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COMPARATIVE ANALYSIS AMONG DIFFERENT ANALYSIS PROGRAMS FOR SEISMIC VULNERABILITY EVALUATION OF A MASONRY BUILDING COMPOUND IN THE DISTRICT OF NAPLES

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Abstract

Masonry building compounds are sets of structural units having at least one common wall. The numerical analysis of the structural units grouped in aggregate, which are very diffused in Italian historical centres, is needed for identifying the structural interactions among them. Starting from these premises, in the current paper a masonry building aggregate built in the early twentieth century in the municipality of Cercola (district of Naples, Italy) and made of four structural units has been investigated as a case study. The structural behaviour under seismic forces has been investigated through non-linear static analyses. In particular, both the whole aggregate and the individual structural units have been modelled. Moreover, the single structural units have been considered both in the grouped and isolated conditions in order to assess either the beneficial or detrimental effect of the aggregated condition. The numerical models have been carried out with three different FEM software, namely 3MURI, CDS Win and Edilus, which schematise masonry buildings in different way. The analysis purpose has been to highlight the different results obtained with the three programs and to assess the most reliable seismic behaviour of investigated structural units. Finally, the susceptibility at damage of the case study aggregate has been evaluated through empirical fragility curves and mechanical vulnerability curves, which have been compared to each other and can be considered as preliminary tools to setup effective rehabilitation interventions.

Keywords: Seismic vulnerability, Building compounds, FEM analysis programs, Macro-element approach, Equivalent frame model.

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1 INTRODUCTION

The structural heritage facing the most part of Italian historical centres is made of masonry buildings without adequate structural performance level against seismic actions. Therefore, these types of buildings have high seismic vulnerability [1,2]. For this reason, the seismic safety assessment of existing masonry buildings is needed by many researchers working in the field of Seismic Engineering [3,4].

Seismic vulnerability is the tendency of buildings to suffer a certain degree of damage during a seismic event. The vulnerability assessment methods proposed in current standards are often based on the knowledge of construction features, i.e. connections between orthogonal walls, floor types and presence of tie beams, which are difficult to detect in old urban centres. The existing masonry buildings in historic centres are often grouped in aggregates. So, clustered buildings are sets of independent structural units (SUs) which interact to each other under seismic actions. Since SUs are often characterized by masonry walls with poor mechanical properties, as well as by poor connections between orthogonal walls and between walls and floors, their seismic behaviour is no easy to be determined [5, 6].

However, the performance of clustered buildings is influenced by several factors, that mainly depend on the interactions between the individual SUs. Moreover, the presence of effective interconnections between SUs prevents the occurrence of local collapse mechanisms. Instead, the presence of geometrical irregularities in height and/or the lack of an effective connection between orthogonal walls can cause the activation of out-of-plane collapse mechanisms [1,7,8].

The bearing capacity of individual SUs may differ significantly from the whole aggregate one. A SU inside of a building aggregate has a highly non-linear and complex behaviour, which can lead to evaluation errors in the evaluation of its seismic behaviour. Therefore, it is essential to consider simplified, but reliable, structural models, which should foresee as well as possible the vulnerability level of the aggregated constructions [9-13].

The main vulnerability factors are the elevation discontinuities between adjacent units, the presence of staggered floors and the structural heterogeneity usually leading to disconnections of walls. All of these factors must be taken into account when studying the global seismic capacity of buildings, because they significantly affect the dynamic response of the structures. In this framework, in various studies many mechanical models accounting for uncertainties associated to the vulnerability factors have been developed to quantify the seismic response of the whole aggregate [14-16].

Based on these considerations, the present study focuses on the seismic response of a masonry aggregate located in Cercola, a municipality near the city of Naples, in the South of Italy. The selected aggregate consists of four SUs (two head units and two intermediate ones) arranged in line, which interact to each other under earthquake. These clustered buildings date back to the 19th century and they are representative of the most common building classes present in the Campania Region. In this study the influence of structural units on the global response of the whole aggregate is investigated. For this reason, non-linear static analyses are carried out to simulate the response of structural units in both isolated and aggregate conditions and their seismic responses are compared with those of the whole aggregate. Finally, by selecting the most unfavourable analysis conditions, the fragility curves proposed in [17] are developed and illustrated for all examined cases in order to estimate their propensity at seismic damage.

2 THE CASE STUDY

The case study is a masonry building aggregate located in the municipality of Cercola (Figure 1), an urban district located near Naples. This agglomerate of constructions was built at the end of the 19th century as one of the most representative example of the classic typology of clustered buildings of the Campania Region historical centres. From a structural point of view, it consists of 4 structural units, two in the head position and two in intermediate one. The head SUs have 3 floors, while the intermediate SUs develop on 4 floors. Buildings have commercial use at ground floor and residential use at other floors. Figure 2a shows the external view of the aggregate main façade, while the geometrical plan layouts of the clustered buildings are shown in Figures 2b, 2c and 2d. The head SUs have the first floor characterized by masonry vaults, while the remaining floors are made of wooden beams. The intermediate SUs have steel floors or RC ones at the first level. As the head SUs, the remaining floors are made of wooden beams. The masonry walls are characterised by Neapolitan yellow tuff stones and have an average thickness of 0.80 m at the first floor and 0.50 m at the other floors. Due to the absence of accurate on-site test procedures, wall mechanical properties are assumed according to the indications provided by the Italian Standard [18] by applying a confidence factor (FC) equal to 1.35, which corresponds to a knowledge level LC1 (limited knowledge) [18,19]. So, the wall mechanical features are as follows: average compressive strength (f_m)= 2.00 MPa; average shear strength (f_{v0})= 0.10 MPa; Young modulus (E)= 1410 MPa; Shear modulus (G) 450 MPa and dead weight (w)=16 kN/m^3.

