Experimental Investigation on the Lateral Strength of Unreinforced Brick Masonry Walls

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ABSTRACT

Damage surveys from worldwide past earthquakes have shown that unreinforced masonry (URM) structures are typically associated with the highest proportion of damage. In Eastern Canada, these structures are widely used as load-bearing or non-load-bearing walls in older residential, industrial, or institutional buildings. Most of them are considered as pre-code buildings, as they were built prior to the introduction of seismic requirements in codes and standards. In order to improve the assessment of their lateral load resistance, an experimental project was carried out to investigate the mechanical parameters and the force-displacement capacity of traditional unreinforced brick masonry (UBM).The objective of this research project is to characterize the behaviour of traditional UBM walls under seismic loading. The experimental programme included the characterization of the mechanical properties of the UBM constituents, and two phases of tests on UBM assembly samples and two-leaf UBM wallets. Assembly samples and wallets were built with manufactured moulded clay bricks typically used as replicas of traditional UBM, and cement-lime mortar used to match the mechanical properties of the original traditional cement-lime mortar. Results of this study will be contributing to a better evaluation of the lateral resistance and seismic performance of UBM buildings, thereby improving damage prediction for seismic risk studies and selection of efficient rehabilitation and strengthening strategies.

Keywords: UBM, compression, shear, diagonal shear, cyclic loading.

INTRODUCTION

The seismic zones in Eastern Canada are West Quebec, Charlevoix-Kamouraska and Lower St-Lawrence which are regularly affected by earthquakes [1-2-3-4]. Large urban centres in Eastern Canada, such Ottawa, Montreal and Quebec City, are located in these zones and have a large stock of older buildings made of unreinforced clay brick masonry (UBM) with load-bearing walls, infill walls, and façades made of brick veneer [5]. During the 1988 Saguenay earthquake, with a magnitude Mw=5.9, damages on unreinforced brick masonry (UBM) components were observed up to a distance of 350 km from the epicentre [6]. This is in agreement with worldwide post-earthquake damage surveys reports where unreinforced masonry (URM) buildings are typically associated with the highest proportion of damage [7-8-9-10-11]. Inspection reports following the 2010 Christchurch earthquake, with a magnitude of 6.3 and depth of 5 km, indicated that damages to URM buildings were attributed to in-plane failure of self-supported UBM walls, and in large proportion, to out-of-plane failures of façade walls and brick veneer [12]. The in-plane resistance of a URM wall, and to a lesser extent its out-of-plane resistance, are highly correlated with the strength of the masonry assembly, which in turn is determined by the mechanical properties of the brick and mortar.

In-plane failure UBM walls can occur by one of the following failure modes: diagonal tension/shear, toe crushing, rocking or bed-joint-sliding failure. Several analytical models are available in literature for the prediction of the failure modes and the lateral resistance of existing masonry walls. One can mention ASCE-41 [13], NZSEE [14], Eurocode 8 [15], and Magenes and Calvi (1997) [16]. They all require site-specific shear and compressive strength values of the masonry assembly as well as diagonal tension strength value for reliable seismic performance assessment [13]. The current challenge in evaluating the lateral resistance and performance of existing UBM walls is in the identification of those material mechanical properties. Furthermore, damage estimation to UBM buildings relies on the force-displacement relation of UBM walls and drift thresholds for damage state definition. Such data are typically based on laboratory experiments on masonry wall elements under static cyclic loading [16-17-18].

This paper presents an experimental characterization of the force-displacement capacity of UBM wallets made of manufactured moulded brick masonry typically used as replicas of traditional masonry in remediation projects and its mechanical properties. Weak cement-lime mortar is used to match the mechanical properties of the original traditional cement-lime mortar, as reported in existing remediation projects [19]. The test program is described and the results are analyzed and discussed. Results include:

compressive strength of masonry components (cement/lime mortar and bricks) and assembly, joint shear bond strength and diagonal shear strength parameters of UBM assembly, as well as drift-shear force envelope under cyclic loading of UBM wallets. The obtained results are particularly useful for seismic vulnerability studies of existing UBM buildings or UBM walls, as well as for preservation engineers in the evaluation of seismic resistance and the decision-making process of selecting efficient upgrading solutions.

EXPERIMENTAL PROGRAM

An experimental program aimed to assess the mechanical parameters and the cyclic behaviour of unreinforced brick masonry wallets composed of manufactured 52-DD Glen-Gery moulded clay brick units joined with Bétomix Plus type O cement-lime mortar commonly used in heritage buildings construction in Eastern Canada. The experimental program consists of two phases. Each phase includes a principal test on several UBM wallets to characterize the diagonal tension strength (6 specimens) and the force-displacement relation under cyclic loading (3 specimens). Parallel tests on masonry components (brick and mortar) and assembly are carried out to complete the characterization. A total of 156 specimens were tested in Phase I and 113 specimens in Phase II.

