Monitoring, non destructive evaluation and testing
Historic multiple-leaf masonry wall models under compression and cyclic shear loads

R. Capozucca
Università Politecnica delle Marche, Ancona, Italy

ABSTRACT: An investigation on historic masonry wall models – in scale 1/3th – characterised by two leaves of brickwork masonry and intermediate mortar has been carried out in the laboratory. Experimental results obtained by tests on wall models under compression and cyclic shear loads are discussed and compared to theoretical results obtained by a non linear procedure of calculus based on a tie & truss modelling for multiple-leaf masonry wall.

1 INTRODUCTION

The preservation of the architectural heritage presents one of the important challenges in civil engineering due to the complexity of the geometry of the structures, the variability of the materials used and the loading history of the buildings. Structures of historic buildings because of their nature and history present a number of typical aspects that limit the application of modern codes and building standards. The knowledge of behaviour of historic masonry under seismic action is fundamental to preserve the architectural heritage. During an earthquake, masonry walls are subjected to shear loads that often carry out to the ruin the whole building. The shear strength of unreinforced masonry (URM) was analysed in the last decades by experimental and theoretical works (Benjamin & Williams 1958; Hendry & Sinha 1969, 1971; Turnesek & Cacovic 1971; Yokel & Fattal 1976; Tomazevic 1977; Bernardini et al.1980; Hamid & Drysdale 1980; Calvi et al. 1985). On the base of theoretical and experimental analysis, the shear criterion for URM known as Coulomb-type failure criterion is adopted (EC6-ENV 1996). The shear failure widely, is characterised by joint failure as a function of the bond strength linked to the frictional resistance at brick-mortar interface and the compressive stress normal to the bed joints. Although many experimental results are available on shear strength of masonry as yet only few data are available for historic unreinforced masonry walls (HURM) (Capozucca & Sinha 2004, 2005, 2007). In fact, shear behaviour of masonry has been investigated extensively for modern masonry. Moreover, between the different types of HURM, a scarcity of data is on multiple-leaf walls with two or three leaves. Multiple-leaf masonry is usual in historic towns and the most common cause of damage during an earthquake is actually due to a ruin of the buildings with this type of wall masonry (Pina-Henriques J. et al. 2004). In this paper, cyclic shear tests on HURM wall models with multiple-leaf masonry are shown and experimental results are discussed to investigate cracking patterns, failure mechanisms and the ultimate shear strength. Experimental results have been compared with those obtained from a non linear theoretical analysis carried out modelling multiple-leaf masonry wall with tie & truss finite elements.

2 EXPERIMENTAL MODEL

2.1 HURM wall specimens

To have the meaningful results, it was essential to have similar materials as used in the HURM. Luckily, a few full-scale solid bricks became available during the renovation of a 18th century Italian building, hence test specimens were built in 1/3rd scale utilizing these. The dimensions of the model bricks were $100 \times 50 \times 17$ mm obtained from sawing the full-scale bricks. The average compressive strength of the model bricks was $34.3 \text{ N/mm}^2$. 1:5 (cement: lime: sand) mortar was used for the construction of specimens.

The model was built with full masonry for flanges and multiple-leaf masonry for web (Fig. 1). The section is double T shape as shown in Figures 2(a) and (b); bricks in plane in flanges and on the list in the web (Fig. 2(a)) with intervals of bricks in plane as ties between two leaves (Fig. 2(b)). 1:5 (lime: sand) mortar has been placed between two masonry leaves of web.

A series of preliminary tests were done on small wallet specimens of HURM to obtain the compressive
allows to transfer both precompression – normal stress equal to 1 N/mm$^2$ – and horizontal cyclic load (Fig. 3). Four load cells measured the applied loads. Before the application of shear load, the pre-compression was applied both to the web and flange of the wall by three vertical jacks (Fig. 3) and kept constant throughout the test.

The cyclic shear load was applied by horizontal jack with double phase at stages till the failure. Deflections and strains were also measured at various steps. In Figure 3 the instrumentation to measure deflections in six points (1...6), vertical strain gauges (D, E, F, G, H) and Rosetta (A, B, C) in the middle of panel, are shown. In Figures 4(a) and 4(b) diagonal cracks on the surface of web at shear failure, due to cyclic tests, for both specimens, respectively, S1 and S2, are shown.

### 2.3 Experimental results

The failure was sudden at a horizontal force value equal to $F_u = 30$ kN and $F_u = 36$ kN, respectively, for S1 and S2 specimens. The average shear stress value referred to the gross area $50 \times 840$ mm$^2$ was equal to $\tau \approx 0.86$ N/mm$^2$ for S2 specimen. In Figures 5(a) and (b) the experimental diagrams of cyclic load, $\pm F$, vs deflection, $\pm \delta$, at the top of model wall (transducer no. 1) are shown for S1 and S2.

The experimental measures of vertical strains recorded at the bottom of S2 specimen are shown only for the increasing load $F$ value (Fig. 6).