In order to estimate the aggregate seismic influence on single SUs, two different cases are studied: (i) the whole aggregate (Figure 2b) and the head structural unit (acronym HSU), both in aggregated (Figure 2e) and isolated (Figure 2f) configurations.

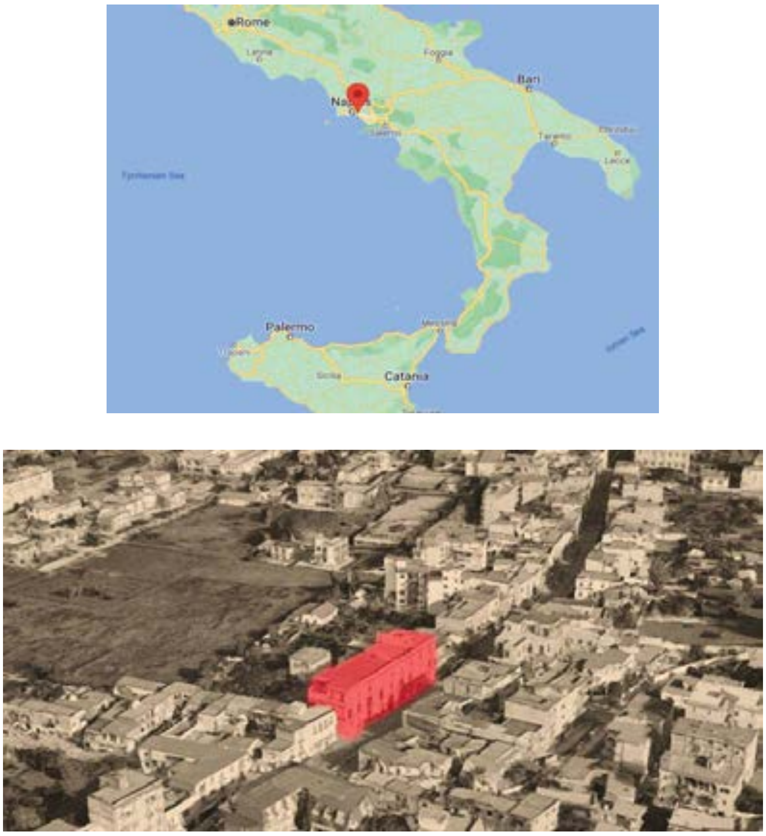


Figure 1: Identification of the case study.

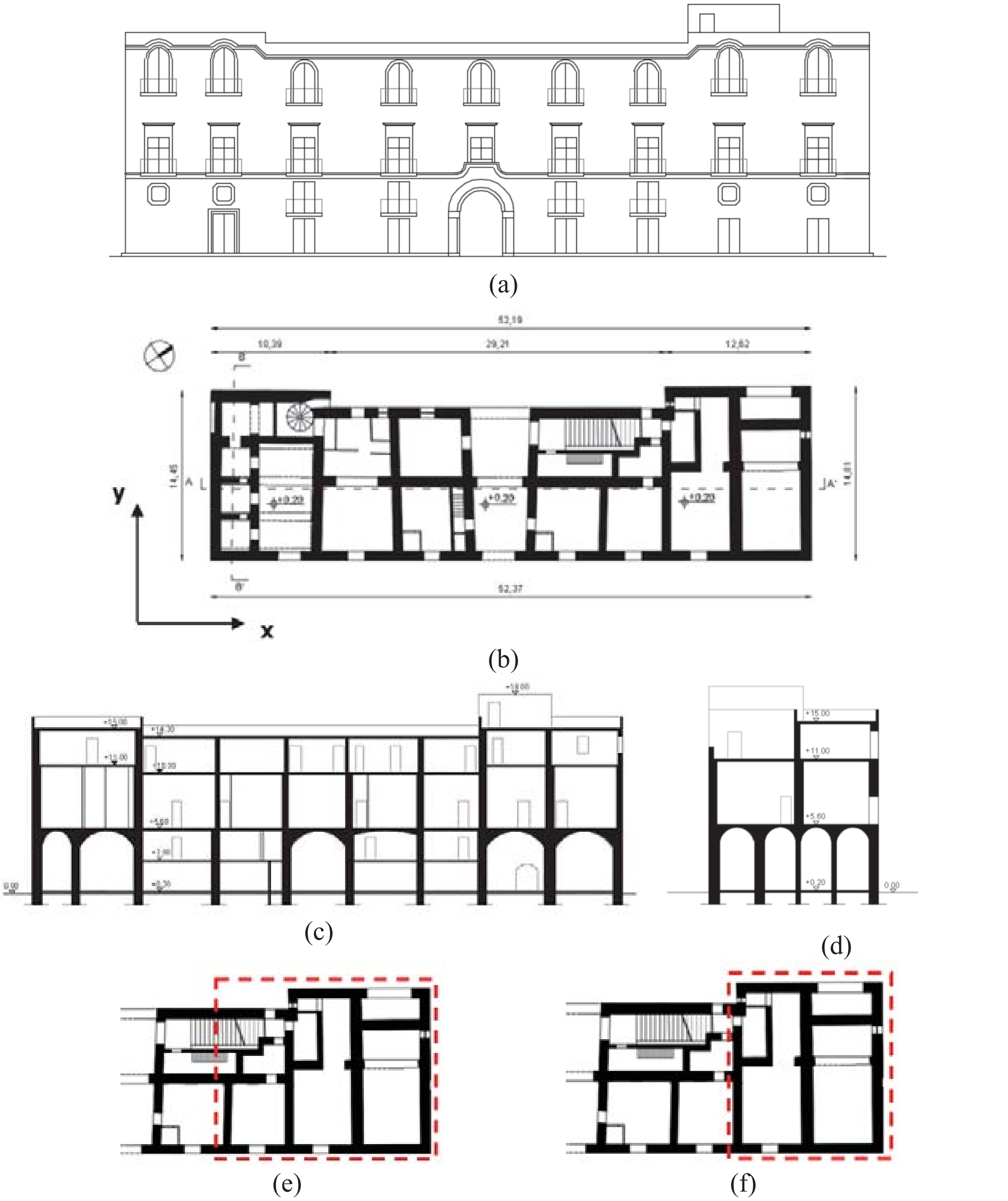
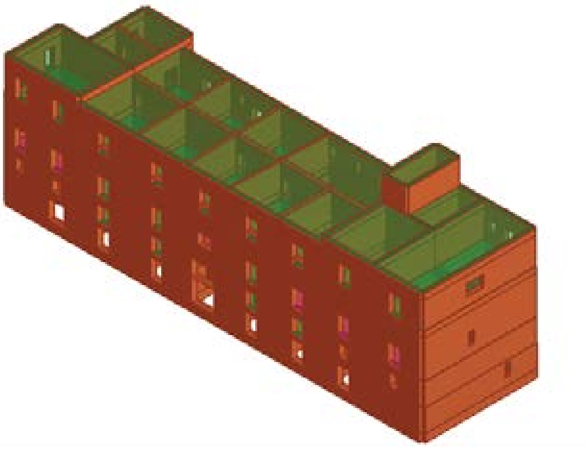


