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DAMAGE-IMPERFECTION INDICATORS FOR THE ASSESSMENT OF MULTI-LEAF MASONRY WALLS UNDER DIFFERENT CONDITIONS

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Abstract. *The complexity of multi-leaf masonry walls suggests further researches on the dynamic behaviour mainly characterized by incoherent response between the different layers. The intrinsic discontinuity and the manufacturing imperfections are amplified by the incremental damage that triggers different failure mechanisms that affect the dynamic parameters, such as modal shapes, frequencies and damping ratios. The dynamic identification with output only methodology has been proposed in this work on different multi-leaf masonry walls subjected to uniaxial compressive load. The responses of full infill, damaged infill and strengthened infill masonry panels with different widespread damage have been recorded. The evolution of the damage scenario changes the modal shapes, the related frequencies and the damping ratios that through the comparison with the data of the initial conditions can detect the anomalies and then the intrinsic vulnerabilities. Through the curvature modal shape methods and the structural irregularity indices applied to different phases, it was possible evaluate the imperfection and the induced damage entity.*

1 INTRODUCTION

Among several historical constructive techniques, multi-leaf is one of the most widely spread typology of masonry walls. It is a multi-layered wall, consisting of two external leaves made of bricks or stones containing an internal cavity filled with incoherent material, usually made with a mixture of scraps coming from the construction site, such as brick potsherds, broken shingles, stones, cobblestones and mortar.

Its wide diffusion in historical architectural heritage claims to the necessity of accurate studies, in particular aimed to an effective evaluation of mechanical properties and structural behavior. Problems are mainly related to the different mechanical properties of the leaves, in particular the different behavior exhibited by the external bearing walls and the weaker internal core and the lacking of connection between them. It is difficult to properly describe the conditions at the interface between the leaves, which play a relevant role in the structural interaction between the layers. The behavior is also affected by the manufacturing features, such as the mechanical properties of constituent materials, thickness of the leaves and size effect, thickness of mortar, presence of "*diatoni*". In particular, defects and manufacturing imperfections – quality of the internal filling, distribution of mortar, presence of voids – without counting the several uncertainties related to the geometric configuration and the state of conservation, may determines or not the load distribution between the leaves, being their stiffness usually very different [1,2].

Several experimental studies can be found in the scientific literature [3, 4] also related to effect of strengthening [5-8] and to the modelling strategies able to properly describe the global behavior of multi-leaf masonry walls [9-11]. Here attention is focused on the dynamic identification of multi-leaf masonry walls. The interest in dynamic monitoring methodology is constantly increasing, providing the possibility to evaluate the effective behavior of existing structures in order to realize reliable numerical models [12], that are fundamental when dealing with historical architectural heritage [13,14], especially in seismic countries like Italy [15-17].

In this work, dynamic identification with output only methodology [18,19] is proposed with the specific target to determine the dynamic parameters of multi-leaf masonry walls subjected to uniaxial compressive load. The work is the continuation of an experimental research activity carried out at University IUAV of Venice [20] aimed at the dynamic identification of multi-leaf masonry walls damaged and consolidated [21] and to the assessment of mechanical properties and the definition numerical models for masonry panels [22].

The dynamic identification was carried out by means of the output-only methodology and the data were processed through the Least Square Complex Frequency (LSFC) estimator by LMS Polymax algorithm [23]. Three different types of multi-leaf masonry specimens: (i) full infill, (ii) damaged infill, (iii) consolidated infill (see Section 2) have been tested at the LabSCo (the Laboratory of Strength of Materials of the University IUAV of Venice, Italy) under compression up to the collapse. Dynamic measures have been collected during the test with the purpose of evaluating both dynamic behavior both structural integrity of the different typologies. In [21] experimental results have been compared with numerical Finite Elements models, in which masonry walls have been modelled as an equivalent continuum obtained through a full 3D homogenization procedure [24].

