Effectiveness of Active Confinement Techniques with Steel Ribbons: Masonry Buildings

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Abstract

In the present paper, we analyzed the main advantages of the active confinement techniques with a particular focus on the CAM system, which is an Italian reinforcement technique with pre-tensioned stainless-steel ribbons. Italian seismic codes classify the CAM system as belonging to the strengthening category of “horizontal and vertical ties”. Therefore, we compared the CAM system to the reinforcement techniques with horizontal and vertical ties in order to understand the actual similarities and possible differences between them. Moreover, we offered a deep analysis of the main critical issues of the CAM system, distinguishing between geometrical and mechanical weak-points. In particular, we analyzed the strengthening mechanism of the CAM system, still poorly understood, by performing a static analysis in the Mohr/Coulomb plane. Finally, we provided suggestions for future developments.

Keywords: CAM system, masonry walls, in-plane loading, out-of-plane loading.

Introduction

Among all the available reinforcement techniques for masonry buildings, active reinforcement is gaining an increasing attention from designers (Angiuli et al., 2011; Micelli et al., 2014; Zuboski, 2013) as, contrarily to passive reinforcement, it acts on structural elements from the moment of its installation, without requiring that a structural damage occurs to start working.

One of the most effective active reinforcement techniques of the past is the use of pre-tensioned metal ties, both with vertical and horizontal arrangements. Pre-tensioned metal ties are very useful for increasing strength, cracking behavior, and ductility of masonry walls subjected to seismic loads (Al-Manaseer and Neis, 1987; Bean Popehn et al., 2008; Ganz and Shaw, 1997; Ismail et al., 2012; Preciado, 2011; Rosenboom and Kowalsky, 2004; Sperbeck, 2009), avoiding brittle tensile failure modes (Ganz, 1990). They also have a restoring or self-centering effect, by reducing residual deformations after loading (Bean Popehn et al., 2007; Dizhur et al., 2013; Ganz, 2003; Ma et al., 2012; Schultz and Scolforo, 1991). Nevertheless, it is not recommendable to use the post-tensioning method with metal bars extensively in a structure, because the excessive concentration of stresses induced by the anchorage could lead to crushing. Therefore, post-tensioning of unreinforced masonry is more suitable to be used for local strengthening of certain vulnerable structural parts (Figure 23), than for a real improvement of the global behavior of the structure against earthquakes, especially when it is applied to ancient masonry structures. This does not allow us to obtain an overall box-type behavior and does not protect the structure from local damages, even in the immediate vicinity of tie rods (Figure 23).

The CAM system (Active Confinement of Masonry) is an active reinforcement technique patented in 1999 by Dolce and Marnetto (Dolce et al., 2001, 2008, 2009; Marnetto and Vari, 2015; Marnetto et al., 2014). We can consider the CAM system as an evolution of the strengthening method with horizontal and vertical tie rods (Ordinanza del Presidente del Consiglio dei Ministri, 2003; Ministero LL.PP., 2008), where steel ribbons substitute the metal bars. What makes the CAM system almost unique in its strengthening category is being a continuous strengthening system. As a matter of fact, the CAM system consists of a three-dimensional net of stainless steel ribbons that ties all the parts of a structure together. The most important consequence of this is the realization of effective connections just where structural connections are compromised or completely absent. The reinforcement net develops in the third dimension because the ribbons pass through the wall thickness, along some openings obtained by drilling the masonry, thus connecting the two opposite faces of the wall. This realizes a strong link between the two opposite faces, which is particularly useful when the masonry wall is made of two or more weakly connected vertical layers.


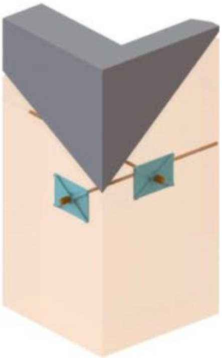

Figure 23. Umbria-Marche earthquake in 1997 (Italy): sliding-plane just over corner tie rods (left); scheme of corner detachment (right) (Marnetto et al., 2014).

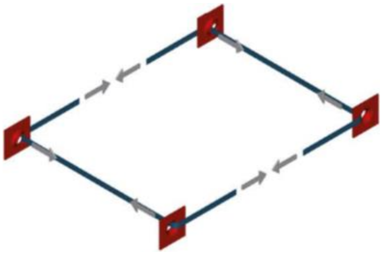

Figure 24. A closed loop of the CAM reinforcement net (Marnetto et al., 2014).

Each ribbon passes through the wall thickness twice and closes on itself forming a closed loop (Figure 24). When clamping the ribbon, we provide a pre-tensioning to the ribbon, which then post-compresses the masonry it wraps.

