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Eccomas Proceedia COMPDYN (2023) 1615-1632

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COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

MECHANICAL-BASED SEISMIC FRAGILITY ASSESSMENT AND RETROFIT INTERVENTION OF CLUSTERED BUILDINGS

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Abstract

In this paper, the seismic behaviour assessment of a masonry building aggregate, one of the most widespread house typologies of historical centres, placed in a small burg in South Italy, is discussed through the definition of both capacity and fragility curves.

In the first part of the work, the historical centre, where the case study is located, is introduced by describing its historical evolution. Subsequently, the main architectonical and structural features of the selected aggregate are illustrated, according to the instructions of the CARTIS Form, developed within the WP2 of the DPC – ReLUIS Italian research project.

After the knowledge phase, in the following step the evaluation of the entire structural aggregate is analysed considering the incapacity to seismically analyse the single structural units without accounting for the dynamic interactions among them under earthquake ground motion. Since the non - linear analyses underline the inadequate behaviour of the aggregate in both seismic directions (longitudinal and transverse), a consolidating intervention, consisting in the application of a seismic coating system, is hypothesized to improve, using an integrated approach, both seismic and energy performances of the basic aggregate.

In the last part of the work, a comparison among results in terms of seismic safety index, intended as the ratio between capacity and demand in terms of PGA, and fragility curves, before and after the intervention, is made in order to evaluate the behaviour of the aggregate structural units after the application of the seismic coat on the heading unit.

Keywords: Clustered Buildings, Masonry Buildings, Seismic Coat, Retrofit Interventions, Fragility Curves.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10506.20324

1 INTRODUCTION

Buildings in aggregate configurations represent a huge percentage of Italian architectural heritage, giving rise to our small and large historical centers, and nowadays embody the witness of the ancient way of construction.

Clustered buildings are the results of a slow and disorganized development occurred in the past centuries. Generally, they are characterized by multiple adjacent structural units that, in some cases, shared intermediate walls, while in other ones they were simply built close to pre – existing constructions. In the latter case, since there is no connection among walls and no "box effect", both useful for a good behaviour of the masonry apparatus, single units are exposed to the first mode mechanisms, also known as local failure mechanisms. They involve single portions of masonry and the most widespread collapse way is the overturing phenomenon, which in turns could regard the entire wall or its some portions. Another problem that could affect these structures is constituted by the vertical bending due to the pushing action deriving from the roof of the other structural cells.

Indeed, clustered buildings are composed by many structural units that could be distinguished by materials used for vertical masonry walls, by horizontal floors, by height and number of storeys [1-4]. All of these above-mentioned parameters influence the behaviour of an aggregate during an earthquake.

The high vulnerability of these structures depends on the fact that, in most of cases, they were erected only with workers' knowledge and experience, to resist only to gravity loads, without any seismic design project. As a consequence, a huge architectonic and artistic cultural heritage is very exposed to seismic actions, as demonstrated in numerous earthquakes happened throughout the past centuries.

Seismic events occurred in the past decades revealed a significant number of deaths in addition to several damages to structures. In order to avoid other similar catastrophic events and to reduce the seismic vulnerability of existing buildings, it is necessary and urgent to intervene as soon as possible so to guarantee the survival of our architectonical heritage [5].

The assessment and the seismic retrofit, especially with regards to clustered buildings, in seismic areas is a very challenging issue in Engineering field. Nevertheless, the vulnerability assessment of historical masonry structures has been investigated in literature through different methods and focusing on different modeling approaches [6-8].

In this framework, the Italian Project DPC-ReLUIS set up, in last years, the CARTIS form so to characterize, from typological and structural viewpoints, clustered buildings on Italian territory.

The form is divided into four parts that start from general information, like the consistency of the territory, and arrive to specific data, like the geometrical and structural features of the examined buildings. The so obtained data with the CARTIS form allow to derive some important outcomes, such as the prevailing construction period, the prevalent range of covered area, number of floors, height, etc. of a set of buildings in a selected area [9].

There are still few research concerning clustered buildings. Firstly, because it is very difficult to find information about constitutive materials, age and any seismic interventions made over the centuries, and, secondly, for the complexity of modeling approaches through computer programs able to correctly evaluate their seismic behaviour and interactions. For these reasons, in this paper an important contribution to the study of urban aggregate, which are still poorly researched and analysed, is provided. In particular, the interaction effects among structural cells due to seismic interventions by a novel seismic-energy coat placed on the facades of the head unit is investigated through fragility curves.

