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Innovative Clay Unit Reinforced Masonry System: Testing, Design and Applications in Europe

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Abstract

In the framework of a recent EU funded research project, innovative construction systems for clay unit reinforced masonry walls were developed and tested. In particular, one system was developed for low-rise residential buildings, whereas the other system was aimed at building mainly tall, load bearing reinforced masonry walls for one-storey high commercial and industrial buildings.

In the first case, experimental tests were carried out to understand the cyclic in-plane behavior of real-scale walls under shear and compression. In the second case, tests were aimed at studying the cyclic out-of-plane behavior of 6 m high walls subject to P-Δ effects. Test results allowed gathering information on the efficiency of the systems, and to check the reliability and calibrate code proposed limitations and formulations for design and assessment of such structural systems. Different types of non-linear models (a FE continuum micro-model; an analytical hysteretic model; a FE macro-model implementing non-linear moment-curvature relationships) were calibrated and used to carry out parametric analyses, to investigate the influence of various parameters.

Keywords *clay units; reinforced masonry; cyclic tests; in-plane behavior; out-of-plane behavior.*

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1 Introduction

Reinforced masonry (RM) was developed to exploit the strength potential of masonry and solve its lack of tensile strength (Tomaževič 1999) while significantly improving resistance, ductility and energy dissipation capacity with respect to unreinforced masonry (URM, see da Porto et al. 2009a; 2010a). In the

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last few decades, a large variety of RM techniques have been made available. Many RM systems around the world are based on the use of hollow concrete (Minaie et al 2010, Voon and Ingham 2006) and clay units (Zilch et al 2008), which are reinforced with steel bars and grouted with concrete. Other RM systems, traditionally developed in Europe, make use of perforated clay units combined with concentrated vertical reinforcement (see, for example, Bernardini et al 1997; Magenes 1998; Tassios and Psilla 2000; Tomaževič et al. 2006).

Generally, RM systems are designed for low rise residential buildings in seismic areas, which resist horizontal earthquake actions with the walls parallel to the seismic actions, according to the box-type behavior (Tomaževič 1999). Therefore the main aim of any experimental and numerical study is to assess the behavior under in-plane cyclic actions. In the case that seismic design of this type of buildings is based on linear elastic methods of analysis, the evaluation of the strength capacity (ULS) and the numerical values of the seismic behavior factor (q-factor) to reduce the elastic design spectrum, are crucial. The shear strength of RM is generally evaluated as the sum of the contribution of masonry and horizontal reinforcement (EN 1996-1-1; DM 14/01/08), where many issues regarding the evaluation of masonry strength and horizontal reinforcement efficiency are still open (Mosele et al. 2009). On the other hand, the q-factor has been recognized in the Italian code (DM 14/01/08) to be implementing an "overstrength" ratio also in the case of masonry buildings (Magenes 2006; Magenes and Morandi 2008), and its values can be higher if capacity design principles are pursued, whereas the European code (EN 1998-1) does not provide these possibilities. Furthermore, more rational design methods, based on non-linear analyses, are being developed (see, for example, Magenes et al. 2006). Nevertheless, to adopt them, it is necessary to give deformation/drift limits that should be used, suitably revised on the basis of the more recent construction systems and available experimental information (Magenes et al. 2009).

