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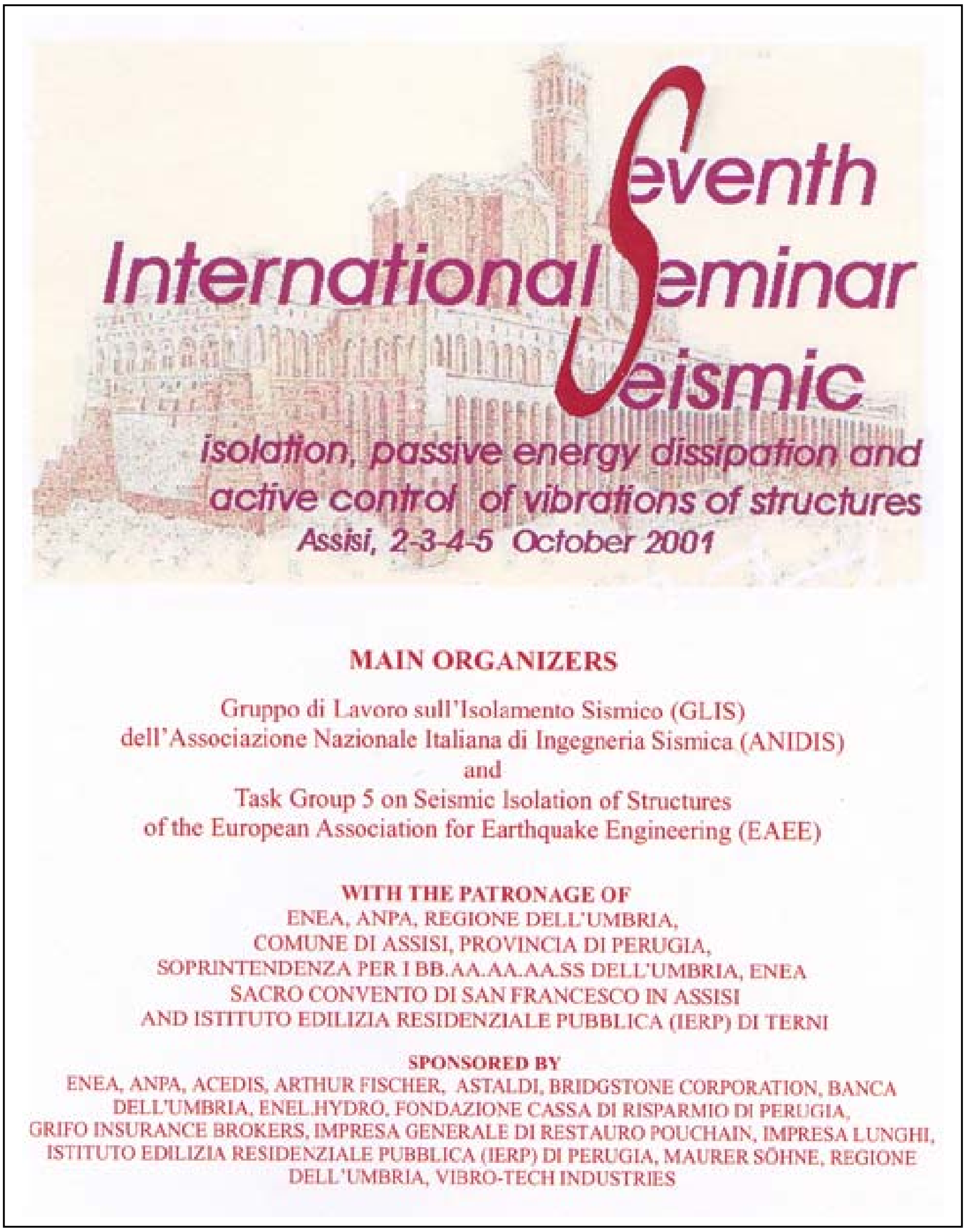

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Assisi, 2-3-4-5 October 2001

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THE CAM SYSTEM FOR THE RETROFIT OF MASONRY STRUCTURES

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ABSTRACT

Old masonry structures are often characterised by irregular or double layer masonry systems, with lack of transverse connections. The need for compacting them suggests the idea of using a three-dimensional tying system. The CAM system, Masonry Active Ties or Manufact Active Confining (patented by Dolce and Marnetto), is based on such idea. Ties are made of stainless steel ribbons and are pre-tensioned, so that a light beneficial pre-compression state is applied to masonry. Using special connection elements, a continuous horizontal and vertical tie system is realised, that improves the shear and bending in-plane and out-of-plane strengths of single panels and entire walls. The main characteristics of CAM are illustrated, along with its application potential, the setting up operation, as well as the first experimental results.