2 THE CASE STUDY: THE CENTRE OF CASTELPOTO

2.1 Placement and historical evolution

The object of the seismic investigation is a clustered building placed in the small historical centre of Castelpoto, in the district of Benevento, a city in the Southern part of Italy. It is a hillside village of medieval origins, whose placement in the Benevento outskirt is shown in Figure 1.

Figure 1: Location of Castelpoto in the district of Benevento (Italy)

Castelpoto overlooks the valley of Calore River (see Figure 2), which contributed over the centuries to provide a remarkably fertile soil, making the area famous for various food specialties.

Figure 2: A view of the Calore Valley

As for many historical centers, also for Castelpoto the study of its historical evolution has been very difficult, since the village is the results of disorganized and undocumented edifications and changes occurred throughout the centuries.

However, an evolutive and quite detailed framework of the evolution of Castelpoto, with identification of the main construction epochs, is herein provided.

Probably, the city was founded in a very ancient period: some archaeological finds suggest that it might already exist in the Roman era. Its actual position dates back to medieval age (year 598), when the Longobardi, a Germanic population, occupied the territory of Benevento and its closest areas.

Castelpoto reached the peak of its glories with the domination of the Normans, after which several important families followed each to other at the power.

Nowadays, after many seismic events, the city of Castelpoto is developed around two main road axes. Along the first axis, requalified or new buildings can be found. On the other side, the most ancient and damaged buildings needing consolidating interventions are located following the route of the second road axis.

2.2 The clustered buildings under study

The examined structural aggregate is placed in Dietro La Torre street and it rises in a portion slightly detached from the ancient medieval nucleus. It is in the area where the current local administration wants to concentrate the economic resources in order to requalify the historical centre that, thanks to the presence of the old Castle, could have a tourist destination. Figure 3 displays the location of the case study aggregate.

Figure 3: The investigated clustered buildings.

The examined masonry aggregate is composed by seven structural units placed on slope with different altitudes due to their position on the hill side. The seven structural cells are distinguished to each other by different materials used for vertical walls and by structural features conditioned from local interventions performed in the past years to improve their state after occurred earthquakes. In Figure 4 the plan configuration of the study clustered buildings is illustrated.

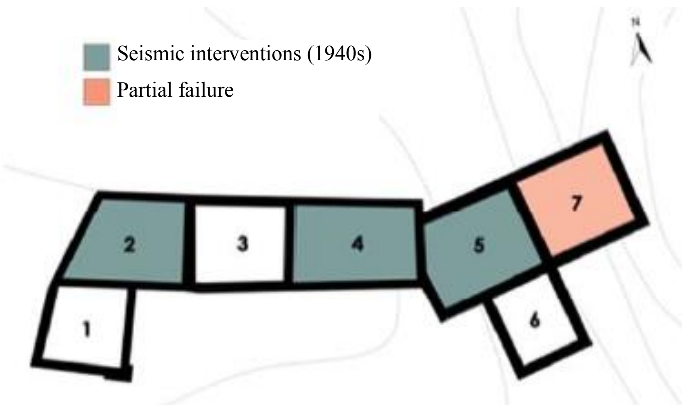


Figure 4: The seven structural units of the inspected masonry aggregate.

The structural units n. 2, 4 and 5 (represented in grey in Figure 4) were subjected to some consolidating operations dates back to the 1940s. The structural unit n. 7 (highlighted in pink in Figure 4) suffered some local collapses, while the remaining structures n. 1, 3 and 6 were never interested by repairing interventions.

The photographic documentation on the state of decay of the whole aggregate is herein reported. In particular, since all the masonry walls are not covered by plaster, it is possible to observe, as shown in Figure 5, the erosion phenomena due to environmental agents causing the pulverization of the mortar. In addition to the crushing of masonry walls, there are some partial collapses in correspondence of wooden beams of intermediate floors (Figure 6) and corrosion phenomena on steel beams within the units n. 2, 4 and 5 (Figure 7). Finally, Figure 8 points out the collapse of some parts of roofs.

Figure 5: Crushing phenomena of vertical masonry walls.