Figure 2: Graphic representation of the case study: main view (a), plan layout (b) and sections (c, d) of the building aggregate; aggregated (e) and isolated (f) HUS plan layouts.

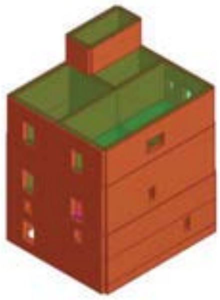
3 NUMERICAL MODELS

The numerical models are carried out using three different FE analysis programs based on 2 different modelling approaches: from one side, the equivalent frame adopted by 3MURI and CDS win and, on the other side, the shell model adopted by Edilus. Figures 3,4 and 5 shows numerical models developed by the three employed software packages. The basic modelling concepts of the implemented FEM models are shown in the following sections.



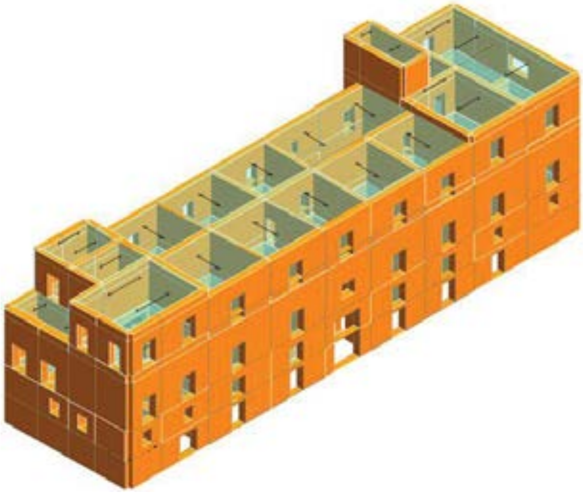
(a)

(b)



(c)

Figure 3: The 3MURI software numerical models: whole aggregate (a) and HSU in aggregated (b) and isolated (c) conditions.

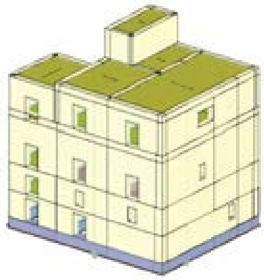


(a)

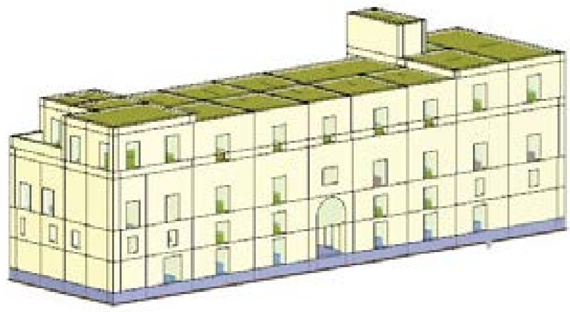
(b)

(c)

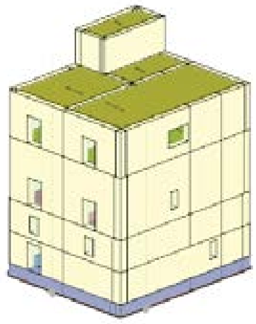
Figure 4: The CDS Win software numerical models: whole aggregate (a) and HSU in aggregated (b) and isolated (c) conditions.