With respect to the previous work [20,21], here attention is focused on the evolution of the damage during the tests and to the changes in the modal shapes, the related frequencies and the damping ratios (see Section 3). The intrinsic discontinuity and the manufacturing imperfections are amplified by the incremental damage: by the comparison between the data of the initial conditions it is possible to detect the anomalies and the intrinsic vulnerabilities.

2 GENERAL DESCRIPTION OF PHYSICAL TEST

The masonry specimens analyzed in this research have been widely explained in previous works [20, 21]. 9 multi-leaf masonry panels, having dimensions 1420 x 380 x 1440 mm (Figure 1a), have been tested by applying uniaxial compressive force in order to assess the different response in serviceability and ultimate state of three typologies of infill: full, damaged and consolidated (Figure 1b).

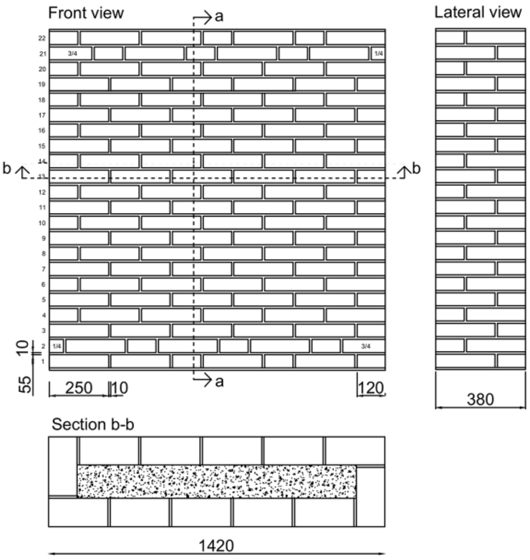


Figure 1a: General sizes of masonry specimens (dimension in millimeters).

In detail, Figure 1b shows the different infill layers characterized by the central part of the core with bricks potsherds mixed with mortar (B1-Full infill) and separated (B2-Damaged infill). The last typology was used to build the third configuration (B3-Consolidated infill) where the discontinuity between the bricks potsherds has been strengthened by a consolidating mixture. The physical and mechanical characteristics of every material have been detailed in [20].

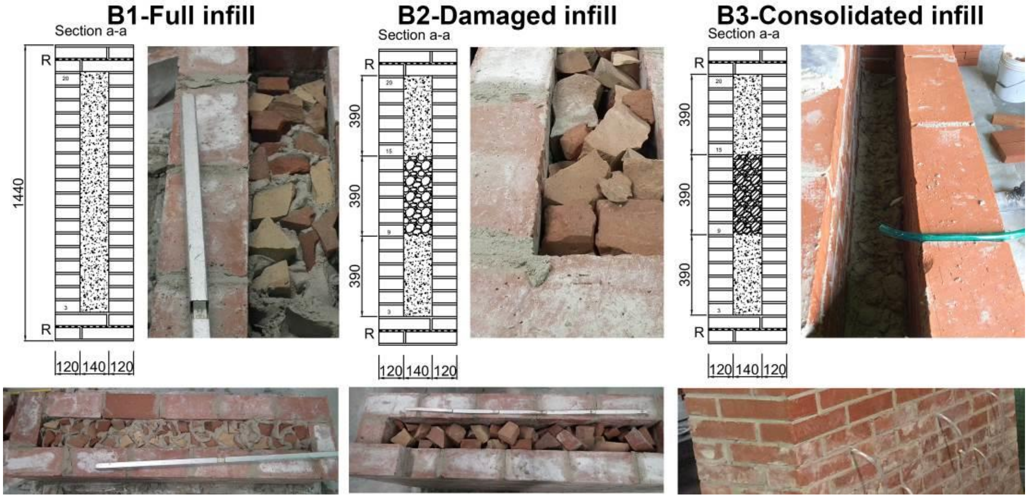


Figure 1b: Different typologies of masonry specimens, B1 full infill, B2 damaged infill, B3 consolidated infill (dimension in millimeters).

