# Dynamic characterization and seismic evaluation of masonry buildings in Lisbon.
# Realization of ambient vibration and numerical modeling tests.

Bruno Daniel Torres da Silva

Instituto Superior Técnico, Universidade de Lisboa

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**Abstract**: A large part of the current built heritage of the city of Lisbon is composed by masonry buildings, with a significant number of the "gaioleiro" typology. This type of buildings is characterized by its low constructive quality and fragility of the materials used.

Many of these buildings are nowadays in a poor state of conservation, being crucial to assess their seismic behavior in the current state. To adequate model these buildings and calibrate the numerical models it is important to carry out ambient vibration tests.

This way, this work consists in the development of ambient vibration tests in three buildings of two zones of Lisbon where there is a vast concentration of “gaioleiros” buildings.

First, a characterization of the "gaioleiros” buildings is done, where it is described the way in which they have been introduced, its main locations in Lisbon, structural characteristics and materials used, as well as constituent elements. Then, it is described the information about and the functioning of the programs used for the modeling and evaluation of buildings, and its use.

In a second phase, the characteristics of the two cases of study are described, as well as the tests performed.

Afterwards, it is executed the processing of data obtained through tests, using the Artemis Modal Pro program, through which it was created a simple model of the buildings, aiming to determine the frequencies and see their respective vibration modes.

Then it is developed a numeric model of the buildings through the program *3Muri* to, in a first phase, perform a comparative analysis between the results obtained, to assess the suitability of the models created, since they would be used subsequently.

Finally, it is performed non-linear static analysis, with the purpose of verifying whether the buildings meet the safety requirements, in accordance with the existing regulations, Eurocode 8.

**Keywords**: “gaioleiro”; vibration modes; ambient vibration tests; *3Muri*; non-linear static analysis; seismic performance.

## 1. Historical background

Before the earthquake of 1755 in Lisbon, the constructive methods used and the territorial organization of the buildings were disorganized and did not have established rules, meaning the growth of the city in this phase was marked by the appearance of constructions of reduced resistance and without an appropriate territorial planning.

Due to these factors, coupled with the destructive effect of the earthquake, a large portion of the buildings with low resistance did not withstand and eventually collapsed or suffered serious damage. After this event (1755 earthquake), the plan for the reconstruction of the city contemplated a set of well-defined rules, which aimed at a regular construction and with a great focus on the resistance to horizontal actions.

Around the 1870s to the 1880s, originated by the increase of the population, the city began a process of expansion, which occurred mainly to the north, given the existing geographical conditions. However, this expansion occurred with a significant loss of rigour in the constructive method and materials used, thus appearing in this context the so-called "gaioleiro" buildings, known by both technicians and population in general for presenting limited performance in terms of functionality and safety, especially in cases of an earthquake.

The construction of the "gaioleiros" stopped around the 30-40 decade of the 20th century, due to the appearance of reinforced concrete. Nevertheless, "gaioleiros" buildings still exist in great number in some of the most important areas of Lisbon, such as Avenida Liberdade Avenue, Avenida Almirante Reis, Avenida da República, and in areas such as Avenidas Novas, Marquês de Pombal and Alameda D. Afonso Henriques, a large part of which is in a poor state of conservation.

*Figure 1 - “Gaioleiro” buildings front façade*

## 2. Building configuration

The resistant walls are the main structural elements with resistant function.

The façade walls usually consist of rubble stone masonry with a air lime mortar (Frazão, 2013), presenting a thickness around 60 to 90 cm on the facades of the ground floor. Along the floors this thickness decreases, to reduce the structure’s self-weight, being this decrease around 5 cm per floor.

In the case of gable walls, also in stone masonry or in solid brick, the thickness is of the order of 30 to 40 cm, maintaining this constant in height, being able, in the case of being of massive brick, to be altered for hollow brick. In the case of adjacent buildings, it is common for the shared gable wall to have a lower thickness compared to the double of the thickness of a single wall (Appleton, 2003).