Even if specifically born as a reinforcement technique for masonry, the CAM system is also useful for seismic retrofitting of R/C buildings (Ponzo et al., 2011) and for connecting masonry to concrete elements in hybrid structures.

In the following Sections, we will analyze some of the main advantages of the CAM system and few weak-points that deserve further deepening.

A Comparison between the CAM System and the Systems of pre-Tensioned Metal Ties

The closed loops of the CAM system are arranged both horizontally and vertically (Figure 25), thus replicating the reinforcement scheme with horizontal and vertical ties. Nevertheless, the overall behavior of the reinforcement system is very far from that of traditional pre-tensioned horizontal and vertical ties. In fact, the loop-shaped ribbons bring several benefits. Among these, the most relevant are listed below:

Since ribbons close on themselves, we no longer need to anchor ties into the masonry. This eliminates the problem of the excessive concentrations of stresses induced by the anchorages. It is worth noting that it is not possible to achieve the same result with traditional horizontal and vertical tie rods, since the stiffness of tie rods does not allow us to shape them in closed loops. On the other hand, however, the rectangular loop may concentrate stresses at the corners of the loop excessively. In order to avoid damages at the loop corners, the CAM system makes use of special stainless steel protective elements (funnel shaped red elements in Figure 24 and Figure 25). Moreover, one of the main advantages of having eliminated the anchorages in the masonry is the possibility of using the CAM system extensively, as a continuous retrofitting system. This ultimately improves the global behavior, establishing new connections between structural elements (Figure 25) and providing an overall box-type behavior to the retrofitted structure.

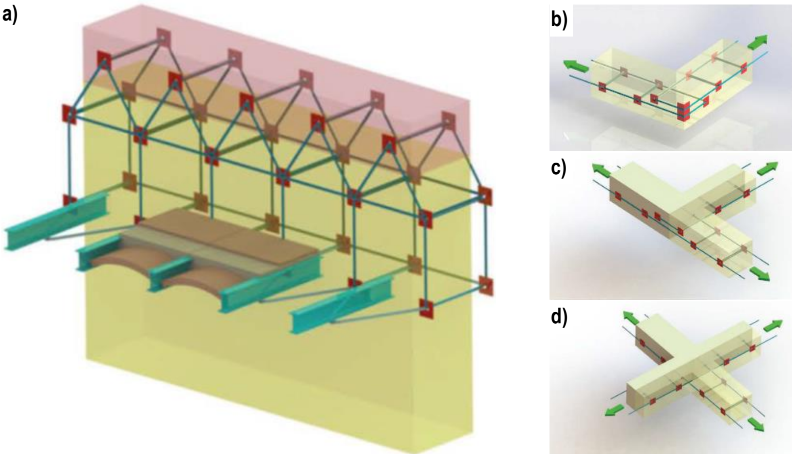

Figure 25. Connections established by the CAM ribbons between: a) the masonry wall, the upper R/C kerb and the metallic beams; b) two orthogonal walls at an external corner; c) spine and front walls in a T-shaped intersection; d) the walls of a X-shaped intersection (Marnetto et al., 2014).

Figure 26. Metallic gabions for retaining walls and slope stabilization.

The ribbons are made of stainless steel. This allows us to avoid the typical corrosion problems of tie rods, which need of a suitable covering or galvanization zinc plating. Moreover, stainless steel is chemically inert, therefore compatible with any kind of mortar or plaster used for covering the wall surfaces. This latest property is of particular importance in retrofitting of historical masonries, where mortar is often lime based.

The cross-section of the ribbons is very small (19×0.75mm). This makes the CAM system to perform better than metal tie-bars for two reasons: the strengthening system is concealable under a plaster layer easily and does not increase the total weight of the structure too much. In effect, the heavy weight of metal bars is a serious disadvantage for the traditional tie rods, since the mass increase enhances the attraction of seismic forces.

Each ribbon is a bi-dimensional device, able to provide in-plane and transversal post-compression at the same time. On the contrary, being a unidimensional device, a metal tie rod can compress the masonry along one direction only, the direction itself of the device. Therefore, we need to use more than one tie rod for achieving the same effect given by a single ribbon. In other words, a retrofitting system with pre-tensioned horizontal and vertical ties does not improve the transversal connections, unless we add specific tie rods in the transversal direction. Conversely, the CAM system always establishes transversal links, without requiring any additional ribbon. Thus, if improving transversal connections is one of the aims of the reinforcement intervention, the CAM system allows a significant saving of material and, in the final analysis, counteracts the excessive mass increase.

