Nonlinear Modelling of Adjacent Masonry Buildings with Floors at Different Heights

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Abstract

The analysis of the surrounding conditions in which a building is inserted is a fundamental issue for the evaluation of the seismic performance of masonry buildings. The lack of information regarding the constitution of existing masonry structures, combined with the complexity inherent to the complete characterization of their non-linear behavior, contributes to the difficulty in establishing methods that characterize the seismic structural response of this type of buildings

The aim of this work is to solve the problems concerning the macro-modeling process of masonry buildings, namely, the consideration of the effect of the different floor levels between adjacent buildings, in the scope of the evaluation of the seismic performance of masonry buildings. Using *MATLAB*, a tool to support macro-element modeling in the *3Muri/TreMuri* program is developed and proposed. The methodology developed is then used in the modeling and seismic assessment of a mixed masonry-reinforced concrete building, located in the Alvalade neighborhood, in Lisbon, subject to the interaction of adjacent buildings with floors at different levels, in accordance with EN 1998.

It is possible to verify that the interaction between surrounding buildings affects the dynamic response of the structure and its seismic performance. Moreover, it is found that the consideration of the difference between floor levels of adjacent buildings does not have a significant influence on the overall behavior, given its reduced value. However, the observed differences in the damage distribution suggest that, for larger values of difference in floor levels, the impact on overall performance may be significant.

Keywords Masonry Buildings, Surrounding Conditions, Macro-Elements, Seismic Performance, *3Muri/TreMuri*

1 Introduction

The seismic assessment of masonry buildings has gained depth in the scientific community since the 1970s, with the development of nonlinear analysis methods based on the use of macro-element models. This approach idealizes the structure as an assemblage of vertical and horizontal elements, constituted by a homogeneous and anisotropic material, which typically follows an elastoplastic law, thus considering the nonlinear behavior of masonry.

Today, masonry structures still represent one of the typologies with the highest seismic vulnerability. In Lisbon, it is estimated that 67% of existing masonry buildings require structural interventions [1]. It is also verified that most of the masonry buildings existing in Lisbon are laid out in aggregates. Mixed masonry-reinforced concrete buildings – commonly referred to as "de Placa " buildings – stand out as one of the most common typology. The joint behavior of elements with different materials in the same structure, as well as the interaction between walls of adjacent buildings, require special attention in the consideration of adequate simplifications to the structural problem. As such, methodologies should be established to allow the definition of models through a systematic process.

2 Nonlinear Analysis of Masonry Structures

A seismic analysis consists in the study of the response a structure has when requested by a base movement, representative of seismic activity [2].

Four types of analysis methods can be distinguished, all of them recommended by the EN 1998-1 [3], depending on whether the structure's nonlinear behaviour is considered or not (Linear/Nonlinear), and whether the seismic action is considered statically or dynamically.

Nonlinear Analyses allow the characterization of existing constructions in terms of resistance and ductility, since the nonlinear behaviour is considered directly. Therefore, this type of analysis is more appropriate for the seismic assessment of masonry buildings.

2.1 Nonlinear Static Analyses

A nonlinear static analysis, also known as pushover analysis, presents itself as a less accurate alternative to the nonlinear dynamic analysis, although easier to apply, allowing a good approximation of the nonlinear behavior exhibited by masonry structures [4].

In this approach, it is considered a set of horizontal forces applied to the structure, distributed in height, simulating the effect of the seismic action. The resistant capacity of the structure is defined in terms of a capacity curve, which relates the shear base force with the control displacement of the structure.

Based on the Capacity Spectrum Method (CSM) [5] and on the Q-model [6], the **N2 method** is developed [7]. Like the CSM, this method considers a transformation to a single degree of freedom (SDOF) oscillator, but the inelastic behavior is considered through an elastic response spectrum reduced by a nonlinear behavior factor. The original version of the method is formalized in the EN 1998-1 [3].

2.2 Nonlinear Modelling

Masonry is a heterogeneous material consisting of units (bricks) and joints (mortar). It exhibits distinct directional properties (anisotropy) and is characterized by a low tensile strength [8]. The weakest link in the set is usually the bonding at the brick-mortar interface, which may rupture by traction or shear. The material degradation induces a reduction of resistance in the elements, and rigidity at the global level [8].

Three types of failure mechanisms can be identified in masonry piers, as showed in Figure 2.1: rocking (bending-compression), shear-sliding and diagonal cracking.

