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Design of the Seismic Upgrading of the Tambour of the S. Nicolò's Church in Catania with the DIS-CAM System

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Abstract The high seismic vulnerability of several monumental masonry buildings can be ascribed to the low strength of the materials employed, to the presence of wide openings and slender panels and to the high stress due to both vertical and horizontal seismic forces. A new upgrading system, named DIS-CAM (DISsipative Active Confinement of Masonry) was proposed to design the seismic upgrading of the tambour of the dome of the S. Nicolò's church in Catania (Italy). The technique, that can be considered reversible and a not invasive, is based on a rocking-damper system, in which the rocking and the re-centring capacity are provided by the behaviour of masonry panels, while the dissipation capacity is mainly relied upon hysteretic elements stressed in flexure beyond their elastic limit. In this paper, the design of the scaled model's seismic upgrading is presented and the main outcomes of preliminary numerical analyses carried out on the tambour, without any reinforcement and retrofitted with the DIS-CAM system, are discussed.

Keywords: Historical building, seismic strengthening, re-centring capacity, energy dissipation

Introduction

Recently the attention of many earthquake engineering researchers has been drawn by a type of behaviour which overcomes the limits of the only dissipating structural systems. These latter, indeed, at the end of a strong earthquake could exhibit significant residual displacements which can compromise the immediate use and, sometimes, even their recovering. It is more and more necessary to privilege the re-centring capacity of a structural system (i.e. the capacity of recovering the undeformed configuration), though acknowledging the importance of the energy dissipation to limit maximum displacements (Priestley 2003, Restrepo 2006). The re-centring properties of a structure can depend either on the characteristics of the internal constraints (i.e. beam-column, column-footing, wall-footing connections) or on the insertion of special strongly re-centring devices, such as those based on the shape memory alloys (Dolce et al. 2000). Although re-centring systems have been mainly studied for R/C structures, it is interesting to evaluate the possibility of application also to masonry buildings and, if the retrofit is not invasive, to monumental buildings too.

An Italian research was aimed at defining the best technique to upgrading of the tambour of the dome of the S. Nicolò's church in Catania, Italy (Zingone et al. 2007). Within this project a new rocking-damper system, called DIS-CAM (DISsipative Active Confinement of Masonry), has been proposed. The re-centring capacity of the system is provided by the behaviour of the slender panels supporting the dome, while the dissipation capacity is mainly relied upon hysteretic steel elements stressed in flexure beyond their elastic limit.

During earthquake the panel oscillates (rocks) rigidly in its plane, forming flexional cracks at its extremities. In absence of compression collapse at panel's ends and if the top displacements of tambour are not so large, at the end of the seismic action the panel comes back to original position due to the vertical load action. This behaviour is not much dissipative, for this reason is necessary limiting the maximum horizontal top displacement to prevent the collapse by placing at the ends of the panel damper devices in order to avoid the panel overturning.

In summary, the proposed system ought to:

- avoid compression collapses at the ends of the masonry panel, through a three-dimensional confinement of the masonry (CAM) realized by applying angle steel plates and steel ribbons all around the openings in the masonry of the tambour;
- dissipate seismic energy to contain the maximum top displacement, without compromising the re-centring capacity of structure, through special shaped dampers (DIS) welded to the angle plates in correspondence of the corners of the panel.

In this paper the proposed seismic upgrading technique is described and applied for the design of the retrofitting of a 1:6-scale masonry structural model, reproducing the tambour of the dome of the S. Nicolò's church in Catania. Here the results of preliminary numerical simulations analyses of the structure retrofitted with the new DIS-CAM system and the executive details are presented.

Model and Retrofit Objectives

The case study is the S. Nicolò's church located in Catania (eastern Sicily, Italy). In past centuries, this area has been affected by moderate and strong earthquakes. Indeed, the church was rebuilt on the ruins of an earlier church destroyed by *Val di Noto* earthquake (1693).