Phase I diagonal tension tests

In Phase I, diagonal tension tests were carried out on six two-leaf UBM wallets according to ASTM E519/E519M specifications [20]. The laboratory equipment did not allow to realize the test on specimens with size as recommended by ASTM E519/E519M [20]. It was therefore chosen to carry out the test on two sizes of wallets to evaluate the potential influence of the specimen's scale on the measured mechanical properties. Two sets of three wallets with different dimensions were considered: Wallets A (459 mm x 459 mm x 204 mm) and Wallets B (861 mm x861 mm x 204 mm). The wallets were constructed in a horizontal position and then rotated 45 degrees for installation in the test setup as shown in Figure 1. To induce a tension/shear failure mechanism, a compressive load is applied progressively on one diagonal of the wallet, resulting in a tension stress on the other diagonal. The diagonal tensile strength f'_{td} is reached at tensile cracking of the masonry on the vertical diagonal. The load is applied in displacement control by a 1500 kN "Material Testing System" (MTS) actuator. Two LVDTs are positioned on both sides of the wallet to measure the deformation according to each diagonal (strain shortening of the vertical diagonal and the extension of the horizontal diagonal), and thereby evaluate the masonry wallet shear modulus G_m.

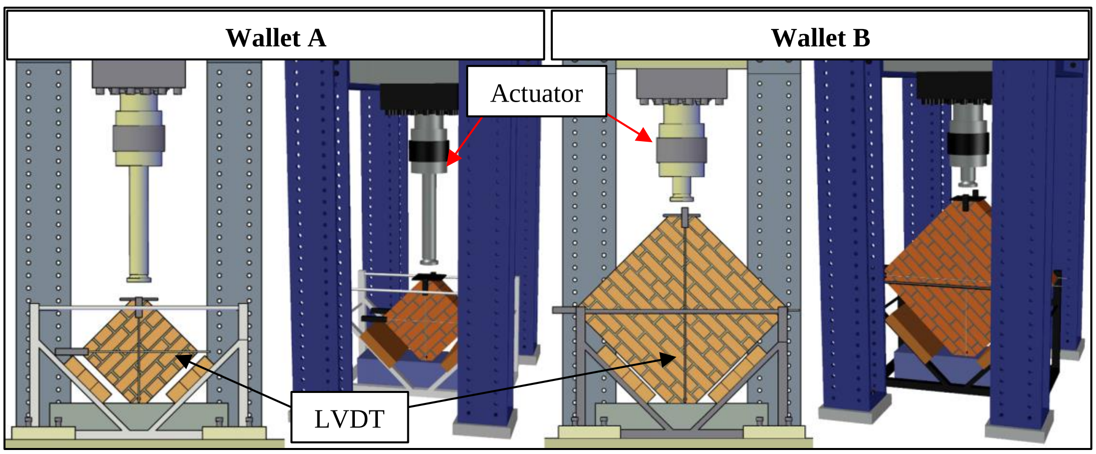

Figure 1. Diagonal tension test setup on masonry wallets

Phase II static-cyclic lateral loading tests

In Phase II, the static-cyclic lateral loading tests were carried out with two MTS actuators (1500 kN and 200 kN) on three wallets of similar dimensions (861 mm x 660 mm x 204 mm), according to the recommendations of ASTM E2126 [21] and several authors [17-18-22-23]. The objective of this test is to identify the lateral strength, the failure modes and the hysteresis behaviour of the URM wallets for three different levels of vertical loading, 70 kN, 140 kN and 300 kN. The first vertical load applied was estimated for a URM residential building with three storeys, to simulate the weight of upper floors on a ground floor wall. The two other vertical loads were estimated in accordance with the predictions of the different analytical models, the values were chosen to represent conditions for which other failure modes could occur. The lateral cyclic load was applied on the top of the wallets by a horizontal actuator (200 kN). Loading protocol was conducted under displacement control and defined according to the method B of ASTM E2126 [21] and Petry (2010) [17]. LVDTs measured the top drift of the wallet to obtain the force-displacement relation.

