Experimental Damage Identification in Masonry Structures by OMA

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Abstract*—This paper presents a study carried out in different types of masonry structures to identify existing damage through dynamic identification techniques using operational modal analysis. A cross vault, a masonry wall and a simple clay brick construction have been analyzed. The three cases have been tested on a full scale in the laboratory. The cross vault has been subjected to a settlement of one of its supports, the damage has occurred and then it has been repaired by using Textile Reinforced Mortars (TRM). In the case of the wall and the simple construction, the damage has been generalized by means of horizontal loads simulating a seismic action by a cyclic incremental load, after the generation of the damage, it has been repaired using TRM. In all cases, a dynamic identification has been carried out prior to the generation of the damage, after the generation of the damage and later after its repair, finally after a new process of damage the structural health changes have been monitored. In the four phases, an identification of the dynamic characteristics of the structures has been carried out, both main frequencies and damping factor associated with each mode shape. Regarding operational modal analysis, the first vibration modes have been identified. Singular Value Plot have been obtained through the EFDD technique. In general terms, the results of the investigation showed that the effect of cracking generated by both horizontal cyclic loads and vertical displacements located in one of the supports generated a decrease in the vibration frequencies and an increase in the structural damping factors for the different vibration modes. On the other hand, in relation to the effect of the reinforcement techniques employed, the results showed the feasibility of recovering or even slightly increasing the stiffness of the original damaged structure. However, the results for the strengthened structures also showed that the intervention on the damaged structure tended to reduce the structural damping factors with respect to the unreinforced structure. In addition, it was also observed that after the tests the reinforced and newly damaged structures showed dynamic characteristics very similar to the unreinforced damaged structures.

Keywords—masonry, TRM, damping, OMA

I. Introduction

Nowadays, existing constructions made of brick masonry materials constitute an important part of buildings all over the world. This fact is even more important in the case of urban areas, historical centers or rural areas, where the majority of buildings were constructed with these materials, especially from the 19th century onwards.

This type of material has particular mechanical properties due to its low tensile strength and the absence of ductile behavior during the cracking process of the material. This fact, combined with the heterogeneity of the material being composed of mortar and brick, cause brick masonry structures to be particularly vulnerable against seismic actions or related to relative vertical displacements between support points in different parts of the structure [1,2].

In the last decades the interest in this type of buildings has increased significantly, especially due to the damages caused in large urban centers where the dynamic action of earthquakes has been a serious problem for the citizens [1]. In this sense, structural analysis and structural assessment play a key role in the conservation of buildings over time [3-5]. In particular, with the aim of continuing to advance in the knowledge of the dynamic behavior of brick masonry structures, it is important to analyze the influence that progressive damage associated with horizontal loads or relative vertical displacements between supports, have on the structure and especially on the vibration frequencies and the values of structural damping [6-9].

Several researchers have proposed different reinforcement techniques for these structural typologies to improve their tensile and shear behavior. Thus, structural reinforcement is carried out by means of fiber-reinforced polymer-based composite materials (FRP) [10] or by means of cement-based matrices also reinforced with fibers or fabrics (TRM) [11]. Although both types of reinforcement present a good alternative for increasing the strength of brick masonry structures, TRM reinforcements present better compatibility with the brick substrate, avoiding problems associated with delamination or permeability in the walls.

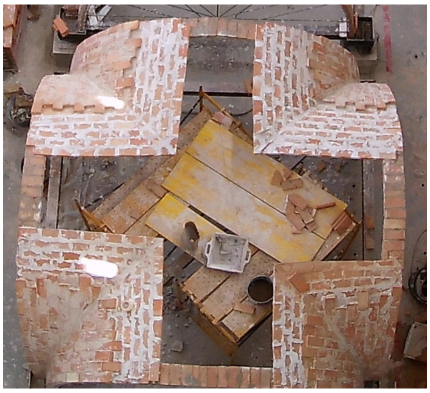

Fig. 1. Construction phase of the cross vault

II. MASONRY STRUCTURAL TYPOLOGIES AND MATERIALS

A. Masonry structual typolgies

In the present investigation, three different typologies have been studied, all of them built with ceramic materials and lime mortar. Firstly, the behavior of a brick masonry cross vault has been analyzed, secondly, a wall to scale has been analyzed and thirdly, the behavior of a simple construction, also to scale, has been studied.