1. INTRODUCTION

Historical Italian buildings are generally characterised by low mechanical properties of masonry, both for its texture and for the bad quality of mortar. Walls are often made of a double layer (see fig.1), without any transverse link (Baratta et al. 1997, Dolce et al. 1999, Baggio et al. 2000). Moreover masonry is not homogeneous, parts of the same wall being made of different materials. The low strength of masonry structures is further reduced by the actual slenderness of the single wall layers, subjected to in-plane vertical compression and shear, as well as to out-of-plane bending. These combined actions produce the typical masonry collapses shown in fig. 1, even for low-medium intensity earthquakes (Baratta et al. 1997). When rehabilitating old masonry buildings, the main problems to solve are, therefore, not only relevant to the connections between structural elements (walls, beams, kerb), but also to the masonry weakness. In this respect the most popular kind of intervention is by far the jacketing of masonry, by using shotcrete and light steel net reinforcement (Modena et al. 2000), as also recommended by the Ministry of Public Work (Min.LL.PP. 1997), along with other kinds of strengthening. Though appealing for simplicity, low cost and speed of application, this intervention presents the following drawbacks:

- The reinforcement plays a passive role, as it becomes effective only when masonry has significant cracks (in the plane) and disconnections (between layers and at intersections),
- The strength of reinforcement is only partially exploited, as its involvement is conditioned

Fig. 1 - Collapse mechanisms of old Italian buildings (Umbria-Marche 1997 Earthquake).

upon the bonding between masonry, shotcrete and reinforcement,

- Heavy changes to the construction have to be made (total elimination of the existing plaster, its substitution with shotcrete, reinforced injection at the intersections, etc.), so that it loose its original features,
- The normal use of ordinary steel, often in contact with masonry, determines the fast decay of the intervention, due to steel corrosion, particularly of transverse ties;
- The continuity between consecutive steel net panels are realised just by overlapping, which usually results to be inadequate (often absent);
- No continuity between the jacketing of two consecutive stories is normally realised, so that the intervention produces only a generic improvement of the shear strength;
- The shotcrete layer determines an increase of the structural masses;
- The effectiveness at wall intersections is very low, if reinforced injection are not executed;
- Cement plastering determines problems and difficulties for the execution of the systems (electrical, water, etc.) and their maintenance, as well as condensate on walls;
- There are no significant ductility increase, because of the fragile mechanism of stress transmission between masonry and reinforcement.

The need for a compaction of the masonry mass suggests the idea of using a three-dimensional system of tying, capable to "package" the masonry structure, eventually giving a beneficial tri-axial compression stress state. On such concept the CAM system is based.

It belongs to the category of "horizontal and vertical ties", which is one of the four categories of strengthening techniques considered in (Min.LL.PP. 1997). It is completely realised with stainless steel, to avoid any durability problem and get good ductility characteristics. Ties are realised with steel ribbons and are pre-stressed, to apply a light pre-compression state, which is particularly useful in the transverse direction. Special connection elements permit to realise a continuous tying system, running all along masonry walls, both horizontally and vertically, to improve not only the shear resistance but also the flexural resistance of masonry walls in their single parts and as a

Fig. 2 – Failure mechanism of a new building.

whole. The potential of CAM in improving also the behaviour of recent masonry constructions is evident when observing fig. 2: horizontal ties would apply the lateral confining forces shown in fig. 2, thus contrasting the shear collapse mechanism.

This paper illustrates the main characteristics of the CAM system, its application potentials with a real example, as well as the first results of an experimental investigation.