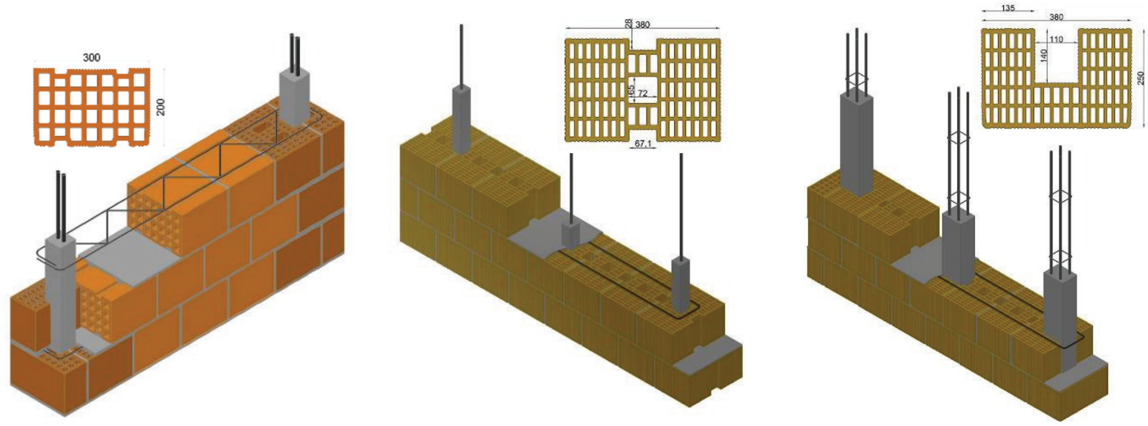
Recently, reinforced and post-tensioned masonry solutions have been proposed also for one-storey buildings, such as those for commercial and industrial purposes, as they can fulfill several functions (Bean Popehn et al 2007). In one-storey buildings, bracing walls are placed at long distance and roof diaphragms are very often deformable. Hence, the walls subjected to transverse loads are affected by large displacements, and second order effects may become relevant. In this case, the study of out-of-plane behavior is crucial. The approach for design under out-of-plane loads is substantially related to limitations of slenderness and thickness, and appropriate structural conception and detailing to prevent out-of-plane driven failures (Magenes et al. 2009). The flexural capacity of the RM section is usually evaluated by means of strength design approach (DM 14/01/08, EN 1996-1-1). However, the work of Doherty et al. (2002), and Griffith et al. (2003) have confirmed that out-of-plane response of walls under seismic excitation, when ultimate conditions are considered, is more a matter of displacement demand vs. capacity rather than a strength issue. In addition, most building codes do not have a consistent approach which takes into account P-Δ effects in masonry structures. In particular, the Italian and European norms (DM 14/01/08, EN 1998-1) only introduce a slenderness limit of 15. The safety check for RM walls having slenderness higher than 12, according to EN 1996-1-1, takes into account second order effects by an additional moment, but calculate walls as if they were URM. Such methods seems to be overconservative and do not provide any reliable explicit method to evaluate the safety level of the out-of-plane walls.

In this context, two RM systems for use in low rise, and in tall single-storey buildings, were recently developed (DISWall 2006-2008) and tested (Mosele 2009). The main aims of the experimental and numerical work were to study the behavior in relation to the above mentioned issues. Details on recent developments in the field of seismic design criteria and code-related issues for new masonry buildings can be found in Magenes et al. (2009) and Magenes (2010).

2 INNOVATIVE REINFORCED MASONRY SYSTEMS

2.1 RM system for low rise buildings

The RM system developed for low rise residential buildings is based on the use of concentrated vertical reinforcement. Special clay units are laid with horizontal holes, with recesses for horizontal reinforcement on the bed faces (Figure 1a). Vertically perforated units are used for confining columns with vertical reinforcement of steel bars (0.130%÷0.173%). Horizontal reinforcement may be made of either steel bars or prefabricated steel trusses (0.045% and 0.040% respectively). The main advantages of the system are related to durability and easier and more precise construction phases. In addition, using units with horizontal holes improves thermal insulation. As regards mechanical behavior, this system is conceived to perform as RM, provided that units with horizontal holes are effective in transferring horizontal loads to the lateral confining columns and that they do not present fragile behavior. More details about this system can be found in Mosele (2009) and da Porto et al. (2010d).



(a) (b) (c)

Figure 1: RM system for low rise buildings (a); RM systems for single-storey buildings (b, c).

