NEW TECHNOLOGIES FOR THE STRUCTURAL REHABILITATION OF MASONRY CONSTRUCTIONS: CONCEPT, EXPERIMENTAL VALIDATION AND APPLICATION OF THE CAM SYSTEM

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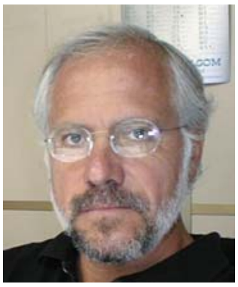

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SUMMARY

Old masonry structures are often characterised by irregular or double layer masonry, with lack of transverse connections. Besides requiring in-plane strengthening, they also need improving transverse connections. The ideal strengthening strategy would therefore be realised by 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, vertical and transverse 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 in the paper, along with its application potential, the setting up operation, as well as the first experimental results on both panels and columns.

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 masonry layer (see fig.1), without any transverse link [1, 2, 3]. Moreover masonry is not homogeneous, parts of the same wall being made of different materials. The low strength of

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

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 [1]. When rehabilitating old masonry buildings, the main problems to solve are, therefore, not only relevant to the connections between structural elements (walls, beams, kerbs), but also to 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 [4], as also recommended by the Italian Ministry of Public Work [5], along with other kinds of strengthening. Though appealing for simplicity, low cost and speed of application, this intervention presents several 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 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;

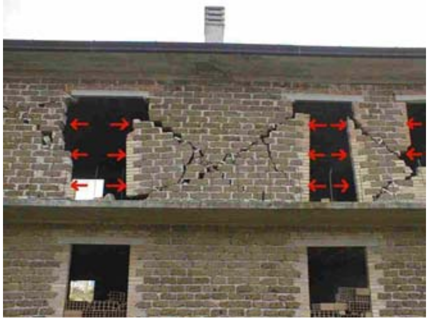


Fig. 2 – Failure mechanism of a new building.

- No continuity between the jacketing of two consecutive stories is normally realised, so that the intervention produces only a generic improvement of shear strength;
- The shotcrete layer determines an increase of 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 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 [5]. 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 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.

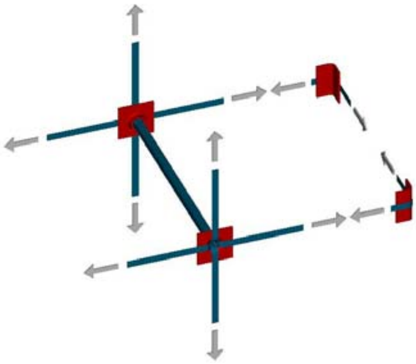
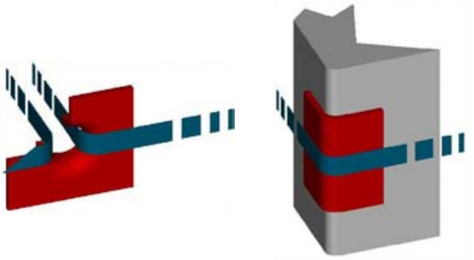


Fig. 3. CAM – basic arrangement.



a) Connection plate b) Terminal angle

Fig. 4 - CAM – basic elements.

In 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 elements between adjacent ribbon loops as well as stress distribution elements on masonry, are usually 125x125 mm, 4 mm thick. Similar sizes are used for angles in current applications. The distance between holes is typically between 1000 and 2000 mm.

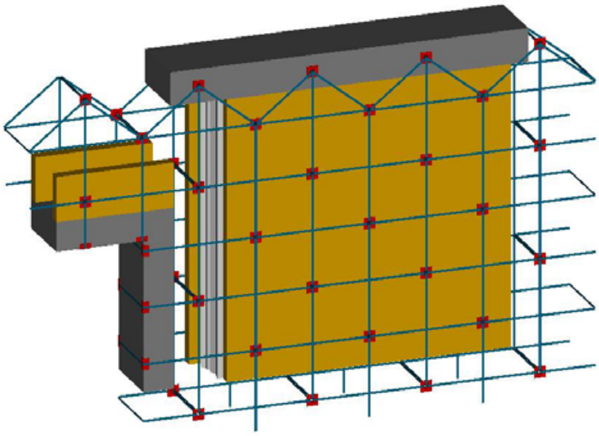


Fig. 5 – CAM - arrangement in a wall with a door and a R/C upper kerb.