2. THE CAM SYSTEM

The CAM system is mainly based on the use of stainless steel ribbons, to tie masonry with loops passing through transverse holes, as shown in fig. 3. The loops are closed with a special tool, which is able to apply a calibrated prestress to the ribbon. The system includes also drawpieces as connection elements and angles as terminal elements, as shown in fig. 4,

In the current applications, the ribbon is 0.75-0.80 mm thick and 18-20 mm wide, with yielding and failure strengths equal to 250-300 and 600-700 Mpa respectively, and more than 40% elongation at failure. The drawpieces, which play the role of connection and force transmission between adjacent loops and stress distribution on masonry, are usually 125x125 mm, 4 mm thick. Similar sizes are used for the angles in current applications. The distance between holes is typically between 1000 and 2000 mm.

The ribbon system can be arranged in a squared, rectangular, rhombic, triangular or even irregular mesh, so that a horizontally and vertical continuous sling is realised. Fig. 5 shows a typical application on a double layer wall, with an alternate arrangement of holes, to minimise their number. The holes can be eventually injected with any kind - there being no corrosion problems - of mortar to improve the masonry characteristics around the hole.

Alternatively, diagonal arrangements of loops can be more effective for regular brick masonry walls, as well as to connect floor kerbs to masonry walls, as shown in fig. 5, to limit any possible kerb-masonry slipping.

There are a number of advantages in using CAM, as summarised below:

- stainless steel ribbons play an active role, due to the light three-dimensional pre-stress compression state induced in masonry,
- the strength of steel is fully exploited, due to the easily controllable mechanical connections,
- the continuity of the strengthening system throughout subsequent stories is guaranteed,
- stainless steel ribbons can be covered by traditional plasters, without altering structural weights and also

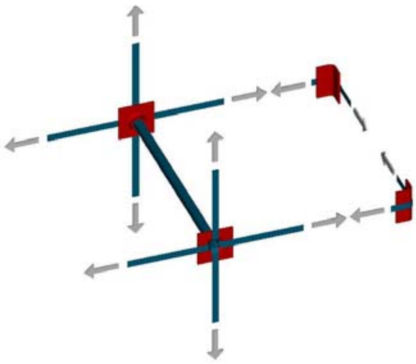
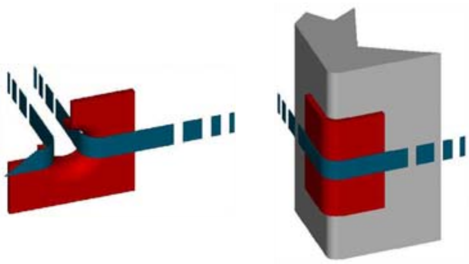


Fig. 3. CAM – basic arrangement.



a) Connection plate b) Terminal angle

Fig. 4 - CAM – basic elements.

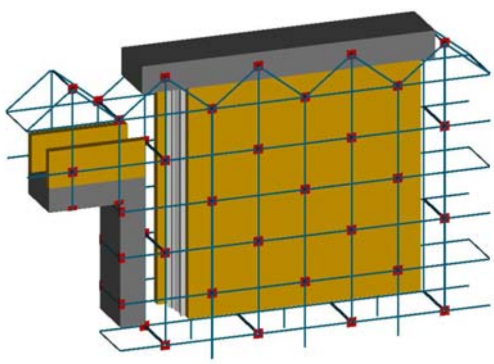


Fig. 5 – CAM - arrangement in a wall with a door and a R/C upper kerb.

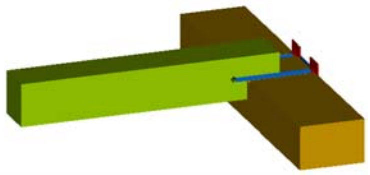


Fig. 6 - Connection of a wooden beam with the masonry wall.

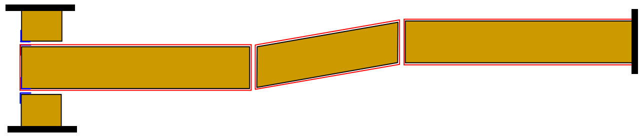


Fig. 7 – Plan arrangement of a tie realised with CAM, which follows the irregularity of the wall.

avoiding thermal/ humidity problems created by concrete jacketing,

- the CAM system automatically solves the connection problems between orthogonal walls,
- the use of stainless steel guarantee the reliability in the long run,
- the effectiveness of the transverse ties reduces the number of holes in masonry,
- the CAM technology is little intrusive and totally reversible,
- the thickness and flexibility of ribbons makes it easy to by-pass systems (water, gas, etc.).