2.2 RM system for tall single-storey buildings

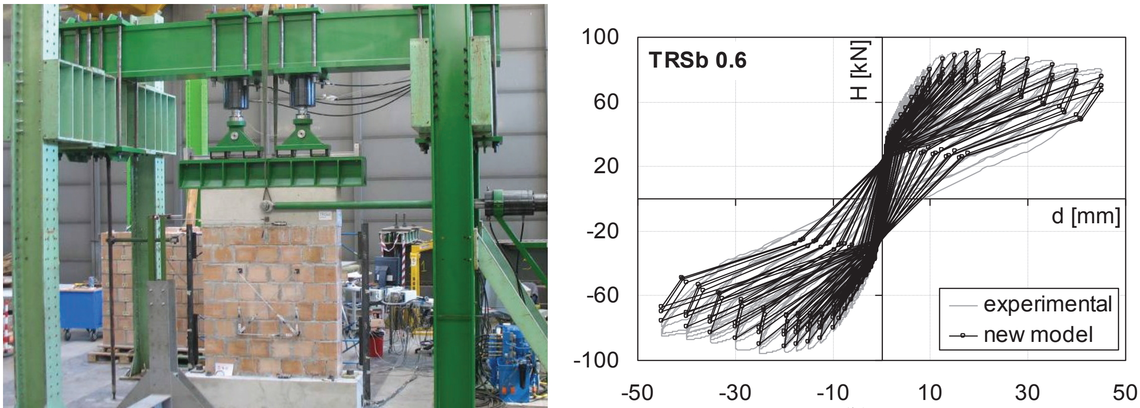
Two similar RM systems were developed for tall single-story buildings, both based on vertically perforated clay units and concentrated vertical reinforcement. The first system (Figure 1b) is made with H-shaped units, having central holes which allow limited vertical reinforcement, aligned on the middle plane of the wall, to be inserted. The second system (Figure 1c) is built with alternate C- and H-shaped units. The C units have large central cores, which allow higher quantity of vertical reinforcement and uncoupled bars to be used. The C shape allows to laid the units after the vertical reinforcement has been placed in position. Hence, the construction process is simplified, and overlap of vertical reinforcement can be avoided. Horizontal reinforcement is made of steel bars (about 0.04%). Vertical reinforcement in the columns is composed of steel bars with various arrangements according to the system, and same spacing (780mm). Percentage of vertical reinforcement is 0.10% and 0.18% respectively for rmH and rmC system. More details about this system can be found in Mosele (2009) and da Porto et al. (2010c, e).

3 RESEARCH PROGRAM AND RESULTS

3.1 *In-plane behavior*

To evaluate the seismic performance of the RM system developed for low rise residential buildings, in-plane cyclic shear compression tests on fourteen full-scale masonry specimens (Figure 2a) were carried out. These were differentiated by: presence or absence of vertical reinforced confining columns, use of steel bars or prefabricated trusses as horizontal reinforcement, and height to length ratio and value of applied axial compression loads, to force both shear and flexural failure modes. The test results allowed evaluating the influence of the above aspects on the main seismic parameters of RM walls, such as strength and displacement capacity, energy dissipation, viscous damping, stiffness degradation (Mosele 2009, da Porto et al. 2009b). The effectiveness of horizontally perforated units in transferring horizontal loads to lateral confining columns was found to be satisfactory, indeed they did not cause premature failure. The ultimate drift θ_u ranged from a minimum value of 0.7% for shear failure to values exceeding 1.7% for flexural failures. These values satisfy the limits associated to ULS for shear (0.6%) and flexural (1.2%) failures of RM walls, adopted by the Italian norms, but the European norms do not provide any drift limit for in-plane response of RM walls. The ratio between dissipated and absorbed energy was around 30%. In general, the failure mechanism strongly influenced all the measured seismic parameters.

