3D DYNAMIC TESTS ON 2/3 SCALE MASONRY BUILDINGS RETROFITTED WITH DIFFERENT SYSTEMS

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ABSTRACT :

The TREMA project (Technologies for the Reduction of seismic Effects on Architectural Manufactured Structures) is aimed at evaluating the dynamic performance of 3D masonry buildings, seismically strengthened with innovative retrofitting techniques. The techniques considered in the extensive experimental programme carried out at the Seismic Laboratory of ENEA Casaccia (Rome) are based on i) a seismic isolation system realized by Added Damping Rubber Isolators devices (ADRI) and ii) on a new Active Confinement of Masonry strengthening system (CAM) consisting in a three-dimensional tie system for the upgrading of existing masonry structures. Towards this aim, two identical 3D masonry 1:1.5 scaled models have been designed and constructed in accordance with traditional construction codes of practice for the Italian Central and Southern Appenine Zones. Dynamic shaking table tests have been carried out applying a natural input (the 1997 Colfiorito earthquake) with increasing intensity. In addition, random tests have been performed before dynamic tests in order to verify model frequency decay and damage propagation on structural elements.
The first model, previously strengthened by means of the CAM system, has been firstly tested in a base isolated configuration. Successively, the same model has been fixed at the base and then tested again in order to verify the effectiveness of the CAM system. The second model has been tested in fixed base configuration up to the failure condition. In this work the early results of the experimental tests carried out on the two models are illustrated.

KEYWORDS: Masonry, Dynamic Test, CAM, Base Isolation, Shaking Table Test, Retrofitting

1. INTRODUCTION

The assessment of strengthening techniques for masonry buildings has gained an ever increasing role in the seismic engineering research over the last years for the important consequences that a correct choice of the seismic upgrading technique can have on the time and costs optimization. The TREMA project "Technologies for the Reduction of seismic Effects on Architectural Manufactured Structures" (De Canio et Al. 2000) presented in this paper is aimed at evaluating and compare the effectiveness of innovative upgrading technologies, namely Seismic Isolation based on high dissipating devices (ADRI) and the CAM strengthening system based on a three-dimensional tie system for the upgrading of existing masonry structures (Dolce et. Al. 2008). The project is partially funded by the Italian Ministry for Research, coordinated by ENEA in partnership with other public (University of Basilicata, Dep. of Italian Civil Protection) and industrial (TIS S.p.A.) partners.
An extensive experimental investigation on two identical 3D masonry building models has been carried out by

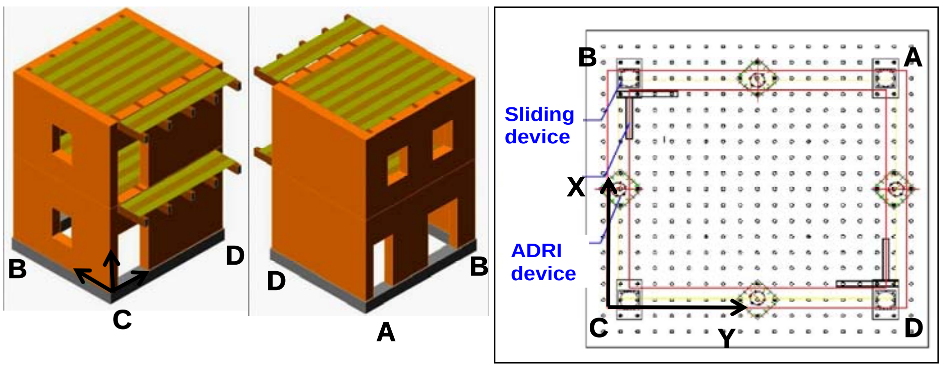
shaking table tests. The structural models, in 2:3 scale, have been designed according to traditional Italian codes of practice used extensively in the historical centres in the Appenine Zones of Central and South Italy. The horizontal components of a natural input record were used in the dynamic tests in both orthogonal directions and applied by increasing progressively the PGA. The first model (Model A) was upgraded with the CAM system, using 3D stainless steel ties, and tested in the base isolated configuration, in order to avoiding any serious damage levels on the structure. Successively, the base isolators were pinned and the same model was tested with a PGA upper than 1g, in order to verify the effectiveness of the CAM system. At the end of tests the model was still able to carry vertical loads. The second model (Model B) was tested unstrengthened in a fixed base configuration up to a collapse condition.
The dynamic testing programme has been carried out on the 4×4m 6-d.o.f. shaking table at the Enea-Casaccia laboratory (Rome). The facility is characterized by a table frequency ranging between 0 and 50Hz, 250mm maximum displacement, 0.5m/s peak velocity, 3g maximum PGA considering 10ton mass at 1m height.