The steel ribbons continue to wrap masonry even after masonry crushing. In particular, since the ultimate load of steel ribbons is much greater than the masonry ultimate load, if an earthquake had damaged the masonry so seriously that the wall became a mass of incoherent material, the CAM net behaves as a system of metallic gabions filled with stones (Figure 26), allowing the wall to keep standing. This is of fundamental importance for safeguarding life, as people do not risk that some part of the structure hits them, due to building collapse. Therefore, the CAM system acts as a reinforcement system before the structural damage occurs and a protection device after the structural damage had occurred. Of course, it is also possible to use the CAM system for restoring already damaged structures, but it is precisely the twofold behavior, before and after damage, that distinguishes the CAM system from the pre-tensioned metal ties. In fact, being not able of wrapping masonry, the tie rods cannot help preventing the building collapse and do not provide any contribution to safeguarding life. Moreover, since we need to anchor the tie rods in the masonry, the crushing of masonry makes ineffective the anchorages, determining the operating limit of the tie rods.

Some deepening on the Strengthening Mechanism of the CAM System

In addition to the several advantages we listed in the previous Section, the CAM system also has some weak-points, not sufficiently deepened in literature so far. Some of them have a geometric nature, while others come from an erroneous understanding of the mechanical behavior of the reinforcement three-dimensional system. In the following, we will analyze both the geometrical and the mechanical limits of the CAM system.

Sensitiveness to the Arrangement of Ribbons

As far as the geometrical limits are concerned, it is worth noting that the ribbon arrangement in Figure 25 is a labile configuration. In fact, the holes drilled in the wall for allowing the ribbons to pass through behave as cylindrical hinges, even when we fill the holes with mortar after having positioned the ribbons. This means that the ribbons of the rectangular arrangement are able to counteract the in-plane deformations only when they occur along either the horizontal or the vertical direction, that is, along the two directions of the ribbons. In other words, this configuration could be suitable for increasing the load bearing capacity of the wall under static conditions only (we have said "could be" because we must verify the actual possibility of increasing the ultimate load for vertical solicitations, as we will explain in the following). Anyway, due to the twofold behavior of the three-dimensional CAM net, which we discussed earlier, an intervention with rectangular arrangement of the mesh is still useful for safeguarding life, as it is able to retain the material that could fall on people when the structure collapses.

Things work differently under dynamic loads, as the prevalent damaging action during an earthquake is the shear stress. As is well known, the rectangular frame structure with hinged nodes is not able to withstand lateral forces and sways laterally (Figure 27). This type of structure needs some kind of bracing in order to resist lateral loads (Figure 27). Consequently, the unbraced rectangular arrangement of the mesh is not able to counteract the in-plane deformations due to shear stress. In other words, the stresses in the horizontal and vertical ribbons do not change during wall deformation for shear stress, at least as long as the displacements are small: they continue to carry the pre-tension stress provided at ribbon clamping, independently of their direction. This means that we cannot expect any increase of load bearing capacity for shear loads when the arrangement of the mesh is rectangular.

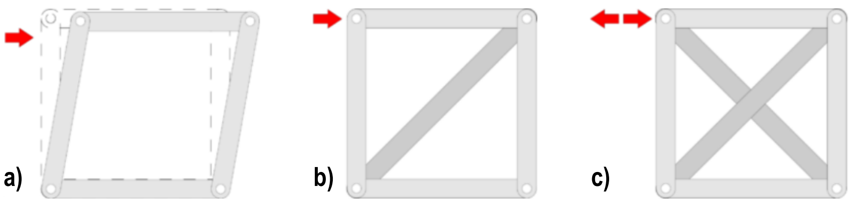

Figure 27. a) A rectangle made of hinged strips collapses when we apply a force to the side; b) By adding a strip along a diagonal will stop the collapse of the rectangle in one direction but not the other, as, having no resistance to bending, the diagonal strip works well as a tie but cannot be a strut; c) By adding strips along both diagonals, the rectangle will stop collapsing in both directions.

More precisely, the vertices of any square element of unitary side subjected to pure shear in its plane move along the diagonals of the element itself (Figure 28) because the principal directions of stress for pure shear have a slope of ±45° (dotted lines in the plane of Mohr of Figure 28, that is, the directions of the principal stresses for pure shear, σ_1 and σ_2). This means that, even if it is a labile configuration, the rectangular arrangement becomes statically determined when we turn it by an angle of ±45°. Actually, since turning the mesh will allows us to have the ribbons disposed along the principal directions of stress for pure shear, the angles formed by the ribbons before the application of the shear load will not change after load application:

$$\gamma_{12} = 0; \qquad (5)$$

where 1 and 2 are the principal directions of stress (Figure 28).

