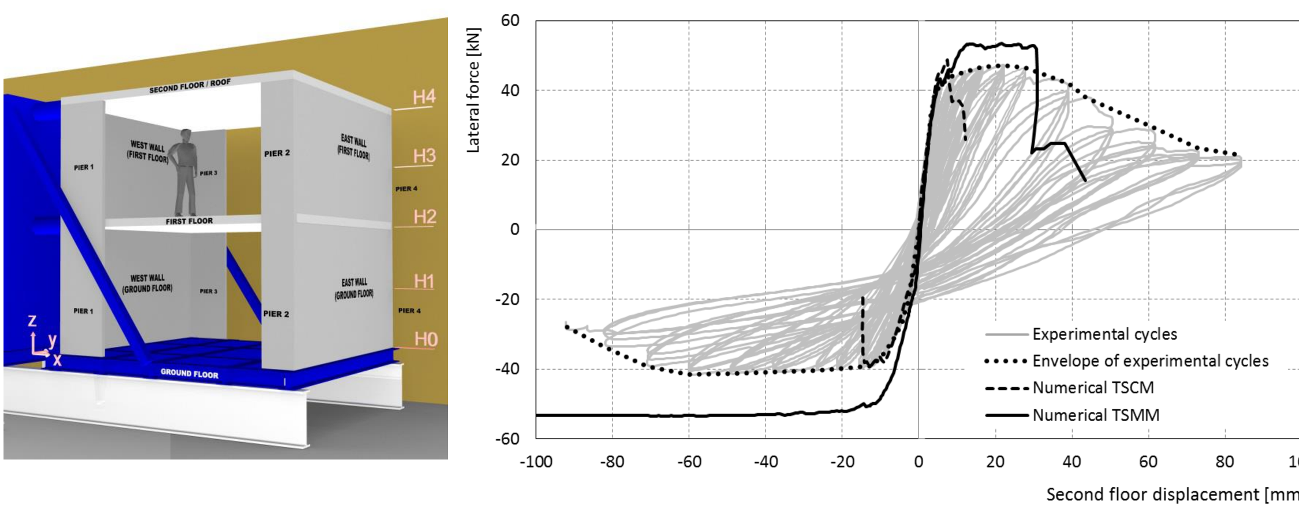
Fig. 8 – COMP-11 OOP test: (a) Observed damage at the end of the experimental test; (b) Numerical damage pattern with TSMM, expressed by principal tensile strains for the maximum positive mid-height displacement.

6. Numerical prediction of the cyclic pushover test on a full-scale masonry house

After the test campaign at component level, a 3D full-scale specimen has been build, resembling a typical 2-storeys terraced house. The building, schematically reproduced in Fig. 9a, is made of CS walls, with 2 long load bearing walls and 2 "simplified" façades, each one consisting of 2 piers of different lengths (660 mm and 1100 mm) without any connecting spandrel. Two reinforced concrete floors are laid on top of the long walls and restrain the piers for the out-of-plane displacements only through anchors casted in the floor and masoned in the piers. The test performed on the assembled structure was a quasi-static cyclic pushover test in displacement control in the direction parallel to façades (x direction of Fig. 9a). More details about the geometry of the specimen and the loading protocol can be found in [14].