### 3 THEORETICAL MODELLING

#### 3.1 Theoretical modelling of the HURM model

Masonry is a material which exhibits distinct directional properties due to mortar joints. In general, the
approach towards its numerical representation can focus on the *micro-modelling* of the individual components of unit and mortar, or the *macro-modelling* of masonry as a composite material. In this research, the theoretical analysis of the HURM model was developed by a macro-modelling considering the masonry as an heterogeneous material with different directions of strength: normal to the bed joints of mortar; parallel to the bed joints of mortar and diagonal directions inclined to an angle of 45° degree respect to the bed joints (Figs. 7(a), (b) and (c)). The theoretical analysis of the HURM model subjected to compression and shear has been developed by FEM code (Straus7) with a non linear procedure.

In Figure 8 the complete modelling is shown: *beam* finite elements both for vertical flanges and horizontal top steel plate have been adopted while *cut-off* finite elements to simulate the behaviour of web. The modelling has been replied for two leaves of model. Finally, rigid links have been used to simulate the ties by full bricks in the web. In the theoretical analysis, the value of tensile strength for cut-off finite elements has been assumed equal to the value of shear in absence of compressive stress $\tau_0 = 0.30 \text{ N/mm}^2$ obtained by triplet tests. The Young’s modulus was initially constant of average value $E_{av}$ between the values shown in Table 1. After the linear phase the Young’s modulus has been assumed decreasing at every step of horizontal load.
3.2 Damage coefficient

In experimental diagrams horizontal load vs deflection like that shown in Figure 9, we can appreciate different phases of loading: first a linear elastic phase characterized by constant stiffness; successively, a non linear behaviour with reduction of stiffness at each increment of load. The initial stiffness is the maximum value that is linked to a undamaged condition of wall. Minor values of stiffness are due to a micro-cracking or slip on mortar joints.

The actual behaviour of the experimental model is non linear up to failure and it may be described by different steps with decreasing stiffness values $K_i = \Delta F_i / \Delta \delta_i$. A damage coefficient was defined as:

$$d = 1 - \frac{K_i}{K_0}$$

where: $K_0 =$ initial stiffness of undamaged wall; $K_i =$ stiffness at ith step.

The damage coefficient $d$ has been evaluated with reference to the experimental diagrams horizontal load, $F$, vs deflection, $\delta$, obtained by shear tests. In Figure 10, values of damage coefficient $d$ for each load ratio $(F_i - F_0)/F_0$ — where $F_0 =$ value of lateral load
evaluated at the end of linear elastic phase; \( F_i \) = lateral load at \( i \)th step – have been calculated by experimental data of test on S2 specimen.

A linear relation for the damage coefficient \( d \) has been evaluated with \( m = 1.37 \):

\[
d = m \left( \frac{F_i - F_0}{F_0} \right)
\]

In the experimental tests, the decrease of the stiffness in the wall model was mainly due to the cracking of web under compression and shear (Figs. 4 (a) and (b)). In the theoretical analysis the web was simulated by tie & truss with cut-off finite elements characterized by axial stiffness \((E_A)_i\). For these elements, the Young’s modulus varies at each step of calculus, taking in account the damage coefficient \( d \) evaluated for S2, as it follows:

\[
E = E_{av}(1 - d)
\]

The theoretical analysis has been developed by a non linear procedure increasing horizontal load to reproduce the experimental tests.

3.3 Comparison between results

The theoretical non linear analysis of S2 specimens allowed to obtain lateral deflection data at different values of horizontal load. Envelope curve has been determinate by the maximum value of lateral force, \( \pm F \), vs deflection, \( \delta \), for every cycle of shear test. In Figures 11(a) and (b) experimental values have been shown by white points.

4 CONCLUSIONS

In this paper, the experimental behaviour of historic masonry wall model in 1/3rd scale with multiple-leaf web is described. A theoretical modelling has been shown and discussed. The theoretical procedure by non linear analysis allowed to obtain lateral force vs deflection diagrams. A comparison by experimental and theoretical data allowed to confirm the validity of theoretical analysis characterized by a damage coefficient useful to describe the reduction of the stiffness of wall model under increasing lateral loads. Experimental tests on two historic models under combined compression and shear, furnished the following results:

1. the capacity of strength of the HURM model with multiple-leaf masonry web was maintained up to failure by shear;

2. the behaviour of the HURM model is linear up to a value of lateral load equal to 65% of ultimate value of lateral load. After this value a decrease of stiffness was recorded;

3. multiple-leaf masonry appears adequate to sustain lateral load during the shear test. The behaviour of two masonry leaves was recorded similar to cause of efficiency of ties represented by brick courses: further, the failure was contemporary reached for the two leaves with typical diagonal shear cracks.

ACKNOWLEDGMENTS

The experimental work has been developed by funds for research of Università Politecnica delle Marche.

REFERENCES