In conclusion, the most effective arrangement of the ribbons for bearing shear loads is rectangular, but with the ribbons inclined by ±45° with respect to the horizontal direction (Figure 29). This acts on the nodes of the CAM net as a cross bracing, counteracting lateral swaying. In particular, the ribbons disposed along the principal direction of compression – that is, the direction of the principal stress of compression, σ_2 – carry a positive stress lower than the pre-tension stress, while those disposed along the principal direction of traction – that is, the direction of the principal stress of traction, σ_1 –carry a positive stress greater than the pre-tension stress. This counteracts the displacements of the masonry wall along the principal direction of traction. Depending on the direction of the seismic forces, the principal direction of traction forms a positive, rather than negative, angle of 45° with the horizontal direction. Thus, by changing the verse of the shear load the collaborating and slack ribbons exchange. Anyway, in both cases we can expect an increase of load bearing capacity.

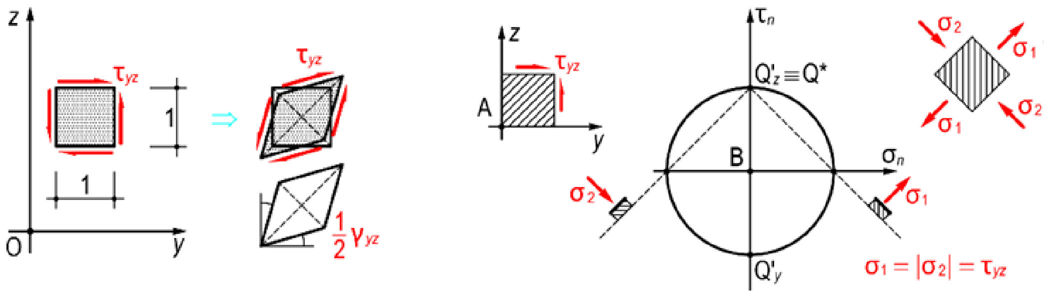

Figure 28. Deformed configuration of a plane square element subjected to pure shear in its plane: determination of the principal directions of stress in the plane of Mohr.

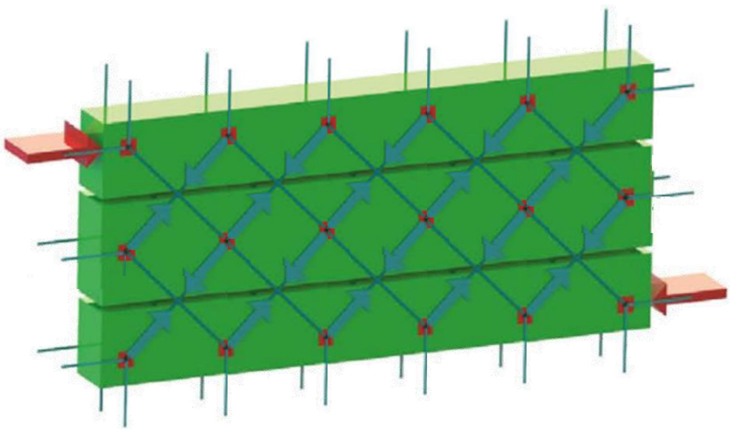

Figure 29. Optimized arrangement of ribbons for in-plane shear loads.

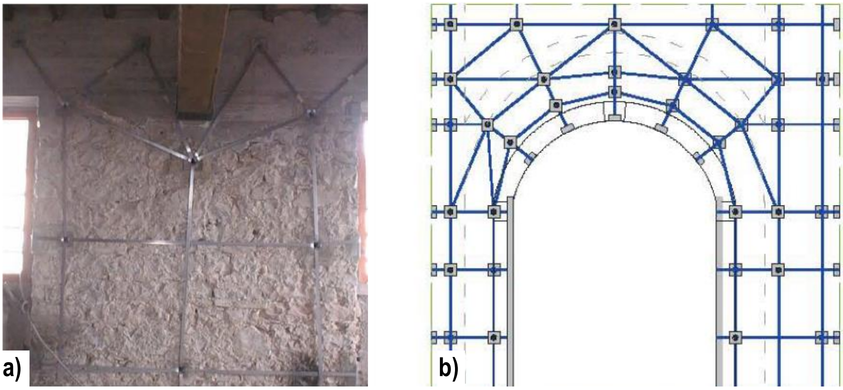

Figure 30. The use of unstructured triangular grids for a) Overcoming a truss-beam; b) Adapting the CAM net to the profile of an arched-shaped opening (Marnetto et al., 2014).