The CAM system can be usefully applied also for scopes other than just masonry strengthening, e.g. to connect different elements, applying some prestress (see fig. 6), to make ties along irregular walls (see fig. 7) and to confine masonry and R/C columns.

3. APPLICATION EXAMPLE

To describe the application procedure and some peculiar aspects of the CAM system, reference is made to the seismic upgrading of a building, damaged by the Umbria ’97 earthquake. The building is in the small town of Sigillo and is part of a larger structural block, being attached to other buildings on two sides. It has rectangular shape in plan, 20x12 m approximately, but is irregular in elevation. The top story area is significantly smaller than the other stories, the floor are not aligned, due to the slope of the ground, some important structural discontinuities occur along the height, with a porch in the main facade.

The CAM system has been applied for both masonry strengthening, with respect to shear and flexural seismic actions, and to improve connections between different structural elements, such as orthogonal walls, masonry and top kerb, masonry and wooden beams.

Masonry strengthening is extended to all the structures in elevation. The CAM application has been calibrated in the different walls, according to the local weaknesses and the global seismic safety of the building, that was evaluated with the MAS3D program (Braga et al.

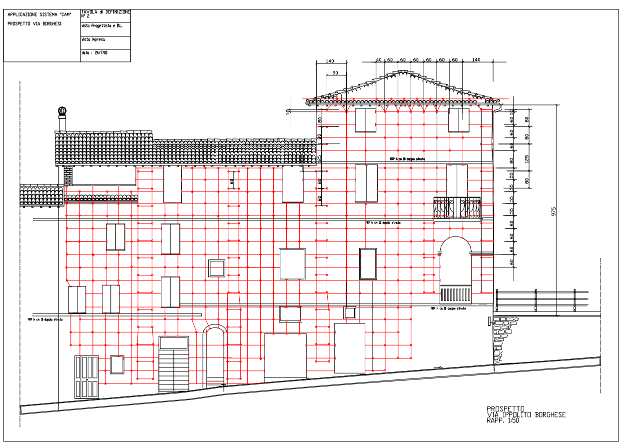


Fig. 8 - CAM arrangement in the facade.

Fig. 9 – CAM arrangement in the facade and link to the top R/C kerb.

Fig. 10 – CAM arrangement in chase.

Fig. 11 - Detail of the connection between orthogonal walls.

Fig. 12 - Detail of the link to the R/C kerb around a wooden truss.

1997). In general terms, two kinds of interventions have been made, differing for the squared mesh size of the steel ribbons (see fig. 8). A 60x60 cm mesh in the longitudinal walls and a 80x80 cm mesh in the transverse walls, with holes at 120 and 160 cm distance respectively.

The original plasters have been removed wherever they had to be remade in any case (fig. 9). On the contrary the system has been applied by only making the strictly needed chases, wherever the plaster was in good conditions (fig. 10). The preparation of the surfaces, by plaster removing or chasing, was finalised to get a linear path, along and near the masonry surface, avoiding any contact between ribbon and masonry. Particular care was put in the correct positioning and bonding of the drawpieces and of the angles.

Figs. 9, 11 and 12 show the capability of CAM to improve the connections between different structural elements: R/C kerb and masonry wall (fig. 9 and 11), orthogonal masonry walls (fig. 11). The big size angles in fig. 11 are used to realise a good connection of orthogonal walls, where the ribbons of the two walls are outset.