*Figure 2 - Back façade balconies.*

The interior walls may have a support function, usually the ones parallel to the facades and those of the stairwell, being usually made of solid brick and presenting thicknesses in the order of 30 cm (Catulo, 2015). If they do not have a support function, they are called partition walls and can be in brick or in a sealed brick, with thicknesses of the order of 10 cm. In addition to the partitioning function, these are useful due to the locking they provide to the structural walls and some resistance to vertical loads.

The pavements are mostly composed of wood beams spaced between 20 and 40 cm (Appleton, 2003), oriented perpendicular to the facades and supported on the walls, both interior and exterior, through small deliveries. In the case of some of the recently constructed buildings, due to the rapid deterioration of the verified wood, the floors in the kitchen and bathroom zones are constituted by metallic profiles that support brick slabs (Frazão, 2013; Monteiro, 2012).

The roof of this type of buildings is generally inclined, formed by a system of wooden scaffolds supported on the walls and under which a set composed of mothers, sticks and slats, which support the tiles (Appleton, 2003).

There are two sets of stairs, one inside and the others outside. The first is located approximately half-way from the building next to one of the gables, being executed in wood, while the latter is located in the back facade connected to the balconies, generally constituted by metallic elements.

Another peculiarity of this type of buildings is the shaft, an open space approximately quadrangular, along the whole height of the building, normally located in one of the gable walls, contributing for the ventilation and natural light of the interior divisions.

### 3. Study case and ambient vibration tests

All the buildings selected for the tests belong to the type I (Simões, 2018), two of them neighbours, located on Avenida Elias Garcia (nº89 and nº91) - Figure 3, in the neighbourhood of Avenidas Novas and the other on Travessa de Santa Marta (nº4) - Figure 4, located in Santo António. All the buildings have widths around 7-8 meters and depths around 19 meters.

The buildings of Av. Elias Garcia have 3 floors above the ground floor and an habitable attic and are situated between a building of reinforced concrete and another “gaioleiro” of the same type with the opposite gable free. On the other hand, the building Travessa Santa Marta nº4 has 4 floors above the ground floor and an habitable attic, located at the end of a series of buildings, thought only the adjacent one is totally parallel.

*Figure 3 - Buildings 89, 91 e 93 of Av. Elias Garcia.*

The measurement units used for the ambient vibration tests were GeoSig branded macro-seismographs, model GSR-24 - Figure 5, programmed to start and end the test simultaneously by a portable computer through software, which later collects and allows the reading of signals collected from all channels.

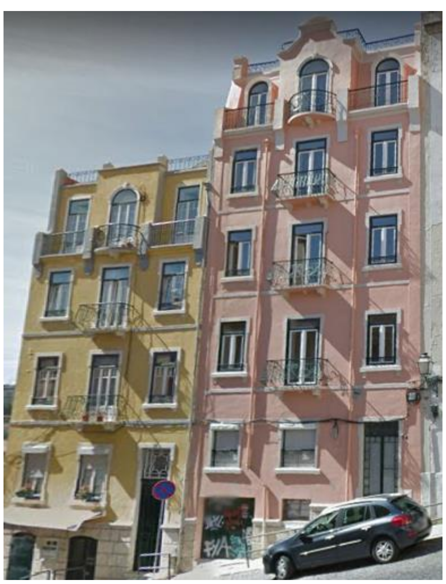

*Figure 4 - Travessa Santa Marta nº4.*

*Figure 5 - Seismograph used in the tests.*

The procedure started with the programing of each of the seismographs for the measurement, inserting parameters such as the start time, measurement duration and frequency of record acquisition, through the QuickTalk ™ program. After the setup was completed, the seismographs were placed at the designated locations for each measurement. In all measurements, one of the seismographs is held at a fixed point, desirably at the top and at one corner of the building, to ensure the homogeneity of the records, while the other two are free and varying their locations between measurements. The duration chosen for the tests (twenty to thirty minutes) should be enough to ensure a sufficiently representative sample of accelerations.

In the building Travessa Santa Marta nº4 the conditions available for the accomplishment of the tests were quite satisfactory, which facilitated the access to the dwellings of all the floors. The tests were performed in ascending order of height, with the two free seismographs placed successively in the southwest and northeast corners of each floor. The reference seismograph was placed in the southwest corner of the top floor (attic) - Figure 6.