Figure 2 shows the setup of compressive test carried out on masonry panels. All compression tests were performed on a 6000 kN capacity loading machine with data control system (Figure 3a); the loading velocity was taken as 0.03 mm/s with displacement control procedure. The compression load was applied through a loading history made up three loading steps until the failure. Each loading step (thresholds A, B and C of Figure 3b) was followed by a pause period of 10 minutes where the reached compression loads are kept constant. In detail Step A corresponds to initial condition without the external load, the threshold of Step B is by 700 kN while Step C is by 1500 kN (see Figure 3b).

The vibration signals have been recorded through the accelerometers sensors widely descripted in [20].

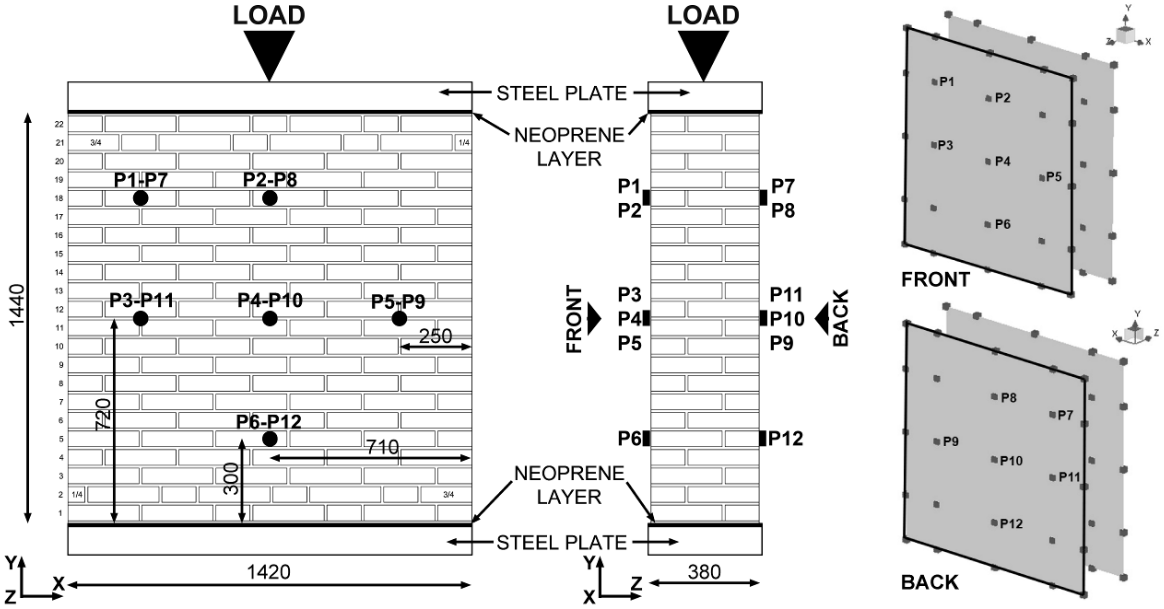


Figure 2: Scheme of test setup (dimension in millimeters).

