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AN APPROACH FOR DERIVING FRAGILITY CURVES OF MASONRY BUILDINGS IN AGGREGATES

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Abstract

Italian historical centers are generally characterized by unreinforced masonry buildings arranged in aggregate configurations. Past and recent earthquakes have underlined the susceptibility of these buildings to out-of-plane failure mechanisms involving their perimeter façades. Recent studies have pointed out the important role of the mutual interaction among masonry units arranged in aggregate configurations (called aggregate effect). Indeed, depending on the construction history of buildings, the connection among adjacent structural units of masonry buildings in aggregate configurations could particularly influence their seismic safety level toward the occurrence of out-of-plane mechanisms. This aspect then plays a paramount relevance for the derivation of reliability fragility curves at the regional scale of Italian historical centers. The aim of this study is to propose an approach for the evaluation of fragility curves for the most probable out-of-plane mechanisms of the perimeter façades of buildings in aggregate configuration taking into account the mutual interaction among adjacent buildings. The proposed approach is here applied to the buildings of a historical town of Central Italy.

Keywords: Fragility Curves, Unreinforced Masonry Building, Out-Of-Plane Mechanisms, Aggregate Configuration, Historical Center.

1. INTRODUCTION

The large-scale seismic vulnerability assessment of masonry building aggregates of historical centres represents, in Italy and in many other European countries, a complex and challenging task, since these centres are the result of an unplanned and discontinuous urban evolution process. Due to such a process, the historical building aggregates are generally characterized by adjacent structural units with heterogeneous structural and typological features, often built sharing the boundary transverse walls. Within a structural aggregate, indeed, it is possible to recognize structural units built before the others - original units - and units built subsequently, by growth or clogging (see Figure 1), between existing walls, called growth and saturation structural units, respectively [1].

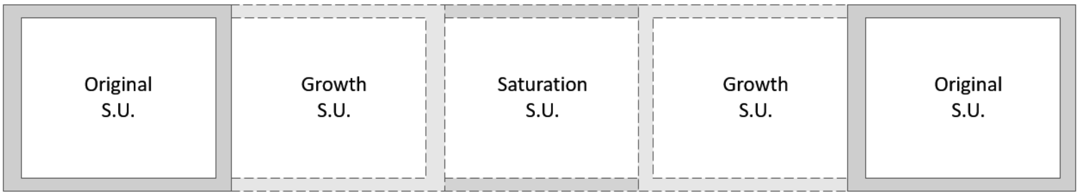


Figure 1: Illustrative scheme of the evolution of a building aggregate.

Each unit, in the event of an earthquake, can mutually interact with the adjacent ones by leading to the so-called *aggregate effect* [2,3]. The connection among adjacent structural units could significantly affect the seismic response of a building in aggregate configuration. In addition, in most cases the structural aggregates were built without taking into account any anti-seismic criterion. Consequently the single structural units composing an aggregate often are lacking in specific construction details necessary to ensure a “like-box” behavior of their structure [4]. Therefore, the façade walls of buildings of historical centres are particularly vulnerable to the out-of-plane failure mechanisms, as shown by the recent earthquakes that struck Italy [5,6].

For the planning of prevention and mitigation actions at a large scale, aimed to safeguard the building heritage of the historical centres, is of fundamental importance to predict the potential damages that buildings may suffer after a seismic event of a certain intensity. The fragility curves are one of the most adequate and useful tools employed to this purpose, as evidenced by numerous studies available in the current literature [7–10].

In the context of historical centres, the knowledge of the main properties characterizing the buildings composing these centres and the *aggregate effect* play a paramount role in the derivation of reliable fragility curves with regards to the out-of-plane mechanisms.

This work proposes a simplified approach for deriving fragility curves for the most probable out-of-plane mechanisms of the façade walls of unreinforced masonry buildings arranged in aggregate configuration on the basis of a preliminary knowledge process by taking into account the possible *aggregate effect* between adjacent units. The approach considers the non-linear kinematic analysis method and allows to consider the *aggregate effect* in terms of frictional forces acting at the interconnecting blocks between the façade wall subject to the mechanism and the adjacent structural units.