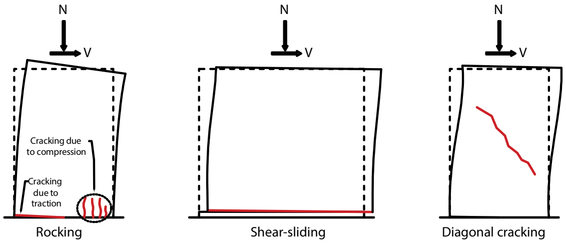

Figure 2.1. Typical collapse mechanisms in piers

Research carried out by several authors during the last decades allowed the development two distinct modelling approaches for masonry structures: (i) micro-element modelling, which takes into account rather precisely the nonlinearity and heterogeneity of masonry [8]; and (ii) macro-element (ME) modelling, which considers an equivalent frame model consisting of vertical (piers) and horizontal (spandrels) elements of a homogeneous composite material intended to represent the nonlinear characteristics of the masonry.

While micro-modelling is suitable for small structures or structural elements, with interest in the study of collapse mechanisms, macro-modelling presents itself as a less accurate approach, but adequate for the global analysis of large masonry structures.

The equivalent frame approach was introduced by [9], with the development of the POR method. Experimental tests showed that the damage due to the seismic action is concentrated on the piers and spandrels, while the joint connections appear to exhibit no significant damage, validating this approach. Furthermore, it is showed that slender elements tend to collapse due to rocking (bending-compression), while less slender elements collapse due to diagonal shear.

Since then, many authors proposed refined versions of this kind of approach. Among them, [10] propose, at the University of Genoa, a ME which contemplates the two main failure modes, rocking and sliding-sliding, through a set of 8 degrees of freedom (DF) – Figure 2.2 – considering the degradation of resistance and stiffness. Further information can be found in [10].

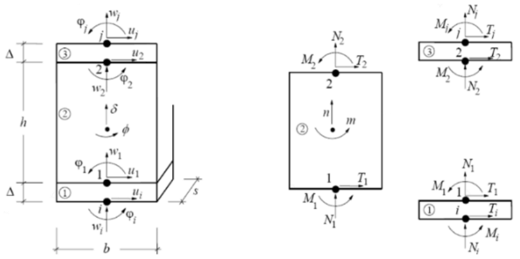

Figure 2.2. Genoa macro-element [11]

3 Case Study

Mixed masonry-reinforced concrete ("de Placa") buildings emerged in a period of transition and expansion of the city of Lisbon, between the 1930s and 1960s, marked by the gradual introduction of reinforced concrete (RC) elements in masonry structures, accompanied by the abandonment of wooden structures [12].

3.1 Structural Behaviour

The introduction of RC slabs in a masonry structure implies a significant increase of mass, and consequently an increase of inertial forces due to the seismic action, without contributing to the overall structural resistance of the vertical elements. Despite this, the arrangement of walls in different directions, properly connected and locked by the existence of a RC slab, rigid in its plane, promotes a good seismic behaviour [13].

Furthermore, buildings inserted in **aggregates** present, in general, better seismic performance than isolated buildings, promoted by their joint behaviour. It is common for "de Placa" buildings in aggregate to have RC side walls, thus increasing the overall resistance of the building in that direction. However, this type of arrangement, particularly when floors are at different levels, may result in local collapse mechanisms, both in and out of plane, induced by the interaction or contact between adjacent structural systems.

3.2 General Characterization

Alvalade neighbourhood appears in the 1940s, amid the urban expansion program promoted by Estado Novo, aimed at increasing the housing supply in Lisbon to compensate for the population growth that took place at the time.

Figure 3.1 shows the studied building located in Alvalade neighbourhood, within its surroundings, as well as its plan (upper floors).

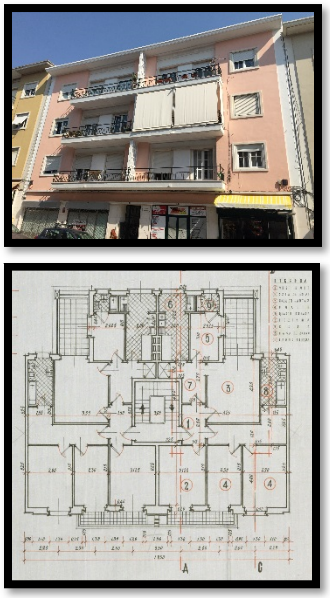

Figure 3.1. Studied building within its surroundings: picture and plan (upper floors).