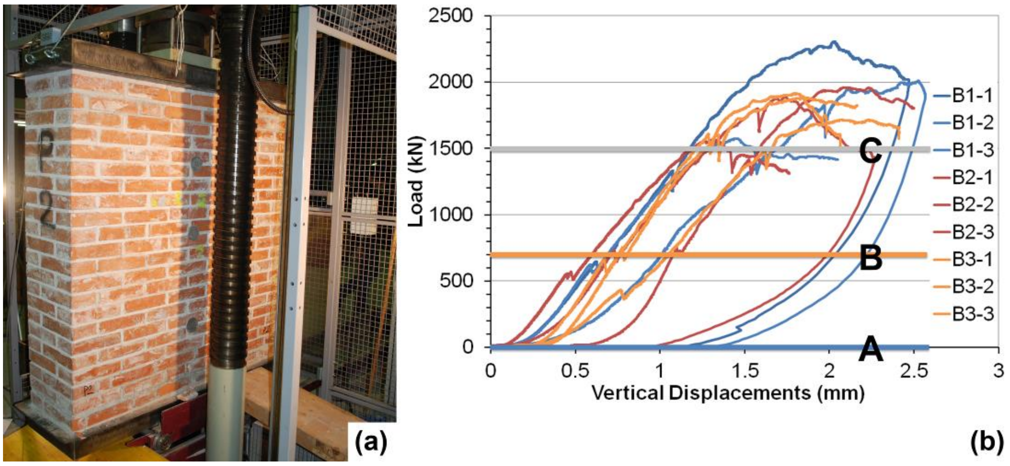


Figure 3: a) detail of test setup, b) Load-vertical displacements relationship with different steps A, B and C.

3 DYNAMIC IDENTIFICATION

The dynamic parameters, such as modal shapes, frequencies and damping ratios, identified in [20], are compared with the values of different damage patterns of every step, A, B and C. In detail the step A considers the intrinsic imperfections only, while the steps B and C evaluate the variation of dynamic parameters increasing the compressive load.

3.1 Identification of intrinsic imperfection

The damage/imperfection indicators based on vibration response can be evaluated by the variation in modal frequencies, modal shapes and damping ratios between the two external layers that constitute the multi-leaf masonry panels (sides FRONT and BACK of Figure 2). These damage/imperfection indices have been analyzed in the initial condition, step A (Figure 3b).

Figure 4 compares the imperfection indicators for the first six modal shapes through the variation of frequency (Var. Freq.) and damping ratio (Var. Damp.); the degree of similarity between two opposite mode shape vectors of sides FRONT and BACK (Figure 2) is quantified by the modal assurance criterion MAC [25], see Figure 4.

A MAC value lower than 90% identifies a discordance between both layers of multi-leaf masonry panels detecting uncoupled and/or local modal shapes.

MAC parameter is compared with the frequency and damping measurements, that to identify a global behavior should be lower than 1%.

The observance of these three indicators (Frequency and damping variation ≤ 1%, MAC ≥ 90%) is able to identify the consistence and homogeneity of specimens and then the global behavior. Instead, the non-compliance of these indices detect the uncoupled modal shapes.

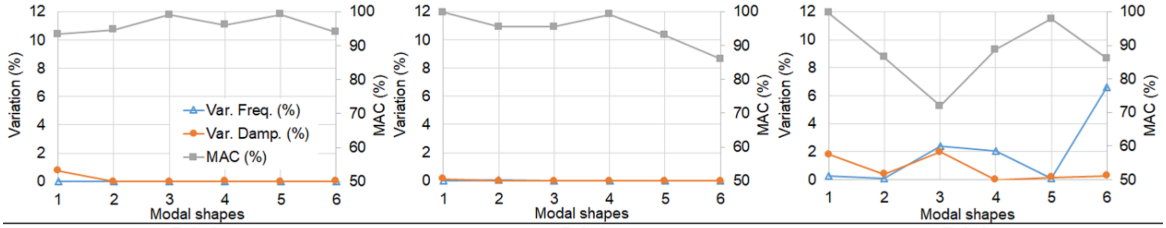
In detail, Figure 4a analyses the full infill masonry specimens (B1), Figure 4b compares the damaged full infill panels (B2) while Figure 4c studies the results of consolidated masonry panels (B2).

As shown in [20] for B1 specimens the modal shapes 1, 2 and 6 are respectively the 1st bending, 1st torsional and 2nd bending; while for B2 and B3 masonry panels the modal shapes 1, 2 and 5 correspond respectively to 1st bending, 1st torsional and 2nd bending.

For B1 specimens, only the B1-3 (Figure 4a) shows parameters out of limits for all main modal shapes (1, 2 and 6), highlighting the intrinsic imperfections.