Figure 6: Degradation phenomena on wooden beams.

Figure 7: Corrosion phenomena on steel beams.

Figure 8: Failures of the roofs.

3 SEISMIC BEHAVIOUR ASSESSMENT

3.1 Method

In order to evaluate the seismic behaviour of the aggregate, the 3Muri computer program developed by the S.T.A.DATA company has been used. It is a calculation software based on the frame by macro-elements (FME) technique, where single masonry panels are divided into three macro-elements, namely masonry piers, spandrels and rigid nodes (achieved from intersection between the mentioned macro-elements and having an infinitely rigid behaviour), which are depicted in orange, green and light blue, respectively, in Figure 9.

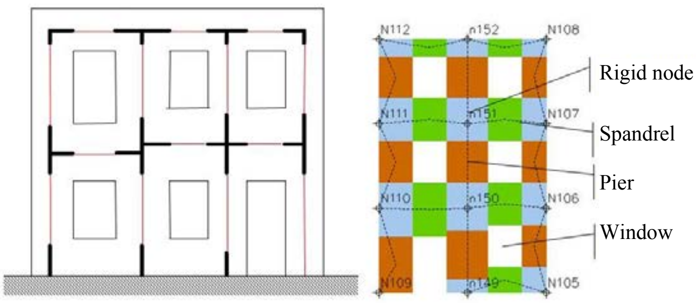


Figure 9: Schematization of a masonry wall in the 3Muri software.

The current software has been utilized for the evaluation of the non - linear behaviour of the clustered buildings. The results of the analyses are represented by the capacity curves identified in the base shear – top displacement diagram [10 - 12].

According to the present Italian technical code, 24 load combinations obtained from two inertial distribution of forces have been considered to be applied to the structure as follows:

- Distribution proportional to the static forces (Group 1);
- Uniform distribution of forces, which is derived from a uniform distribution of accelerations over the height of the construction (Group 2) [13, 14].

3.2 Pushover Analyses

Firstly, during the modeling phase, the wall axes of the structure have been plotted importing the cad file of the clustered building in the 3Muri software.

Secondly, the mechanical characteristics of structural materials have been defined considering the lowest level of knowledge (LC1) according to the current legislation due to the limited mechanical investigations carried out. Therefore, the minimum value for strength and the average one for elastic modulus have been assumed for masonry.

Finally, the intermediate floors and the roof structure have been modelled over the masonry structure. In particular, two floor typologies have been recognized: one with wooden beams (units n. 1, 3 and 6) and another with steel beams and masonry vaults (units n. 2, 4 and 5). The unit n. 7 does not have any intermediate horizontal floor, because it develops on one story only.

After the three – dimensional model has been implemented, the mesh dividing each masonry panel in the three already mentioned macro-elements (piers, spandrels and rigid nodes) has been generated.

A view of the three – dimensional model and the macro-elements one of the clustered buildings is depicted in Figure 10 and Figure 11, respectively.

Once finished the modeling phase, pushover analyses have been carried out on the building aggregate selecting the design spectrum of the case study site based on the definition of both the soil type (C) and the topographic category (T_1).

The results of the two worst analyses referred to the structural unit n. 1 are shown in Table 1, where the seismic safety factor at Life Safety Limit State, intended as the ratio between the capacity acceleration and the demand one, is provided for each analysis direction.

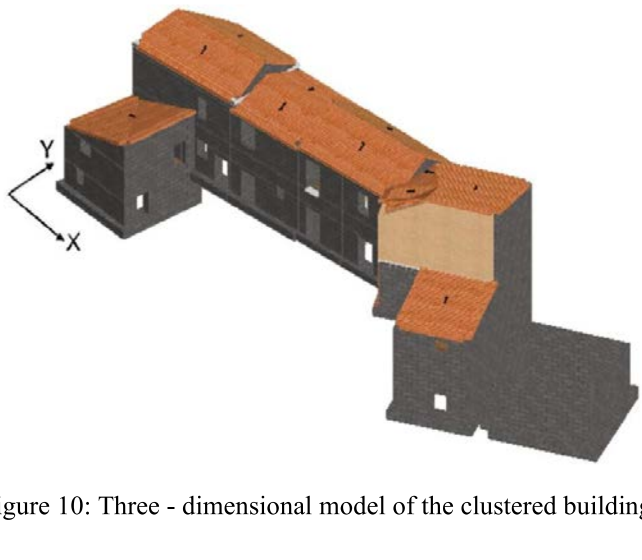


Figure 10: Three - dimensional model of the clustered buildings.