It has 4 floors. The ground floor is characterized by large spans and lack of interior walls. The difference between floor levels of adjacent buildings, due to the ground inclination, is 0.70 m and 0.84 m to each building.

3.3 Structural Characterization

The **façades** are constituted by a RC frame structure, filled with two solid brick masonry panels, separated by an inner air box of 0.08 m and a total thickness of 0.40 m. The **gable walls** are described as RC, 0.20 m thick. However, further study by [14] concluded that they may be, in fact, constituted by concrete blocks.

The **interior walls** of the first 2 floors are of solid brick, with 0.25 m and 0.15 m of thickness, respectively. The stairwell and the separating dwellings walls are of hollow brick, 0.25 m thick. The remaining partition walls, on the 3rd and 4th floors, are of hollow brick as well, 0.15 m thick.

RC frame elements are distributed mainly on the façades, and on the whole ground floor. The pillars suffer a reduction in their section between the ground floor and the remaining ones. The **floors** are RC slabs, 0.10 m thick.

4 Structural Modelling

EN 1998-3 [15] does not indicate any specific analysis method for the seismic assessment of mixed masonry-RC buildings. NTC 2008 [16], recommends the use pushover analyses due to the high stiffness and deformation capacity variation in the structural elements. Thus, pushover analyses were applied using ME modelling in 3Muri/Tremuri software [17].

4.1 3Muri/TreMuri

3Muri/TreMuri [18] is based on the Frame by Macro Elements method (FME), which adapts the equivalent frame concept. It uses ME based on those originally proposed by [10] with the three-dimensional formulation proposed by [11], which integrates piers and spandrels linked to rigid nodes established on a global cartesian coordinate system (X, Y, Z), representing the main collapse modes of masonry walls.

The walls are identified by the global coordinates of a reference point and the angle formed with the global X axis, allowing the definition of its elements in a local coordinate system.

3Muri/TreMuri is an efficient tool, in that it allows to represent the overall nonlinear response masonry buildings using few computational resources. However, it presents many limitations to its use, lacking effectiveness in some aspects.

The program defines the equivalent frame model through an automatic process, considering the arrangement of openings (Figure 4.1). According to [19], there is no systematic procedure that defines strict criteria in the mesh generation.

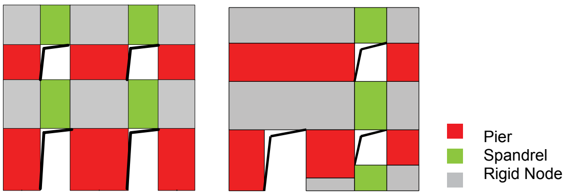

Figure 4.1. Model mesh in 3Muri/TreMuri [17]

In case of regular walls, the definition of the ME configuration is almost straightforward. However, for buildings with an irregular distribution of openings in the walls, the generated meshes present incoherent and sometimes incorrect configurations, rendering the analysis impossible. Figure 4.2 illustrates this problem.

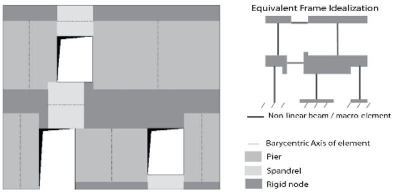

Figure 4.2. Generated mesh in a wall with an irregular opening distribution [19]

The same happens for sets of adjacent buildings with floors at different levels, as in the present case study, and the works of [20, 14]. It was found that the automatic mesh generation process is quite unpredictable in in these situations.

4.2 Mesh Editing MATLAB Tool

Although 3Muri provides mesh editing tools, this option becomes impracticable for meshes with a high degree of complexity, which can be composed of thousands of elements. The program developed in MATLAB aims at establishing a systematic procedure to modify the 3Muri/TreMuri model file.

For this purpose, a simple test model was defined, which includes all the features of the studied building on a smaller scale.

4.2.1 Model File

3Muri defines the model in a text file, through a series of commands that control the parameters of each element, node, or any other action essential to its operation. All elements are identified, grouped and listed depending on their type. Additional information can be found in [21].

4.2.2 Interaction Solution

The in-plane interaction between walls from adjacent buildings is established through vertical elastic frame elements, connecting nodes at different levels.