This monument has an RC dome placed on a circular tuff masonry tambour, characterized by a high seismic vulnerability. Indeed, the tambour has 8 wide openings and 8 slender panels. Many seismic upgrading systems were proposed to retrofit this element. The applicability of the proposed DIS-CAM techniques has been verified considering the experimental 1:6 scaled model (Fig. 1a) reproducing the tambour of the church (Fig. 1b).

The model 230 cm high is characterized by an external 290 cm diameter. It leans on a RC slab. The 112 cm high masonry panels, having a length and thickness of 54 cm 18 cm respectively, are built in continuity with two lower and upper 36 and 28 cm high spandrels. On the top of the model a RC 20 cm thickness shell element simulating the effect of the RC dome has been placed. The weights of the masonry model and of the top RC plate are of 30 kN and 33 kN respectively. 88 kN additional masses have been placed on the RC roof shell in order to respect similitude laws for the scaled model.

The retrofit design of the tambour was developed considering two main objectives: i) to increase strength, ductility and damping of structure so as to counteract the design earthquake; ii) to realize a low invasive, reversible and not visible intervention at end of retrofitting work.

The level of seismic hazard was defined by referring to the actual seismic rules (OPCM 3274/03). The building site is characterized by a stiff soil, corresponding to a B soil profile type, and by a medium seismicity (zone 2).

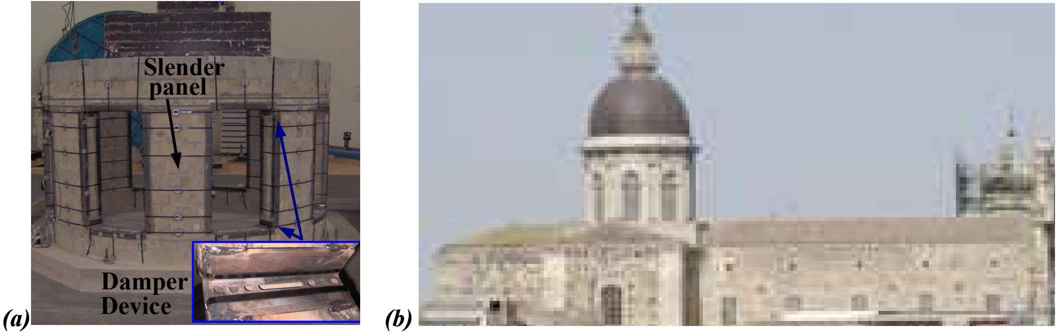

Figure 1: (a) experimental model upgraded with DIS-CAM system; (b) S. Nicolò's church

The DIS-CAM System

The DIS-CAM system (Dolce et al. 2006) has been originally defined for the RC building retrofitting. It aims at upgrading shear and bending behaviour of structural elements and at controlling input seismic forces by introducing concentrated energy dissipation. The special application of DIS-CAM system to the masonry tambour falls within the rocking-damper systems (Dolce, Di Croce 2007). It combines the rocking effect of slender panels at the dissipation capacity of steel devices placed in correspondence of the corners of piers.

In Fig. 2a the rocking bearing of panels is summarised. The slender panel will be subject to an overturning moment MV respect to X point if stressed by horizontal force V. This moment will be mainly balanced by a stabilizing MW moment due to the gravity and vertical load W. The overturning starts when MV>MW. If the total overturning is avoided and the horizontal force decreases or changes its direction, the panel comes back to the original position. In Fig. 2b the effect of a single damper device positioned at the corner to prevent the tipping of the panel is showed. The hysteretic loop of device dissipates rather a lot seismic energy. The behaviour of the rocking-damper system, obtained by the combination of these two bearings, is shown down in Fig. 2c.