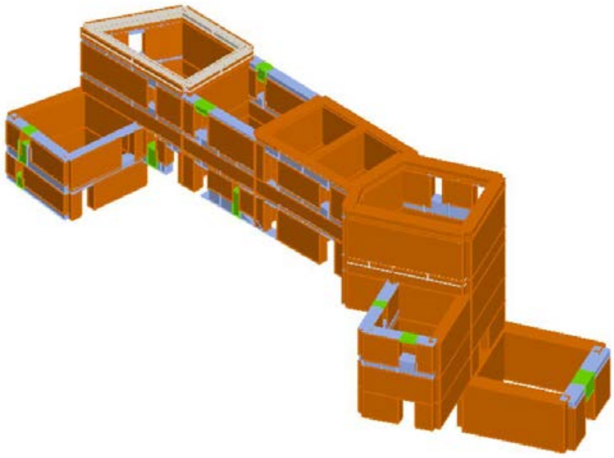


Figure 11: Macro-elements model of the clustered buildings.

Analysis number	Seismic direction	Seismic load	Eccentricity [cm]	α_{SLV}
11	+X	Static forces	67,76	0,267
19	+Y	Static forces	173,86	0,313

Table 1: Results of the pushover analyses on the structural unit n. 1

4 CONSOLIDATION INTERVENTION

4.1 The MIL 15.s seismic coat

The results of pushover analyses on the structural unit n. 1 of the clustered building have highlighted its high vulnerability degree towards seismic actions in both directions (X - longitudinal and Y – transverse). For this reason, a consolidation intervention has been hypothesized. Among the different existing seismic-energy integrated retrofitting techniques, a light metal exoskeleton continuously connected to the external facades of the construction has been chosen. It is an innovative and few invasive technique, that allows, at the same moment, the improvement of both the seismic and energy performances of masonry buildings. In fact, in addition to the metal exoskeleton acting as seismic device, the system is completed with insulating panels, placed in the empty spaces among the vertical profiles, having the task to reduce the thermal dispersions of the building.

Although seismic coats are a very modern retrofitting technique, in the recent years several different versions have been launched on the construction market. Some of them are based on heavy solutions made of cast-in-place reinforced concrete shear walls, while other solutions foresee lightweight systems composed of galvanized steel or aluminium alloy profiles [15 – 19].

In the current case, the adopted solution is the MIL 15.s seismic coat, whose configuration is illustrated in Figure 12. This coating system is produced on the basis of a precise on-site survey of the building by laser scanner to speed up the erection phases.

The MIL 15.s system, patented in 2022 by the TM Group Srl company, uses aluminium alloy extruded profiles (identified with Nr. 1 and 2 in Figure 12), which are attached to the masonry walls through chemical anchors (identified with Nr. 6 in Figure 12). Sandwich panels (indicated with Nr. 8 in Figure 12) are inserted between two subsequent vertical profiles. These panels are connected to the aluminium columns by self-drilling screws (Nr. 7 in Figure 12). The thermal insulator (Nr. 3 in Figure 12) and the EPDM tape (Nr. 5 in Figure 12) are necessary to avoid any thermal dispersion between the different elements of the coating system.