As for levelled adjacent buildings, interaction is established by horizontal elastic frame elements connecting adjacent buildings, separated by an offset distance.

4.2.3 Program Development

The proposed solution involves the copy of the model of an isolated building, along the global X axis, modifying the parameters that define the height of all its nodes and structural elements. For this a series of routines was developed through a process of trial and error, where it was certified that each one's performance verified the function for which it was designed. Figure 4.3 presents a diagram with the program's operation.

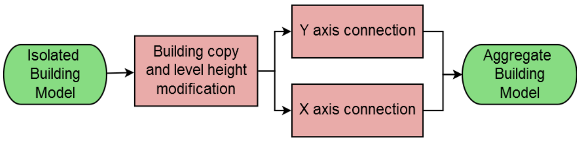

Figure 4.3. Program operation summary

Firstly, model data is **imported** from the text file and stored into a cell structure, which contains the matrices with the parameters that define each element/command.

The **copied** substructure is then defined in terms of the local coordinates of each copied element, in each wall, which include the X position offset and the level height difference, as showed in Figure 4.4.

To establish the connection between adjacent buildings' **side walls**, a routine defines all nodes and elements belonging to contiguous gable walls in a vertical alignment only. Elements from each building, although defined in the same vertical alignment, remain attached to nodes belonging to independent substructures. Interaction, if required, is then idealized in to distict ways, depending on the problem: (i) **type 1 connection**, where each superimposed element is divided and bound to the nodes of the two substructures, by modifying the dimension parameters, acting together on the same plane – Figure 4.5; and (ii) **type 2 connection**, where each wall section is defined by an element with the thickness of the assembly, eliminating overlaps – Figure 4.6 [21].

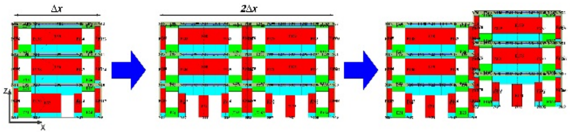

Figure 4.4. Copy and level height definition process

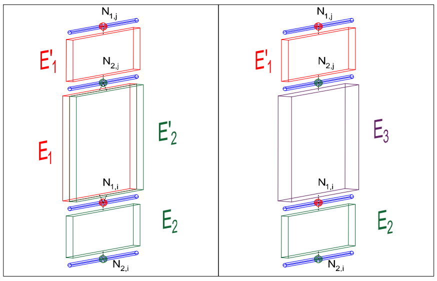

Figure 4.6. Type 2 connection procedure

The interaction between **façade walls and those in parallel to them** is modelled by vertical elastic frame elements, with 6 DF, connecting the nodes of the respective walls of adjacent buildings, distributing stresses in each wall – Figure 4.7.

Since walls from adjacent buildings are defined in different vertical alignments, although in the same plane, the element definition procedure can be done in a process analogous to that described before, now

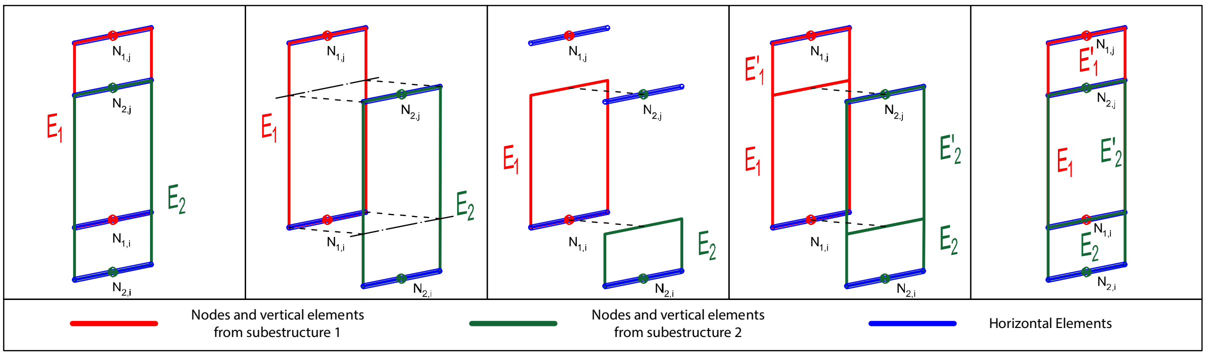

Figure 4.5. Type 1 connection procedure

accounting for local coordinates of the elements on the walls of the copied building.