Then, the paper presents an application of the proposed approach to the buildings belonging to the two structural typologies most recurrent in the historical centre of Sora, a medium size town of Central Italy, herein assumed as case study. The two building typologies have been identified within the CARTIS project (DPC/ReLUIS 2019–2021), a research project promoted by the consortium RELUIS (the Network of University Laboratories of Earthquake Engineering) in collaboration with the Italian Department of Civil Protection (DPC), with the aim to develop a database where store data on the structural and typological features of Italian ordinary buildings [11]. The proposed approach is illustrated in Section 2. The application to the case study is reported in Section 3.

2. PROPOSED APPROACH

Starting from the knowledge of the building typologies of the area under study, in terms of geometrical and mechanical features, and structural details, the proposed approach aims to derive the fragility curves of unreinforced masonry buildings arranged in aggregate configuration, with specific reference to out-of-plane collapse mechanisms. The approach is articulated in six steps:

1. identification of the most probable out-of-plane mechanism for the buildings belonging to each typology;
2. subdivision of the buildings belonging to each typology into building categories having the same number of floors and the same most probable out-of-plane mechanism and subsequent generation, for each defined category, of virtual buildings through a Monte Carlo method;
3. nonlinear kinematic analysis of each virtual building for the evaluation of the capacity curves of the mechanisms;
4. selection, through the technique of disaggregation of the seismic hazard of the site [12], of natural spectra compatible with target spectra of the site under examination and subsequent derivation of the corresponding ground spectra and floor spectra, depending on whether the out-of-plane mechanisms occur at the base of the ground floor of the building ($z=0$) or at the base of upper floors ($z>0$), respectively;
5. definition of Damage Indices for two damage state (DS), the first corresponding to the achievement or exceeding of the Damage Limit State (DS1) and the second corresponding to achievement or exceeding of the Safeguard Life Limit State [13] (DS2);
6. evaluation, for each building category, of the fragility curves for the two considered damage states.

Each step is described in details in the following subsections.

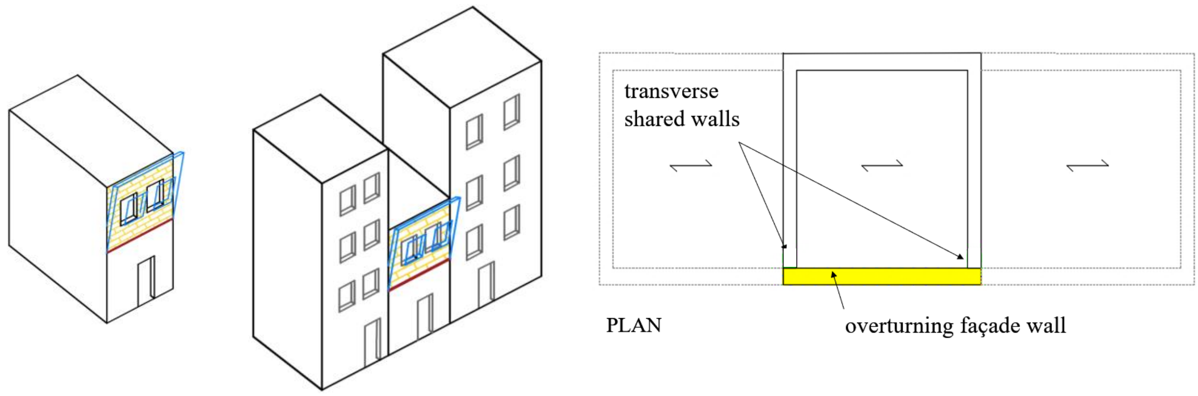
2.1 Identification of the building categories and generation of virtual buildings

The proposed approach starts with a qualitative vulnerability analysis of the buildings belonging to each examined typology, aimed at identifying the most probable out-of-plane mechanisms in case of seismic events. The qualitative analysis proposed in [14], is carried out by comparing the typological and the constructive features of each building with those that predispose or prevent the activation of a certain mechanism. The necessary data for the identification can be obtained through a quick survey on sight supported by historical archival researches and by the employment of interactive online maps or databases that report the typological-structural characteristics of the national building heritage.