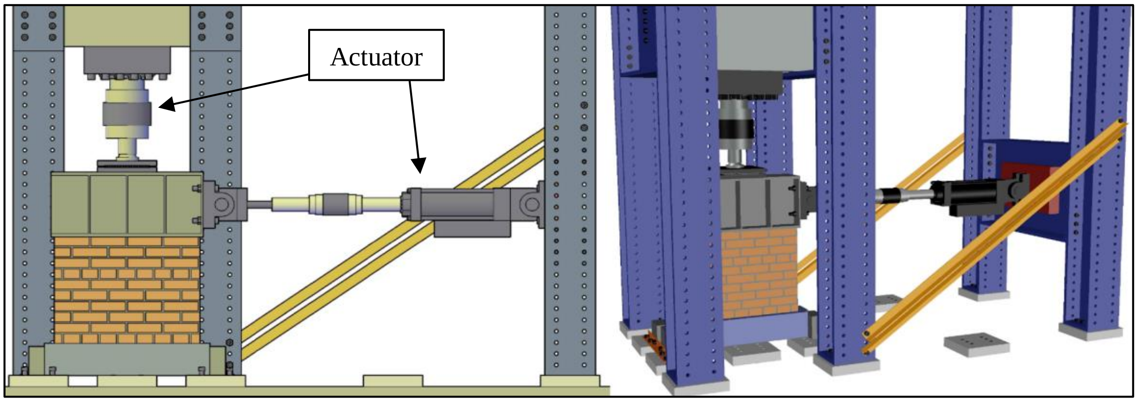

Figure 2. Static-cyclic lateral loading test setup on masonry wallets

Parallel tests on UBM masonry assemblies and components

Series of tests were conducted to characterize the mechanical properties of the moulded brick, cement-lime mortar and masonry assemblies include: compression tests on bricks and mortar according to ASTM C109/C109M [24] and ASTM C67 [25], respectively, compression test on masonry assembly according to ASTM C1314 [26], and shear bond test on masonry assembly as recommended by RILEM TC 127-MS [27]. All cement-lime mortar (type O) used was extracted from batches prepared to build the wallets for the main tests and the bricks were randomly selected.

Three 50 mm cubes were made per batch of mortar, for a total of 133 specimens. They were tested to determine compressive strength f'_j using a 500 kN "Matest S.p.A Treviolo" actuator under force control (see, Figure 3). All other compression tests were conducted using an MTS press with axial compression force capacity up to 4500 kN under displacement control.

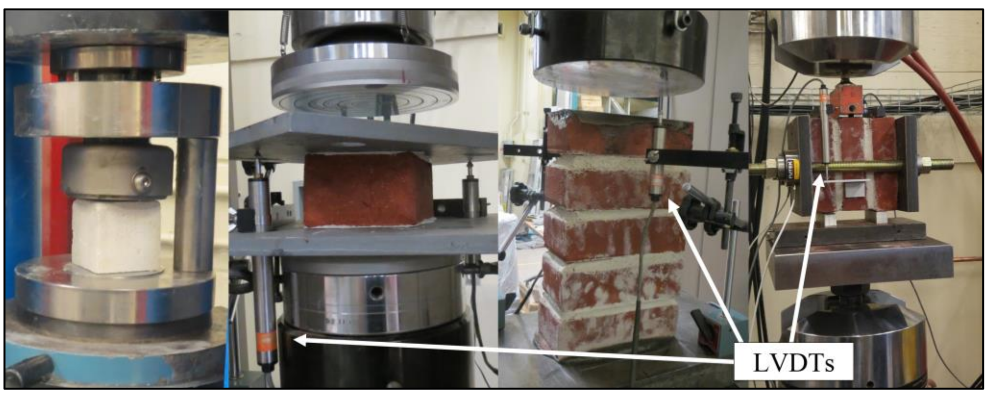

Figure 3. Test setups for compression and shear strength characterisation on masonry assemblies

Compressive strength of brick f'_b was determined from 28 half-brick samples. All samples were capped on top and bottom using a DryStone^{TM} grout for better stress distribution and LVDTs were positioned on both sides of each brick to measure its deformation and determine the Young modulus E_b (Figure 3).

Specimens made of five stacked bricks bound by four mortar joints were tested to define the compressive strength f'_m of the UBM assembly. Three specimens were made per wallet using three different batches of mortar, for a total of 27. All samples were capped with epoxy resins and LVDTs were installed on both sides of the specimens to measure its deformation to determine the peak stress deformation ε'_m and the Young modulus E_m. (Figure 3).

Specimens for joint shear bond tests were made of three stacked bricks bound by two mortar joints. Nine specimens were made per wallet, three specimens per batch of mortar, for a total of 81. Tests were carried out for three levels of compressive stresses, 0.2 MPa, 0.6 MPa and 1.0 MPa, by applying a load perpendicularly to the joints of the specimen. A vertical load was then applied parallel to the joints (Figure 3) until the shear failure of the first joint to define the Mohr-Coulomb relation between shear strength and compressive stress.

RESULTS OF TESTS ON UBM MASONRY ASSEMBLIES AND COMPONENTS

Compressive tests on brick units and mortar cubes

Average compressive strength of the 133 mortar cubes was $f'_j = 5.35 \pm 1.04$ MPa, which is representative for type O mortar. Average compressive strength of brick was $f'_b = 26.3 \pm 4.8$ MPa, which agrees with the value specified for 52-DD Glen-Gery brick as 27.5 MPa. Standard deviation is however relatively important. The Young modulus was determined by the method of least squares between $0.15\,f'_b$ and $0.70\,f'_b$, for a value of $E_b = 3.63 \pm 1.1$ GPa, which shows an important standard deviation.