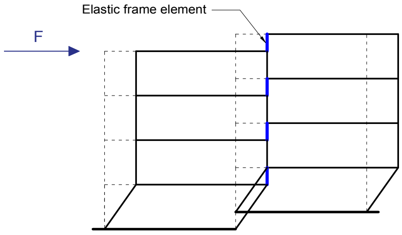

Figure 4.7. XZ plane interaction

Finally, the finished model is **exported** to a new text file, allowing for it to be opened in TreMuri.

4.2.4 Graphical User Interface (GUI)

To allow an accessible use of the program, a graphical user interface (GUI) was developed, incorporating all the routines described above, allowing an accessible approach to the problem in question. Each step is organized and arranged so that the procedure is continuous and coherent.

Furthermore, routines were developed to allow two and three-dimensional visualization of the mesh, as presented in Figure 4.8.

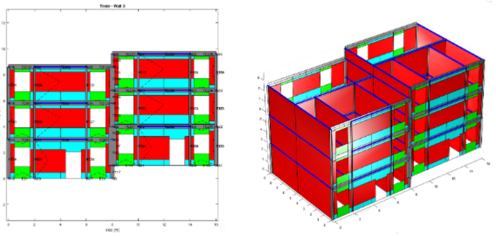

Figure 4.8. GUI two and three-dimensional visualization of ME mesh (MATLAB)

4.2.5 Verification and Validation

Verification of the program is carried out in each step of its development, certifying that the routines work in a systematic and predictable way according to the conditions and procedures described above. Validation is done by comparing the results from modal and pushover analyses performed on three test models: isolated building, aggregate with interaction only on X direction and aggregate with interaction on both directions (type 2 connection on Y direction). Both are described with detail in [21].

4.3 Model Definition

Two types of models were defined, for each case: (i) isolated building; and (ii) building aggregate. The modelling of the aggregate was based on the modification of the ME mesh obtained in the definition of the isolated building model, using the developed MATLAB program.

4.3.1 Isolated Building Model

Material properties were based on EN 1998-1 [3], NTC 2008 [16] and studies of other “de Placa” buildings [14, 22], and are presented on Table 4.1. Resistant values were reduced by a “knowledge factor” of 1.35, defined by EN 1998-3 [15], which depends on existing knowledge about the structural material conditions. The Young and distortion moduli were calibrated based on results obtained *in situ* tests performed by [14], and frequencies obtained by modal analyses performed on the aggregate model [21].

Table 4.1. Material properties

Material	w ***[kN/m³]***	E ***[GPa]***	G ***[GPa]***	f_m ***[MPa]***	τ ***[MPa]***
Stone Masonry	21	0.82	0.27	1.73	0,057
Solid Brick Masonry	18	3.40	1.13	5.32	0,020
Hollow Brick Masonry	15	1.80	0.60	1.22	0,020
Concrete blocks Masonry	14	2.15	0.89	4.30	0,178
Concrete C16/20	25	21.75	9.06	24.0	-
Steel S235	78	210.0	80.77	126.7	-

The **resistant walls** and RC **frame elements** are defined based on the structural plans, obtained in the municipal archives of Lisbon. Doors and windows are defined as **openings**. **Floors** and **stairs** are defined as rigid diaphragms, 0.10 m thick.

The values of the **permanent and live loads** are defined based on the building descriptive memory, the Technical Charts [22] and EN 1991-1-1 [23], according to the most conditioning situation.

A 3D view of the model is presented in Figure 4.9.

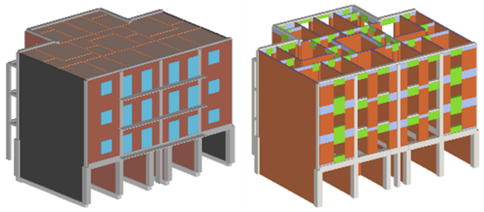

Figure 4.9. Isolated building model: 3D structure and ME mesh view (3Muri, commercial version)

4.3.2 Aggregate Models

Two different structural aggregate models were defined: one with uneven floor levels between adjacent buildings and one with all the floors even – Figure 4.10.