As an unfavorable point, there was the fact that the reference seismograph was installed on the wooden floor due to the lack of windows near that corner. For the rest, whenever possible, care was taken to place them on the windowsill, in the transition between the kitchen and the balcony (rear facade) or on the floor of the balcony, in order to have contact directly with the stone wall or with a more rigid floor.

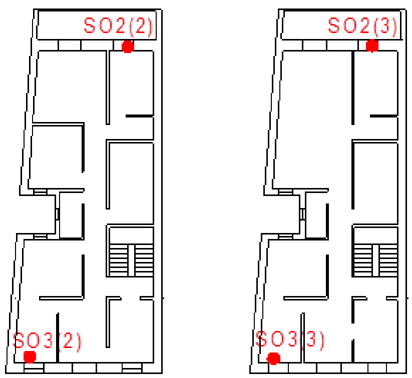


*Figure 6 - Scheme with the locations of the free seismographs on the 2nd and 3rd floors.*

Regarding the two buildings of Av. Elias Garcia, the access to all floors unfortunately was not achieved, which limited the execution of the tests. In building number 89, the reference seismograph was placed on the top of the staircase on the 4th floor, and two tests were performed. The first with the two seismographs in the second floor and the second with both in the stairwell, one on the 1st and the other on the third floor.

In the Garcia 91 building, three tests were executed. Since at first it was not possible to access to the top floor, the reference was placed on the third floor - Figure 7. The order of the tests was as follows:

1. Both seismographs in the stairwell, one on the first and another on the second floor;
2. Both seismographs on the fourth floor, one on the southwest corner and another on the northeast corner;
3. Both seismographs on the first floor, one on the southwest corner and the other on the northeast corner.

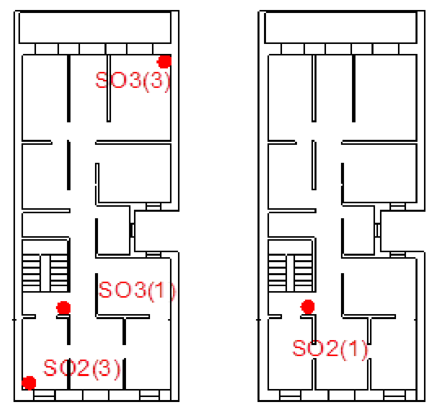


*Figure 7 - Scheme with the locations of the free seismographs on the 1st and 2nd floors.*

**4. Modelling**

The Artemis Modal Pro program (SVIBS 2013) was used to process the results registered with the ambient vibration tests.

The first step included the insertion of the geometry of the structure - Figure 8, carried out through Excel, with the values of the dimensions of the buildings. In a first phase, the buildings, in which the registers were obtained, were modeled isolated and in a second one they were modeled together with the neighboring buildings.

After creating the geometry of the model, the records were imported and assigned to the point where they were obtained, divided between the setup's, corresponding to the different tests.