The approach continues with the second step which consists in dividing each building typology into categories on the basis of the most probable out-of-plane mechanism and the number of storeys and, then, in generating virtual sets of buildings for each defined category. The objective of this step is to determine the categories of buildings to analyze and consider in the procedure the uncertainty due to the randomness of the characteristics of the buildings. To this purpose a total of 3000 buildings are simulated with the Monte Carlo Method, by considering as aleatory variables the parameters that mostly affect the out-of-plane capacity, i.e. the wall thicknesses s, the storey heights h, the percentage of holes in the façade b and the compressive strength of the masonry f_c.

2. 2 Nonlinear kinematic analysis of the mechanisms

For each building category, the third step of the proposed approach is devoted to evaluate the capacity curves of the generated buildings by adopting the nonlinear kinematic analysis [13]. The curves are derived firstly with reference to the façade wall in isolated configuration (see Figure 2a), assuming the hypothesis of rigid block, no-tensile strength, limited compressive strength [15] and absence of sliding between blocks. Then, the *aggregate effect* among contiguous structural units is introduced [3] referring to the aggregate depicted in Figure 2b, in which the central unit is built in adherence with the adjacent ones by sharing the boundary walls. By neglecting the hypothesis of absence of sliding between blocks, the interaction effect is introduced in terms of frictional forces acting on the interconnecting semi-blocks that connect the overturning façade wall both with the transverse walls, shared with the adjacent units, and with the side coplanar façade walls. Three possible types of interaction are examined: 1) the portion of the overturning façade is connected only to the transverse walls and, consequently, the frictional forces act at the interconnection semi-blocks along these walls (see Figure 3a); 2) the portion of the overturning façade is connected to the side walls of the adjacent units through side blocks (see Figure 3b); 3) the portion of the overturning façade is connected both to the transverse adjacent walls and to the coplanar walls (see Figure 3c).



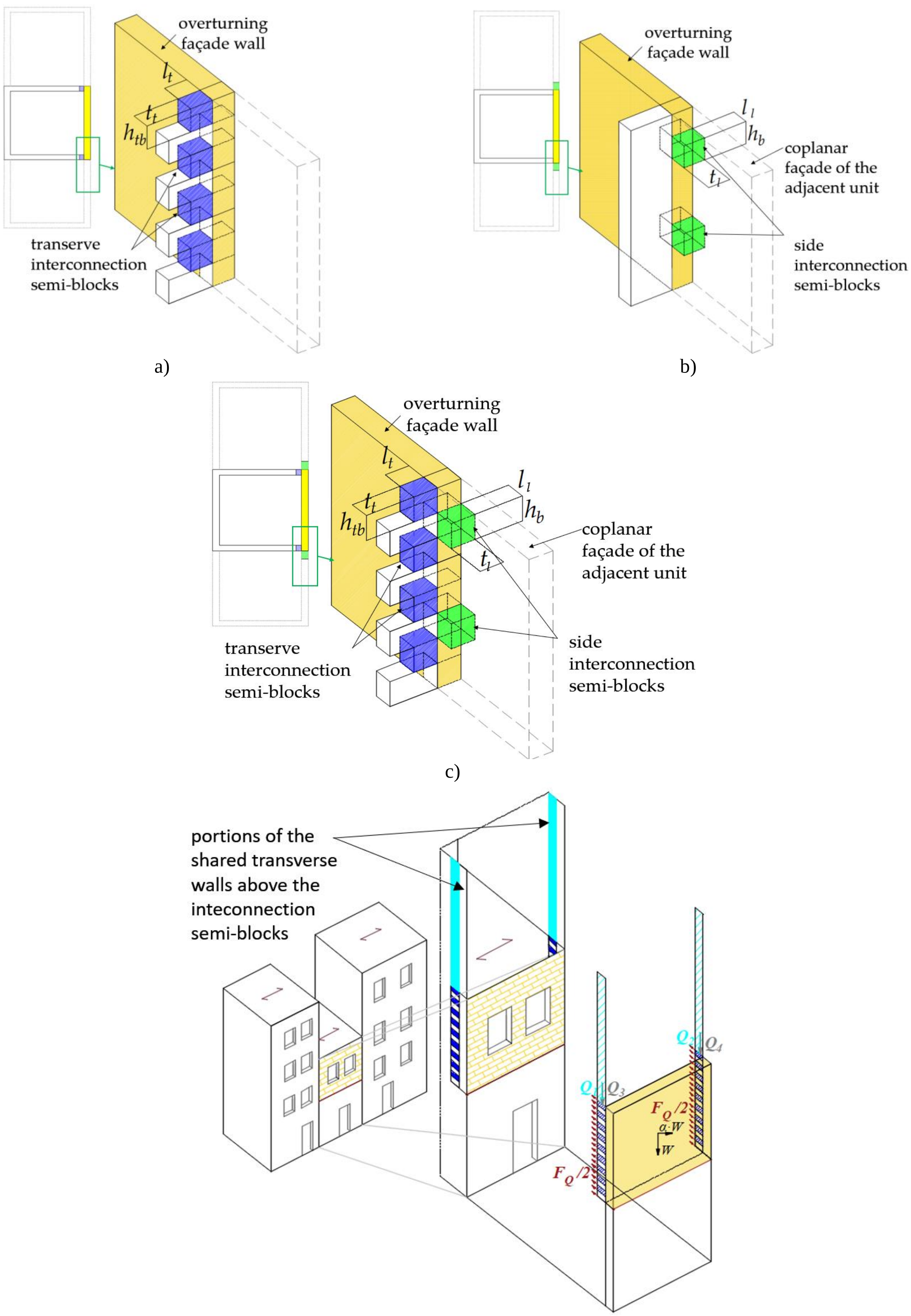
a) b)