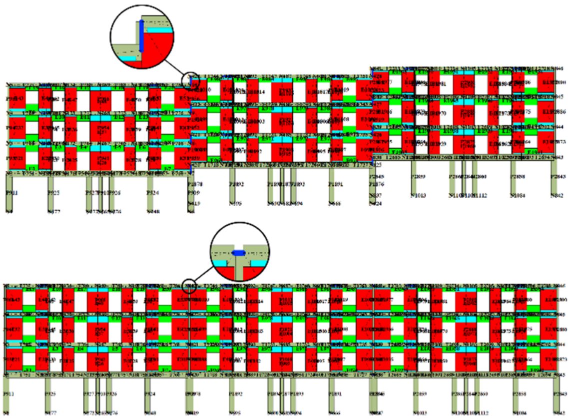

Figure 4.10. Main façade view of aggregate models: uneven and even floors (TreMuri, scientific version)

Since there is no connection between side walls from adjacent buildings, interaction in their plan is not considered. Thus, each side wall acts as an independent structure in the YZ plane.

5 Seismic Assessment

In the present work, it is important to highlight the impact of considering the surroundings in the evaluation of the seismic performance of a structure. As such, pushover analyses are performed in 3 different situations (Figure 5.1): (a) isolated building; (b) aggregate as a set of adjacent buildings, considering the overall behaviour 3 adjacent buildings; and (c) building inserted in aggregate, considering the aggregate interaction, but plotting the capacity curve in terms of basal shear force and top displacement of the study building only.

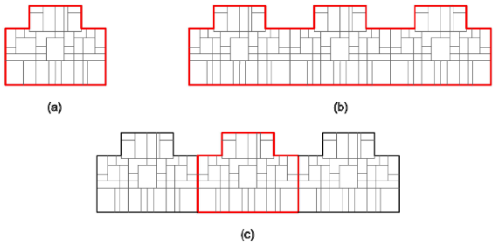

Figure 5.1. Analysed situations

The **seismic action** is defined through an acceleration response spectrum. EN 1998-1 [3] considers two types of earthquakes: type 1 and type 2. According to different studies performed on mixed masonry-RC buildings situated in Alvalade neighbourhood [13, 14], type 1 earthquake proves to be the most conditioning. Therefore, within the scope of this work, seismic action is defined based on the type 1 earthquake.

Analyses were performed for each main direction of the building and considering two load cases: (i) triangular, proportional to the product between the mass and height and (ii) uniform, proportional to the mass. The ultimate displacement was defined by two different criteria: (i) development of a collapse mechanism and (ii) reduction of 80% of the maximum base shear force. According to the Norm NP EN 1998-3 [15], existing masonry buildings must be evaluated to the Limit State of Significant Damage.

5.1 Results – Impact of Surroundings

To study the impact of the surroundings in seismic assessment of a “de Placa” building, results are compared between the isolated building model and for the building inserted in aggregate. The plotted capacity curves for the most conditioning load cases, for each model, are presented in Figure 5.2.

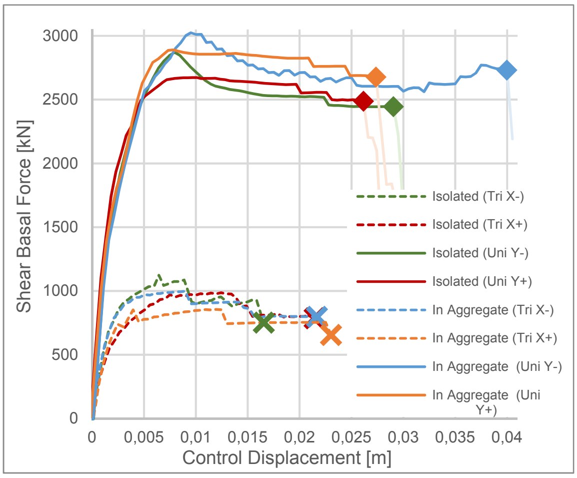

Figure 5.2. Capacity curves for pushover analyses performed on isolated and aggregate building models

For both situations the resistant capacity of the building is greater in the Y direction, since the walls aligned in the X direction have more openings, which contributes to a decrease in global rigidity in this direction [13, 14].

On X direction, triangular load distribution seems to be more conditioning. It is possible to verify a reduction of the resistant capacity of the structure when considering the interaction between adjacent buildings, which can be justified by the rupture of masonry elements by shear in the rear façade. However, the structure exhibits more ductility in this direction because of the aggregate arrangement, which allows a distribution of the forces through the walls of the various buildings. Analyzing Figure 5.3, it is verified that there is localized damage at the ends of the walls with connections to those of adjacent buildings, due to stress resulting from the difference in height between buildings. Bending yielding damage is extensive in the interior wall, a typical behavior exhibited by slender elements, whereas the façades, with less slender elements, exhibit shear yielding damage.