The experimental values of shear strength were compared with those provided by the European and the Italian norms, which adopt an additive approach, where the contribution of horizontal reinforcement is added to the shear strength of URM. The main difference is that the maximum tensile capacity of shear reinforcement is multiplied times a reduction factor of 0.6 in DM 14/01/08 and 0.9 in EN 1996-1-1. The first value, which was proposed by Tomaževič (1999) and confirmed by Magenes (1998), and reflects experimental values of shear reinforcement effectiveness (Tomaževič 1999; da Porto et al. 2009b), yields strength evaluations which appear to be more realistic (Mosele et al. 2009). The two types of horizontal reinforcement did not significantly affect the global behavior of the walls.



(a) (b)

Figure 2: Shear-compression test setup, a); experimental and numerical hysteresis loops, b).

A finite element model of the tested RM walls was calibrated to perform parametric analysis and investigate the influence of vertical load, slenderness and vertical reinforcement ratio on the behavior of the masonry system. A simplified micro-modeling strategy with continuum elements and no unit-mortar interface elements was adopted. In general it was possible to find linear relation between maximum shear stress and both vertical load and vertical reinforcement percentage. The maximum shear stress presented a non-linear decrease with increase of H/L ratio. The ultimate drift generally presented non-linear trends, due to the variation of ductility caused by the change of failure mechanisms in the RM walls (da Porto et al. 2010b).

A new hysteretic model (Figure 2b), based on energy considerations and stiffness degradation rules, was developed and implemented into a numerical procedure, to evaluate reduction of elastic response of RM walls due to their hysteretic behaviour. In this case, the results of the non-linear dynamic analyses mainly confirmed the load reduction factors value of 2.5 and 3.0 that the Italian norm suggests respectively to RM failing in shear and in flexure, the latter being associated to the application of capacity design principles (da Porto et al. 2008). It should be pointed out that the same range of values, regardless of the failure mode, is also given by EN 1998-1 (2005), but as final values of *q*-factors to be adopted (i.e. neglecting overstrength).

3.2 Out of Plane behavior

The out-of-plane behavior under P-Δ effects of tall load-bearing walls was investigated by means of out-of-plane cyclic tests on two RM frames. Each frame was made of two cantilever walls, 6 m high, 2 m long and 0,38 m thick (Figure 3**Error! Reference source not found.**a). Horizontal displacements and roof dead loads (100 kN) were applied at the top of each specimen, to study the out-of-plane behavior of such walls in large-displacement regime under the influence of P-Δ effects (Mosele, 2009). The ductility of under-reinforced RM sections (rmH) in out-of-plane flexure could not be exploited, as the influence of P-Δ effects dominated the behavior as soon as the reinforcements started yielding. On the other hand, the tests showed the positive influence of higher vertical reinforcement percentage (0.18%), close to balanced failure for the masonry section. In this case, the top displacements that activated the influence of P-Δ effects, in terms of achievement of 10% stability ratio (generally adopted for reinforced concrete elements, EN 1992-1-1), were of 100 mm (1.7% of wall height). The maximum lateral load capacity (which was three times higher than rmH) corresponding to top displacements of 5.2% of wall height, was almost twice that at 10% stability ratio, and the maximum top displacement corresponded to deflection of 6.6% of wall height (Figure 3b; da Porto et al 2010c).