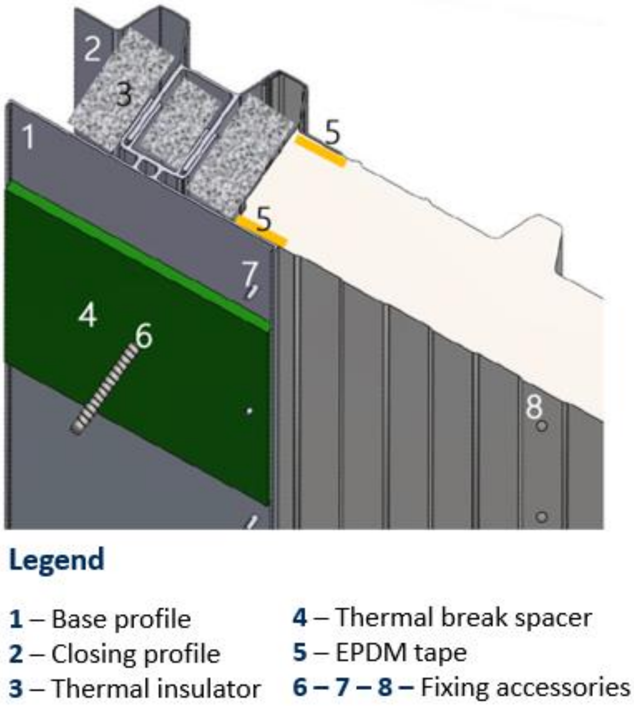


Figure 12: The MIL 15.s seismic coat system

4.2 Design and modelling of the seismic coat

Once the seismic coating system has been introduced and described, its dimensioning and FEM modelling phases have been performed.

In order to implement this reinforcing system in the software used to perform the seismic analyses, an equivalent diagonal system in correspondence of each masonry pier at every level has been foreseen.

Considering that the MIL 15.s system is composed of different modules placed on each pier and, therefore, it is made of several sandwich panels acting as seismic devices, for modelling purpose it is necessary to replace the mentioned panels with an equivalent diagonal system with a full circular cross-section. The estimation of the diagonal diameter to be inserted in the calculation software has been obtained determining the equivalent system stiffness using the following equation:

$$K_{eq} = \Sigma K_i \tag{1}$$

where Ki is the stiffness of each diagonal representing the sandwich panel connected to each masonry pier.

Therefore, starting from the equivalent stiffness, it has possible to derive the area A_p, and then, the diameter φ, of the equivalent diagonal by means of the following formulation:

$$K_{eq} = E_p \cdot A_p/l_p \cdot \cos^2\alpha \tag{2}$$

where:

- $E_p = E_s$ is the elastic modulus of the material.
- l_p = equivalent length, equal to b/cosα, being b the frame width, h the frame height and α = arctg h/b (see Figure 13).

From eq. (2), the following relationship has been derived:

$$A_p = K_{eq} \cdot l_p / (E_p \cdot \cos^2\alpha) \quad (3)$$

One calculated the bracing area, the related diameter ϕ can be found through the following formula:

$$\varphi = \sqrt{(4 \cdot Ap)/\pi} \quad (4)$$

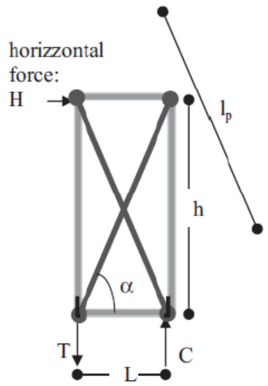


Figure 13: Geometrical parameters used for design phase of the seismic coat equivalent diagonal.

In Figure 14, the three-dimensional model of the clustered buildings with the seismic coat (schematized with equivalent diagonal) installed on the structural unit n. 1 has been reported.