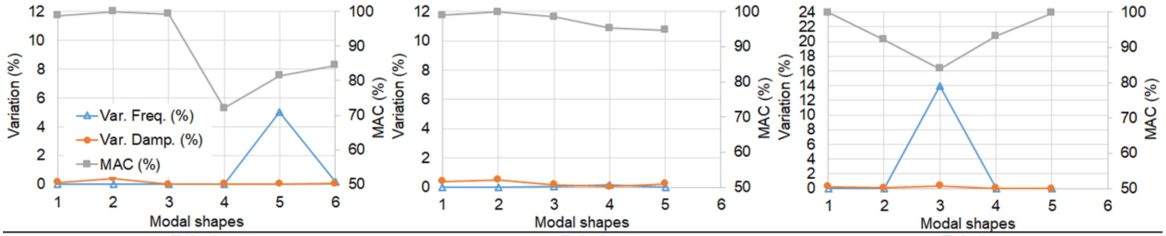
For B2 typology, the lack of continuity between the three layers does not generate evident decoupled modes as characterized by the single but synchronized response of the two outer layers characterized by high slenderness. Only the 2nd flexural modal shape (mode 5, see Figure 4b) records a variation of frequency greater than the limit by 1% and a MAC value lower than 90%.

For consolidated infill masonry panels (B3, see Figure 4c), the specimens with different behavior between side FRONT respect to side BACK are B3-1 and B3-3, with the dynamic parameters of the second flexural modal shape (mode 5) out of limits.



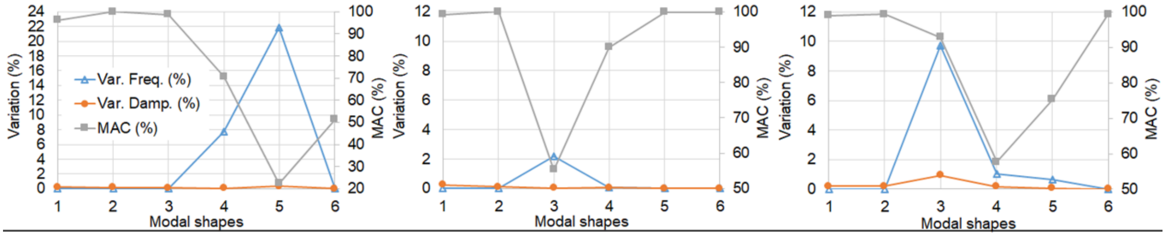
B1-1 **B1-2** **B1-3**

Figure 4a: Imperfection indicators for B1-Full infill masonry specimens, step A.



B2-1 **B2-2** **B2-3**

Figure 4b: Imperfection indicators for B2-Damaged infill masonry specimens, step A.



B3-1 **B3-2** **B3-3**

Figure 4c: Imperfection indicators for B3-Consolidated infill masonry specimens, step A.

3.2 Dynamic parameters variation with increasing damage conditions

The imperfections investigation addressed in previous chapter allows to contextualize the damage patterns identified in the steps B and C (Figure 3b).

For all typologies – B1, B2 and B3 – the variation of the dynamic parameters increasing the compressive load is shown in Figures 5, 6 and 7 for the main modal shapes. Passing from step A (initial condition) to step C (before the failure state) the frequency values of the first flexural modal shape (Figure 5) tend to increase for all typologies (Figure 5a, c and e). In detail for the full infill masonry panels (B1) the frequency values increase by circa 30% from initial condition (step A) to the damaged conditions (steps B and C). For the typologies B2 and B3 this trend is kept but with a greater deviation (65%) between the step A and steps B-C.

The damping ratios decrease with the constant trend for full infill typology (B1) while it changes inconsistently for B2 and B3.

For the torsional modal shapes (Figure 6) is not possible to define a law that controls the behaviors both between the different typologies and between the specimens of the same typology.

The second flexural modal shape allows to re-establish an order for the trend of the frequency values (Figure 7a, c and e); this behavior is not respected for the trend of damping ratios (Figure 7b, d and f).