2. MODEL AND STRENGHTENING

The two experimental 2:3 scaled models, two-storey, 3m and 3,5m in the X and Y directions respectively, 4.2m total height were realized with 250mm constant thick walls made of tuff stone masonry and low quality mortar with an irregular texture. Floors and roof were made by fixing 2cm thick wooden boards to 10×18cm wooden beams, while doors and window openings had wooden lintels. The overall weight of the building was 201.32 kN, including the model (169kN), r.c. basement (28.24kN) and wooden element (4.08kN) contributions. Additional masses of 250kN were placed at the floor and roof levels to respect the scaling laws.
In order to characterise the model mechanical properties, several tests were previously carried out on mortar specimens, namely compression and bending tests as well as diagonal compression tests (Dolce M. et al. 2008). The mean values of the mortar resistance obtained from compression and bending tests were 0.716MPa and 0.137MPa respectively. In Table 2.1, the shear resistance outcomes carried out by diagonal compression test for 3 masonry specimens, tested at different vertical pre-loading levels (q) are given.

Table 2.1 diagonal compression test on masonry specimens

Test	Date	q (MPa)	Fmax (kN)
MT-1	4/4/2006	0.1	37.1
MT-2	5/4/2006	0.15	27.79
MT-3	5/4/2006	0.2	51.46



a) b)
Figure 1. Geometry of both models (a), plans of isolation system.

The isolation system applied to Model A was made of 4 slow friction sliding devices placed in the corners of the structure and by 4 ADRI (Added Damping Rubber Isolators) re-centring devices characterised by a large energy dissipating capacity (Dolce et al., 2006a), placed in the middle of the r.c. foundation, as shown in figure 1. The base isolation system was designed to have a period of vibration equal to 1.2-1.5sec, corresponding to 1.5-1.85sec for the 1:1 scaled structure, and an overall damping ratio of about 25%. The model was previously strengthened by the CAM system, consisting of stainless steel horizontal and vertical tie ribbons to reinforce masonry with loops passing through transverse holes 350 mm spaced in both horizontal and vertical direction. The ribbons had a 19×0.75mm cross section and a single loop in order to respect the scaling laws (a double loop with a 50×50cm spacing in the two directions would be used in a 1:1 scale structure). The loops were closed by applying pre-stressing force of approximately 5kN by means of a special tool (Dolce M. et al., 2008). In correspondence of the ribbon contact points (corners and transverse holes), the masonry surface was protected by special steel detailing plates designed to reduce local stresses and to mitigate damage. In figures 2 and 3, details of the CAM system and of the model setup are shown respectively.