Figure 2: Structural unit: a) in isolated configuration; b) in aggregate configuration.

Specifically, with reference to a structural unit included between two buildings of greater height (Figure 2b), the resultant of the friction forces, F, can be evaluated through the following expression:

$$F = F_i + F_q \tag{1}$$

where:


overturning façade wall
l_t
t_t
h_{tb}
transerve interconnection semi-blocks
overturning façade wall
l_l
h_b
t_l
coplanar façade of the adjacent unit
side interconnection semi-blocks
overturning façade wall
l_t
t_t
h_{tb}
l_l
h_b
t_l
coplanar façade of the adjacent unit
transerve interconnection semi-blocks
side interconnection semi-blocks
portions of the shared transverse walls above the inteconnection semi-blocks
Q_1
Q_2
Q_3
Q_4
$F_Q/2$
$F_Q/2$
$\alpha \cdot W$
W

a) b)

c)

d)

Figure 3: a) 3D and plan views of the interaction between the overturning façade and the transverse walls; b) 3D and plan views of the interaction between the overturning façade and the coplanar walls of the adjacent structural units; c) 3D and plan views of the interaction between the overturning façade and the transverse and the coplanar walls of the adjacent structural units; d) friction forces due to overloads acting on the semi-blocks.

- F_i is the resultant of the friction forces acting at the interconnection blocks between the façade wall and the wall of the adjacent units due to the weights of semi-blocks, given by the following equation [16]

$$F_i = \sum_{i=1}^{n} f_i = \mu \cdot w_b \cdot \frac{n \cdot (n+1)}{2}; \tag{2}$$

- F_q is the resultant of the friction forces acting at the interconnection semi-blocks between the wall and the wall of the adjacent units due to the overloads Q_i acting on the interconnection semi-blocks, given by the following equation

$$F_q = \mu \cdot \sum_{i=1}^{n} Q_i. \tag{3}$$

In eqns 2 and 3:

- μ is the friction coefficient between the blocks [13];
- n is the number of rows of blocks crossed by the vertical crack line, equal to h/h_b, being h the height of the overturning portion of the wall and h_b the height of the block (see Figures 3a, b, c);
- Q_i represents the generic overloads acting on the interconnection semi-blocks, due both to the weights of the portion of the walls placed above the interconnection semi-blocks, respectively on the right and on the left side of the façade and to the loads transmitted to the interconnection semi-blocks by the slabs (see Figure 3d);
- w_b is the weight of the generic interconnection semi-block, given by the expression:

$$w_b = \gamma_m \cdot t \cdot h_b \cdot l \tag{4}$$

where:

- γ_m is the specific weight of the masonry;
- t is the thickness of the interconnection semi-block, equal to the thickness t_t of the transverse wall or to the thickness t_l of the coplanar side wall (see Figures 3a, b, c);
- l is the length of the contact surface between two overlapped blocks, equal to l_t in case of transverse connection or to l_l in case of lateral connection (see Figures 3a, b, c), respectively.