Regarding the geometric characteristics of these three typologies, the first one, the masonry cross vault, has a plan layout of 3.6 x 3.6 m for the lateral arches in the form of a semicircular section, with a thickness of 160 mm. The main section of the vault has a thickness of half the section of the arches. The construction of the vault began with the construction of the perimeter arches and then the vault was closed with layers to prevent its collapse without the use of intermediate formwork, in order to respect the classic construction technique of this structural typology, Figure 1. The second structural typology, the simple brick wall, has dimensions of 3.0x2.5x0.2 m, without the presence of any openings or windows in it. Finally, the third structural typology consisted of a simple construction formed by three brick walls of dimensions 3.1x2.1x0.2 m in a "U" shape and a unidirectional concrete slab over the walls to ensure the correct connection between them, Figure 2. However, unlike typology two, in this case, the structure has two openings in the side walls. One of them associated with the access door and the other with the window.

Fig. 2. Accelerometers configuration during dynamic test of simple clay brick construction.

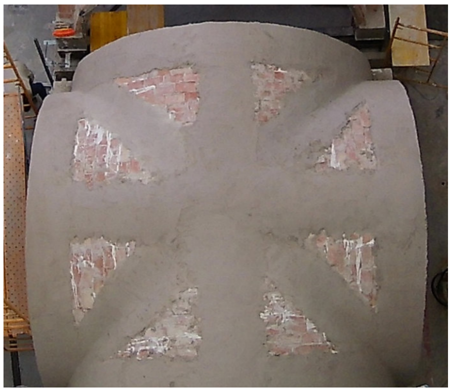

Fig. 3. General view of the arrangement of the reinforcement in the case of the cross vault structure.

B. Materials

Regarding the materials used, in all three cases solid brick and hydraulic lime mortar were used. Only cement mortar and gypsum plaster were used during some phases of the construction process of the cross vault. For the solid bricks, 230x110x26 mm units were used for the cross vault with a compressive strength equal to 47.6 MPa and 230x110x50 mm for the other typologies, with a compressive strength of 14 MPa. On the other hand, for the lime mortar used, compressive strength values of 9.4 MPa were obtained for the first structural typology and 6 MPa for the other typologies. Finally, the cement mortar and gypsum plaster showed compressive strengths of 16.1 MPa and 7.2 MPa, respectively [12].

Finally, regarding the materials used for structural reinforcement, in all three cases, fiber-reinforced mortar (TRM) with a compressive strength of 15 MPa was used. In relation to the fibers for the tensile reinforcement, fiberglass grids were used, with bidirectional weight g220, and tensile strength of 45 kN/m. This reinforcement was arranged with a total thickness of 10 mm in all structural typologies and the manufacturer's prescriptions for its execution were followed [13].

III. METHODOLOGY OF REINFORCEMENT AND TEST SETUP

The main objective of this preliminary research is based, on the one hand, on determining the influence of damage associated with tensile cracking in brick masonry constructions on the dynamic properties of the system. On the other hand, the aim is to show the feasibility or not of repairing these structures once the damage has occurred by determining the dynamic properties in the different phases of the damage and repair process of the structure. For this reason, together with the need to be able to use materials that are compatible with the masonry and reversible in nature, TRM type mortars have been used [14]

A. Methodology of reinforcement

The application of the reinforcement material was based on the good results obtained by other authors with both polymeric and cement-based materials on structures with low tensile strength [7, 10, vaults]. In this sense, the reinforcement was applied after analyzing the cracking pattern obtained after the application of the damage on unreinforced structures. In general terms, the process consisted of filling the cracks with superfluid mortar and repairing or replacing the badly damaged bricks. Subsequently, the fiber-reinforced mortar was placed on certain surfaces of the structure to be repaired. Specifically, in the case of the cross vault, a total of 8 bands of 450 mm wide were arranged radially on the upper part of the vault, as well as 4 curved bands on the outer face of the arches, Figure 3. In this case, it is important to note that the reinforcement bands were arranged in this way to minimize damage to the structure, to reduce the effects on aspects related to heritage conservation in this type of structure, and to seek the greatest optimization of the reinforcement material. On the other hand, in relation to the structural typology of the simple masonry wall, the same type of reinforcement was applied as the one used in the vault but applied continuously on the entire exterior and interior surface of the wall. That is to say, a first layer of 5 mm was applied to regularize the surface, then the mesh was applied and finally a second layer of 5 mm was applied on top of it. Finally, in the case of the third structural typology, it was carried out in the same way as the previous typology, but reinforcing only the exterior face of the construction.