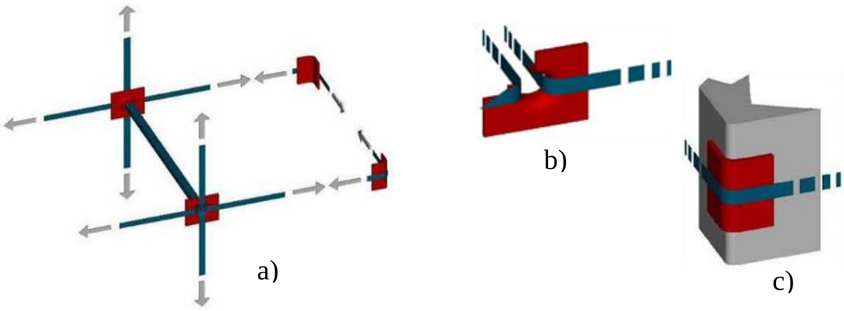


Figure 2. CAM system details: a) a typical setting; b) steel funnel shaped plate; c) angle plate

Figure 3. CAM system reinforced model

3. SEISMIC INPUT

The dynamic tests were performed using scaled natural input records. In each test, the NS and EW horizontal components of the 1997 Colfiorito earthquake were contemporarily applied (figure 4). The records were scaled in time by a factor equal to the square root of the geometric scale of the model (SL=1.5). For the three experimental model configurations considered, defined in the rest of the paper as i) Base Isolated with ADRI, ii) Fixed at the base and reinforced with CAM system and iii) No Reinforced, the tests were carried out by applying an increasing PGA, starting from a low intensity up to a PGA levels greater than 1g for ADRI and CAM, and 0.49g for Fixed Base respectively. Random tests were also performed after seismic tests in order to verify fundamental frequency decay and damage propagation.
During testing, the shape and amplitude of the acceleration recorded on the shaking table was somewhat altered respect to the theoretical input because of an high frequency noise due to the system pump malfunction that altered the table peak acceleration (PGAtab). In order to better characterise the table records in terms of their destructive potential for the tested model, a normalisation procedure was applied, as described in (Dolce M. et al., 2006b, Dolce M. et al., 2007). The input signal was first filtered with a 0.33-30Hz pass-band filter, then the

maximum acceleration was normalised according to the Housner intensity calculated in the range of periods between 0.11 and 1.3s. The Normalised table Peak Acceleration value (NPA) was then obtained by equating the Housner intensities of the original and filtered table signals. In figure 5, NPA values are reported as a function of the peak acceleration recorded on the table (Table acceleration), for all the dynamic tests.

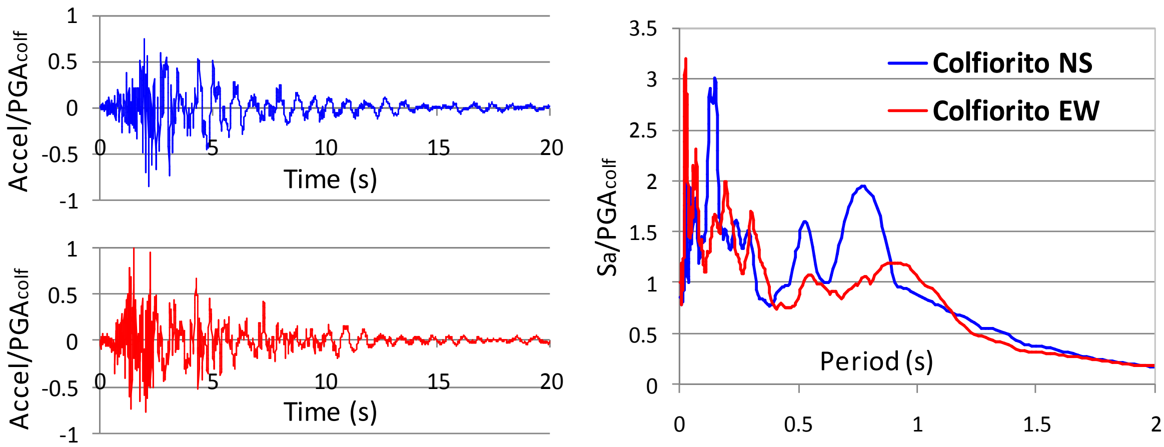
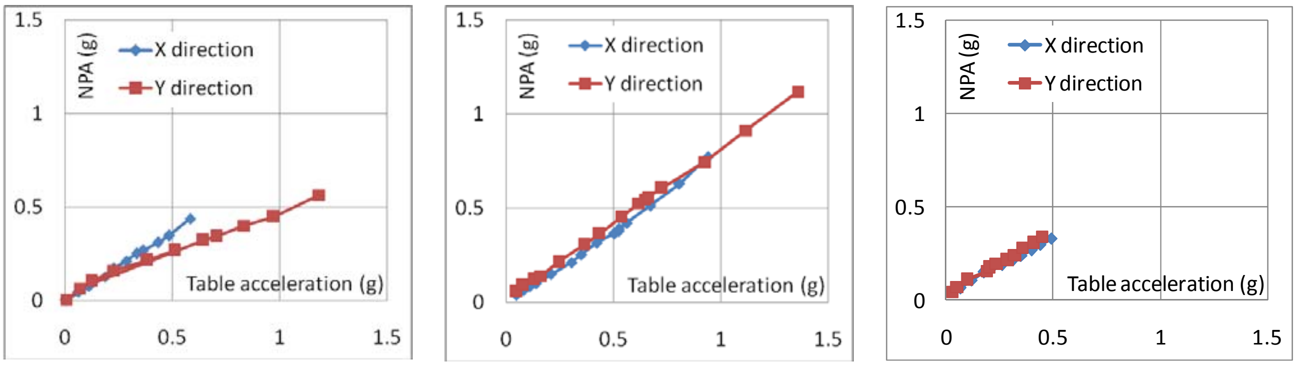