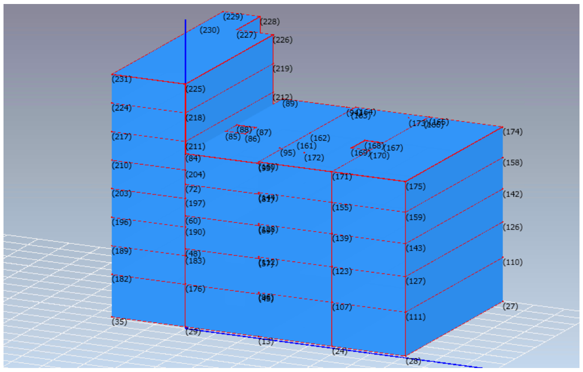

*Figure 8 - Modelling of the Elias building block in Artemis*

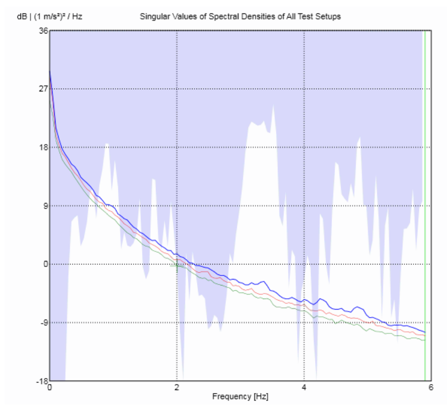


*Figure 9 - Visualization of frequencies.*

At this point, through the observation of the various acceleration graphs - Figure 9, it was possible to identify several parts with very significant peaks in comparison with the average. So it was tried to eliminate the most undesirable ones to the maximum, defining for each setup a sufficiently representative interval which could exclude most of the worst peaks. The records were also centered with the horizontal axis, to remove the asymmetry that some of the graphs presented.

The frequencies and their modes could be identified through the generated graph. For each of the chosen frequencies the graphic display of the corresponding mode of vibration was analyzed, to check whether if that frequency could correspond to a global mode of the building. The previous steps were executed for each one of the buildings, so that it was possible to build a comparative table with the frequencies and modes of vibration that were considered possible to be the real ones for each building.

In order to obtain a numerical frequency matching with the experimental results, the buildings were modelled with the help of the 3Muri program (2005). The model of the buildings of the Av. Elias Garcia had already been created, therefore the task was to create the one referring to the building located at Travessa Santa Marta nº4 - Figure 10. Since the building is not isolated, it was chosen to include in the modelling the adjacent building, also "gaioleiro", with one more floor and the same plant, as well as type of windows, to obtain results possibly closer to the real behaviour.

Regarding the modeling, it should be noted that the roofs were replaced by the application of the equivalent loads on the walls of the last floor.

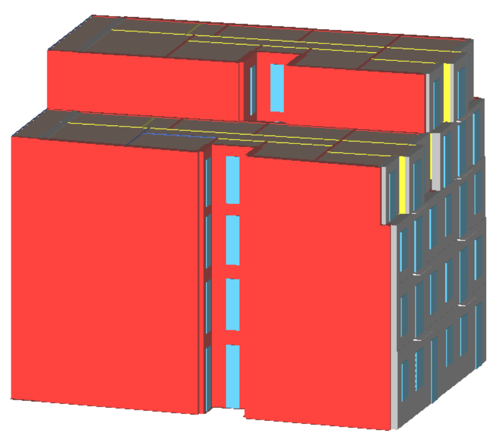

*Figure 10 - 3muri Model of the building Travessa Santa Marta nº4.*

Since the walls have possibly been constructed with a long time spacing between each other and given their difference of materials and characteristics, their connections show some fragility, especially in the case of connection between the outer and inner wall. Since the program does not assume this fragility, it was simulated through the introduction of fictitious beam elements between the walls -Figure 11, in which the values of the area and inertia inserted were very low, found through an iterative process according to (Simões, 2018).

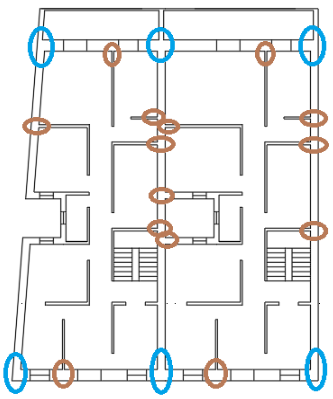

*Figure 11 - Locations where link elements were created.*

## 5. Modal Analysis

After the 3Muri model was complete, modal analysis was performed and a comparison between experimental and numerical results was made between the values of the frequencies the modes of vibration - Figure 12, Tables 1 and 2.