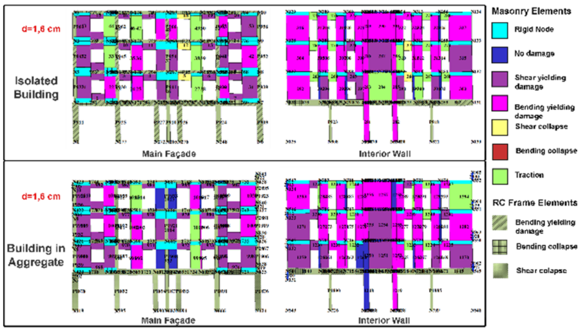

Figure 5.3. Damage patterns of main X walls for ultimate displacement from isolated model, for both situations

As for Y direction, the capacity of the building depends strongly on the load distribution, with soft-storey collapse forming in interior walls when uniform load distributions are applied, exhibiting less ductile behavior. Contrary to what happens in X direction, there is an increase in the building's resistant capacity when considering the aggregate interaction. This is justified by the methodology adopted in the calculation of the basal strength of the building. Since it is calculated as the sum of the base reactions of each wall, the existence of overlapping side walls in the same vertical alignment, resulting from the modelling hypotheses, contributes to an increase of the total basal force of the building.

Moreover, for the isolated building model, the main façade appears to influence significantly the global capacity of the structure, which was concluded by analyzing correlations between global and single walls capacity curves. When the adjacent building interaction is considered, the rear façade appears to gain influence, while the main façade has no significant role on the main capacity. This is because rear façades are not connected with adjacent buildings, since they lie on the building's protrusion, not being able to distribute stresses between buildings, while sustaining significant damage.

The seismic performance was assessed for the two models in study, using N2 method, considering the most conditioning situations for each direction. The safety verification criterion is based on the ratio between the ultimate and target displacements. Results are presented in Figure 5.4.

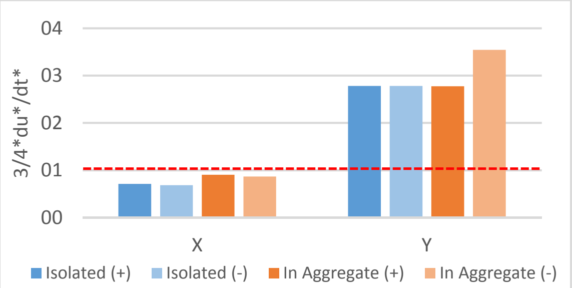

Figure 5.4. Seismic performance-based assessment (surrounding impact)

The consideration of surroundings in the modeling of the building leads to less conditioning situations, with greater ratios verified between ultimate and target displacements in both directions. The increased ductility and stress redistribution due to the interaction between walls of adjacent buildings is a beneficial effect in the safety check. For, Y direction, safety is always verified, regardless of the situation.

5.2 Results – Impact of different levels

Figure 5.5 shows the capacity curves obtained through the most conditioning load distributions, for both even and uneven floor level building models.

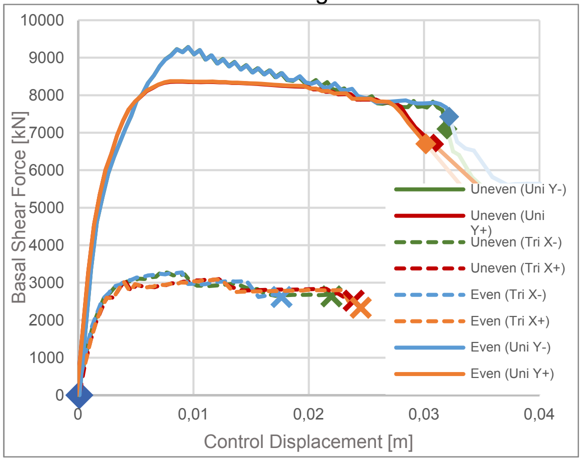

Figure 5.5. Capacity curves for pushover analyses performed on uneven and even adjacent building aggregates