Figure 4. Colfiorito scaled accelerograms and corresponding 5% damping response spectra



a) ADRI b) CAM c) Not Reinforced

Figure 5. NPA Vs PGA in X and Y directions.

4. TEST AND SENSOR SET-UP

For the ADRI and CAM models, the project partners provided an integrated acquisition system including the following instrumentation:

- 8 accelerometers (UNIBAS): n.3 piezoelectric 2g accelerometers on the table, n.3 “Columbia” 1g accelerometers on the r.c. base beam. Two “Columbia” 1g accelerometers on the top of model;
- 16 accelerometers for model horizontal acceleration measurement (DPC-USSN): 12 for measuring in plane wall accelerations and specifically 4 placed at the basement level, 4 at the 1st floor , 4 at the 2nd floor and 4 for acceleration at the 2nd floor normal walls. All of the accelerometers were connected to a LEANE “NET-RECORDER” 16 bit A/D embedded converter acquisition system;
- 8 displacement transducers (UNIBAS), for horizontal relative displacement measurements between the model and the table;
- 17 accelerometers (ENEA): 5 for measuring table accelerations and 12 for model accelerations.

For the Fixed Base model setup, the supplied integrated acquisition system features were:

- 8 accelerometers (UNIBAS): the accelerometers are located on the two floors, each with 4, for measuring

the horizontal accelerations of model;
- 8 displacement transducers (UNIBAS), for horizontal relative displacement measurements between the model and the table;
- 5 accelerometers (ENEA): 3 for table and 2 for model horizontal accelerations respectively.