Compressive tests on masonry assembly

In general, the onset of softening of the masonry assembly specimens tested under compression was caused by vertical splitting cracks in the central bricks once the peak compression stress was reached. This was typically followed by more cracking and crushing of the mortar layers until the specimen fails. Flaking of the mortar joints was observed as well as detachment between brick and mortar.

The average compressive strength f'_m of specimens was 14.8 MPa with a deviation of 2.1 MPa. The modulus of elasticity E_m was evaluated from the least squares method between $0.15\,f'_m$ and $0.70\,f'_m$ (as recommended by [28] and [29]), and the average value was 3.21 ± 0.83 MPa. The strain, corresponding to maximum strength ε'_m, was measured and the average value was $6.15\times10^{-3} \pm 1.04\times10^{-3}$ mm.mm^{-1}.

Equations relating the brick and mortar compressive strengths, f'_b and f'_j, to the masonry compressive strength, f'_m, offer an interesting and useful tool for predicting the lateral resistance of URM walls [30], [31]. However, only a few authors have focused on the characterization of older type of brick masonry constructed using weak cement-lime mortar. Figure 4 compares the results of this study to the model proposed by Lumantarna and al. (2014) [29] and given by:

$$f'_m = K f'^{\theta}_b f'^{\lambda}_j \qquad (1)$$

With the following values for the parameters : $K = 0.75$; $\theta = 0.75$; $\lambda = 0.31$. Three curves are drawn on Figure 3 for Eq. (1), with median, lower and upper values of the brick compressive strength f'_b according to the standard deviation given from the tests on brick samples. 68.2% of the bricks have a compressive stress between 21.5 MPa and 31.1 MPa. Most results are included between the upper and the lower limits of the model.

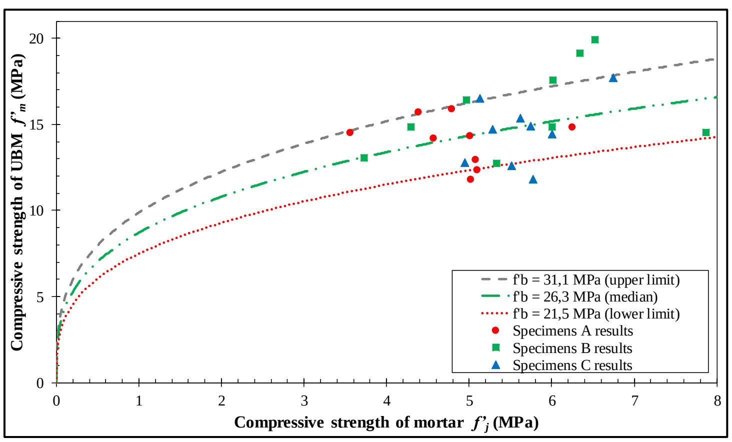

Figure 4. Relation between the masonry compressive strength f'_m, and the mortar compressive strength f'_j, for median, lower and upper values of the brick compressive strength f'_b

Joint shear bond test on masonry assembly.

For most specimens shear failure occurred on one side of the joint, at the interface between mortar and the brick. Bricks had one side less rough than the other, and cracking spread generally on that side. Results of the joint shear bond test are used to obtain the cohesion c and the coefficient of friction μ from the Mohr-Coulomb envelope as shown by Eq (4) and Figure 5. Cohesion is determined to be 0.29 MPa and the coefficient of friction is 0.94. This later value is relatively high compared to the value of 0.4 given by Eurocode 6 [32].

$$\tau_m = \mu.\sigma_m + c \qquad (4)$$

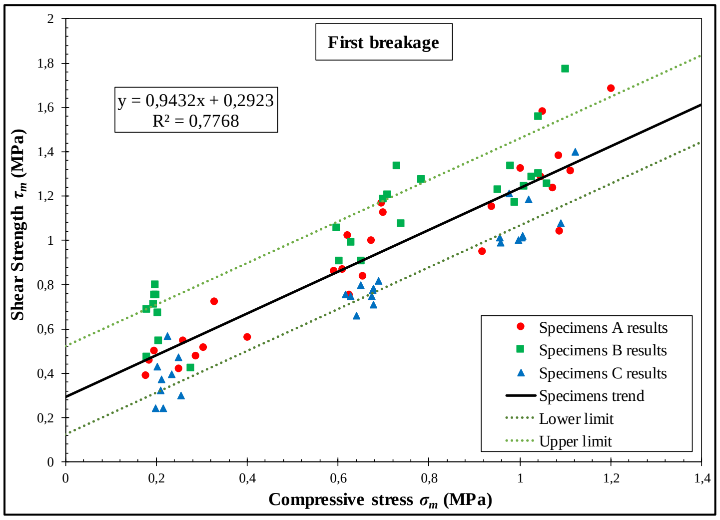

Figure 5. Mohr-Coulomb relation from the joint shear bond tests

Figure 5 shows that all results tend to be in zone limited by an upper and a lower limit for the cohesion values, but the coefficients of friction are the same for the upper and lower limits. Note that there is an important variation in the compressive stress around the values initially chosen (0.2, 0.6 and 1.0 MPa). It's partly due to some difficulties to make a good adjustment of the compression system. It is also due to an increase in the compressive stress during testing, which may be caused by a dilatation of the mortar in the joints.