4. EXPERIMENTAL TESTS

A compete and exhaustive evaluation of the potential of the CAM Systems requires a very extensive investigation, mainly carried out on existing or existing-like masonry specimens, i.e. with disorganised texture, with double layer and no or scarce transverse connection. However, in order to clarify and quantify in a short time and at low cost some of the different aspects of the CAM strengthening, an investigation on brick masonry panels has been started. Its main objective is to evaluate the improvement of the strength and ductility on in-plane stressed brick masonry with regular texture. At this end 50 panels, 90x90x12 cm, have been built, to be subjected to diagonal compression tests. They are realised with different types of

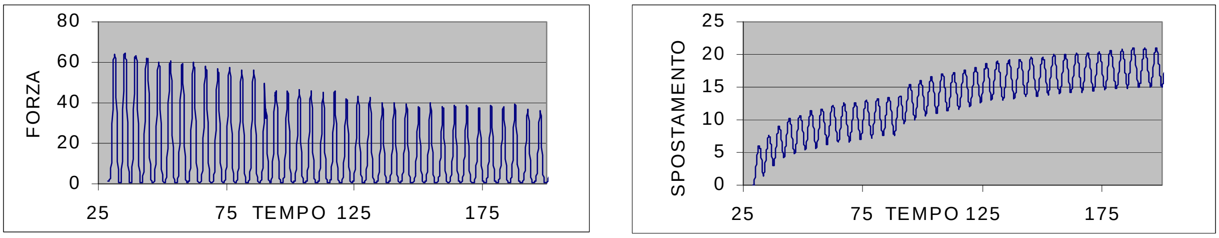


Fig. 13 – Testing procedure of the cyclic loading-unloading tests.

a) b) c)

Fig. 14 - a) Failure of the unstrengthened panel b,c) failure of the same pannel repaired and strengthened with the CAM System.

mortars, as defined in (Min.LL.PP. 1987) as M2 (cement mortar), M3 (cement lime mortar), M4h (hydraulic lime mortar), M4c (cement lime mortar).

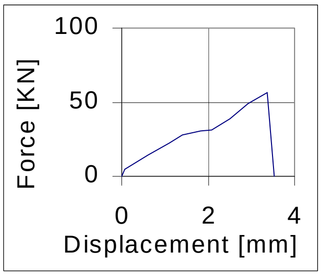
Up to now only two M3 panels have been tested, with the aim of setting up the testing procedure and draw the first indications on the improvement that can be obtained by applying CAM on failed panels. Each panel has been first tested up to failure without any strengthening, then repaired and strengthened by applying CAM and tested again. The initial test on the unstrengthened panels have been both carried out with monotonic load, while the tests on the strengthened panel have been carried out one monotonically the other with loading-unloading cycles, as described in fig. 13, through the force-time and displacement-time diagrams.

Fig. 14 shows the state of panel M3-B2 without strengthening at the end of the first test (picture a), and with strengthening, at an intermediate step and at the final step (pictures b, c). The repairing with CAM stops the crack separation started in the previous test and favours a crack distribution involving the entire panel, thus dissipating a large amount of energy.

	M3-B2 (monotonic)	M3-B2-CAM (monotonic)	M3-B1 (monotonic)	M3-B1-CAM (cyclic – 4 groups)
Max displacement (mm)	3.4	50.7	3.9	2,3/3,7/10,3/45.0
Max force (kN)	56.4	85.07	80.6	93.0
Dissipated energy (J)	103.3	3049.3	112.4	34+125+2300+3845=**6304**
No. Cycles / cycl.displac.	1	1	2	2/1, 12/2, 72/3, 84/5

Tab. 1 – Summary results of the experimental tests on two panels.

Table 1 summarizes the main quantities obtained in the tests. The maximum attained displacement in the strengthened panels has been at least one order of magnitude greater than that attained in the unstrengthened panels. The increase of maximum force is about 50% in one case and 15% in the other case. The dissipated energy is about 30 times greater when both



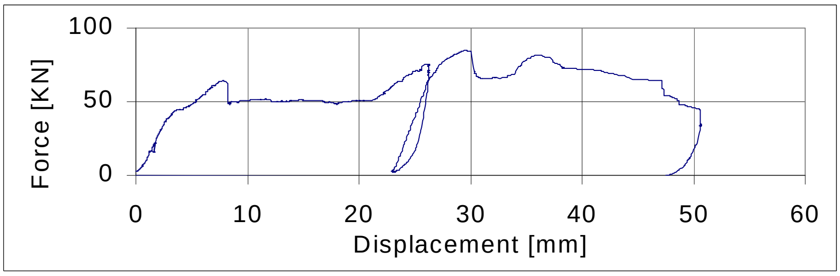


Fig. 15 - Diagonal force-displacement diagram of panel M3B2 without and with CAM strengthening.