5. EXPERIMENTAL RESULTS

For the ADRI model, the test sequence began by applying a low intensity random signal to characterise the initial dynamic behaviour of the frame. The Colfiorito earthquake was then applied starting from 0.124g PGAtab (Y direction) corresponding to 0.106g NPA. The intensity was increased up to 1.184g PGAtab, corresponding to 0.56g NPA.
The spectrograms determined by the Gabor Trasform for the first test and last one (figure 6) show the low damage suffered by the model in terms of decay of the first structural frequency. In fact, the 1st structural frequency of about 6 Hz registered before the first test (figure 6a) remain practically unchanged at the end of dynamic test series (Figure 6b). It is also evident the isolated frequency of about 1.1-1.2 Hz, coherent with design hypothesis.
During testing of the CAM strengthened model, the test sequence began with the application of a low intensity random signal for characterisation purposes. The Colfiorito earthquake was then applied beginning with an intensity of 0.096g NPA. The input intensity was further increased up to 1.12g NPA. Only one low intensity random test was performed in order to better characterise the frequency decay of model at the beginning of the experimental session. At the end of the testing session some damage was observed at 2nd floor in the upper part of the corners, but the model was still able to carry vertical load. The damage was also evidenced by some frequency decay as shown by comparing figure 6c and 6d.
For the Not Reinforced model (Model B) the testing sequence began again with the application of a low intensity random signal in order to characterise the structure. The Colfiorito earthquake record was then applied starting with a 0.043g NPA. The NPA was increased up to 0.34g NPA. Random tests were performed before any dynamic test in order to verify the frequency decay of the model and the damage progress. The first partial collapse of the model occurred at 0.24g NPA in Y direction. Damage was observed in the upper parts of corners as well as the activation of an out of plane collapse mechanism due to a complete disconnection of the walls without compromising the vertical load capacity of the structure. Two more tests were then performed in order to assess the building residual capacity. The first test yielded the simultaneous collapse of three walls at the second floor at an 0.31g NPA in Y direction, while the second test was performed in order to achieve total structural collapse.
In Figure 7 a comparison of maximum roof accelerations (in both directions) between the ADRI, CAM and Not Reinforced models, is made. The analysis of the results shows that for 0.2g NPA in the X direction, the maximum roof acceleration of the CAM and No Reinforced models are approximately equal to twice the ADRI model values. While, for 0.4g NPA, corresponding to the maximum value for the ADRI model in the X direction, the maximum roof accelerations of the CAM strengthened model are approximately three times larger than those of the ADRI model.
In Y direction (figure 7b) the max roof accelerations between CAM and Not Reinforced model are quite different. The trend of the second ones, in fact, is similar to ADRI. This behaviour could be determined by a pre-existing damage that conditioned the global response of Model. This effect can be observed also in the figure 8 that show the initial frequency decay of the experimental model registered during the dynamic tests. The twice bigger frequency of the Model A respect to the Model B, in both horizontal directions, can be justified only partially by the CAM contribute. In fact the principal reason of this difference can be ascribed mainly to a previous damage on the model B. It is also interesting to note that in CAM tests the 1st frequency decay in both horizontal directions, occurs in the range 0.15g-0.55g NPA, corresponding to the activation of all cracking mechanism in the masonry. After that, any increasing of input signal intensity in both directions doesn't produce further frequency decays, because of the strengthening action due to CAM system.
The effectiveness of the CAM system is also evidenced by the improvement of connections between different structural elements, such as orthogonal walls, masonry and top kerb, masonry and wooden beams that prevents out of plane mechanism. The same mechanism is, instead, completely developed on not reinforced model B. In Figure 9, in fact, a photographic sequence shows Model B before and during three tests performed. In the first test, the out of plane mechanism for the two walls parallel to the Y (AB and CD) direction is clearly observed,

corresponding to an NPA value of 0.24g, where Then there is reported the configuration of model in the last two tests.