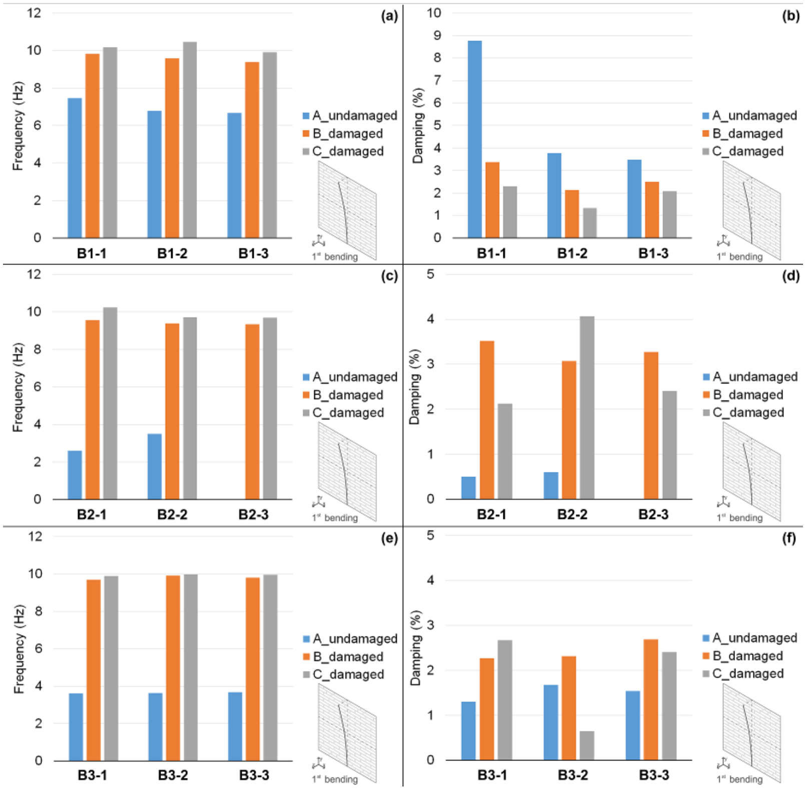


Figure 5: Comparison of dynamic parameters, frequency and damping ratio of 1st bending modal shape.

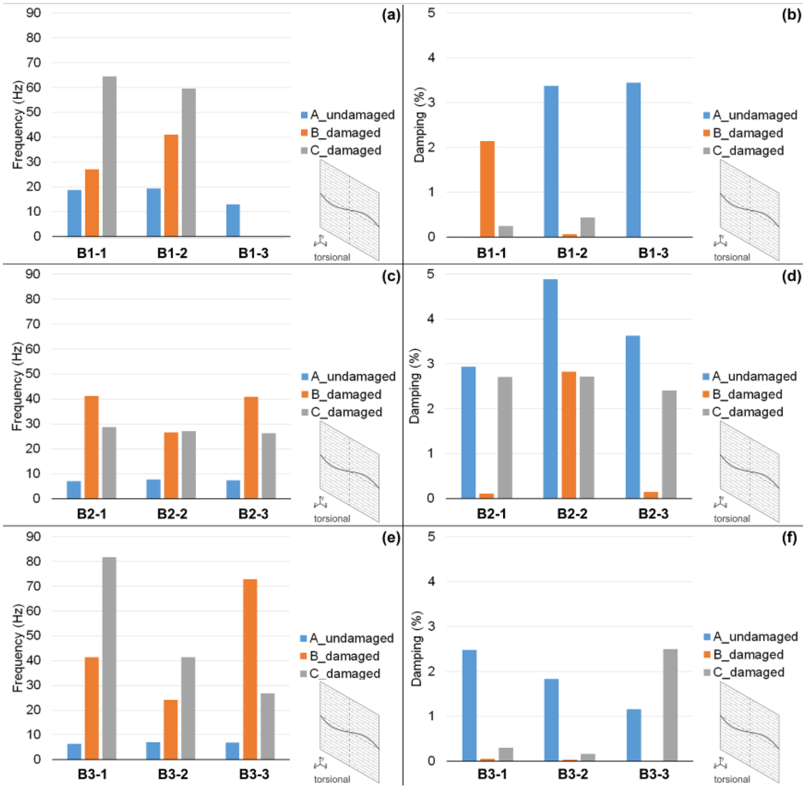


Figure 6: Comparison of dynamic parameters, frequency and damping ratio of 1st torsional modal shape.