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 masonry characteristics around holes. 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 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 controlled 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 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.).

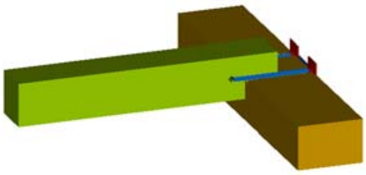


Fig. 6 - Connection of a wooden beam with the masonry wall.

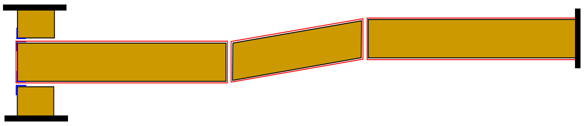


Fig. 7 – Plan arrangement of a tie realised with CAM, which follows the irregularity of the wall.

The CAM system can turn out to be very effective also to confine masonry as well as R/C columns. In such case the application of CAM is very easy and fast. As a matter of fact, for compact sections (squared or nearly squared), the CAM system is only made of angles and steel ribbons, and does not need any hole to be made in masonry. In case of rectangular sections, ribbons can be arranged through intermediate holes, to get a better distributed confinement. Its simplicity, effectiveness and speed of application can make it to be preferred to classical, but heavier solutions (welded angles and brackets), or modern solutions (FRP – Fiber Reinforce Polymers).

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), or to make long ties along irregular walls (see fig. 7).

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 improvement of 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. 1997). In general terms, two kinds of interventions have been made, differing for the squared mesh size

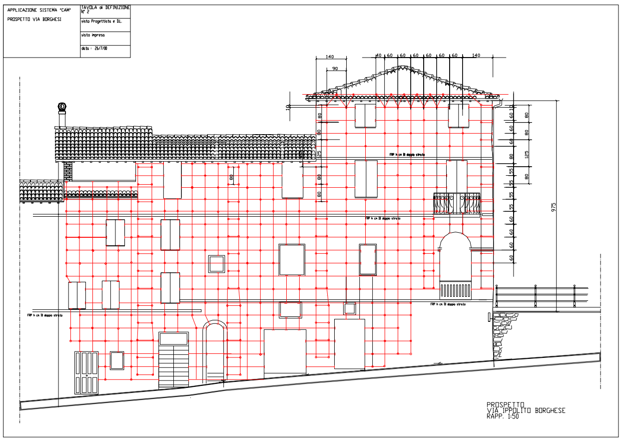


Fig. 8 - CAM arrangement in the facade.

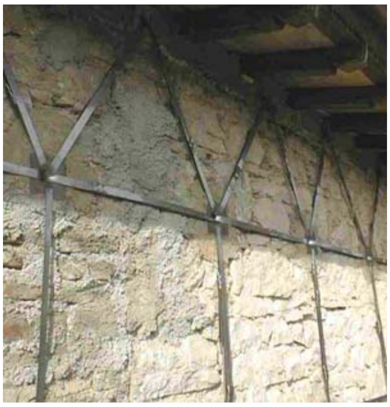


Fig. 9 – CAM arrangement in the facade and link to the top R/C kerb.

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.

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 System requires a very extensive investigation, mainly carried out on existing or existing-like masonry specimens, i.e. with random texture, double masonry 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 new brick masonry panels and columns has been started. Its main objective is to

Fig. 13 – Panels and columns before testing.

evaluate the improvement of strength and ductility on in-plane stressed brick masonry with regular texture and on squared cross-section columns. At this end 50 panels, about 90x90x12 cm, to be subjected to diagonal compression tests and 20 columns, about 32x32x82 cm, to be subjected to simple compression tests were built. The panels are made of different types of mortars, defined in [7] as M2 (cement mortar), M3 (cement lime mortar), M4h (hydraulic lime mortar), M4c (cement lime mortar). The columns were made of an external brick masonry stretcher layer and cast masonry inside. Masonry panels and columns are shown in fig. 13.

Before testing masonry specimens, stainless steel ribbon specimens, also including the connection joint, have been tested in traction, to evaluate their strength and ductility characteristics.