Another possibility for counteracting lateral swaying is using structured or unstructured triangular meshes, which could brace the wall thanks to the ability of triangles of keeping the shape when loaded in their plane. To date, we know only local applications of this kind of meshes, integrated into wider rectangular meshes for solving some specific problems, as overcoming structural obstacles (Figure 30a) or reinforcing walls with arched-shaped openings (Figure 30b). In the opinion of the author, it might instead be appropriate to investigate how to exploit the triangular arrangements for bracing purposes.

Sensitiveness to the Direction of Load

The discussion on the geometrical limits of the CAM system does not end with the analysis on the best arrangement of ribbons in the plane of the wall. In fact, whatever the ribbon arrangement in the plane of the wall, the CAM system can improve the load-bearing capacity for in-plane loads, in particular for shear loads (Figure 31a), but it is not able to counteract the out-of-plane loads (Figure 31b). In other words, while it is possible to find a statically determined ribbon configuration in the plane of the wall, we cannot do the same in the transverse direction, unless we drill the wall along directions not orthogonal to the wall, with positive and negative slopes alternately. Though theoretically possible, this is obviously impracticable because too complicated from the technological point of view. Therefore, if we want to increase the load-bearing capacity for out-of-plane loads we must develop some new solution, eventually by combining different reinforcement techniques.

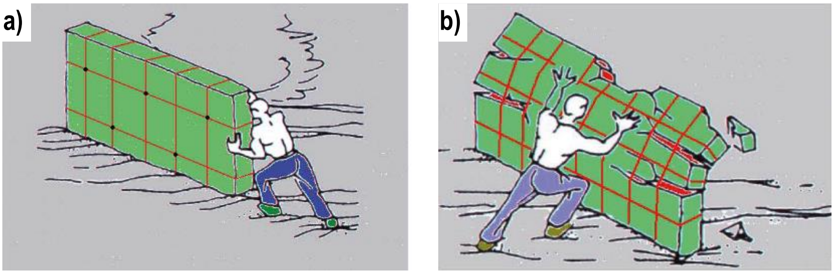

Figure 31. a) In-plane loading of a wall reinforced with the CAM system: the case of shear load (Marnetto et al., 2014); b) Out-of-plane loading of a wall reinforced with the CAM system (Marnetto et al., 2014).

It is worth noting that, even if not useful for increasing the out-of-plane bearing capacity, applying the CAM system is still advantageous for out-of-plane loads. That is, it becomes advantageous after the wall breaks, because it can act as a device of safeguarding life from the moment of masonry cracking on.

Moreover, the previous analysis applies to isolated walls, like those of Figure 31. In real buildings, the new connections established by the CAM system between walls, floors and the other structural elements, leading to an overall box-type behavior, do not allow any wall to deform independently of the rest of structure. Therefore, any wall subjected to out-of-plane loads will always benefits of the contribution given by the other structural elements. In other words, the CAM system indirectly also provides a slight improvement to out-of-plane bearing capacity, due to the box-type behavior it restores. The degree of improvement depends on the constraint conditions. Since the improvement may be very low, the possibility of increasing the out-of-plane bearing capacity in the applications with the CAM system deserves further deepening.

A Discussion on the Stress Field Provided to Walls by the CAM System

The fundamental assumption underlying the CAM system is that the transverse holes divide the wall into units of masonry, each one stressed by the ribbons as shown in Figure 32, that is, hydrostatically. The aim of the CAM system is to transform the wall into a juxtaposition of gabions, like those in Figure 26, with the only difference that the three-dimensional net of ribbons adds a hydrostatic state of stress to each masonry unit. In this sense, the action of the CAM ribbons on the masonry is often referred to as “packing”.

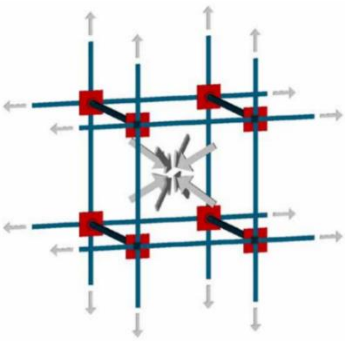

Figure 32. Assumption of hydrostatic state of stress provided by the ribbons to the masonry unit: at each corner of the unit, the resultant of the forces transmitted to the masonry is directed toward the barycenter of the unit.

In terms of stress field, adding a hydrostatic state of stress causes the three circles of Mohr to shift along the horizontal axis of the Mohr/Coulomb plane for an amount equal to the hydrostatic stress. In Figure 33 – where σ_T is the transverse stress (out-of-plane stress), σ_V is the vertical stress, σ_L is the lateral stress, and σ_H is the hydrostatic stress (provided by the retrofitting system) – we have taken the stresses in absolute value, therefore positive even if of compression. Consequently, the three circles shift along the positive semi-axis of the normal stresses. Moreover, the limit domain is the parabolic domain of Leon:

$$\tau_n^2 = \frac{c}{f_c}\left(\frac{f_{tb}}{f_c} + \sigma_n\right); \qquad (6)$$

which is the most suitable limit condition for masonry (Ferretti et al., 2008) and, more generally, for brittle materials (Ferretti, 2004a, 2004c, 2004d, 2009, 2013; Ferretti et al., 2003).