B. Test setup

The methodology followed for the dynamic characterization of the three structural typologies analyzed has been divided into four phases for each of them. Thus, the first phase will consist of the analysis of the structures prior to the generation of the damage. The second phase will reevaluate the structure after the application of the damage. The third phase will consist of measuring the dynamic properties after the strengthening process. And finally, the fourth phase will consist of reevaluating the reinforced structure after the application of the damage.

Regarding the generation of the damage, it has been introduced in a different way for each of the analyzed structures. In the case of the cross vault, the damage was introduced by the controlled displacement of one of the four supports of the structure to a total depth of 40 mm. This settlement was generated manually by the use of two mechanical jacks under one of the supports. Specifically, the structure rests on four supports facing each other two by two. Supports 2 and 4 have freedom of movement in the horizontal plane, but are restricted from moving in the vertical direction. On the other hand, support 3 is restricted from both horizontal and vertical displacements. In addition, support 1 also has freedom of horizontal displacement by resting the system as metal steel rollers, freedom of controlled movement in the vertical direction by resting on the displacement control jacks. Finally, it should be noted that all the supports are connected to a horizontal frame of steel beams to avoid the relative horizontal displacement of some supports with respect to the others, Figure 4.

In relation to the second structural typology, the damage introduced in the simple brick masonry wall was generated by the application of a point load at the top of the wall and arranged parallel to the plane of the wall. This load consisted of a cyclic displacement that varied between 0.2 mm and 12 mm in amplitude, and was applied by means of a hydraulic jack with displacement control. In this regard, it should be noted that the test configuration took into account the restriction to horizontal movement of the support points of the wall with the base. In addition, the previous stress state associated with the weight of the rest of the structure that would be arranged above the structure was also taken into consideration by applying a vertical prestressing load of 300 kN, Figure 5.

Fig. 4. Accelerometers configuration during dynamic test of the cross vault.

Regarding the third structural typology, the damage introduced on the simple masonry wall construction was generated in the same way as described in the previous paragraph. The main difference between them lies in the fact that the load was applied punctually on the upper ends of the two lateral walls of the construction, and no vertical prestressed load was applied except for the weight of the roof slab itself, Figure 2.

For data acquisition, 11 piezoelectric accelerometers of sensitivity equal to 10 V/g were employed for the cross vault structure and 8 for the simple wall structure and simple construction formed by three brick walls. They were located according to Figure 4, Figure 5 and Figure 6. Signals have been registered using a data acquisition device model Kyowa PCD-320 and signal conditioner model PCB 482A22. The sampling frequency for the three typologies were 200 Hz, 1000 Hz and 1000 Hz, respectively. The source of excitation for the first and third structural typology consisted of ambient noise. However, for the second typology, a white noise signal was used by means of an exciter placed in the central area of the wall.

Finally, Operational Modal Analysis (OMA) was used to analyze the vibration frequencies and the damping factor. The technique used is the Enhanced Frequency Domain Decomposition (EFDD), according to the Artemis software.

Fig. 5. Accelerometers configuration during dynamic test of the masonry wall.

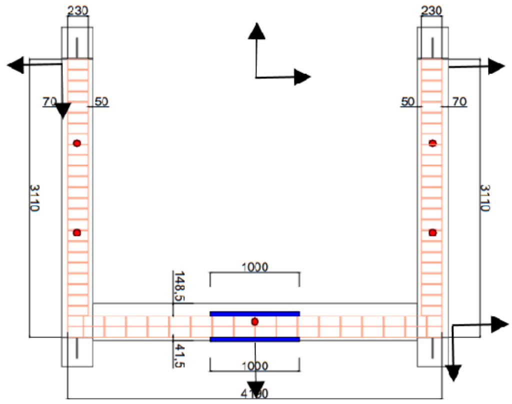

Fig. 6. Accelerometers configuration during dynamic test of simple clay brick construction.

IV. Analysis of Results

The results of the analyzed structures were based, on the one hand, on the description of the cracking pattern associated with the type of damage introduced, and on the other hand, on the analysis of the variation of vibration frequencies and damping factor for the different phases of the test.