(b)



(a)



(b)

Figure 5: The Edilus software numerical models: whole aggregate (a) and HSU in aggregated (b) and isolated (c) conditions.

3.1 Equivalent frame model

3MURI and CDS analysis programs adopt a mathematical model based on Frame by Macro-Elements (FME) theory, which implements the Equivalent Frame Model approach (Figure 6). The reference model is a three-dimensional equivalent frame, where the walls represent the vertical elements able to resist both vertical and horizontal loads. The horizontal elements, namely the floors, transfer the horizontal forces to the walls according to the stiffness they have in their own plane. Therefore, the numerical modelling of a building is carried out by inserting walls, which are discretized into macro-elements representative of deformable components (piers and spandrels), while nodes (rigid links) are masonry portions typically less subjected at seismic damage. Usually, rigid links connect piers and spandrels which are contiguous to the openings. The numerical analyses allow to foresee the expected damage mechanism into masonry buildings, which can occur in deformable elements by either shear or compression-bending. So, each pier is composed by three parts: one deformable in the element central part, having a certain strength value, and other two placed at the element ends, having infinite strength and stiffness. Instead, spandrels are represented with frame elements having horizontal axis. It is assumed that the deformable part corresponds to the opening length, while the element remaining part is modelled with infinitely rigid beams. Floors are modelled as finite elements with 3-node orthotropic membrane, having 2 degrees of freedom per node and connected to the three-dimensional nodes of the building model.

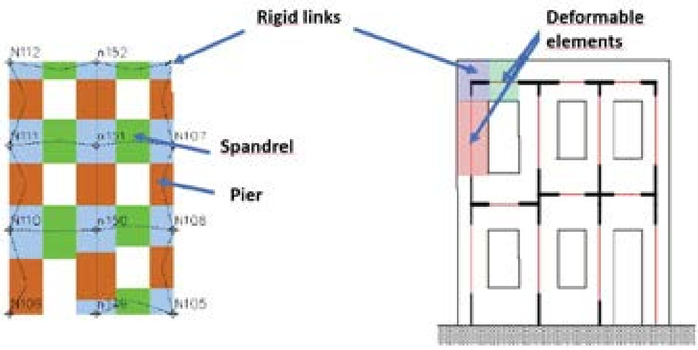


Figure 6: Schematic representation of the Equivalent Frame Model.

3.2 Shell model

Edilus software adopts the *Shell60* model, which consists of high-performance shell elements composed of a membrane part and a flexural one, whose effects can be coupled in order to have plates having large thickness and different layers, which can be anyway oriented. The membrane element has stiffness to normal rotation, which allows for a more faithful schematization of shell structures not completely connected to a plane and linked with beam elements. The implemented elements have triangular or quadrangular shape with three and four nodes, respectively. The quadrangular elements are obtained by automatically assembling several triangular elements. The triangular elements are High Performance Elements (HPE). However, the use of only triangular elements has undoubted advantages. In fact, the triangular elements allow for a faster analysis execution. The subdivision of any surface is also easier and more accurate.

The *Shell60* element (Figure 7) has a formulation that makes it rather insensitive to distortion. This feature is particularly useful in a pre-processing phase, which generate the mesh automatically. The formulation of the HPE Shell60 element is based on the composition of an *AnDeS* triangular membrane element with drilling degree of freedom with the *DKT* (Discrete Kirchhoff Triangle) element. The degree of freedom towards rotation (drilling DoF) is added by describing the deformation of each side.

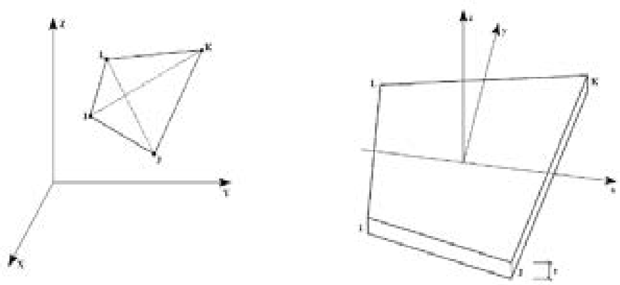


Figure 7: Linear shell model definition.

4 PUSHOVER ANALYSES

The seismic behaviour of the buildings facing the case study is investigated through pushover analyses. Based on the provisions of the Italian standard [19], these analyses are performed along the two main directions "X" and "Y" of the building aggregate (see Figure 2b). For each direction, the positive and negative accidental eccentricities are considered. Furthermore, 4 different verses of the seismic forces (±X, ±Y) and 2 dissimilar force distributions (proportional either to masses or to the first vibration mode of the building) are considered.

So, 24 pushover analyses are performed. Figures 8, 9 and 10 show the pushover analysis curves in the ‘X’ and ‘Y’ directions performed with 3MURI, CDS Win and Edilus programs, respectively. In particular, for the sake of representation, among the 24 combinations, the worst one, that is the analysis minimizing the capacity acceleration of the aggregate, is considered.