4.1 Tests in stainless steel ribbon

20 specimens of AISI 304 stainless steel were tested. Ten specimens were made of two ribbon pieces joined together. The force-displacement diagram was recorded on a 109 mm measurement base around the joint and on plane ribbons and on a 400 mm base, as shown in fig. 14. In fig. 15 there are reported some typical stress-strain diagrams. In fig. 15 a) the behaviour of just stainless steel is shown. Elongation at failure of the order of 60% are attained. The mean value of stress, obtained from the ten specimens tested, is 610.20 N/mm^2, with 0.6% coefficient of variation. In the same diagram there is also reported the curve relevant to the ribbon with joint. As can be seen the failure strength is reduced by about 25%, the mean value being equal to 446.55 N/mm^2, with 1.5% coefficient of variation. Nevertheless, even the

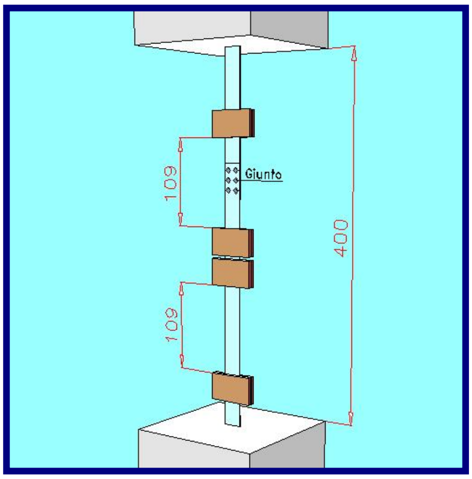
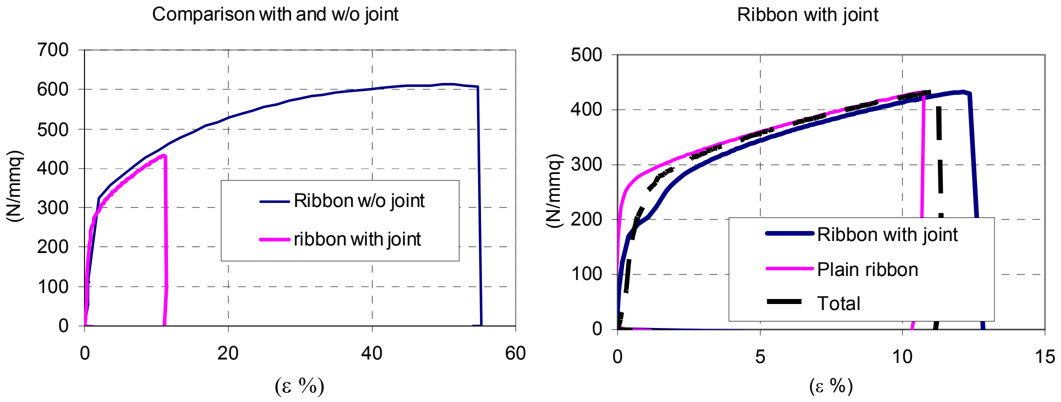


Fig. 14 – Test set up for steel ribbons.



a) b)

Fig. 15 – Experimental stress-strain diagrams of stainless steel ribbons.

ribbon with joint shows a considerable ductility, as the average elongation at failure is greater than 10%. In fig. 15 b) the curves taken on the three different bases, as shown in fig. 14, clarify the behaviour of the ribbon with joint. The elongation measured on the parts of ribbon with and without joint are of the same order, resulting in the spread of yielding beyond the joint, all along the ribbon, due to the marked strain hardening of stainless steel of ribbons. The large elongation capacity of the stainless steel ribbon results in a great ductility capacity of the CAM system when applied to masonry panels.

4.2 Brick Masonry Panel tests

Only two M3 panels have been tested until now, with the aim of setting up the testing procedure and draw the first indications on the improvement that can be obtained by strengthening failed panels with CAM. Each panel has been first tested up to failure, then strengthened by applying CAM and tested again. The initial test on both unstrengthened panels have been carried out with monotonic load, while the one of the strengthened panels has been tested monotonically, the other under loading-unloading cycles, as described by the force-time and displacement-time diagrams of fig. 16.