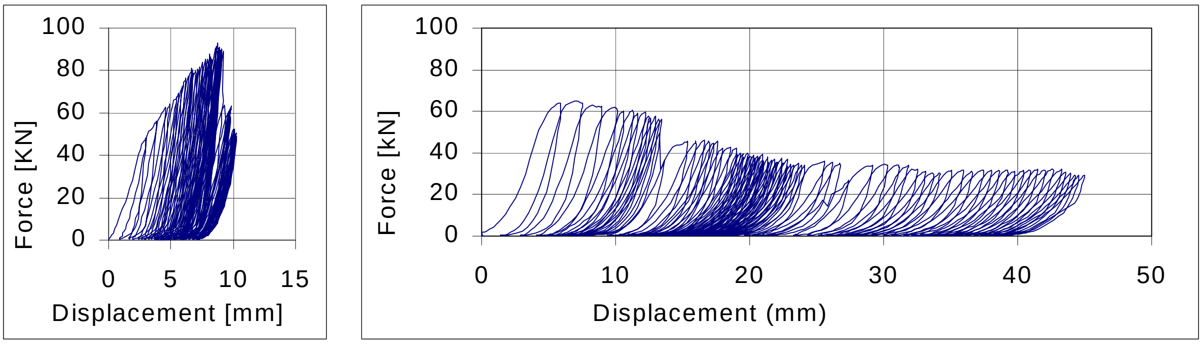


Fig. 16. Diagonal force-displacement diagram of panel M3B1 with CAM strengthening in the third an fourth series of cycles.

tests are monotonic, while it becomes 60 times when the strengthened panel is cyclically tested. Four groups of loading-unloading cycles have been carried out, with constant cyclic displacement within the group and increasing from the first to the last group, as shown in table 1. This was done because cycles stabilize when keeping displacement constant, with a mechanism having almost no decay. It was therefore necessary to increase the displacement amplitude from one group to the other to get failure conditions. In the last two groups of cycles, whose amplitude were 3 and 6 mm respectively, the number of cycles were 72 and 84, which proves the high low cycle fatigue resistance of CAM-strengthened panels.

Fig. 15 shows the force-displacement diagrams of panel M3-B2, without and then with CAM strengthening, under monotonic load in both cases. Strength and ductility gains are evident. A considerable percentage of diagonal load capacity is kept up to 4-5 cm displacement.

Fig. 16 shows the force-displacement diagrams of panel M3-B1, tested with CAM strengthening, in the 3rd and 4th series of cycles. In the third series the maximum strength value has been reached for 9 mm displacement (in that series). In the fourth series the residual strength, equal to about 30% of the maximum strength, is kept constant for very large displacement and a very large number of cycles.

5. CONCLUSION

The observation of the collapse mechanisms of masonry structures has suggested the conceptual development of the new CAM strengthening system (Masonry Active Tying). Its main objectives are the improvement of the transverse link between masonry layers, the increase of the in-plane and out-of-plane strength and ductility, the improvement of connections between intersecting walls.

The main application aspects have been examined, with reference to a recently completed retrofit intervention, which has emphasised the flexibility of use and the easy operation control.

A recently started experimental investigation on brick masonry panels subjected to diagonal compression tests allows some qualitative and quantitative considerations to be made:

- The applications of the CAM system on already failed panels not only restores the original strength but also increase it, thus favouring the development of alternative mechanism and the propagation of cracks, involving all the masonry mass in the energy dissipation;
- Ductility improvements of one order of magnitude can be obtained;
- The behaviour can be further improved by using the complete CAM arrangements, not

only angles, as in the tests made;

- The use of long angles, instead of short ones, or of a diagonal (rhombic) mesh, instead of an orthogonal (squared) one, will surely improve the overall behaviour of brick masonry panels.

Although the first results appear already satisfactory, the mechanical features of the CAM system can be better exploited on the typical masonry of existing buildings. Actually the double layer stone masonry with low quality mortar can take profit of the transverse link given by CAM, the better functioning of the orthogonal CAM arrangement for irregular masonry and a generally greater margin of improvement, due to the low masonry strength.

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