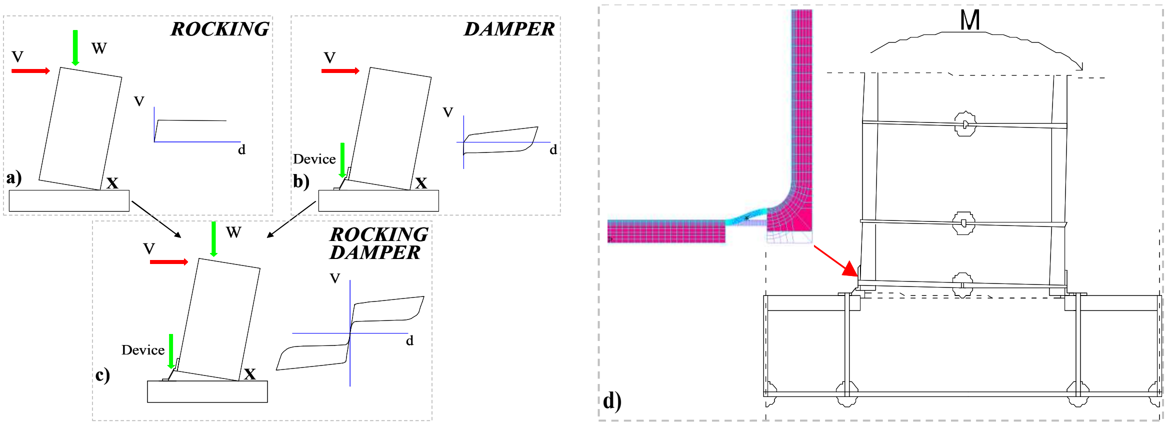

Figure 2: Behavior of (a) Rocking, (b) Damper and (c) DIS-CAM systems; (d) damper's position on pier

The upgrading system of tambour is realized by applying 4 angle steel plates near to the edges of panels and 4 angle steel plates horizontally disposed to completely surround the openings. Moreover, some steel ribbons are willing all around the panels, the spandrels and their angle steel plates.

The installation is completed by inserting damper devices at 4 corners of each panel (Fig. 2d). They are welded to both vertical and the horizontal angle plates in correspondence of the corners and joined with the masonry by further winding steel's ribbons.

The confinement effect and the strengthening of the masonry due to the CAM system (Dolce et al. 2001) and the energy dissipation provided by special shaped dampers (DIS) assure a favourable increasing of the masonry strength and a considerable reduction of displacements, without changing of the stiffness of the structure.

The devices should: i) provide tensile strength in correspondence of the corners of panels; ii) dissipate seismic energy; iii) help to shift the compression stress from panel to the spandrel.

Some simplifications have been considered: i) only the panels parallel to seismic action are considered reacting; ii) the extreme panel's sections are partialized, on the tension side of the panel only the device works in tension while, on the other side, the device helps the masonry in compression (Fig. 2d).

The damper is made from a L-shaped steel profile opportunely weakened along a wing by reducing the section through a groove and more holes (Fig. 3a). This process gives at the device the desired resistance and ductility. S235 steel profiles, 60x60x6 mm, 180 mm wide were considered for the retrofitting design, weakened by a 12 mm wide and 10.5 mm deep groove, 12 mm diameter 6 holes and a buttonhole of 60 mm. The capacity of the device has been validated by F.E.M. analysis (ADINA$^{®}$ 2004) and by experimental tests. They showed that the damper is able to perform many highly dissipative cycles (3mm amplitude) without breaking.

The angles steel plate should: i) reinforce the panels and avoid the local compression break; ii) distribute the contact stress of CAM ribbons; iii) forward forces to devices them welded. Angles are made by S235 steel, 40x40x5 mm size, with rounded corners.

The inox steel ribbon considered for the scaled structure are 10 mm wide and 0.5 mm thick. The pre-tensioned CAM ribbons should: i) improve shear resistance of masonry; ii) apply a lightly and favourable pre-compression state; iii) connect the new steel elements to the masonry.

In the considered design the distance and number of ribbons were influenced by cracks due to previous experimental shaking table tests carried out on unreinforced structure (Zingone et al. 2007). Some details of the DIS-CAM reinforcement system applied to the tambour are shown in Fig. 3b.