2.3 Selection of seismic input

The fourth step of the proposed approach is finalized to derive the seismic demand by selecting natural accelerograms of characteristics compatible with the seismicity of the site under examination. To this purpose, the reference spectra (target spectra) for the site are firstly defined according to the Italian Code for eight different return periods TR, equal to 30, 50, 72, 101, 140, 201, 475, 975 years. Then, the selection of natural records is carried out by using the technique of disaggregation of the seismic hazard of the site under examination [17] in order to obtain groups of records which have characteristics similar (in terms of magnitude and distance) to those coming from the disaggregation. Successively, combinations of natural accelerograms compatible with the target spectra are defined.

In particular, the compatibility is imposed on the target spectra in such a way that the average spectrum derived by natural records is included, at a predetermined range of periods, within a tolerance band, having as lower extremum -10% and as upper extremum +30% [18]. The predetermined range of periods corresponds to the range of the fundamental periods of the buildings [19], in the case the mechanism occurs at a certain altitude, z, from the ground floor (z>0), or to the range of periods characteristic of mechanisms [13], in the case the mechanism occurs at z=0.

Next, for each spectra combination, the average spectra and those corresponding to the 84th and the 16th percentile of the selected ones are evaluated.

In the end, from the spectra obtained in terms of acceleration, the corresponding displacement spectra are derived in terms of:

- ground displacement spectra for the study of the collapse mechanisms occurring at the base of the ground floor of the building (z = 0),
- floor displacement spectra [13] for the analysis of the mechanisms activating at the upper floors (z > 0).

2.4 Definition of the Damage Indices

The approach is developed to provide the fragility curves with reference to two distinct damage state in compliance to the current guidelines of Italian Code: the first, here named DS1, corresponds to the formation of the first cracks, at the achievement or exceeding of the Damage Limit State; the second, here named DS2, corresponds to the collapse due to the achievement or exceeding of the Safeguard Life Limit State [13]. To this aim, the fifth step here described is devoted to the evaluation, for each damage state, of a Damage Index, DI_{DSi}, given by the ratio between the maximum displacement demand request to the out-of-plane mechanism for the given DS and the corresponding damage threshold, namely d_{DSi}.

The maximum displacement demand is evaluated through the Capacity Spectrum Method [20] by using the spectra obtained from the previous step.

Concerning the damage thresholds:

- the threshold of the DS1, is assumed equal to:

$$d_{DS1}=d_y, \quad (5)$$

where d_y is the spectral displacement corresponding to the Damage Limit State SLD proposed by the Italian Code, given by the intersection between the capacity curve of the mechanism and a pseudo-elastic branch (see Figure 4);

- the threshold of the DS2, is assimilated to the displacement corresponding to the achievement of the Safeguard Life Limit State, SLV, assuming:

$$d_{DS2}=d_u=0.4 \cdot d_0 \quad (6)$$

where d_0 is the spectral displacement corresponding to a spectral acceleration equal to zero (see Figure4).

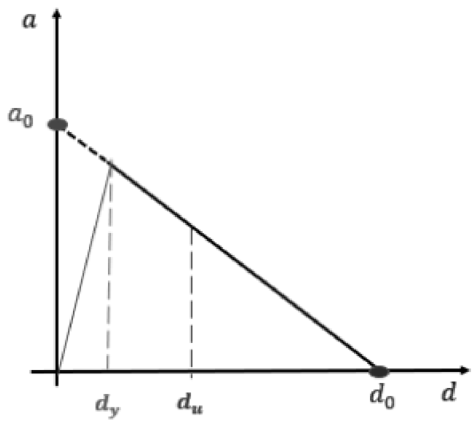


Figure 4: The damage thresholds of the considered damage states.