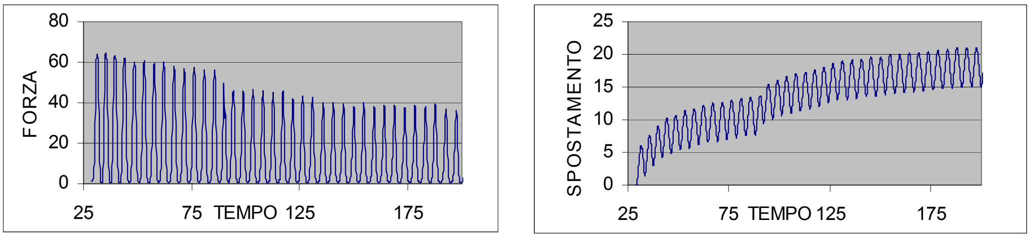
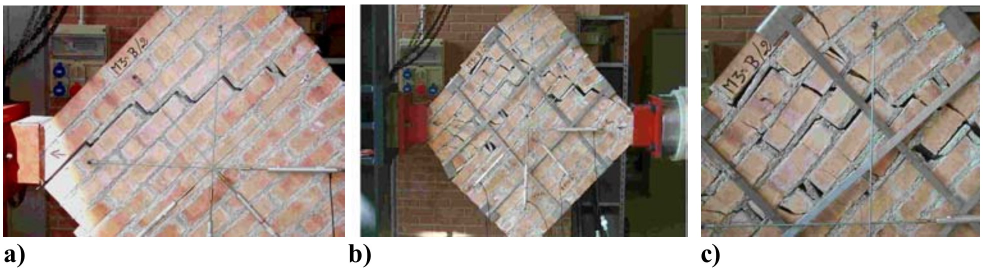


Fig. 16 – Testing procedure of the cyclic loading-unloading tests.



a) **b)** **c)**

Fig. 17 - a) Failure of the unstrengthened panel b,c) failure of the same panel repaired and strengthened with the CAM System.

Fig. 17 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.

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 tests are monotonic, while it becomes 60 times when the strengthened panel is cyclically tested.

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

	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, 84/6

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

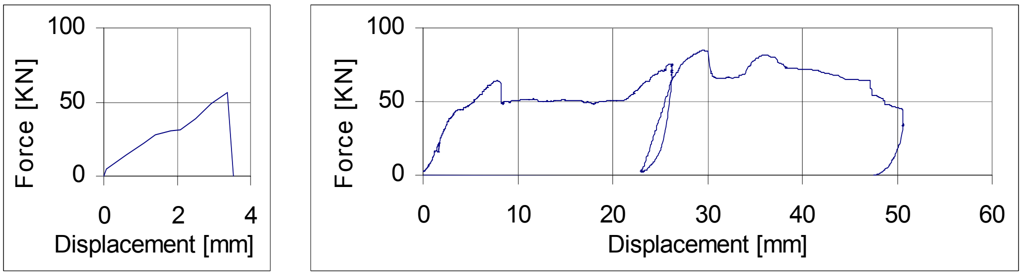


Fig. 18 - Diagonal force-displacement diagram of panel M3B2 without and with CAM.

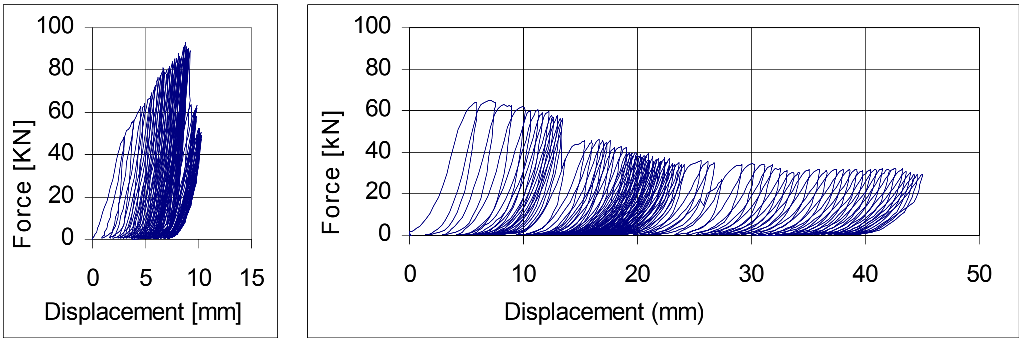


Fig. 19. Diagonal force-displacement diagram of panel M3B1 with CAM strengthening in the third an fourth series of cycles.

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. 18 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. 19 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.