TEST ON MASONRY WALLETS

Diagonal tension tests

This section presents the results obtained from the diagonal tension tests on six UBM wallets. The failure pattern is mostly characterized by stair-stepped cracking along the mortar joint, with some cracks going through the bricks. All smaller samplers of wallets A tend to exhibit the same cracking pattern along the same mortar joints, except near the loading points (Figure 6). Larger wallets B show slightly different failure patterns (Figure 6). For wallet B-W3, the crack tends to avoid the middle zone of the wallet. Mortar compression tests showed that the mortar used in this zone has larger compressive strength than the mortar used in the other joints, explaining this crack pattern.

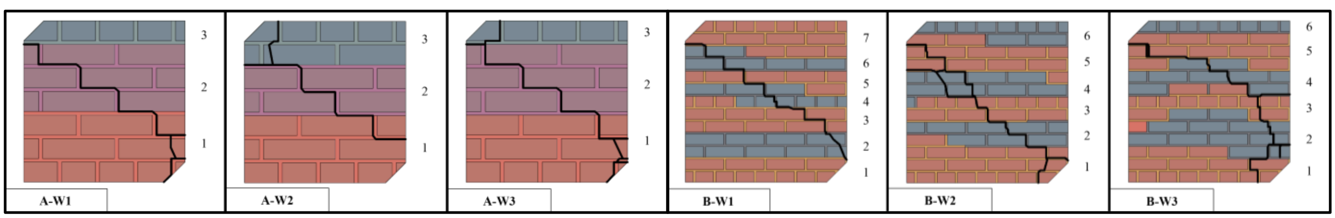

Figure 6. Cracking patterns of wallets A and B samples for diagonal tension tests

Diagonal tensile strength f'_{td} is calculated according to two different assumptions for the state of stress: pure shear in the centre of the specimen, as expressed by Eq. (5) (ASTM [20]), and non-uniform shear stress state, as given by Eq. (6) (Russell [18] and Alecci and al. [33]). This assumption was deducted from modelling a masonry panel considered as an isotropic and homogeneous material. The following equations give the principal stresses acting at the centre of the wallet (σ_1 is the tension stress, σ_2 is the compressive stress, τ is the shear stress) and the diagonal tensile strength f'_{td}, for the two states of stress. The principal directions coincide with the two diagonals of the wallet for both state of stress.

$$\sigma_1 = \sigma_2 = \tau = \frac{0.707P}{A_n} \qquad f'_{td} = \frac{0.707P_{ult}}{A_n} \tag{5}$$

$$\sigma_1 = \frac{0.5P}{A_n} \qquad \sigma_2 = -\frac{1.62P}{A_n} \qquad \tau = \frac{1.05P}{A_n} \qquad f'_{td} = \frac{0.5P_{ult}}{A_n} \tag{6}$$

Average value of diagonal tension f'_{td} is 0.79 MPa or 0.55 MPa using ASTM (Eq. (5)) [20] or Russell (Eq. (6)) [18] state of stress, respectively. The coefficient of variation is 4.1 % in both cases, which can be considered as very low for such a heterogeneous material such as masonry.

Test results can also be used to calculate the shear modulus of the wallets. It's defined as the slope on the linear part of the shear stress-strain curve using the method of least squares between 0.05 τ_{max} and 0.70 τ_{max}. The average value for G_m is 1.98 GPa or 2.94 GPa using ASTM (Eq. (5)) [20] or Russell (Eq. (6)) [18] state of stress, respectively. In both cases the coefficient of variation is 15%, which is within the expected values considering the material studied.

Lateral static-cyclic loading test

This section presents the results obtained from the lateral static-cyclic test on the three UBM wallets for three different levels of vertical loading: C-W1: 70 kN, C-W2: 140 kN and C-W3: 300 kN. Despite these three different compression stress conditions, all wallets failed in a rocking failure mode, as shown in Figure 7. This is characterized by the occurrence of a horizontal crack along the lower mortar joint due to a tension failure between mortar and brick. On wallet C-W3, some vertical cracks were observed in a bottom corner brick, typical of a toe crushing occurring after the rocking failure.