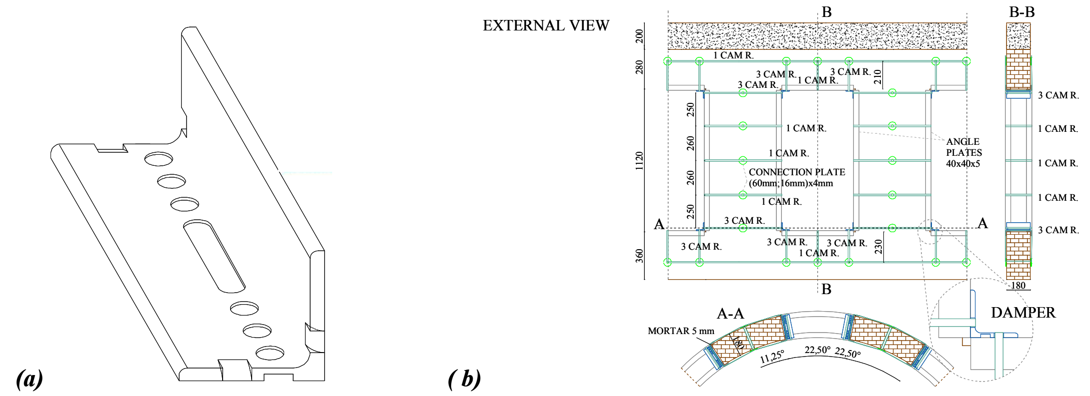

Figure 3: (a) Damper; (b) Design details of upgrading technique applied to S. Nicolò's tambour

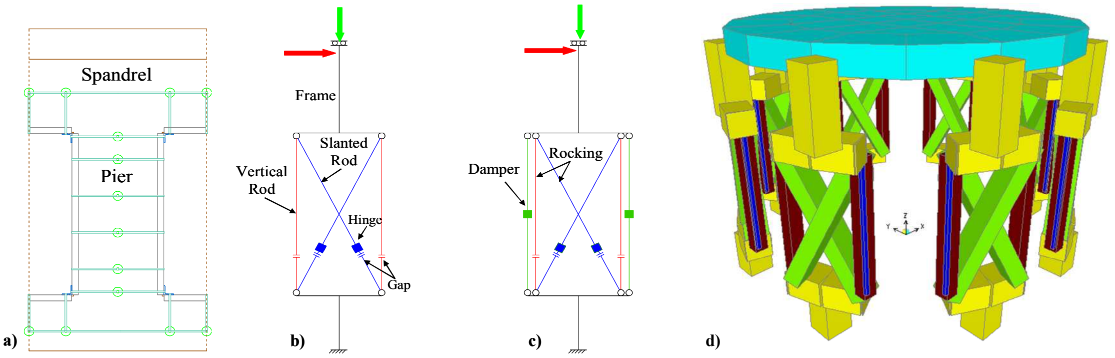

Figure 4: (a) DIS-CAM upgrading of a panel; (b) Numerical model of N.R. or CAM upgrading; (c) Numerical model of DIS-CAM upgrading; (d) 3D complete SAP2000$^{®}$ numerical model

Numerical Analyses and Main Results

A numerical model has been developed to simulate the masonry panel's behaviour in different conditions. Several numerical analyses were carried out before shaking table testing. They were aimed at evaluating the dynamic behaviour of the structure and the effectiveness of the considered upgrading system. The numerical model of the tambour was set up by assembling 8 panels and carrying out static and dynamic analyses. Three different testing models were evaluated: i) Not Reinforced (N.R.), ii) CAM Reinforced (CAM) and iii) DIS-CAM Reinforced (DIS-CAM).
The numerical simulations were carried out using the F.E.M. code SAP2000 (SAP2000$^{®}$ 2004).

The numerical model was built considering frame elements for spandrels and rod elements for the panels. Both real structure and equivalent numerical model are represented in Fig. 4. The panel is schematized by two slanted rods and two vertical ones, all connected to spandrels through horizontal elements. All rods are characterized by gap and gap + hinge elements respectively, in order to take into account the characteristics of the masonry (no tensile strength). The constraints imposed on the model are shown in Fig. 4b. Furthermore, for DIS-CAM model two more vertical rods, endowing hinge elements, are included. The modal analyses provided a fundamental period for the 3D analyzed structures ranging between 0.12 and 0.13 sec.