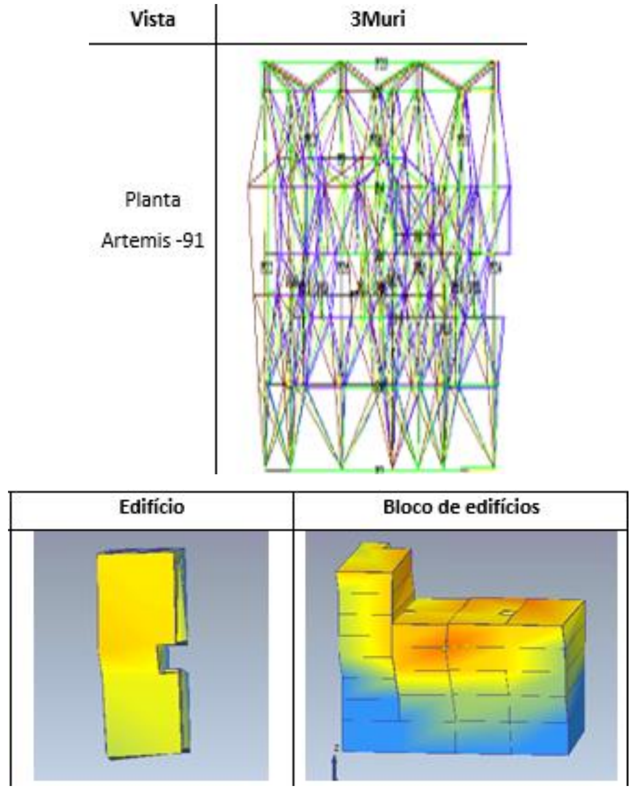


*Figure 12 - Example of the comparison between the deformed shapes of the two models for a 2nd mode in x.*

*Table 1 – Results obtained for the frequencies (Hz) of the Av. Elias Garcia buildings.*

| Mode | 3Muri | Artemis 91 | Artemis 89 | Bloco 91 | Bloco 89 | Proposal |
|---|---|---|---|---|---|---|
| 1st x | 0.73 | 0.73 / 0.88 | 0.73 | 0.73 | 0.73 | 0.73 |
| 1st y (local) | 1.94 | - | 2.05 | 2.34 | 2.15 | 2.15 |
| 2nd y (local) | 2.08 | 2.15 | - | 2.34 | 2.15 | 2.34 |
| 2nd x | 3.11 | 3.13 | 3.22 | 3.03/3.13 | 3.13 | 3.13 |
| 3rd y | 5.58 | 6.01 / 5.96 | 5.96 | 5.96 | 6.01 | 5.96 – 6.01 |

*Table 2 - Results obtained for the frequencies (Hz) of the Travessa Santa Marta nº4 building.*

| Mode | 3Muri Model 1 | 3Muri Model 2 | Artemis | Proposal |
|---|---|---|---|---|
| 1st x | 0.7 | 0.92 | 0.88 | 0.88 |
| 1st torsion (x) | 0.83 | 1.21 | - | 1.00 |
| 1st y | 1.72 | 2.24 | 1.66 | 1.66 |
| 2nd torsion | 1.86 | 2.41 | - | 2.00 |
| 2nd x (local) | 1.89 | 2.52 | 2.15 | 2.15 |
| 2nd y | 4.44 | 5.67 | 4.88 | 4.88 |

For both cases, a large part of the frequencies obtained through Artemis were difficult to locate and most of them were chosen based on the comparison with the 3Muri model.

## 6. Push-Over Analysis and N2 Method

In order to verify the safety of the buildings under study, the N2 method was used, which considers the seismic action response spectrum format, which can later be compared with the capacity curve of the structure in order to determine the objective displacement. The latter is the displacement that the structure must support in case of earthquake; this displacement is compared with the ultimate displacement, obtained through the push-over analyses.

The push-over analyses consist of non-linear static analyses, in which a controlled increase of an horizontal load of a certain type is carried out, keeping constant the gravitational force of the building, until the ultimate displacement of the structure $d_u$ (i.e. the one which lead to the collapse) is reached. According to the Part 1 of Eurocode 8 (CEN, 2010), two distributions of forces were considered: one uniform in height and one triangular.

Through this analysis it is possible to graphically define the resulting curve, with the displacement as a function of the applied force, named capacity curve, that describes the variation of the sheer force

at the base of the building with the displacement at its top. (Monteiro, 2012). A total of eight analyzes were performed -Figure 13, varying between the x and y direction, the positive and negative direction and uniform and triangular load format applied, in order to obtain one for each variation of these parameters.