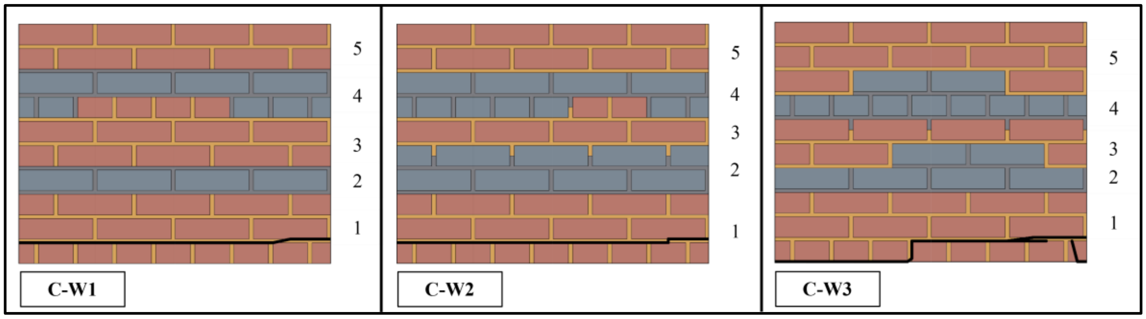

Figure 7. Cracking patterns of wallets C samples for lateral static-cyclic loading tests

Hysteresis curves for each wallet are shown in Figure 8. They exhibit typical characteristics of a rocking failure: narrow loops typical of fragile behaviour and low energy dissipation by deformation, and large displacements without a loss of lateral strength [16]. Diagonal shear failure would have exhibited strength and stiffness degradation after cracking.

A

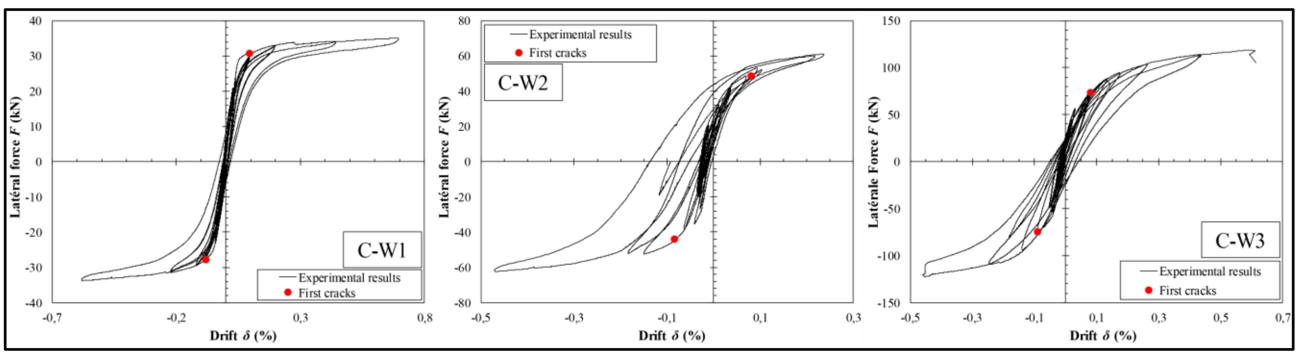

Figure 8. Hysteresis of wallets C samples for lateral static-cyclic loading tests

The lateral force-displacement relations in Figure 8 are obtained from the backbone curve of the hysteresis idealized by a bilinear curve, as recommended by several authors [16-23-34]. V_e and δ_e are, respectively, the idealized lateral strength and drift and K_{eq} is the equivalent stiffness. Results for each wallet are given in Table 1. As expected, actual strength V_R, idealized strength V_e and equivalent stiffness K_{eq} increase with the vertical load *P* applied on the wallet. Drifts are similar for all wallets. Actual drift δ_R at the maximum strength varies between 0,083% and 0,089% while idealized drift δe varies between 0,103% and 0,127%. Drift values can be used as threshold displacement for the evaluation initiation of first cracking of UBM walls and the development of simplified bilinear lateral force-deformation curves.

Table 1.Idealized strength, drift and stiffness

Wallet	Failure mode	*P* (kN)	V_R (kN)	δ_R (%)	V_e (kN)	δ_e (%)	K_{eq} (mm.mm^{-1})
C-W1	Rocking (flexion)	70	29,3	0,089	33,9	0,103	46,9
C-W2	Rocking (flexion)	140	46,1	0,083	60,6	0,109	79,3
C-W3	Rocking (flexion)	300	71,8	0,085	110,4	0,127	123,9