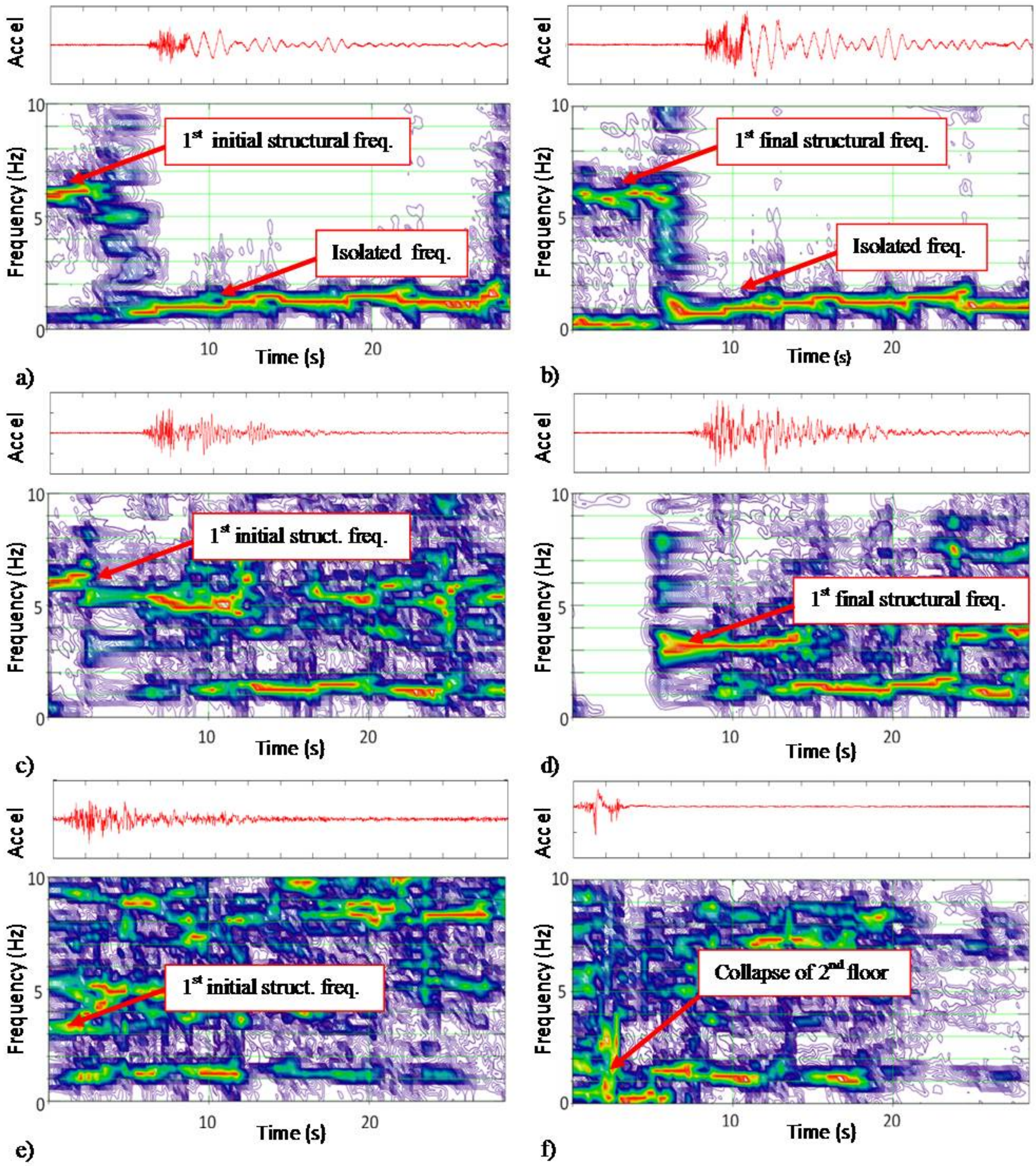
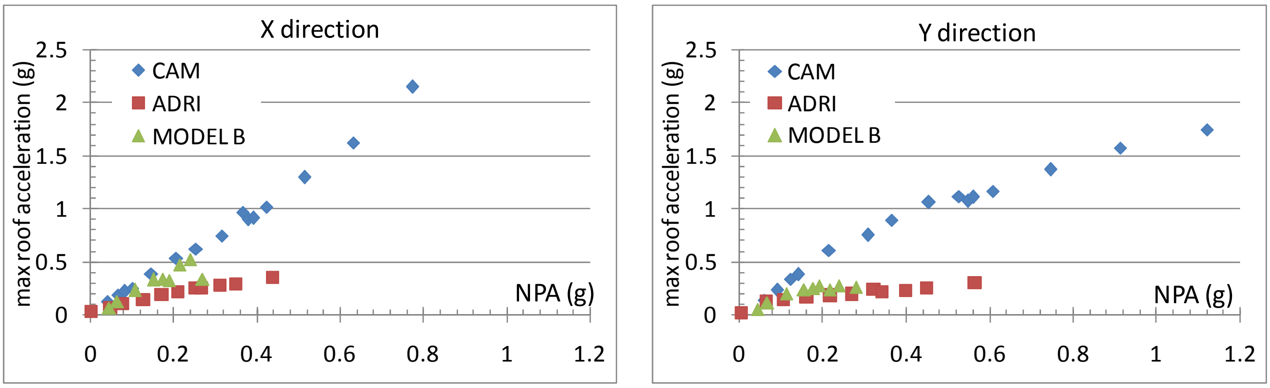
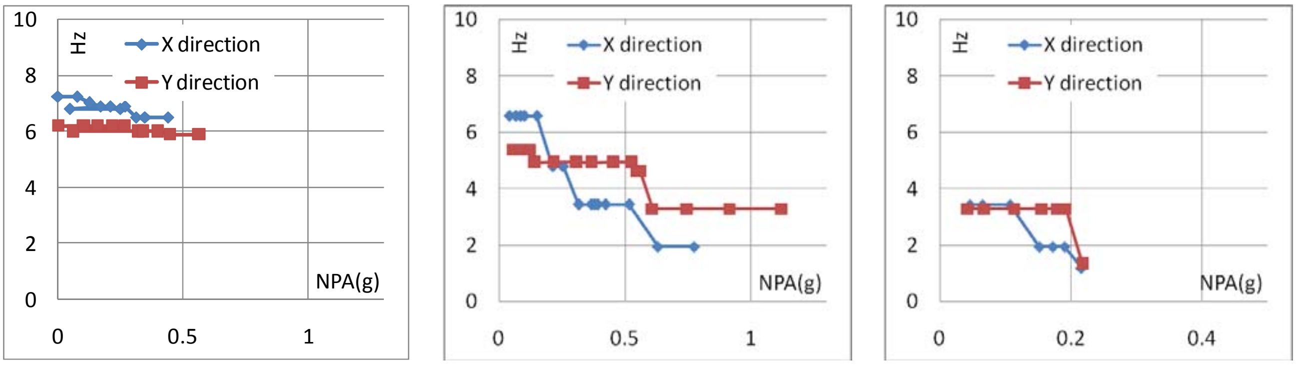