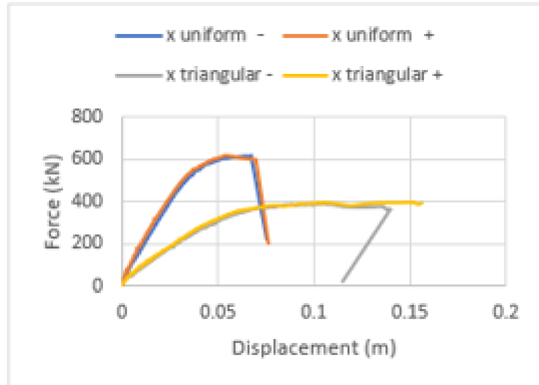


*Figure 13 - Push-over curves for the positive direction*

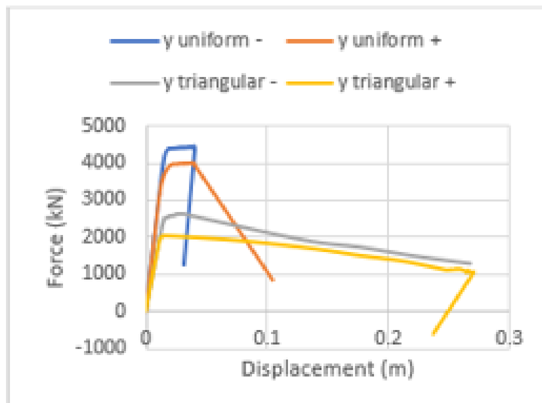


*Figure 14 – Push-over curves for the negative direction.*

The values of force and displacement obtained were then transformed in the values corresponding to the equivalent structure with one degree of freedom (SDOF, denoted with *) through the transformation coefficient $\Gamma$, and then the mass of the SDOF, m*, is provided by the program, which allowed the definition of the bilinear curve - Figure 15.

This curve is suggested in the Annex B of the Part 1 of Eurocode 8 (CEN, 2010) to represent the behavior of the structure, with a first path represented by a constant stiffness obtained at 70% of the maximum force and the second of constant force, $F^*_y$, given by the force for which the area below these two lines is equal to the area below the capacity curve of the equivalent SDOF structure. The curves obtained for the positive direction are shown in Figure 16.

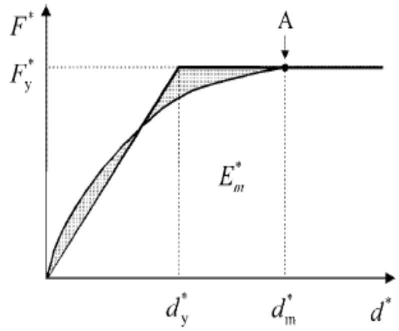


*Figure 15 - Basic scheme of the bilinear curve.*

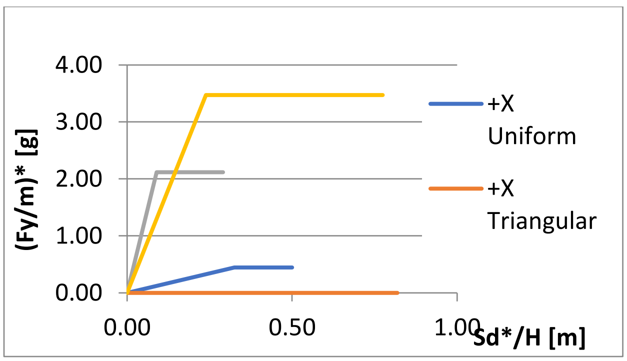


*Figure 16 - Bilinear curves obtained for the positive-sense analyses.*

As it is possible to observe, it was not possible to obtain the curve for certain cases, specifically in the x direction, where the stiffness obtained was too low to obtain a valid value for the yield force $F^*_y$.

The period of the SDOF system was obtained by the expression:

$$T^* = 2\pi \times \sqrt{\frac{m^* \times {d_y}^*}{F_y^*}}$$

After obtaining *T** it was possible to determine the target displacement of SDOF system and then, multiplying this value by the transformation coefficient $\Gamma$, the target (objective) displacement of the building is obtained.