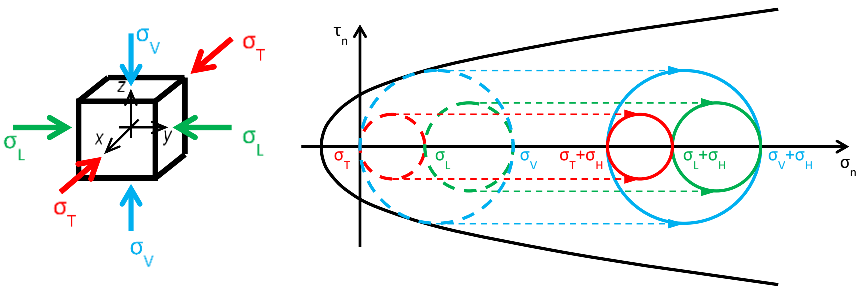

Figure 33. How the assumption of hydrostatic state of stress modifies the circles of Mohr (Mohr's circles before retrofitting in dashed lines, for comparison).

In Eq. 6, c is the cohesion, f_c the compressive strength, and f_{tb} the tensile strength.

It is worth noting that, before the retrofitting system is applied there are no constraints along the transverse direction of the wall. Therefore, the initial out-of-plane stress is equal to zero:

$$\sigma_T = 0. (7)$$

Consequently, the total transverse stress after the application of the retrofitting system is equal to the hydrostatic stress provided by the retrofitting system itself:

$$\sigma_T + \sigma_H = \sigma_H. \quad (8)$$

In Figure 33, the three circles of Mohr at the initial stage (that is, before the retrofitting system is applied) represent a state of stress in limit condition, because the greatest circle is tangent to the limit domain. It is worth recalling that a state of stress with circles that intersect the limit domain is not allowable in the Mohr/Coulomb plane, since it represents an impossible state of stress. This means that we cannot increase σ_V further without causing material crushing. In fact, by increasing σ_V, the greatest circle would intersect the limit domain (its radius would increase and the circle would continue to pass from the origin).

After shifting, the three circles have moved away from the limit surface and no circle is tangent (or secant) to the limit surface. This means that the material is no longer in limit condition. Thus, in the final stage (that is, after the application of the retrofitting system) the material is able to bear further increments of σ_V before reaching a new limit condition (that is, a new tangent condition). Moreover, the minimum distance between the greatest circle and the limit domain provides a measure of the safety factor in retrofitted state. The greater the safety factor, the greater the load the material can bear further.

In these assumptions, the benefit of applying the CAM system is theoretically unlimited, as, being possible to shift the circles limitless along the positive semi-axis of σ_n, we can also increase the safety factor limitless (the only upper limit is the crushing of the retrofitted system (Ferretti, 2004b, 2004e). In other words, we can increase the load-bearing capacity of the masonry how much we want, simply by increasing the pre-tension and/or the number of ribbons (1-4 per loop). On the contrary, the experimental results do not confirm any relationship between increased load-bearing capacity and pre-tension stress or number of ribbons per loop.

In the opinion of the author, the reason for this lies just in the assumption of hydrostatic state of stress, which is not the actual state of stress provided by the CAM system to the masonry. In fact, the additional state of stress in a masonry unit would be effectively hydrostatic if that unit were the only "packed" unit of the wall or if there were some dilatation joints, which would allow each unit to deform independently of the surrounding units. On the contrary, the vertices of a unit are common to multiple units, as some of the ribbons constraining adjacent units pass through the same hole (Figure 34a). This makes impossible for a unit to deform independently of the surrounding units. Thus, each vertex of a unit is constrained by the surrounding units to an extent that depends on the position of the unit in the wall and the number of surrounding units.

In this configuration of mutual constraints, even the evaluation of the ribbon stress is not simple at all. In fact, even though we pre-tension the ribbons by means of a special tool that allows us to check the pre-tension stress at ribbon clamping, the stress in a ribbon may change when we pre-tension an adjacent ribbon. Moreover, as clamping takes a long time, relaxation and creep (Ferretti and Di Leo, 2008) may intervene during the pre-tensioning operations, modifying the stress inside the ribbons further. In conclusion, the order in which we clamp and tension the ribbons is decisive in determining the actual stress inside the ribbons.