Figure 6. Spectrograms Model A: ADRI, a) 0.162g NPA test, b) 0.56 NPA test g - Model A: CAM c) 0.216 NPA test, d) 1.129g NPA test - Model B: No reinforced e) 0.043g NPA test, f) 0.31g NPA test



a) b)

Figure 7. Max roof accelerations of model Vs NPA in X and Y direction.



a) b) c)

Figure 8. 1st structural frequency decay of model reinforced with a) ADRI, b) CAM and c) Fixed base, in both horizontal directions, the values are plotted vs the NPA.

6. CONCLUSION

The tests carried out within the TREMA project will provide a great amount of data on the seismic behaviour of both unreinforced and seismically upgraded masonry buildings. In this paper, the early results obtained on two identical 3D masonry model are shown: the first (Model A) was tested in a base isolated configuration and reinforced by the CAM strengthening system. The second (Model B) was tested without any reinforcement systems. The two models were subjected to a suite of increasing intensity natural earthquake records, namely the 1997 Colfiorito (Italy) event.

Comparison with early results has highlighted the great effectiveness of both the seismic isolation technique as well as of the CAM strengthening system even for poorly constructed and highly vulnerable buildings such as the ones considered. Model A was tested with a base isolation system up to an earthquake intensity equal to 0.56g NPA without displaying any damage. The same model reinforced with the CAM strengthening system was tested up to 1.12g NPA, suffering only light damage levels. Model B was tested without any reinforcement, in order to compare the effectiveness of the two innovative strengthening techniques considered. The obtained results show that the CAM strengthened structure is five times more strength than its unreinforced counterpart. Moreover, the maximum roof acceleration on model tested with ADRI is more little than the one measured on organism reinforced with CAM system. Actually the irregular 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.