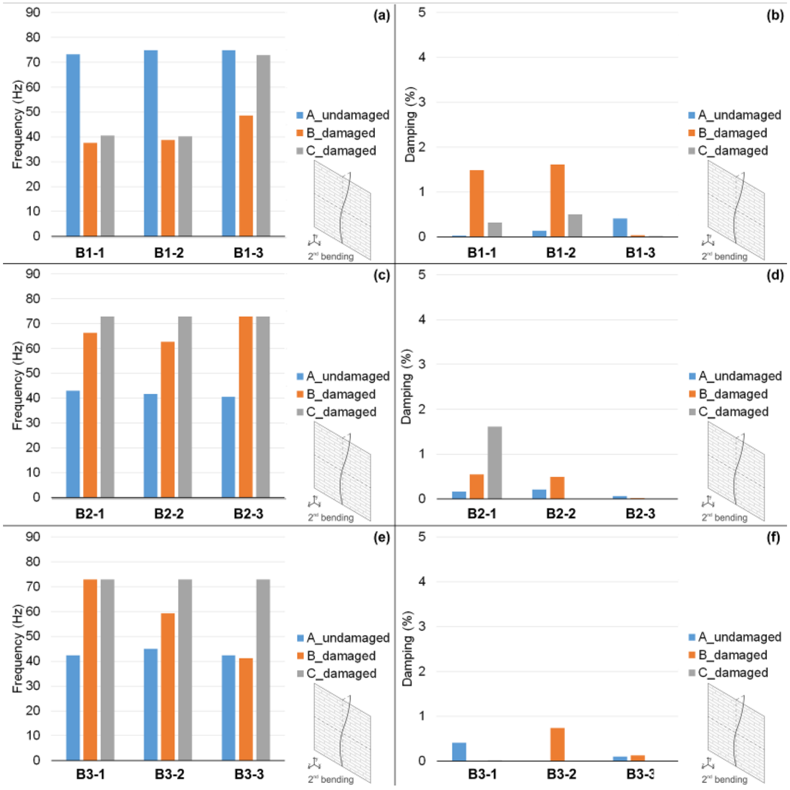


Figure 7: Comparison of dynamic parameters, frequency and damping ratio of 2nd bending modal shape.

4 CONCLUSIONS

Through the first results on damage/imperfection indicators based on vibration response the following evaluations can be drawn:

- the size effects affect the structural performances of three typologies that do not vary between full, damaged and consolidated infill multi-leaf masonry panels;
- the procedure adopted - based on damage/imperfection identification through different steps: investigation, localization, description, estimation and prediction – is reliable to analyze the complex systems characterized by multi-leaf masonry panels;
- the intrinsic imperfections can be evaluated through the comparison between the different indices: variation in modal frequencies and damping measurements to detect the degradation of structural characteristics (mass and stiffness); variation in MAC indicators that localize and quantify the degree of correspondence between two related mode shape vectors identifying the uncoupled and local modal shapes;
- with respect to the main modal shapes the torsional behavior amplifies the degree of the structural continuity between the different layers. The first and second bending modal shapes involve globally the masonry panels with out of plane mechanisms.

Further analysis will be carried out to compare the identified damage/imperfection indicators with other indices COMAC (Coordinate Modal Assurance Criterion), curvature damage factor and Stubbs-Cornwell damage index in order to make the prediction more reliable.

Non-linear static analysis will be carried out on numerical model calibrated through the identified dynamic parameters to verify the correspondence between the numerical and experimental structural response.

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