If, for the sake of simplicity, we assume that:

the pre-tension stress is the same for all ribbons;

the ribbons arrangement is rectangular;

then, the problem of mutual constraints in the CAM net is the two-dimensional equivalent of the mono-dimensional sequence of tie rods and nodes in the frontage arches of a long portico (Figure 34b). In particular, the tie rods eliminate the horizontal thrusts (outward-directed horizontal forces) by counteracting the outward-directed horizontal movements of the arches. Nevertheless, each internal node of the portico of Figure 34b receives equal and opposite thrusts from the two arches on its left and right. Therefore, the total horizontal thrust on the internal nodes is equal to zero and it is not necessary to use any internal tie rod for counteracting the outward-directed movements. For the same reason, the nodes of the CAM net in Figure 34a, subjected to pairs of equal and opposite forces in the plane of the wall, do not receive any in-plane force from the retrofitting system and do not have neither horizontal nor vertical displacements. The only nodal force not balanced by an equal and opposite force is the transverse force. Therefore, the actual mechanism of stress-transfer from the CAM net to the masonry wall is the one depicted in Figure 35, which substitutes Figure 32.

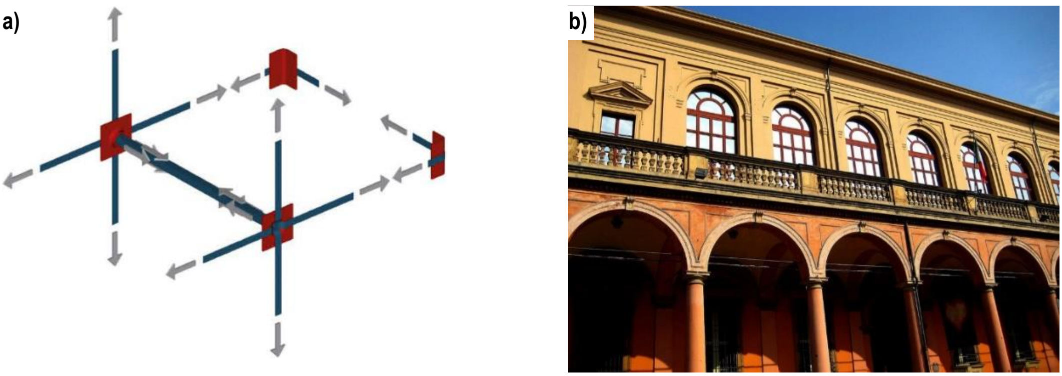

Figure 34. a) Forces acting on the internal nodes of the CAM net, provided by the ribbons passing through a common drilled hole (Marnetto et al., 2014); b) Tie rods in the portico of Teatro San Salvatore, Bologna, Italy.

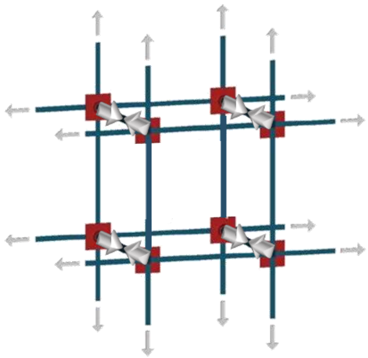

Figure 35. Mechanism of stress transfer in the assumption of perfect balancing of the in-plane forces: the thick arrows represent forces transmitted to the masonry, while the thin arrows represent forces on the ribbons.

Obviously, if the CAM net is not rectangular, even the in-plane forces may not be perfectly balanced, but the additional state of stress provided by the CAM net to the masonry wall is not hydrostatic in any case. Moreover, Figure 35 provides a reliable stress description for the internal masonry units only, as the low constraint degree near the free borders of the wall may not guarantee a perfect balancing of in-plane forces also for rectangular meshes.

In conclusion, the actual mechanism of stress transfer in the most general case is much more complicated than the one depicted in Figure 32 and deserves further deepening. In absence of more information, we will limit our analysis to the internal masonry units stressed by a rectangular net of ribbons, as the masonry unit in Figure 35. In these assumptions, the incremental state of stress provided by the retrofitting system when the ribbons are poorly pre-tensioned modifies the circles of Mohr as shown in Figure 36, where σ_T, σ_V and σ_L are the final transverse stress, vertical stress and lateral stress, respectively (for the meaning of symbols, see Figure 33).