The preliminary push-over analyses carried out considering all configurations (Fig. 5a) show that the CAM model exhibits the same maximum base shear of N.R. one but a twice displacement capacity, while the DIS-CAM model shows the maximum base shear, but about the same displacement capacity of N.R. model.

Several numerical simulations were carried out imposing top displacement cycles with maximum amplitude increased up to the collapse displacement. The collapse displacements of N.R., CAM and DIS-CAM models were respectively 18, 30 e 20 mm. All collapses were caused by the crushing of the diagonal rods. For cycles larger than 6 mm, the DIS-CAM model shown high dissipative capacity due at the damper device activation, while CAM and N.R. ones were little or no dissipative (Fig. 5b).

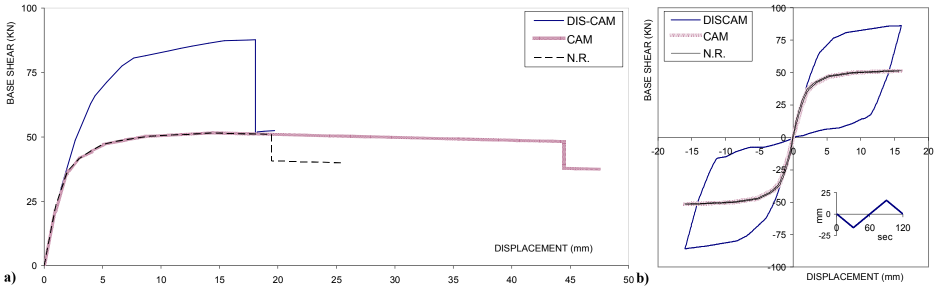

Figure 5: Results of (a) push-over analyses; (b) controlled top displacement analyse.

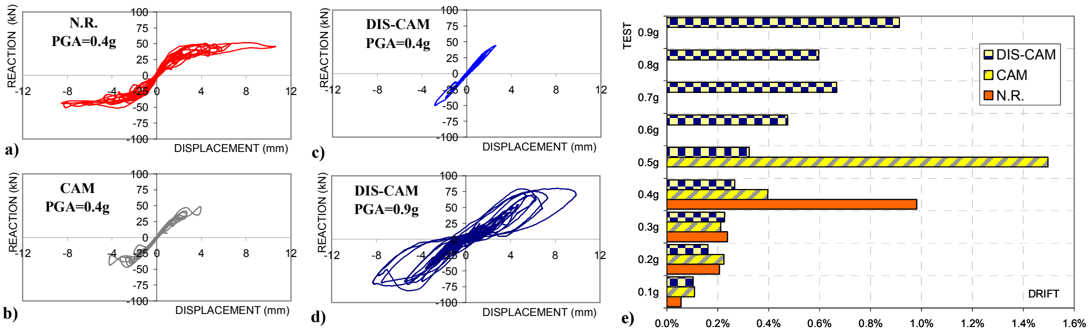

Figure 6: Hysteretic cycles during 0.4g PGA test of (a) N.R. model, (b) CAM model and (c) DIS-CAM model; (d) results of 0.9g PGA test of DIS-CAM model; (e) maximum drift of dynamic tests

Numerical dynamic simulations were carried out using contemporarily both N-S and E-W horizontal components of the Colfiorito record, scaled in time. The earthquake intensity was gradually increased starting from 0.1g PGA up to the models collapse, corresponding to 0.5g for NR, 0.6g for CAM, and 1.0g for DIS-CAM respectively. Fig. 6a, Fig. 6b and Fig. 6c show the hysteretic behaviour of all models for 0.4g PGA. Finally, the test at 0.9g PGA with the DIS-CAM model is shown in Fig. 6d. At end of this strong earthquake the model, even if damaged, showed no residual displacement. Fig. 6e shows the numerical drift vs PGA for the different configurations considered in the analyses. The DIS-CAM model was able to resist almost a twice acceleration than the other two models, with a drift less than 1% for 0.9g PGA. All these results, carried out considering bi-directional seismic action, agree with the previous tests carried out considering a mono-directional actions.