The value of the objective displacement was then compared with the $d_u$ of the structure, given by three quarters of the existing displacement after a decrease of 20% of the force with respect to the maximum (as for the existing residential building the safety verification should be performed for the Significant Damage (SD) limit state. The comparison between the target displacement (dt) and ultimate displacement (du), for the cases where it was possible to obtain the objective displacement, is shown in Figure 17.

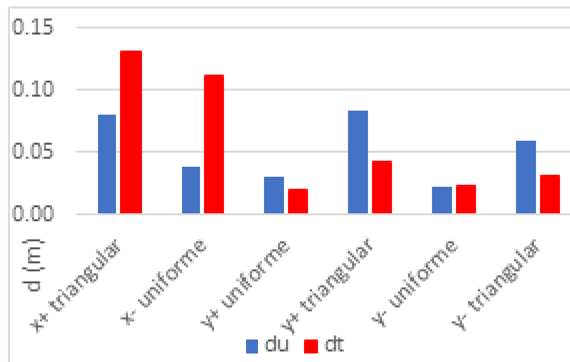


*Figure 17 - Ultimate displacement and objective displacement for each analysis.*

In a brief analysis, one can easily verify that the values obtained for the x-direction, as opposed to the y direction, are far from the required, thus not meeting the requirements of code seismic safety. Thus, to improve the seismic behavior of the building, a solution could be the increase of the stiffness of the structure in the x direction, through the inclusion of more resistant walls or the increase of the existing ones, to prevent the damage seen in Figure 18 and Figure 19.

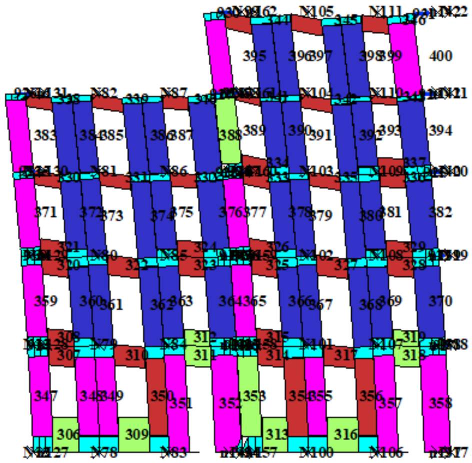

*Figure 18 - Damage distribution for the severe damage displacement in the x direction, with the negative direction in the main façade.*

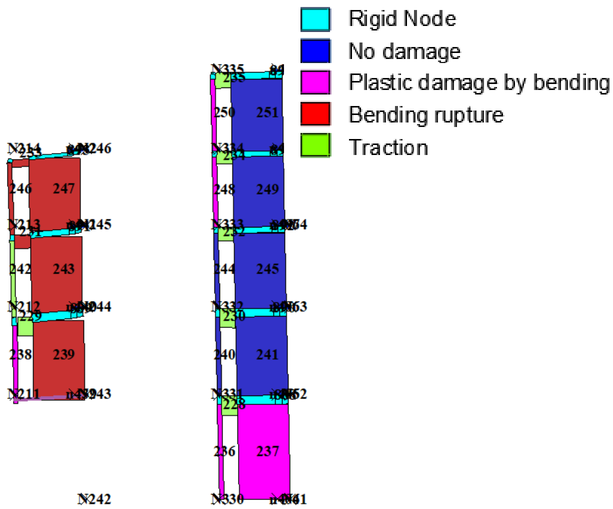


*Figure 19 - Damage distribution for the severe damage displacement in the x direction, with the negative direction in an interior wall where structural changes occurred.*

### 7. Final Comments

Aiming the dynamic identification "gaioleiros" buildings in Lisbon, several in-situ ambient vibration tests were carried out in different buildings. The modal properties obtained experimentally were crucial to calibrate the numerical models developed 3Muri program. The numerical models are then used to perform non-linear analyses and to verify if the buildings meet the code safety requirements. In this work, this condition was check only for one "gaioleiro" building.

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