2.5 Evaluation of the fragility curves

The last step of the proposed approach involves the construction of fragility curves of each identified category. To this purpose, by considering the Peak Ground Acceleration, PGA, as indicative parameter of the intensity of the seismic input and by assuming for the variable DI_{DSi} a log-normal distribution conditioned on a given value of PGA, the fragility curves for each damage state are evaluated according to the following equation [21]:

$$f_{DSi} = p\left(DI_{Dsi} \geq 1_{|PGA}\right) = 1 - \Phi\left(\frac{ln1 - \mu_{lnDI_{Dsi|PGA}}}{\sigma_{lnDI_{Dsi|PGA}}}\right) = \Phi\left(\frac{\mu_{lnDI_{Dsi|PGA}}}{\sigma_{lnDI_{Dsi|PGA}}}\right) \quad (7)$$

where:

- $\Phi[\bullet]$ is the lognormal standard distribution function,
- $\mu_{lnDIiIPGA}$ is the mean value of the natural logarithm of the variable DI_{Dsi} conditioned on the given value of PGA,
- $\sigma_{lnDIiIPGA}$ is the total dispersion of the natural logarithm of the variable DI_{Dsi} conditioned on the given value of PGA.

The conditional mean values of the natural logarithm of the variable DI_{Dsi} are defined by performing a linear regression of the logarithm of the damage indices, obtained in the step five, versus the logarithm of the values of PGA used for the evaluation of the seismic demand in the step four (see Figure5). From the regression, indeed, it is possible to estimate the logarithm of the limit state variable DI_{DSi} conditioned on the level of PGA through the expression [22]:

$$\mu_{lnDI_{Dsi|PGA}} = A_{Dsi} + B_{Dsi} \cdot ln\,(PGA) \quad (8)$$

where A_{DSi} and B_{DSi} are coefficients obtained by the linear regression.

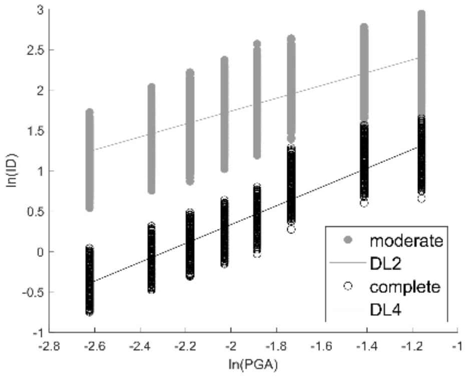


Figure 5: Linear regression of the logarithm of DI versus the logarithm of the PGA.

The total dispersion values are evaluated as:

$$\sigma_{lnDI_{DSi|PGA}} = \sqrt{\sigma_{mDSi}{}^2 + \sigma_{rtrDSi}{}^2} \quad (9)$$

where:

- σ_{mDSi} is the modelling uncertainty which takes into account for both the variability of the characteristics of the buildings and the variability of the accuracy of the analytical model adopted to capture the behavior of the buildings;
- σ_{rtrDSi} is the uncertainty related to record-to-record the variability of the natural seismic records [23].

The modelling uncertainty values are estimated by applying the following relation [24]:

$$\sigma_{mDSi} = \sqrt{\frac{\left(\sum_i^{nPGA} lnDI_{DSi} - \mu_{lnDI_{DSi|PGA}}\right)^2}{n-2}} \quad (10)$$

where:

- *nPGA* is the number of PGA considered for the evaluation of the seismic demand;

- DI_{DSi} is the i-th damage state evaluated by considering the average spectra of the selected records;

- *n* is the number of the generated virtual buildings.

The record-to-record dispersions, instead, are estimated through the following formula [25]:

$$\sigma_{rtrDSi} = \frac{1}{2} \cdot \left| \overline{lnDI_{DSi\,16}} - \overline{lnDI_{DSi\,84}} \right| \tag{11}$$

where $\overline{lnDI_{16}}$ and $\overline{lnDI_{84}}$ are the mean values of the natural logarithm of the Damage Indices evaluated by considering the 16th and the 84th percentile of the selected spectra, respectively.