If compared to the three circles we would obtain in the assumption of hydrostatic state of stress, with the same value of ribbon stress (Figure 37), the three circles in Figure 36 represent a more advantageous state of stress. In fact, the safety factor evaluated for the greater circle in Figure 36 is higher than the safety factor evaluated for the greater circle in Figure 37. This means that the intervention is actually effective for low values of the ribbon stress and the mechanical model used so far underestimates the increase of both the safety factor and the load-bearing capacity. Nevertheless, the safety factor cannot increase indefinitely. Actually, we reach the upper limit of the safety factor when the ribbon stress equals the vertical stress, σ_L. Finally, for values of the ribbon stress greater than σ_V, the effectiveness of the intervention decreases and requires a case-by-case assessment. Therefore, not all out-of-plane stress values are beneficial for the masonry wall and it is possible that high post-compression stresses lead the safety factor to decrease (Ferretti, in prep. b).

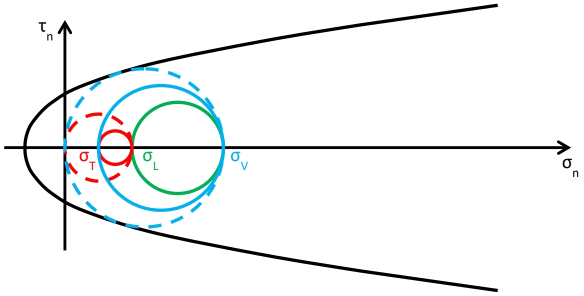

Figure 36. State of stress after the application of the CAM system for $0 < \sigma_T \leq \sigma_L$: assumption of perfect balancing of the in-plane forces (Mohr's circles before retrofitting in dashed lines, for comparison).

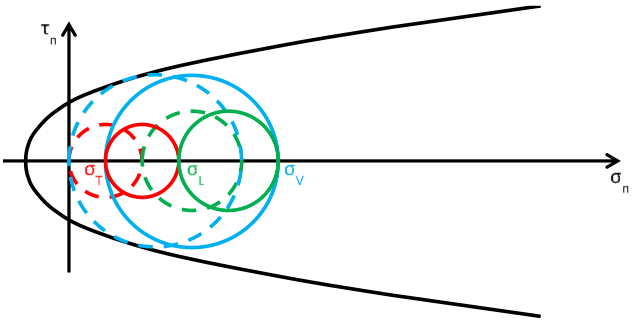

Figure 37. State of stress after the application of the CAM system for $0 < \sigma_T \leq \sigma_L$: assumption of hydrostatic state of stress provided by the retrofitting system (Mohr's circles before retrofitting in dashed lines, for comparison).

Conclusions

The CAM system is a new reinforcement technique that exploits the main advantages of both the active confinement techniques and the continuous reinforcement techniques. Its main merit as a reinforcement technique is to provide an actual overall box-type behavior to the reinforced structure, by improving the connections between structural elements. Nevertheless, classifying the CAM system as a reinforcement technique would be reductive, as the net of the CAM system survive the collapse of the structure, allowing the building to keep standing. In this sense, we may also consider the CAM system as a device of safeguarding life, integrated into the structure.

Unfortunately, an erroneous disposition of ribbons may allow us to exploit the great potentialities of the CAM system only in part. In particular, we have shown that it is sufficient to rotate the most commonly used CAM net (rectangular, with horizontal and vertical ribbons) by an angle of 45° for improving the load bearing capacity under shear loads. This happens because the rotated net would act on the masonry wall as a bracing for lateral loads, while the non-rotated net does not. Even the triangular mesh has a bracing effect, although less effective, and can provide an improvement of load bearing capacity for shear loads.

It is worth noting that a better disposition of the ribbons can increase the ultimate load for in-plane loads only, being irrelevant how the ribbons are arranged when the wall is loaded out of the plane. Nevertheless, the CAM system can bear out-of-plane loads satisfactorily due to the collaboration of all the structural elements, as allowed by the box-type behavior provided by the reinforcement system. In the case of isolated or very wide walls, for which reaching a box-type behavior with the CAM system is not possible, we must instead combine the CAM system with some other kind of reinforcement for improving the out-of-plane behavior.

Finally, as far as the vertical loads are concerned, we found that the mechanical models commonly used for the CAM system are not useful for estimating the actual improvement of load-bearing capacity. In particular, the CAM system does not provide a hydrostatic state of stress to the masonry wall, as believed so far. The mechanism of stress transfer is much more complex and sensitive to the constraint conditions. For the sake of simplicity, we studied the mechanism of stress transfer for a masonry unit far from the boundaries and the openings. The results show that we cannot increase the load bearing capacity indefinitely – as it would happen if the CAM system would transfer a hydrostatic state of stress to the masonry wall – since the increase in the safety factor is bounded above.

Further developments

Recently, we started an experimental program at the University of Bologna (Ferretti, in prep. a, in prep. c), in order to investigate how to couple the basic scheme of the CAM system with other retrofitting systems, for improving the out-of-plane ultimate load of masonry walls.

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