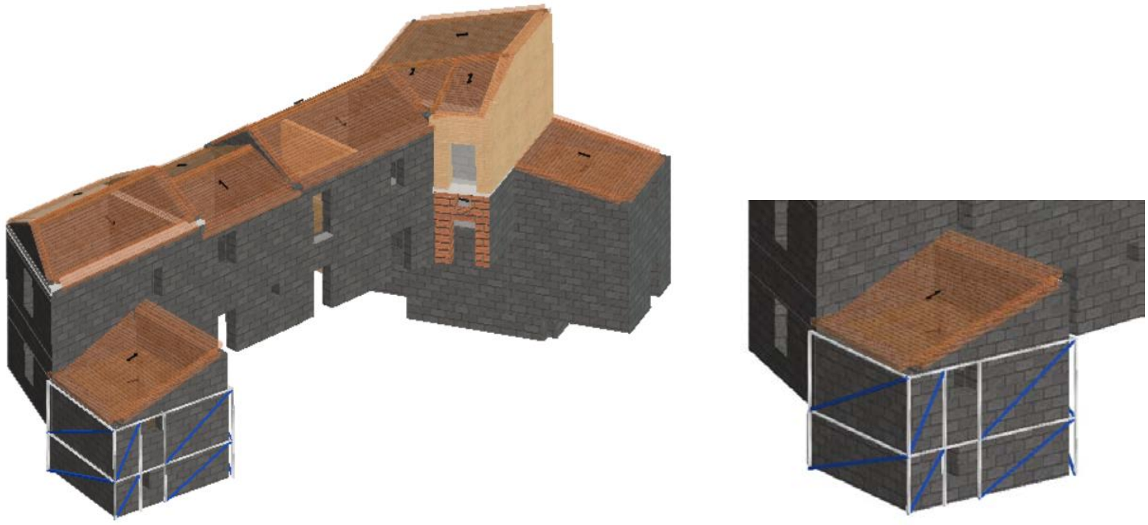


Figure 14: Three – dimensional model of clustered buildings with modelling of the seismic coat on the structural unit n. 1.

The MIL 15.s seismic coat has been applied to the three free facades of the structural unit n. 1. This reinforcement choice has been done with the purpose to investigate the effects that the coating system produce not only on the reinforced building, but also on the other six structural cells considering that, as underlined several times, within an aggregate the behaviour of a single structural unit is strongly influenced by the other ones during a seismic event.

In order to evaluate the influence and the effects of the seismic coat on all the other structural units, pushover analyses have been carried out monitoring the displacement of a control node belonging to each of the cells composing the clustered buildings. Figure 15 shows the different control nodes chosen to derive the pushover curves of different structural cells.

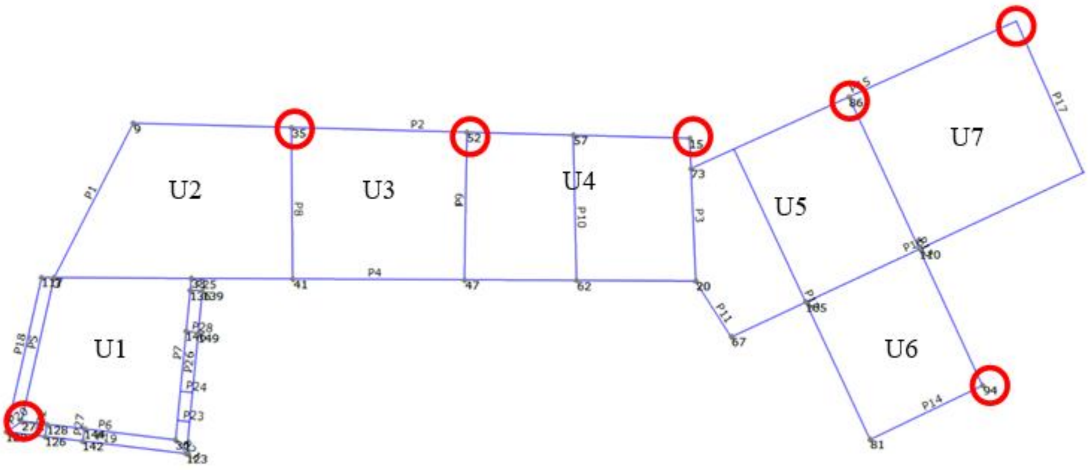


Figure 15: The selected control nodes of the seven structural units

5 SEISMIC BEHAVIOUR OF THE STRUCTURAL UNIT BEFORE AND AFTER INTERVERTION

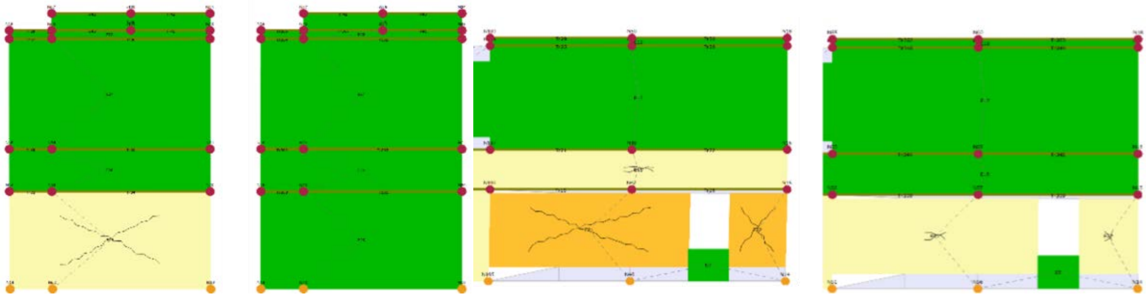
5.1 Comparison of results

Table 2 illustrates the comparison of the results in terms of seismic safety factor α_{SLV}, defined as the ratio between the capacity acceleration and the demand one, for each structural unit before and after the consolidation intervention. In particular, for each analysis direction, the factors α related to the two worst analyses in the two main directions of the structural cells have been reported.