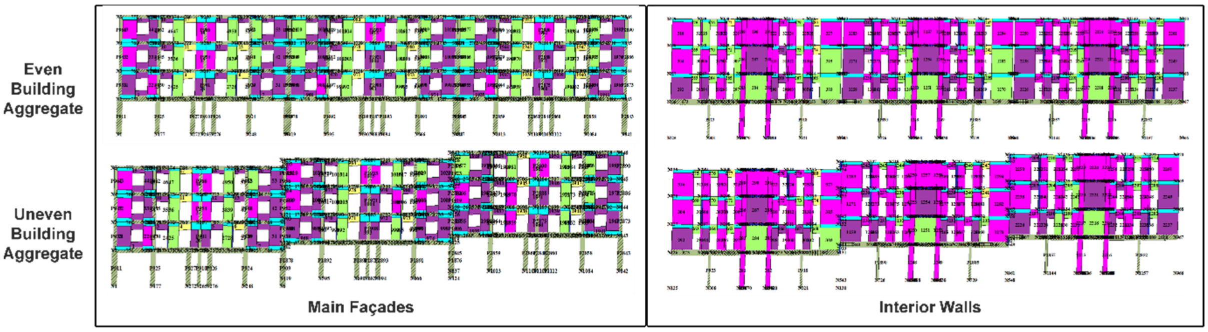

Figure 5.6. Damage patterns of main X walls for ultimate displacement from isolated model, for both situations

The difference in overall behaviour between the structures is practically non-existent, in the elastic phase. This can be justified by the reduced difference of floor levels between the floor.

However, for ultimate displacements in each situation, there are some differences, although not significant, between the damage patterns in the main walls, as can be seen in Figure 5.6. In the main façade, it is possible to identify an apparently identical distribution of damages in each building, with plastic damages mostly due to shear, in the even floor aggregate. When considering the difference between floor levels, plastic damage by bending is verified in the elements close to the connections between buildings, justified by the moments that develop in this situation, due to the impact of the adjacent building's floors. In the case of the interior wall assembly, the damage distribution seems to be conditioned in the same way, with damage being observed in piers near adjacent buildings.

Analysing Figure 5.7, safety check is conditioned by the direction of application of the force distribution, in X direction. In fact, there is a significant difference between the results obtained for any distribution of forces, according to the direction of application of the loads, in the model of uneven buildings. Since the unevenness gives asymmetry to the set of buildings in band, the direction of application of the loads conditions the performance of the structure.

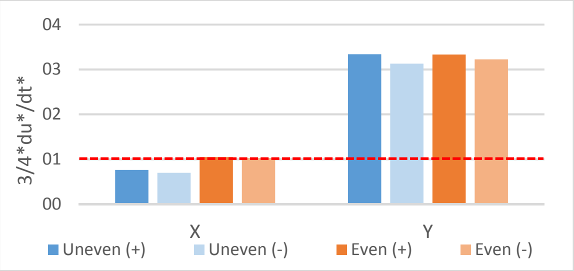

Figure 5.7. Seismic performance-based assessment (floor level impact)

As for the Y direction, the differences between ratios are not significant, and safety is verified in any situation. In fact, for the study building, the Y-resistant strength is sufficient to verify safety whatever the assumptions considered in building modelling.

6 Conclusions

This work focused mainly on the development of a tool that would assist on the definition of suitable ME meshes in the modelling of masonry structures, considering surrounding conditions, in the 3Muri / TreMuri program. The tool developed allowed the study of the impact of the aggregate influence in the seismic assessment of a mixed masonry-RC building, validating the assumed hypotheses.

It was found that the study building has bigger capacity in Y direction, due to high stiffness and strength conferred by the walls aligned in that direction. Load distributions seem to condition the seismic performance, with soft-storey collapse mechanisms forming in the interior walls with uniform loads. Aggregate interaction introduces a ductility to the structure, in the X direction, justified by the possibility of distributing forces between adjacent walls.

Regarding the difference of dimensions between adjacent buildings, it is concluded that, for the study building, its influence does not introduce significant changes in the overall behaviour of the structure. There are, however, different patterns of damage to the main walls, especially on the interior walls of the building.

The seismic performance evaluation shows that the structure verifies the safety in the Y direction, in any given situation. In the X direction, verification depends greatly on the situation under consideration. It is also interesting to verify that the safety check of the uneven aggregate depends significantly on the direction of the distribution of forces due to its asymmetry.

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