4.2 Masonry Columns

20 columns were realized with an external 5 cm-thick brick layer and filled with mortar of low quality and brick pieces (see fig. 13). Low quality mortar, having 0.8 N/mm^2 compression strength and 0,29 N/mm^2 flexural strength, was used. Different CAM configurations were analyzed, as shown in figure 20. They differ each other for the number of ribbons and the continuity of the steel angles along the height of the column.

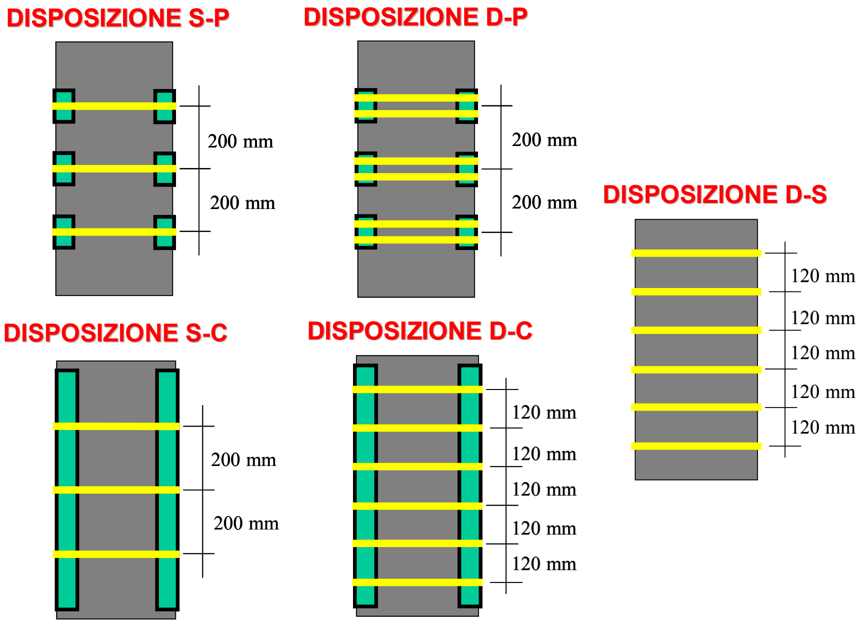


Figure 20 - Configurations of the ribbons used for the tests

The results that are shown here are referred to 13 specimens. Two different testing procedures were applied to two groups of specimen. The first group of eight specimens was treated with the "double test" procedure, as follows:

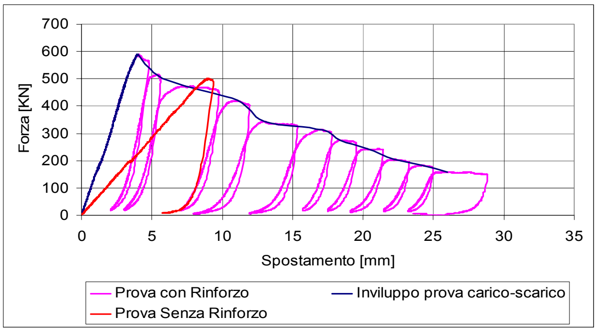


Fig. 21 – Force-displacement diagram of column 1

1. each specimen was first tested in simple compression up to reaching its maximum strength, stopping the test when the residual strength reduced to 98% of its maximum strength;
2. the same specimen was then strengthened with the CAM system and tested again with loading-unloading cycles; unloading at each cycle was started at 95% of the maximum force reached at that cycle.

The second group of 5 specimens was directly strengthened and then tested (direct test). In both cases the tests on the strengthened specimens were stopped when the maximum force reached at a cycle was less than 30% of the maximum force at the first cycle.

Fig. 21 shows a typical force-displacement diagram of a column. The curves relevant to the initial test on the unstrengthened specimen, to the cyclic loading-unloading test on the strengthened specimen and the envelope curve of the cyclic test can be distinguished. The increase of strength and the much greater stiffness (about 2.5 times) of the specimen after

a) **b)** **c)** **d)**

Fig. 22 – Column specimens under tests: a) typical failure mechanism of unstrengthened specimens due to brick layer instability, b) failure of column 1 before strengthening, c) failure of column 1 after strengthening, d) failure of column 6.

strengthening are apparent, as well as the sudden drop of force of the unstregthened column and the capability of the strengthened column to undergo several loading-unloading cycle. However, while the increase of strength is due to the CAM strengthening, the increase of stiffness is to be ascribed to the bad quality of the mortar in the joints, specifically to its porosity. It is compressed during the first cycle, reducing its volume and increasing its stiffness, independently of CAM strengthening.