First, in relation to the cracks observed in the cross vault, two types of damage were detected. On the one hand, cracking of the perimeter arches in the position of approximately 30% of the length of the arch measured from the start of the arch. On the other hand, cracks were detected along the major diagonals in plan of the vault body. It is important to note that although the application of the reinforcement and repair of the structure increased the maximum displacements during the test, no significant variations were noted with respect to the cracking pattern observed for the unreinforced structure. Secondly, in relation to the variation of frequencies and damping during the test, it was observed that when comparing the unreinforced-uncracked state with the unreinforced-cracked state that negative variations of frequencies between 7% and 5% have been detected after damage generation. Likewise, positive increases in the damping factor between 15% and 25% have been evaluated, with values of 0.61% and 0.357% for the first two vibration modes of the undamaged structure and values of 0.76% and 0.41% for the damaged structure, respectively, Figure 7. On the other hand, in relation to the reinforced structure, comparing the results between the unreinforced and undamaged structure versus the repaired and reinforced structure after the second phase of the test, then the results show that the type of reinforcement applied allows recovering the initial dynamic properties prior to the application of the damage, increasing the vibration frequencies and reducing the damping factor. In addition, the results obtained after comparing the reinforced structure after the new damage versus the damaged structure without reinforcement showed a similar dynamic behavior for similar damage levels, Figure 8.

Regarding the second structural typology, masonry wall with and without reinforcement, in relation to the cracking pattern observed, a classic pattern was evaluated with diagonal cracks arranged along the mortar joints with low cracking in the brick units, Figure 9. On the other hand, regarding the dynamic results, Table I and Table II summarize these results for each of the test phases. In general terms, a behavior similar to that detected in the cross vault can be observed. That is, for unreinforced structure, vibration frequencies decrease with damage and the damping factor increases. Specifically, frequency reductions of 21%, 22% and 57% were observed when comparing the structure with and without damage prior to the application of reinforcement. Along the same lines, damping factor increases of 10%, 70% and 12% were detected for the three vibration modes detected. In addition, in the case of the reinforced structure, slightly higher vibration frequencies and slightly lower damping factors have been evaluated than those obtained in the unreinforced structure pre- and post-cracking.

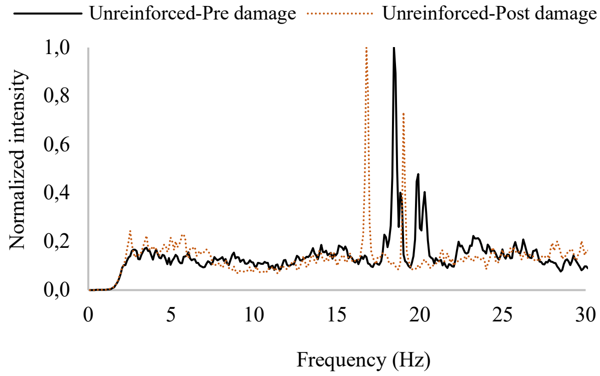

Fig. 7. Normalized frequency spectrum pre-reinforcement before and after cross vault damage.

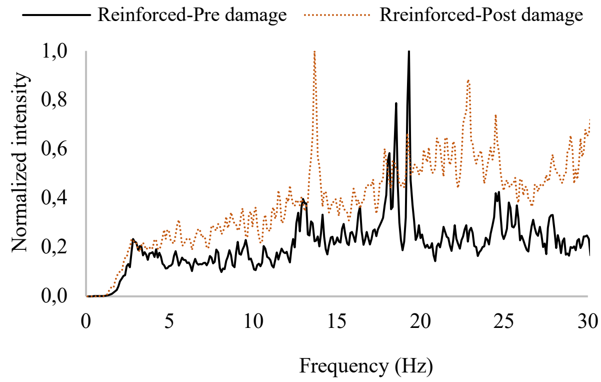

Fig. 8. Normalized frequency spectrum post-reinforcement before and after cross vault damage.

TABLE I. NATURAL FREQUENCIES DURING THE EXPERIMENTAL TEST OF MASONRY WALL IN HZ

Mode	*Pre-damage*	*Post damage*	*Reinforced pre-damage*	*Reinforced post-damage*
1º	4.95	3.91	6.99	5.21
2º	12.39	9.66	16.47	11.23
3º	22.35	9.58	29.82	14.25

TABLE II. DAMPING FACTOR DURING THE EXPERIMENTAL TEST OF MASONRY WALL IN %

Mode	*Pre-damage*	*Post damage*	*Reinforced pre-damage*	*Reinforced post-damage*
1º	2.96	3.26	2.34	2.86
2º	1.22	2.07	1.47	1.98
3º	1.57	1.76	0.68	1.25

Fig. 9. Damage pattern during the test of masonry wall.