The analysis results show that the most deformable direction is the "Y" one for the whole aggregate and the "X" one for HSU, both in aggregated and isolated conditions. In general, strength and stiffness increase switching from the HSU isolated, passing through the HSU (aggregated), to the whole aggregate. With respect to ductility, an opposite behaviour occurs.

“X” Direction “Y” Direction

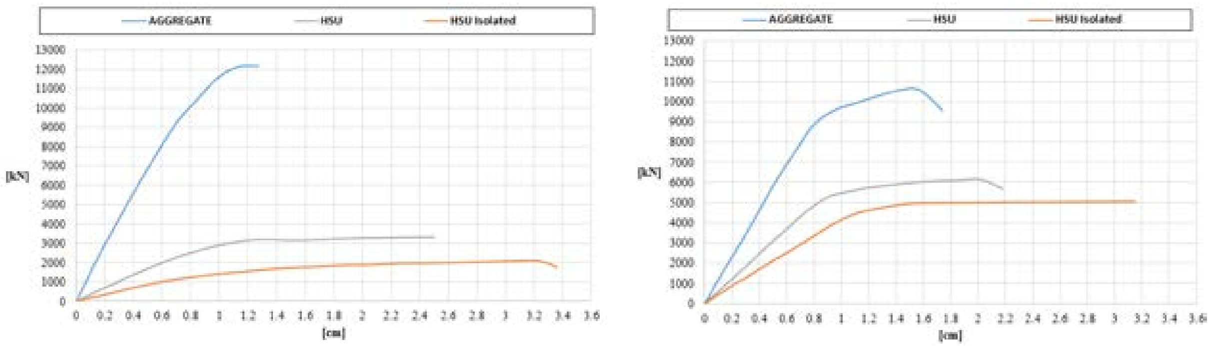


Figure 8: Pushover curves along X and Y directions carried out by the 3MURI software.

“X” Direction “Y” Direction

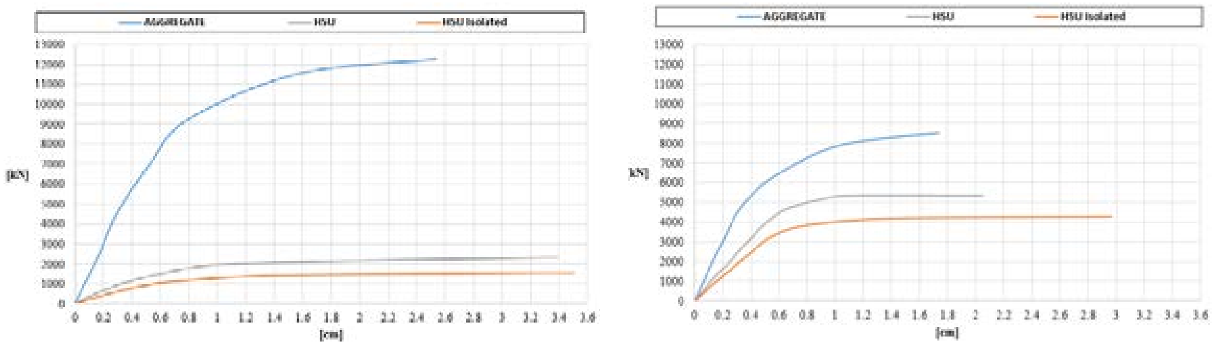


Figure 9: Pushover curves along X and Y directions carried out by the CDS Win software.

“X” Direction “Y” Direction

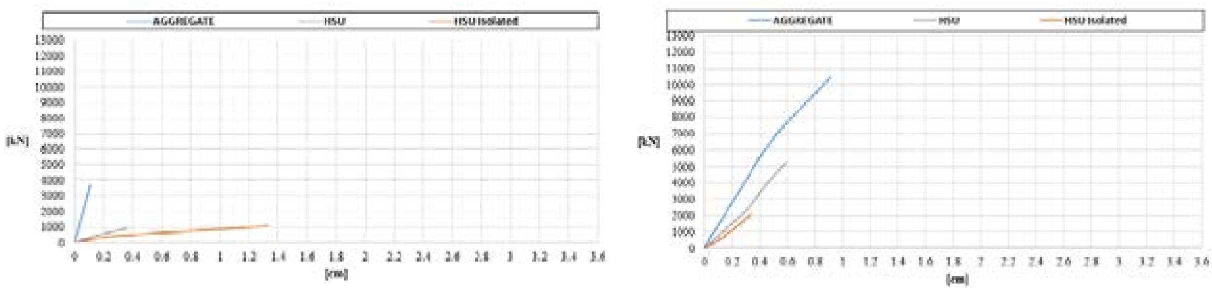


Figure 10: Pushover curves along X and Y directions carried out by the Edilus software.

The three models use different calculation solvers and the solutions obtained are not always like each other. Therefore, a comparison in terms of pushover curves is made. In this case, only one curve for each software is taken into account. In particular, among the worst analyses performed with each analysis program, only the pushover curve proving the lowest resistance value of the aggregate is chosen. This curve is then compared with the corresponding curves of the other 2 programs, as shown in Figure 11.