The numerical analyses confirmed that the proposed method and the corresponding numerical model well reproduce both the rocking and rocking-damper behaviours.

The N.R. and the CAM models are perfectly re-centring, though with low dissipation capability. The re-centring is guaranteed until occurs the plasticisation of the slanted rods or the complete panel overturning. The ductility of masonry is respectively 1.5 and 4 for N.R. or CAM model. Hence, the N.R. model quickly comes to breaking than CAM one, that could support displacements biggest than N.R. one increasing the panel's deformation capacity. The DIS-CAM model showed both the re-centring and a high dissipation capacity. This model did not reach the maximum displacement showed by the CAM model, because of the presence of the damper which leads to a greater diagonal compression loads on the panel than the CAM system.

Conclusions

The availability of the experimental model of the tambour of the S. Nicolò's church in Catania (Italy) gave the possibility to verify the applicability and effectiveness of the new rocking-damper system DIS-CAM to upgrade monumental structures.

The authors focused the retrofit design of the tambour in order to reach the desired performance level without changing its behaviour and limiting the retrofit invasiveness.

In this paper the results of preliminary numerical analyses carried out on a 1:6 scaled model upgraded with DIS-CAM system, with CAM system and not reinforced are been presented. The behaviour of the models was evaluated through pushover analyses, cyclical displacement analyses and seismic dynamic analyses.

The study shows that DIS-CAM system is very effective in limiting the seismic drift and in strengthening the structure, reaching as large a resistance about twice than other analysed solutions. Indeed, the DIS-CAM model was able to resist to 0.9g PGA with a drift less of 1%, thanks to high dissipative capacity of damper devices and the masonry strengthening of CAM system.

Acknowledgements

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References

[1] *Automatic Dynamic Incremental Nonlinear Analysis*. ADINA R&D Inc., Watertown, MA, 2001.

[2] Dolce, M, and Di Croce, M (2007). "Intervento di rafforzamento di una struttura monumentale mediante un sistema dissipativo-ricentrante." in *Proc. XI° Convegno ANIDIS,* Pisa, Italy.

[3] Dolce, M, Cardone, D, and Marnetto, R (2000). "Implementation and testing of passive control devices based on shape memory alloys." *International Journal of Earthquake Engineering and Structural Dynamics*, 29(7), 945-968.

[4] Dolce, M, Cardone, D, Moroni, C, Nigro, G, Ponzo, F C, Santarsiero, G, Di Croce, M, De Canio, G, Ranieri, N, Renzi, E, Goretti, A, Nicoletti, M, Spina, D, and Marnetto, R (2006). "TREMA Project: Experimental evaluation of the seismic performance of a R/C ¼ scaled model upgraded with the DIS-CAM system." in *Proc. 2nd Fib Congress*, Napoli, Paper 0986.

[5] Dolce, M, Marnetto, R, Nigro, D, and Ponzo, F C (2001). "Rafforzamento delle strutture murarie: Il sistema CAM di Cuciture Attive per la Muratura." in *Proc. X° Convegno ANIDIS*, Potenza, Italy.

[6] OPCM 3274/2003. "Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e normative tecniche per le costruzioni in zona sismica*."* Ordinanza del Presidente del Consiglio dei Ministri n.3274, 20 marzo 2003

[7] Priestley, M J N (2003). "*Myths and fallacies in Earthquake Engineering, Revisited.*" IUSS PRESS Ed., Pavia, Italy.

[8] Restrepo, J I (2006). "New generation of structural concrete system for seismic resistance." in *Proc. 1ST European Conference on Earthquake Engineering and Seismology*, Ginevra, Svizzera.

[9] *Static and Dynamic Finite Element Analysis of Structures,* SAP2000, Computers and Structures Inc., Berkeley, CA, 2004.

[10] Zingone, G, La Mendola, L, and Cucchiara, C (2007). "La mitigazione del rischio sismico del patrimonio costruito di interesse storico-monumentale." in *Proc. XI° Convegno ANIDIS*, Pisa, Italy.