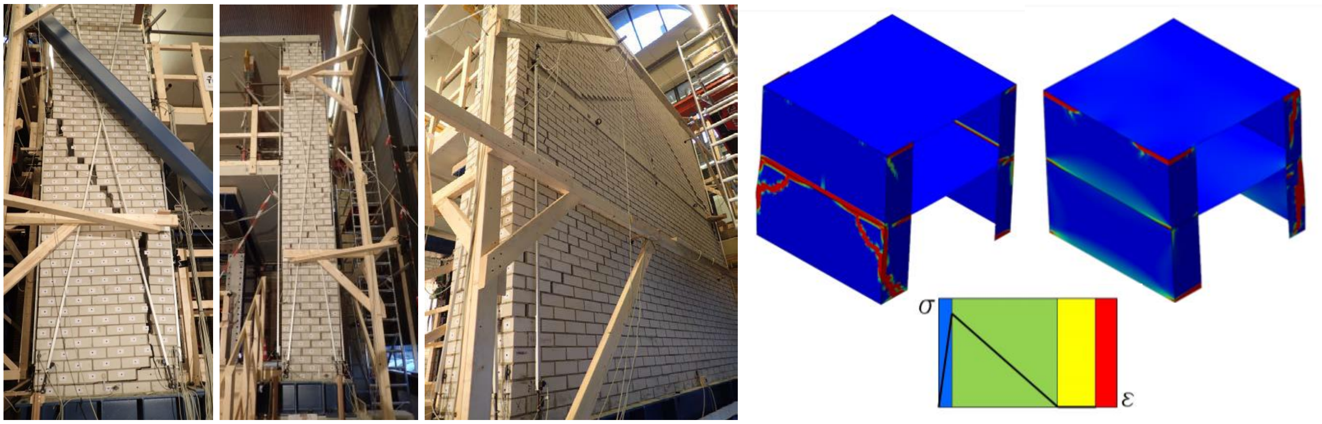
The experimental test showed that the assembled structure was able to react to the quasi-static cyclic load with a quite remarkable ductility. A horizontal plateau was observed in the –x direction for displacements up to 60 mm, whereas in the +x direction a decay of capacity of 20% was observed for displacements larger than 40 mm (Fig. 9b). Both the IP and OOP behavior of the walls composing the structure were activated with development of large rocking and shear cracks in the piers (Fig. 10a-b) and diagonal cracks, associated to two-ways bending OOP behaviour with substantial flange effect, in the load bearing walls (Fig. 10c).

The masonry test house has been modelled in Diana with quadratic shell elements and preliminarly subjected to a mass-proportional monotonic pushover test with both TSCM (dahsed line of Fig. 9b) and TSMM (solid line of Fig. 9b). The numerical pushover curves have been compared with the experimental backbone curve, i.e. the envelope of all the displacement-shear cycles of the quasi-static test (dotted line of Fig. 9b). The numerical results show a quite reasonable prediction of the shear capacity, somewhat overestimated for the TSMM. Nevertheless it should be kept in mind that this preliminary comparison has been done for the execution of a monotonic rather than a cyclic numerical pushover. Additionally, the analysis with TSCM shows a quite brittle decay of capacity for relatively low displacements (+/-10 mm), associated to numerical instability. On the other hand, the application of TSMM provides a higher displacement capacity in both directions. Morover, similarly to what experimentally observed, the numerical analyis with TSMM shows a larger ductility in the –x with respect to the +x direction. Concerning the preliminary comparison in terms of crack patterns (Fig. 10), the numerical analysis shows rocking of the piers with formation of diagonal cracks in the late stages and a remarkable OOP damage of the long walls, similarly to what observed in the experiment.



(a) (b)

Fig. 9 – (a) Schematic 3D view of the full-scale specimen; (b) Comparison of the envelope of experimental cyclic pushover test (dotted line) and the numerical monotonic pushovers with TSCM (dashed line) and TSMM (bold line) in terms of top displacement-base shear curves.



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

Fig. 10 – Experimental crack pattern at the end of the cyclic pushover test: (a) pier 1 of South wall; (b) pier 2 of South wall; (c) East wall. (d) Numerical damage with TSMM, expressed by principal tensile strains pattern for monotonic pushover in +x and –x directions.

7. Conclusions

The present paper reports the results of the numerical activities performed in the framework of a wide research program aimed at assessing the vulnerability of the urban environment of the Groningen area to potential induced seismic events. The first analyses performed with the classical TSCM highlighted the need for the definition of a direction dependent constitutive masonry model, able to differentiate the nonlinear behaviour in pre-defined damage directions and, consequently, to capture the different failure modes that can occur in a more realistic way. Numerical instability and low energy dissipation related to the inherent secant loading/unloading relationship of the TSCM were also reasons for the development of the new TSMM. Such model is currently under refinement and, although it already showed substantial improvements with respect to the classical TSCM, more enhancements could be obtained in future.

Concerning the application at component level, for the replication of IP and OOP tests, the new TSMM resulted extremely beneficial in terms of stability of the solution. No convergence troubles have been encountered and the analyses have been all run for the whole loading protocol. The shear capacity always resulted in good agreement with the experimental tests and also the capacity degradation in the OOP tests was quite consistently reproduced. A noticeable improvement in terms of energy dissipation was observed for the IP tests with respect to the application of the TSCM, whereas some underestimation of energy dissipation is still present for the OOP tests. Damage patterns tend to be too widespread compared to experiments, therefore damage localization should be improved.