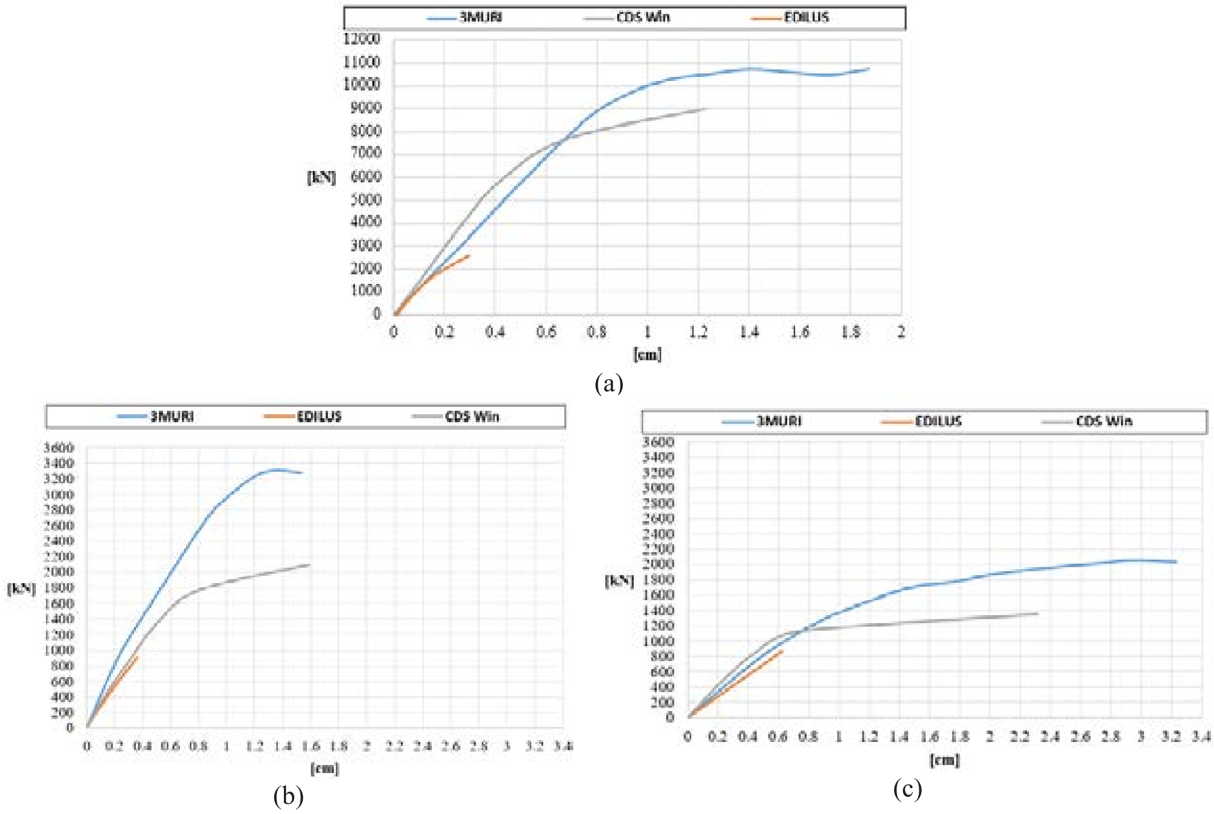


Figure 11: Comparison between analysis programs in terms of pushover curves: results for aggregate (a) and head structural unit in aggregated (b) and isolated (c) conditions.

From the analysis results presented in Figures from 8 to 11 it can be observed that the curves provided by the Edilus software have a different trend compared to the other ones. In fact, these pushover curves have an almost linear behaviour. This is because the software does not adopt a multi-collapse analysis procedure, but, when the first collapse mechanism occurs in the structure, the software stops the pushover curve. Conversely, 3MURI and CDS Win programs work with a multi-collapse analysis, where the analysis is not blocked when some elements attain the ultimate displacement, but the structure is pushed until collapse. This type of analysis is allowed by the Italian Standard [19] for existing masonry structures.

5 FRAGILITY ANALYSIS

In the last part of the study, the fragility curves of investigated buildings are derived. These curves represent the probability of exceeding a certain damage state varying the intensity measurement, generally represented by either the PGA or the spectral displacement. The evaluation of the fragility curves is carried out according to the methodology proposed in [17]. In particular, four damage levels, namely D1 (slight), D2 (moderate), D3 (near collapse), and D4 (collapse), are considered (Table 1). These damage states are defined starting from the yielding displacement (d_y) and ultimate displacement (d_u) of the SDoF system associated to the MDoF structural system. The fragility curves are analytically defined as follows:

$$P[DS|PGA]=\Phi\cdot\left[\frac{1}{\beta}\cdot\ln\left(\frac{PGA}{PGA_{DS}}\right)\right] \quad (1)$$

where Φ is the cumulative distribution function, PGA_{DS} is the median acceleration value associated to each damage threshold and β is the standard deviation of the log-normal distribution.

Damage thresholds, DS_i		
D1	$0.7\cdot d_y$	Slight
D2	$1.5\cdot d_y$	Moderate
D3	$0.5\cdot(d_{y+}\ d_u)$	Near-collapse
D4-D5	d_u	Collapse

Table 1: Evaluated damage thresholds D_i [19]

Based on these above considerations, the fragility functions are plotted considering the most unfavourable structural analysis conditions both for the whole aggregate (Figure 12) and the head structural unit in aggregated (Figure 13) and isolated (Figure 14) conditions.