3. APPLICATION TO THE CASE STUDY

The proposed approach has been applied to define the fragility curves of the building populations generated on the basis of the characteristics of samples of buildings belonging to the typologies identified in the historical centre of Sora in province of Frosinone, here assumed as case study. In this historical centre, investigated within the CARTIS project (DPC/ReLUIS 2019-2021), two masonry building typologies have been recognized. The first typology, named “MUR1”, is characterized by buildings made of irregular masonry with rubble rough stones, with the age of construction prior to 1860 and mostly with wooden slabs. The second typology, named “MUR2”, presents buildings made of regular masonry with square stones, built between 1861 and 1945, mainly characterized by slabs in hollow core concrete. Both the typologies are characterized by buildings of 2 and 3 floors, with an average height of the floors between 2.50 m and 3.49 m, which have residential, commercial or storage use and slabs and roofs parallel oriented to the façade.

The application of the first step of the approach to the samples of buildings belonging to each typology, allowed to gather the buildings of the two typologies in ten building categories, as reported in Table 1: one category for the global simple overturning mechanisms (“GOi”); three categories for the simple partial overturning (“POi_j”); two categories for the global overturning along the openings (“GOAOi”); two categories for the horizontal bending (“HBi”) and two categories for the vertical bending (“VHi”). The index “i” in the labels of categories indicates the number of storeys of the buildings belonging to the considered category, while “j” indicates the floors involved in the simple partial overturning mechanisms.

Category	OOP Mechanism	Number of floors
GO3	global simple overturning	3
PO2_2	simple partial overturning of the 2nd level	2
PO3_3	simple partial overturning of the 3rd level	3
PO3_2-3	simple partial overturning of the 2nd and the 3rd level	3
GOAO2	global overturning along the opening	2
GOAO3		3
HB2	horizontal bending	2
HB3		3
VB2	vertical bending	2
VB3		3

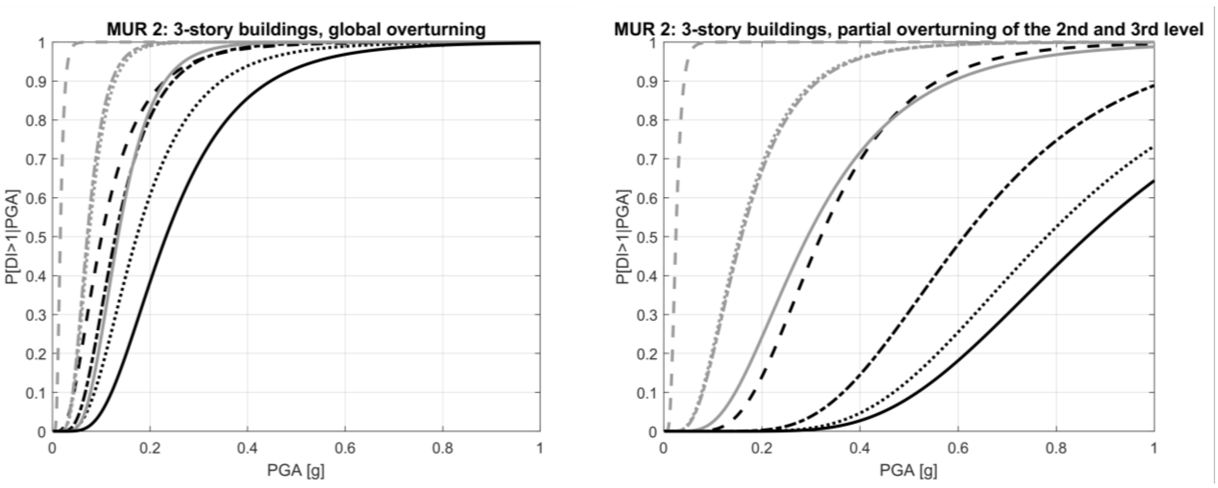
Table 1: Building categories identified in the historical centre of Sora.