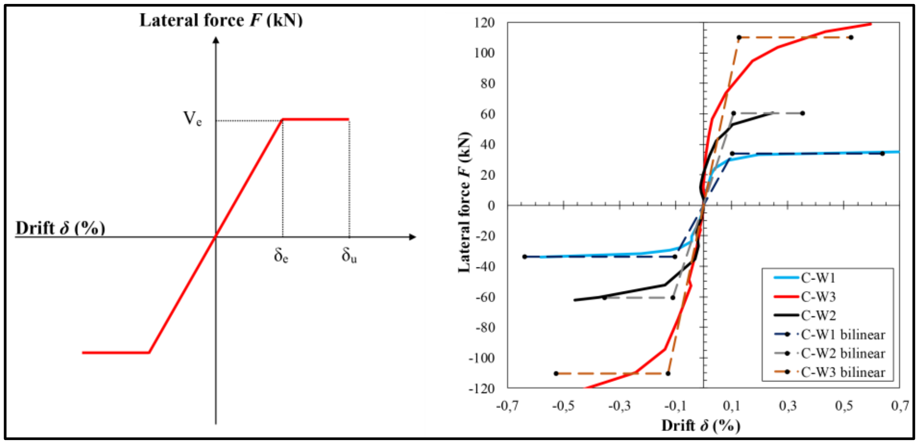

Figure 9. Lateral load-displacement relation of wallets C samples and bilinear model

CONCLUSIONS

An experimental program was presented for the characterization of mechanical properties of UBM wallets with material selected to match the UBM used in heritage buildings construction in Eastern Canada. Thereby it was composed of manufactured moulded clay bricks, typically used as replicas of the traditional masonry units, and a cement-lime mortar. Tests were conducted on masonry assemblies characterised with the following mechanical properties: average compressive strengths of the mortar, brick and masonry assembly are, f'_j = 5.35 ± 1.04 MPa, f'_b = 26.3 ± 4.8 MPa and f'_m = 14.8 ± 2.1 MPa, respectively. The Young Modulus of the brick and the masonry assembly are E_b = 3.63 ± 1.1 GPa and E_m = 3.21 ± 0.83 GPa, respectively. The Mohr-Coulomb parameters were deducted from the joint shear bond test, which gave a cohesion c = 0.29 MPa and a coefficient of friction μ = 0.94. Diagonal tension tests were carried out on six wallets. Diagonal tension was determined using two different states of stress as recommended by ASTM E519/E519M-15 [20] and Russell (2010) [18]: the average values were, respectively, f'_{td} is 0.79 MPa and 0.55 MPa, with a coefficient of variation of 4.1 %. The average value of the shear Modulus G_m is 1.98 GPa or 2.94 GPa using ASTM or Russell (2010) states of stress, with a coefficient of variation of 15 %. Lastly, three wallets were tested under lateral static-cyclic loading, for three different vertical loads. Failure modes and hysteresis behaviour were characteristic of rocking failure for all wallets. The actual strength V_R, the idealized strength V_e and the equivalent stiffness K_{eq} increase significantly with the vertical load while the actual drift δ_R and the idealized drift δ_e tend to vary between 0,083% and 0,089% or 0,103% and 0,127%, respectively. The results obtained from this study are particularly useful for better evaluation of the seismic vulnerability of existing UBM buildings in Eastern Canada and for efficient selection of appropriate rehabilitations and strengthening strategies.

ACKNOWLEDGMENTS

The financial support from the Natural Sciences and Engineering Research Council (NSERC) and the Fond Québécois Recherche sur la Nature et les Technologies (FRQNT) through the Centre d'Études Interuniversitaire des Structures sous Charges Extrêmes (CEISCE) is gratefully acknowledged.

REFERENCES

[1] Cassidy J.F., Rogers G.C., Lamontagne M., Halchuk S. and Adams J. (2010). "Canada's earthquakes: 'The good, the bad, and the ugly'". *Geoscience Canada*, vol. 37, no 1, p. 1-16.

[2] Lamontagne, M. (2008). *Les dommages dus aux tremblements de terre dans la région de Québec entre 1608 et 2007*. Commission géologique du Canada, Ottawa, Ont. Dossier Public, vol. 5547.

[3] Lamontagne M. (2002). "An overview of some significant eastern Canadian earthquakes and their impacts on the geological environment, buildings and the public". *Natural Hazards*; 26(1): 55-68.

[4] Government of Canada, Natural Resources Canada, (2002) *Earthquake in southeastern Canada*.< http://www.earthquakescanada.nrcan.gc.ca/pprs-pprp/pubs/GF GI/GEOFACT_earthquakes-SE-Canada_e.pdf >.

[5] Houalard C., Abo El Ezz A. and Nollet M.J. (2015). "Seismic Displacement Response Analysis of Out-of-Plane Loaded URM Walls: Comparison with Shake Table Tests". *Proceedings of 11th Canadian Conference on Earthquake Engineering*. Victoria, BC, Canada: Paper 94204.

[6] Paultre P., Lefebvre G., Devic JP. and Côté G. (1993). "Statistical analyses of damages to buildings in the 1988 Saguenay earthquake". *Canadian Journal of Civil Engineering*. 20(6): 988-998.

[7] Klingner R.E. (2006). "Behavior of Masonry in the Northridge (US) and Tecomán–Colima (Mexico) Earthquakes: Lessons learned, and Changes in US Design Provisions". *Construction and Building Materials*, 20(4):209-219.