Structural unit	Seismic direction	Before intervention α_{SLV}	After intervention α_{SLV}
1	X	0,267	0,323
	Y	0,313	0,311
2	X	0,581	0,643
	Y	0,290	0,287
3	X	0,574	0,642
	Y	0,435	0,453
4	X	0,573	0,638
	Y	0,359	0,340
5	X	0,619	0,452
	Y	0,345	0,349
6	X	0,643	0,657
	Y	0,436	0,399
7	X	0,585	0,579
	Y	0,479	0,532

Table 2: Comparison of pushover results before and after the application of the seismic coat MIL 15.s

Regarding the reinforced structural unit n. 1, it is possible to highlight a light increase of the coefficient α_{SLV} only in x direction, while in the transverse one (y) the seismic coat is not able to increase the seismic behaviour, since the α_{SLV} remains almost stable. Conversely, there is an improvement of the seismic behaviour of masonry panels after application of the MIL 15.s system, since a reduction of shear damage has been noticed, as displayed in Figure 16.



(a) (b) (c) (d)

Figure 16: Behaviour of masonry panels of the structural unit n. 1 before (a, c) and after (b, d) insertion of the seismic coat (green: no damage; yellow: plastic shear; orange: shear failure)

Concerning the other structural cells of the building aggregate, the achieved results have demonstrated that for the nearest units to the cell n. 1 (n. 2, 3 and 4) there are some benefits deriving from the application of the seismic coat, especially in x direction, in terms of α_{SLV}, while the remaining three cells (n. 5, 6 and 7) have not taken profit of the intervention, since their seismic safety factor has decreased or remain unchanged.

5.2 Fragility curves

In addition to the results provided in terms of seismic checks, a fragility study has been performed to provide the seismic behaviour of structural units after insertion of the MIL 15.s system in terms of fragility curves. These curves have been obtained based on the displacements achieved from the pushover analyses carried out on each structural unit.

The fragility curves can be defined through a function expressing the probability that a specific damage level is reached or exceeded in terms of the spectral displacement S_d using the following equation:

$$P(d > D_{Si}|S_d) = \Phi \cdot \left(\frac{1}{\beta} \cdot \ln \frac{S_d}{\overline{\overline{S_d}}} \right) \tag{5}$$

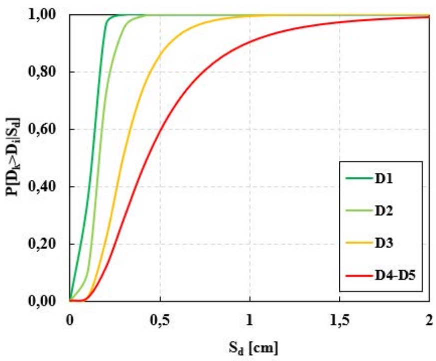
where:

- Φ is the cumulative normal distribution;
- S_d and β are the median and the standard deviation of the corresponding normal distribution, respectively.

The damage thresholds have been assumed according to [21] and they have been evaluated based on the yielding and ultimate displacements. The used damage levels and the corresponding standard deviations are presented in Table 3. Figure 17 illustrates the fragility curves before and after the intervention in x direction for all the cells of the clustered buildings.

Damage level	Limit displacement	Damage type	Standard deviation βi
D1	$0{,}7d_y$	Slight	0,25+0,07ln(μ)
D2	d_y	Moderate	0,20+0,18ln(μ)
D3	$d_y + 0{,}5(d_u - d_y)$	Near Collapse	0,1+0,40ln(μ)
D4-D5	d_u	Collapse	0,15+0,5ln(μ)