Regarding the third structural typology, Figure 2, the cracking pattern observed varied slightly with respect to the two previous structures. In this case, the most damaged walls correspond to the exterior walls, which present cracking at 45º following the mortar zone and starting at the corners of the door and window openings, respectively. However, the wall transversal to the lateral walls did not present cracking or overturning problems around its longitudinal axis. On the other hand, regarding the dynamic results, Figure 10 show the normalized energy density spectra for the first two phases on the test. The results show the same trend as for the previous cases in relation to frequencies and damping, both with respect to the effect of damage. For the unreinforced case, the effect of cracking causes an average decrease in the vibration frequencies for the first four modes of 28.7%. Likewise, an average increase of the damping factor by 117% is also observed with initial values prior to cracking of 2.41%, 1.53%, 0.74% and 0.50% for the first four modes, respectively. In the case of the reinforced structure, the damage pattern was very similar to that observed in the case of the unreinforced structure. However, in this case, less important cracks were observed in the window zone than in the unreinforced case.

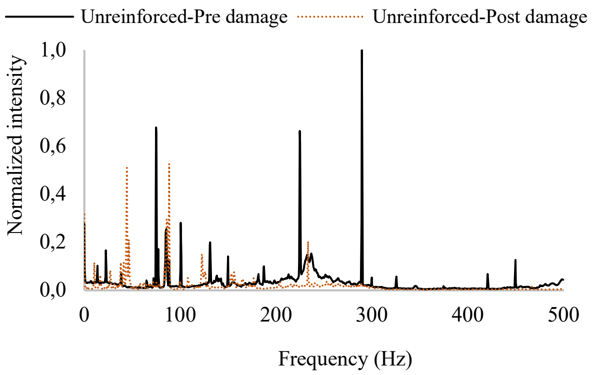

Fig. 10. Normalized frequency spectrum pre-strengthening before and after simple clay brick construction damage.

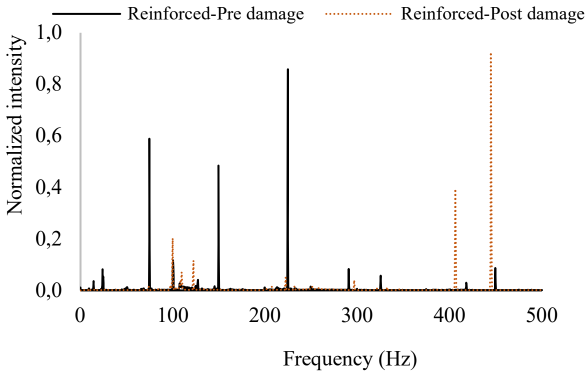

Fig. 11. Normalized frequency spectrum post-strengthening before and after simple clay brick construction damage.

On the other hand, with respect to the dynamic results, similar patterns are maintained to those defined for the case of the unreinforced structure, Figure 11. Specifically, the reinforced structure prior to damage showed frequencies significantly higher than those of the original structure with an average increase of the first four modes of 157%. However, after the application of the last phase of the test, the values of the frequencies of the reinforced model returned to values very close to the frequencies of the damaged and unreinforced structure, with an average relative error of 10%. Likewise, after cracking of the reinforced model, an average increase of the damping factor by 200%, with respect to the values of the reinforced structure, was also observed. The final damping factor values at the end of the test were 4.26%, 3.46%, 2.19% and 0.86% for the first four modes, respectively.

V. Conclusions

This paper has presented a combined research where three structural typologies of brick masonry have been analyzed. On the one hand, a cross vault has been analyzed, on the other hand, a simple wall and finally a building consisting of three walls and a unidirectional slab. In all cases, the dynamic properties related to vibration frequencies and damping factors have been analyzed for four different states: a) initial state without reinforcement and without damage; b) state without reinforcement after damage generation; c) reinforced state after state (b) but without including new damage and d) reinforced state and damaged again. The damage introduced in the flat brick masonry wall structures was done by introducing a horizontal load; however, in the case of the cross vault structure, the damage was introduced by means of a differential vertical displacement in one of its supports.

Based on the above and to conclude this document, it can be preliminarily established that the three analyzed structural typologies showed similar behavior in relation to the effect of damage on their dynamic properties, as well as the effect of reinforcement on them. Thus, after the cracking of the structures, all cases experienced a decrease in vibration frequencies showing a loss of structural stiffness. In addition, they also showed an increase in the damping factor due to the increase of the cracking. On the other hand, in relation to the effect of the reinforcement, in the three cases the capacity of the reinforcement to recover the structural stiffness of the analyzed elements prior to the damage was evaluated, increasing the vibration frequencies and decreasing the damping factor.

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