[8] Ingham J. and Griffith M. (2011). *The Performance of Unreinforced Masonry Buildings in the 2010-2011 Canterbury Earthquake Swarm*. Report to the Royal Commission of Inquiry, New Zealand.

[9] Park J., Towashiraporn P., Craig J.I. and Goodno B.J. (2009). *Seismic Fragility Analysis of Low-rise Unreinforced Masonry Structures*. Engineering Structures; 31(1):125-137.

[10] Zhao B., Taucer F. and Rossetto T. (2009). *Field Investigation on the Performance of Building Structures During the 12 May 2008 Wenchuan Earthquake in China*. Engineering Structures; 31(8):1707-23.

[11] Indirli M., Kouris L.A., Formisano A., Borg R.P. and Mazzolani F.M. (2013). "Seismic Damage Assessment of Unreinforced Masonry Structures after the Abruzzo 2009 Earthquake: The Case Study of the Historical Centers of l'Aquila and Castelvecchio Subequo". *International Journal of Architectural Heritage*; 7(5):536-78.

[12] Ingham J., Griffith M. (2010). "Performance of Unreinforced Masonry Buildings during the 2010 Darfield (Christchurch, NZ) Earthquake". *Australian Journal of Structural Engineering*;11(3):207-24.

[13] American Society of Civil Engineers - ASCE. (2013). *SEI/ASCE 41-13: Seismic Rehabilitation of Existing Buildings*. Washington D.C..

[14] New Zealand Society for Earthquake Engineering - NZSEE. (2006). *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes*. New Zealand.

[15] Eurocode. (2005). *Eurocode 8: Design of Structures for Earthquakes Resistance*. European Committee for Standardization, Brussels.

[16] Magenes, G. and Calvi G.M. (1997). "In-plane seismic response of brick masonry walls".

[17] Petry, S . (2015). *Force-Displacement Response of Unreinforced Masonry Walls for Seismic Design*. EPFL

[18] Russell, A.P. (2010). *Characterisation and Seismic Assessment of Unreinforced Masonry Buildings*. The University of Auckland, New Zealand.

[19] Canadian Standard Association - CSA. (2014). *CAN/CSA-A179-F04 (C2014): Mortier et coulis pour la maçonnerie d'éléments*. Prepared by the CSA, Toronto, Ontario :

[20] American society for testing material - ASTM. (2015). *E519/E519M-15: Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages*. ASTM International.

[21] American society for testing material - ASTM. (2011). *E2126-11: Standard test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings*. ASTM International.

[22] Mazzon, N. (2010). *Influence of Grout Injection on the Dynamic Behaviour of Stone Masonry Buildings*.

[23] Vanin, F., Zaganelli D., Penna A. and Beyer K. (2017). "Estimates for the stiffness, strength and drift capacity of stone masonry walls based on 123 quasi-static cyclic tests reported in the literature". *Bulletin of Earthquake Engineering*, 15(12), 5435-5479.

[24] American society for testing material - ASTM. (2016). *C109/C109M-16a: Standard Test for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).* ASTM International.

[25] American society for testing material - ASTM. (2016). *C67-16: Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*. ASTM International.

[26] American society for testing material - ASTM. (2014). *C1314-14: Standard Test Method for Compressive Strength of Masonry Prisms*. ASTM International.

[27] RILEM. (1996). *TC 127-MS: Tests for Masonry and Structures*.

[28] American society for testing material - ASTM (2017). *E111-17: Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus*. ASTM International.

[29] Lumantarna, R., Biggs D.T. and Ingham J.M. (2014). "Uniaxial Compressive Strength and Stiffness or Field-Extracted and Laboratory-Constructed Masonry Prisms". *Journal of Materials in Civil Engineering*. 26(4), 567-575.

[30] Gumaste K.S., Rao K.N., Reddy B.V. and Jagadish K.S. (2007) "Strength and Elasticity of Brick Masonry Prisms and Wallettes Under Compression". *Materials and Structures*;40(2):241-53.

[31] Kaushik H.B., Rai D.C. and Jain S.K. (2007). "Stress-Strain Characteristics of Clay Brick Masonry Under Uniaxial Compression". *Journal of Materials in Civil Engineering*;19(9):728-39.

[32] Eurocode. (2005). *Eurocode 6: Design of Masonry Structures*. European Committee for Standardisation, Brussel.

[33] Alecci, V., Fagone M., Rotunno T. and De Stefano M. (2013). "Shear Strength of Brick Masonry Walls Assembled with Different Types of Mortar". *Construction and Building Materials*, 40, 1038-1045.

[34] Bosiljkov V., Totoev Y.Z. and Nichols J.M. (2005). "Shear Modulus and Stiffness of Brickwork masonry: An experimental perspective". *Structural Engineering & Mechanics* (Vol. 20).