With reference to the building categories susceptible to the overturning mechanisms, for each of two typologies, virtual populations of 3000 buildings have been generated by applying the second step of the approach. Subsequently, for each category, the capacity curves for each generated building have been evaluated by performing the nonlinear kinematic analysis of the wall portion involved in the mechanism. In particular, the curves have been obtained both with reference to the wall in isolated configuration and in aggregate configuration, by considering the three types of connections foreseen in the approach. Next, according to the step four, eight combinations of seven spectra, derived by natural records, have been selected for each considered damage state and for each investigated building category through the software REXEL, freely available on the site of the Italian Network of University Seismic Engineering Laboratories (RELUIS, http://www.reluis.it/) [26].

Subsequently, the damage thresholds, the maximum demands required to the mechanisms and the related damage indices, DI_{DSi}, have been determined according to step five, for each category and for both damage states considered within the approach, with reference to both isolated and connected walls configurations, in order to define the corresponding fragility curves according to the step six of the proposed approach.

The obtained fragility curves for the categories of 3-storey buildings belonging to the "MUR2" typology and prone to the global and partial overturning of the 2nd and 3rd level are reported in Figures 6a and 6b, respectively. In each figure:

- the curves DS1_i and DS2_i are the ones obtained by considering the façade wall in isolated configuration, for moderate damage DS1 and complete damage DS2, respectively,
- the curves DS1_tc and DS2_tc are the ones obtained by considering the façade wall connected with the transverse walls for moderate damage DS1 and complete damage DS2, respectively,
- the curves DS1_sc and DS2_sc are the ones obtained by considering the façade wall connected with the side coplanar walls for moderate damage DS1 and complete damage DS2, respectively,
- the curves DS1_tsc and DS2_tsc are the ones obtained by considering the façade wall connected with both the transverse and side coplanar wall for moderate damage DS1 and complete damage DS2, respectively.



a) b)

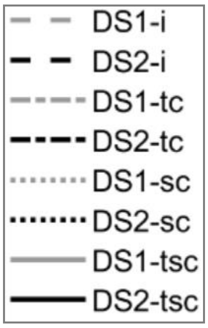


Figure 6: Fragility curves for 3-storey buildings belonging to the “MUR2” typology and susceptible to: a) the global overturning; b) the partial overturning of the 2^{nd} and the 3^{rd} level.

From Figure 6, it is possible to observe that by introducing in the analysis the interaction between the façade wall overturning with adjacent ones, due to the aggregate configuration, the vulnerability of the overturning mechanisms reduces, for both the damage states, i.e. each of them is reached for higher PGA values. The curves related to the configuration with side connection are less vulnerable than those related to the case with transverse connection. If both types of connections (transverse and side) are present, the vulnerability is further reduced.

CONLUSIONS

The research activity presented in this work has proposed an approach for the evaluation of fragility curves for the most probable out-of-plane mechanisms of the perimeter façades of buildings in aggregate configuration taking into account the mutual interaction among adjacent buildings. To this purpose, the contribution of friction developing at the connections between the façade wall prone to the failure and the walls of adjacent buildings has been introduced in the analysis.

Then, the approach has been applied to derive the fragility curves of unreinforced masonry buildings of two and three storeys susceptible to the overturning mechanisms and representative of the historical centre of Sora, a town of Central Italy. The obtained results in terms of fragility curves highlight the beneficial influence of the *aggregate effect* on the out-of-plane vulnerability of buildings in aggregate configuration.

The proposed approach represents a practical tool to carry out a large-scale vulnerability assessment of specific geographical area with reference to two distinct damage levels in compliance to the current guidelines of Italian Code: the first corresponding to the formation of the first cracks, at the achievement or exceeding of the Damage Limit State, and the second corresponding to the collapse due to the achievement or exceeding of the Safeguard Life Limit State. In addition, it should be noted that the proposed approach allows to evaluate the fragility curves depending on the specific type of out-of-plane mechanism (global overturning, partial overturning or overturning along the openings) and the specific number of floors of the buildings. For its application, the presence of specific databases able to provide data at territorial scale on the ordinary masonry buildings, as that one developed within the research project CARTIS (DPC/ReLUIS 2019-2021, DPC/ReLUIS 2022-2024), are of fundamental importance for the construction of reliable fragility curves.

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