Fig. 22 shows some examples of column specimens under tests. Picture 22a) shows a typical failure mechanism of an unstrengthened specimens, compressed up to reaching a residual strength less than half its maximum strength. The failure is clearly due to the instability of the brick layer, occurring when some bricks break up near the corners. Picture 22b) shows the failure of column 1 before strengthening, when the residual strength was 98% its maximum strength. It is again due to the incipient instability of the brick layers, favoured by the failure of some bricks at the corners. Pictures 22c) and 22d) show the failure of column 1 and column 6 after strengthening. Even in this case the failure is generated by the instability of the external brick layer, which is however contrasted by the confining actions of the ribbon-angle system.

Table 2 – Summary table of the experimental results

No CAM							**Strengthened with CAM**					
Column	**Steel**	**Conf.**	**Fmax**	**S***	**Ed**	**K**	**Fmax**	**S***	**K**	**Ed(50)**	**S(50)**	**S(50)/S***
1	H.S.	SC	501,20	9,04	2075	57,01	590,22	4,02	151,25	7547	18,39	4,57
2	Stainl.	DC					566,20	12,37	51,06	10175	25,88	2,09
3	Stainl.	SC	459,78	7,39	1548	64,16	481,55	4,58	153,69	5904	16,08	3,51
4	H.S.	DC	472,83	8,50	1876	59,21	647,41	6,50	146,92	13979	29,04	4,47
6	Stainl.	SC	473,22	8,23	1875	63,47	542,01	4,52	161,93	6697	16,91	3,74
8	Stainl.	SC					782,03	11,55	68,64	11562	21,73	1,88
9	Stainl.	DC	469,59	7,52	1673	66,35	557,32	5,81	140,08	11972	26,97	4,64
10	H.S.	SC	554,88	8,45	2124	70,39	600,79	4,87	158,06	7601	15,17	3,11
11	H.S.	DP					763,46	9,90	78,06	6912	14,78	1,49
13	H.S.	DP					769,90	9,78	77,79	8412	15,78	1,61
14	H.S.	DC	389,56	6,77	1154	57,87	638,75	6,49	142,75	13647	27,77	4,28
19	H.S.	DC					781,35	10,45	80,58	11068	19,95	1,91
20	H.S.	DC	488,10	7,15	1644	74,52	531,37	4,44	180,73	5072	17,15	3,86
Average	Double test		476,15	7,88	1746	64,12	573,68	5,15	154,43	9052	17,30	4,02
Average	Direct test						732,59	10,81	71,23	9626	19,62	1,80

Table 2 summarizes the experimental results relevant to the two groups of specimens tested with the different testing procedure. “Conf.” stands for configuration of the strengthening system, “Fmax” is the peak force (strength) reached during the test, “S*” is the corresponding displacement, “Ed” is the dissipated energy in the test of the unstregthened specimen, “Ed(50)” and “S(50)” are the dissipated energy and the displacement of the strengthened specimen when it reaches 50% of its strength, “S(50)/S*” is the ductility of the strengthened specimen corresponding to the above said condition.

The following observations can be made:

1) the confinement produced by the CAM system increases the compressive strength of a virgin specimen by more than 50%;

2) the retrofit of failed columns by the CAM system increases their original compressive strength by about 20 % in the average;
3) The energy dissipation capability and the ductility of a column is drastically increased by the CAM strengthening. Referring the maximum displacement to the attainment of 50% of the maximum force, the energy dissipated is about 4 times that dissipated in the unstrengthened specimen, while the average ductility is more than 3, in the double test, and about 1,8 in the direct test. This latter result is due to the lower initial stiffness of the virgin specimen.
4) The compressive stiffness is not affected by the CAM strengthening, as already observed. A considerable stiffness increase (2-2,5 times) however occurs after the first loading cycle of the specimen.
5) The use of high strength steel improves the performance of the CAM system in terms of all the quantities considered, except for the axial stiffness.

6. 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.

A parallel experimental investigation on column specimens subjected to axial compression has been completed. The results demonstrated the high effectiveness of the confining action of the

CAM system. It results to be effective both on virgin specimens, producing strength increases of the order of 50%, and on already failed specimens, producing more than a full recover of the initial strength, with 10-30 % strength increase.

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