The model also showed good potentials for the application at the assemblage level, for the seismic assessment of full-scale building typologies. Presented results are preliminary, nevertheless a reasonable agreement is observed in terms of prediction of shear capacity and failure modes development.

8. Acknowledgements

This research was funded by Nederlandse Aardolie Maatschappij (NAM) BV under contract number UI46268 “Physical testing and modelling – Masonry structures Groningen”, which is gratefully acknowledged, and developed in cooperation with the engineering company ARUP and the European Centre for Training and Research in Earthquake (EUCentre). The Total Strain Masonry Model was developed in cooperation between TU Delft and TNO DIANA BV. The implementation of the model into the DIANA development version and product version 10.1 was carried out by TNO DIANA BV, which is gratefully acknowledged.

9. References

[1] Feenstra PH, Rots JG, Arnesen A., Teigen JG, Hoiseth KV (1998): A 3D constitutive model for concrete based on co-rotational concept, *Computational modelling of concrete structures. Proc. EURO-C 1998*, Eds. R. de Borst et al., pp. 13-22, Bakelma, Rotterdam.

[2] DIANA finite elements analysis – Development version March 2016 – TNO Building and Construction Research, Department of Computational Mechanics, A.A. Delft, NL; 2016.

[3] Magenes G, Calvi GM, Kingsley G (1995): Seismic Testing of a Full-Scale, Two-Story Masonry Building: Test Procedure and Measured Experimental Response, University of Pavia, Italy.

[4] Anthoine A, Magonette G, Magenes G (1995): Shear compression testing and analysis of brick masonry walls, *Proc. 10th European conference on earthquake engineering*, Vienna.

[5] Magenes G, Morandi P, Penna A (2008): Enhanced Safety Efficient Construction of Masonry Structures in Europe – ESECMaSE work package 7, deliverable D7.1 c, Test results on the behavior of masonry under static cyclic in plane lateral loads.

[6] Anthoine A. and Capéran P, (2008): Enhanced Safety Efficient Construction of Masonry Structures in Europe – ESECMaSE work package 8, deliverable D 8.3 Earthquake tests and analysis of the experimental results (incl. Annex A), ESECMaSE.

[7] Griffith MC, Vaculik J, Lam NTK, Wilson J, Lumantarna E (2007): Cyclic testing of unreinforced masonry walls in two-way bending, *Earthquake Engineering & Structural Dynamics*, 36(6), 801-821.

[8] Magenes G, Morandi P, Penna A, (2008): In-plane cyclic tests of calcium silicate masonry walls, *Proc. 14th IB2MAC*, Sydney, CD-ROM paper n. 193.

[9] Mendes N., Lourenco PB (2010) “Seismic assessment of masonry "Gaioleiro" buildings in Lisbon, Portugal”, Journal of Earthquake Engineering 14:80-101.

[10] Mendes N, Lourenco PB, (2013): Seismic performance of ancient masonry buildings, *Proceedings of COMPDYN 2013*, eds. Papadrakakis M. et al, Kos Island, Greece.

[11] Rots JG, Messali F, Esposito R, Jafari S, Mariani V (2016): Computational modelling of masonry with a view to Groningen induced seismicity. *10th international conference on Structural Analysis of Historical Constructions, SAHC 2016*, 13-15 Sept. 2016, Leuven, Belgium.

[12] Esposito R, Messali F and Rots JG, (2016): Material characterization of replicated masonry and wall ties. Delft University of Technology. Final report 18 April 2016..

[13] Messali F, Ravenshorst G, Esposito R and Rots JG (2017): Large-scale testing program for the seismic characterization of Dutch masonry structures. *16th World Conference on Earthquake, 16WCEE 2017*, Santiago, Chile.

[14] Esposito R, Terwel KC, Ravenshorst GJP, Schipper HR, Messali F, Rots JG (2017): Cyclic pushover test on an unreinforced masonry structure resembling a typical Dutch terraced house. *16th World Conference on Earthquake, 16WCEE 2017*, Santiago, Chile.