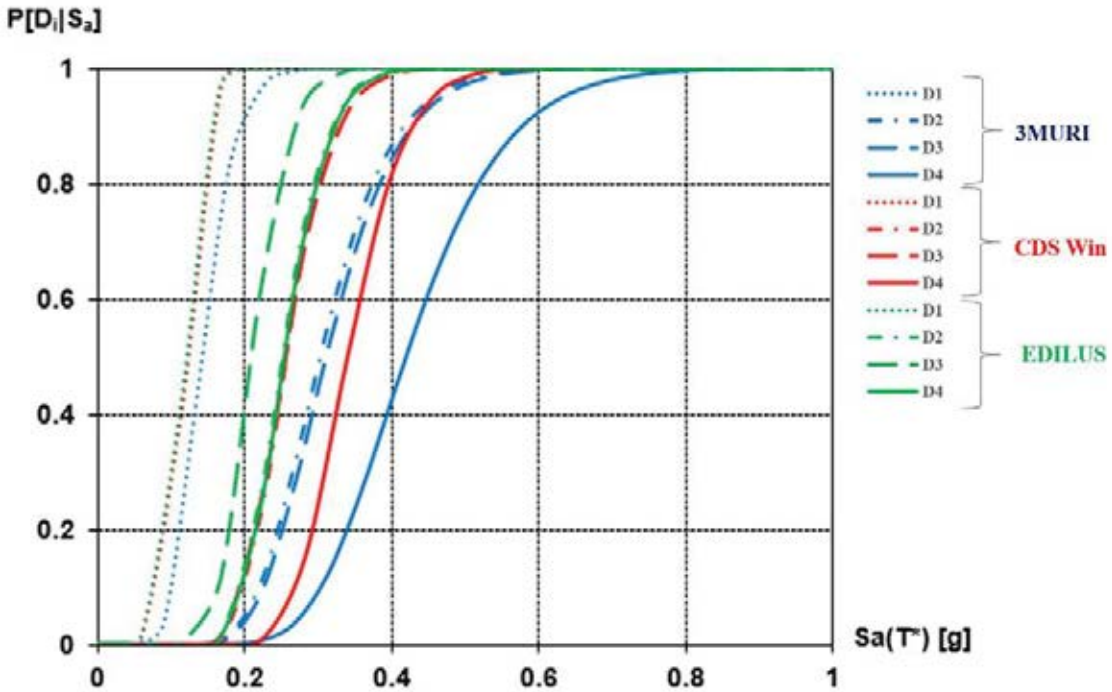


Figure 12: Comparison among fragility curves of the whole aggregate in "Y" direction based on the pushover curves deriving from the three used programs.

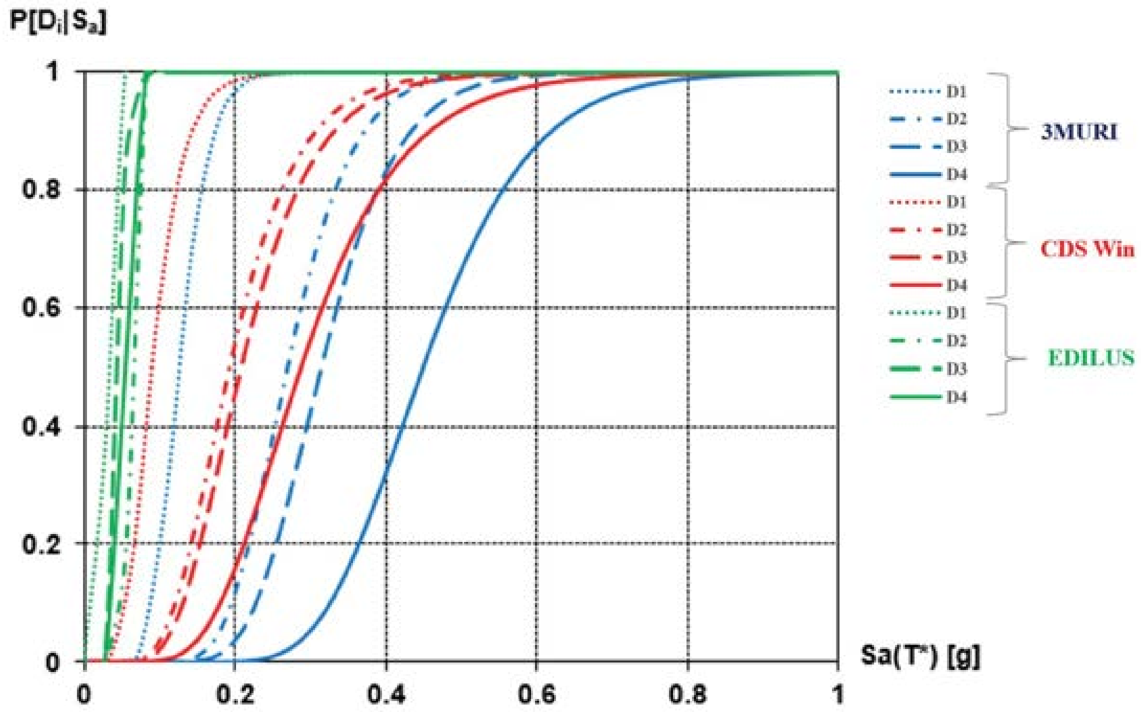


Figure 13: Comparison among fragility curves of the aggregated HSU in "X" direction based on the pushover curves deriving from the three used programs.