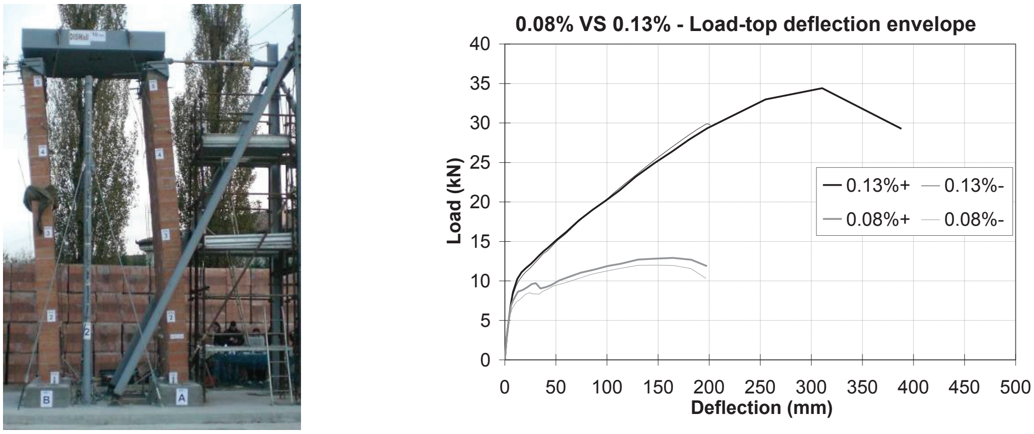
The slenderness limit of 15, fixed by the European and the Italian seismic norms (EN 1998-1; DM 14/01/08) assuming simple support boundary conditions, is quite severe when compared to these results. The tested walls had a slenderness of 15.8 in terms of height-to-thickness ratio, which doubles (31.6) when the effective height, i.e., the actual cantilever boundary condition, is taken into account. This was further demonstrated by numerical analyses, which took into account both material non-linearity, by means of moment-curvature relation, and geometrical non-linearity, and studied the influence of axial load, wall slenderness and percentage of vertical reinforcement on the out-of-plane response of the walls. The model identified two slenderness limits: one marking the change from attainment of maximum capacity exploiting full sectional resistance to failure due to instability, and the second characterized by attainment of maximum capacity near the cracking limit. The first limit occurs at a wall height of 8 m (h/t=21.1) in both systems. The second limit occurs at a wall height of 12 m (h/t=31.6) in rmC. The variations in roof dead load did not significantly influence the out of-plane behavior. The minimum vertical reinforcement recommended to avoid failure dominated by second-order effects is 0.08%, in agreement with EN 1998-1, although the lower percentage given by the Italian norms, which is 0.05%, is adequate for in-plane walls (Magenes 1998; Mosele et al. 2009). It is also significant that excessively high reinforcement percentage, in out-of-plane as well as in-plane walls, can be useless, and even harmful, as they bring the masonry section towards brittle failure modes. Nevertheless, the European norms do not provide any indication of this type, whereas the Italian code establishes a maximum limit of 1.0% (DM 14/01/08) that can be inadequate for out-of-plane loads in tall walls.

The application of analytical models, usually adopted to take into account second order effects in reinforced concrete columns (EN 1992-1-1), gave promising results also when applied to RM walls (Mosele 2009). The use of simplified moment magnifier methods to account for P-Δ effects in RM is thus consistent, and may be adopted by the norms to overcome some of the current limitations.

4 CONCLUSIONS

The trend to develop specific construction systems, in relation to traditional or innovative application fields, together with the technological evolutions of products, led to the necessity of continuous review and experimental verification of structural performances of the various systems. In general, the RM systems proposed for low-rise and for tall single-storey buildings demonstrated to have acceptable performance in relation to the main structural problems entailed by the envisaged use. The experimental research provided new inputs for improving the available design procedures for walls subjected to in-plane and out-of-plane seismic excitation.

The improvements manly concerned shear strength formulation and load reduction factors for in-plane walls, revision of code limitations and proposal of analytical models to account for P-Δ effect in slender walls loaded out-of-plane, and definition of not only strength, but also deformation capacity and other parameters in both cases, to be adopted and implemented in non-linear analyses. The results of the tests and analyses carried out were strictly related to the current European and Italian norms, to check their applicability, to identify required design parameters, and to calibrate or develop specific procedures that can overcome some of the current code limitations.



(a) (b)

Figure 3: Cyclic out-of-plane test setup and final deflection a); load-top deflection envelopes of both RM systems b).

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