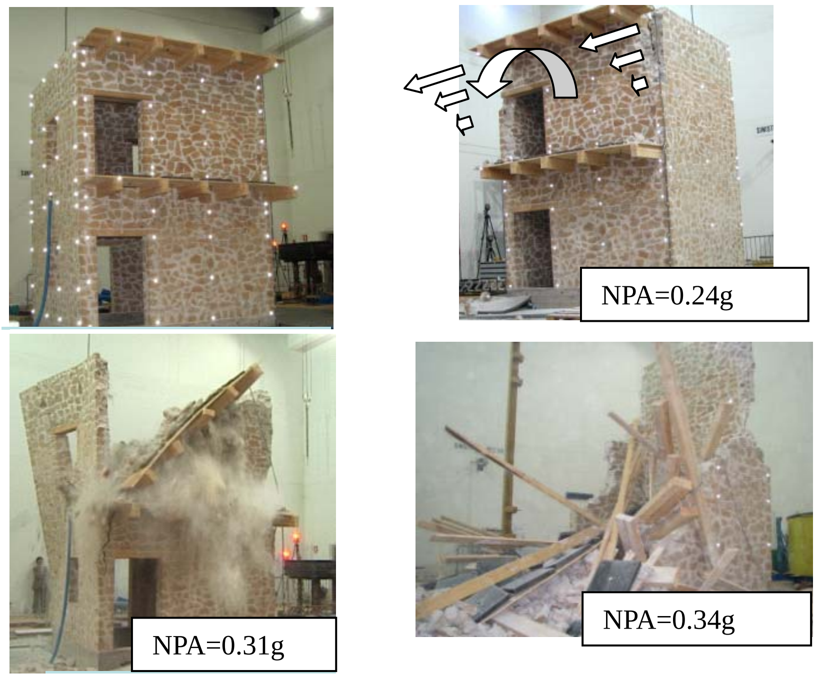


Figure 9 Model B collapse sequence

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REFERENCES

De Canio G., Dolce M., Goretti A., Marnetto R. (2000). Progetto TREMA - Tecnologie per la Riduzione degli Effetti sismici sui Manufatti Architettonici in muratura e in c.a. MURST Legge n.449/1997, D.M. 10 Maggio 2000.

Dolce M., Ponzo F.C., Moroni C (2008). Le Cuciture Attive nell'Adeguamento Sismico delle Strutture in Muratura, Collana di ingegneria strutturale corsi CISM.

Dolce M, Cardone D, Moroni C, Nigro D, Palermo G, Ponzo F.C., Di Cesare A, Ventura G, De Canio G, Ranieri N, Goretti A, Marnetto R. (2006a). TREMA Project: Experimental evaluation of the seismic performance of a R/C ¼ scaled model upgraded with seismic isolation. *2nd Fib Congress*. June 5-8, 2006, Naples.

Dolce M, De Canio G, Goretti A, Marnetto R, Nicoletti M, Cardone D, Moroni C, Nigro D, Ponzo FC, Ranieri N, Renzi E, Spina D. (2006b). SICURO and TREMA Projects: the seismic performance of R/C frames seismically upgraded with different systems. *2nd Fib Congress*, June 5-8, 2006, Naples.

Dolce M., Moroni C., Nigro D., Ponzo F.C., Giordano F., Goretti A., Spina D., Lamonaca B., Santinelli F., De Canio G., Ranieri N., Marnetto R. (2007). PROGETTO TREMA: Valutazione Sperimentale del Comportamento Sismico di un Telaio 3D in CA in Scala ¼ Rinforzato con FRP, *12° Convegno Nazionale "L'Ingegneria sismica in Italia"*, Pisa 2007.