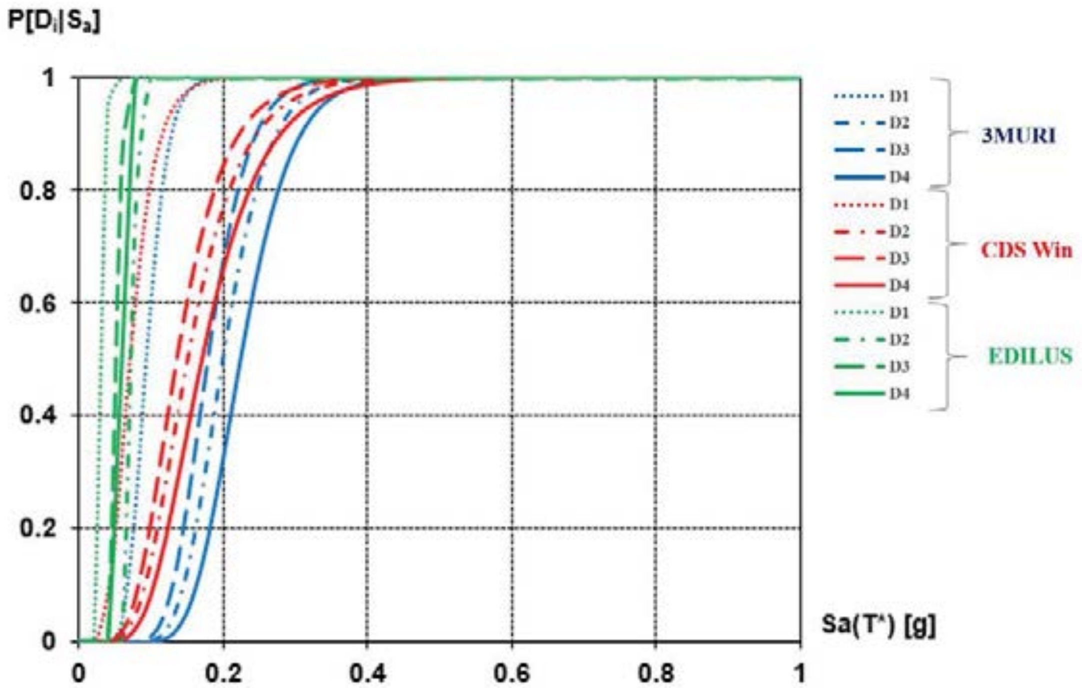


Figure 14: Comparison among fragility curves of the isolated HSU in "X" direction based on the pushover curves deriving from the three used programs.

From the acquired results it is observed that for all cases the probability of exceeding a certain threshold of damage D_i (i = 1, ..., 4) is greater for the HSU in isolated condition. Furthermore, the probability increases passing from the whole aggregate to the HSU in aggregated condition.

Finally, it is possible to make some considerations on the results achieved from different programs used. In particular, it is found that the Edilus software shows the most conservative results, while the CDS Win exhibits safety thresholds higher than those of the 3MURI Software. Considering that the PGA of Cercola at Collapse Limit State (CLS) is 0.263g [18], in Tables 2,3 and 4 the expected damages evaluated with the different programs for the whole aggregate, the aggregated HSU and the isolated HSU are respectively shown.

Whole aggregate				
Software	**D_1**	**D_2**	**D_3**	**D_3**
3MURI	99.35%	28.18%	25.07%	2.03%
CDS Win	99.95%	55.55%	55.55%	8.50%
Edilus	100%	86.85%	60%	56.88%

Table 2: Expected damages for the whole aggregate.

Aggregated HSU				
Software	**D_1**	**D_2**	**D_3**	**D_3**
3MURI	99.54%	64.76%	23.60%	3.36%
CDS Win	100%	80%	74.15%	40.16%
Edilus	100%	100%	100%	100%

Table 3: Expected damages for the aggregated HSU.

Isolated HSU				
Software	**D_1**	**D_2**	**D_3**	**D_3**
3MURI	100%	94.18%	86.75%	74.84%
CDS Win	100%	96.04%	92.55%	86.81%
Edilus	100%	100%	100%	100%

Table 4: Expected damages for the isolated HSU.

6 CONCLUSIONS

In this paper the seismic response of a masonry building aggregate located in Cercola, a municipality near the city of Naples, was investigated. The aggregate is made of four SUs, namely two in heading position and two in intermediate one. Both the whole aggregate and the single SUs, both in isolated and aggregate conditions, were analysed to estimate the influence of the mutual interaction among adjacent structural units. Non-linear static analyses were carried out according to the Italian standards using three Italian popular programs, namely 3MURI, CDS Win and EDILUS, which work with different modelling approaches to schematise the seismic behaviour of existing masonry buildings. From the non-linear analysis results it was observed that in most cases the maximum strength and stiffness are offered by the whole aggregate and they reduced with the aggregated SU and much more with the isolated SU. On the contrary, the structural ductility offered by the US in isolated condition is more pronounced than the one of the aggregated US, which exhibited greater ductility than that of the aggregate. Finally, the fragility curves of the buildings under study were plotted to estimate expected damages as a function of different PGA levels. The results achieved showed that the Edilus software provides the most conservative results, while CDS Win exhibits safety thresholds higher than those of the 3MURI Software.

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