Table 3: Damage levels and corresponding standard deviations


1,00
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0,00
P[D_k>D_i|S_d]
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2
S_d [cm]
D1
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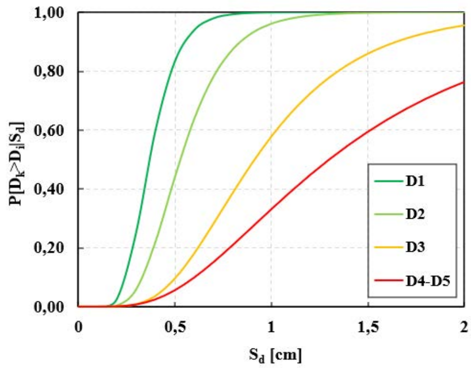
D3
D4-D5
(a)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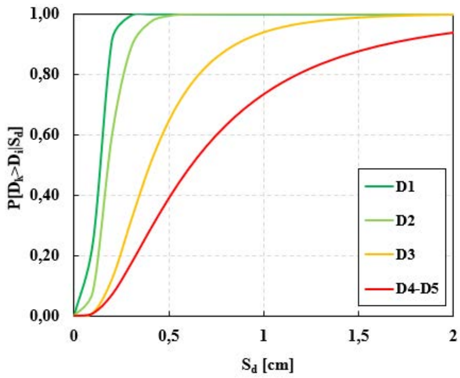
(b)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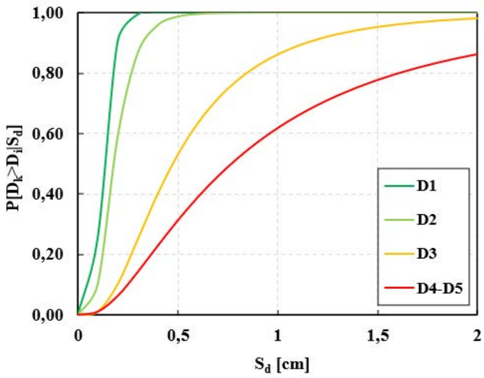
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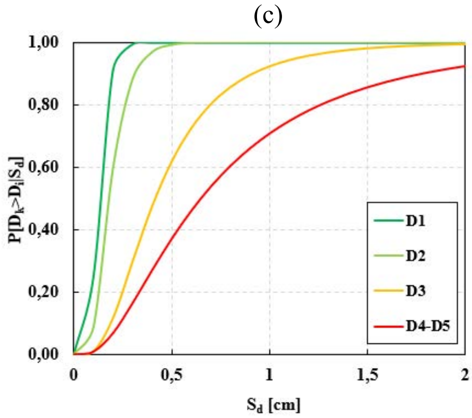
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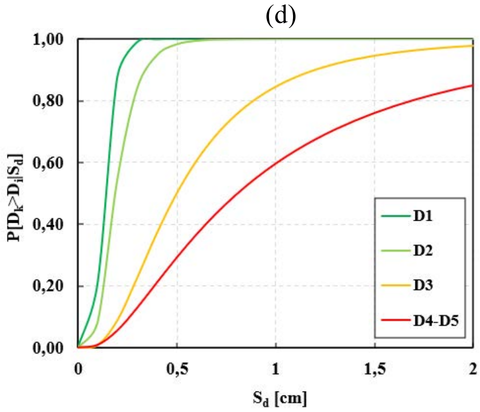
D4-D5
(e)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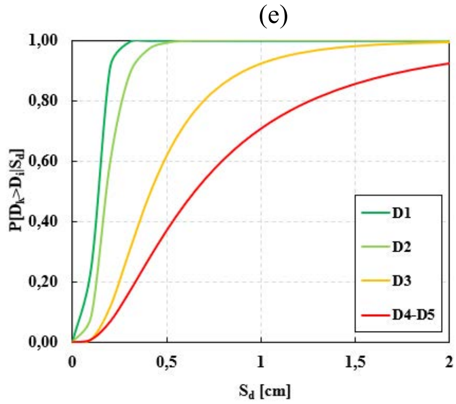
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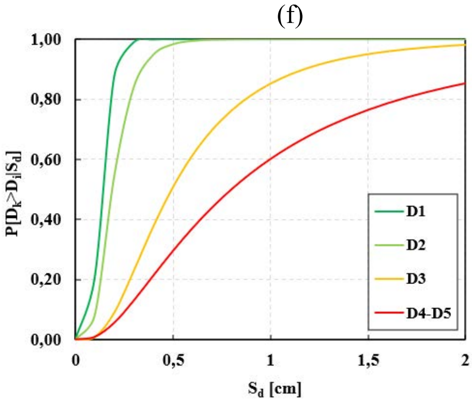
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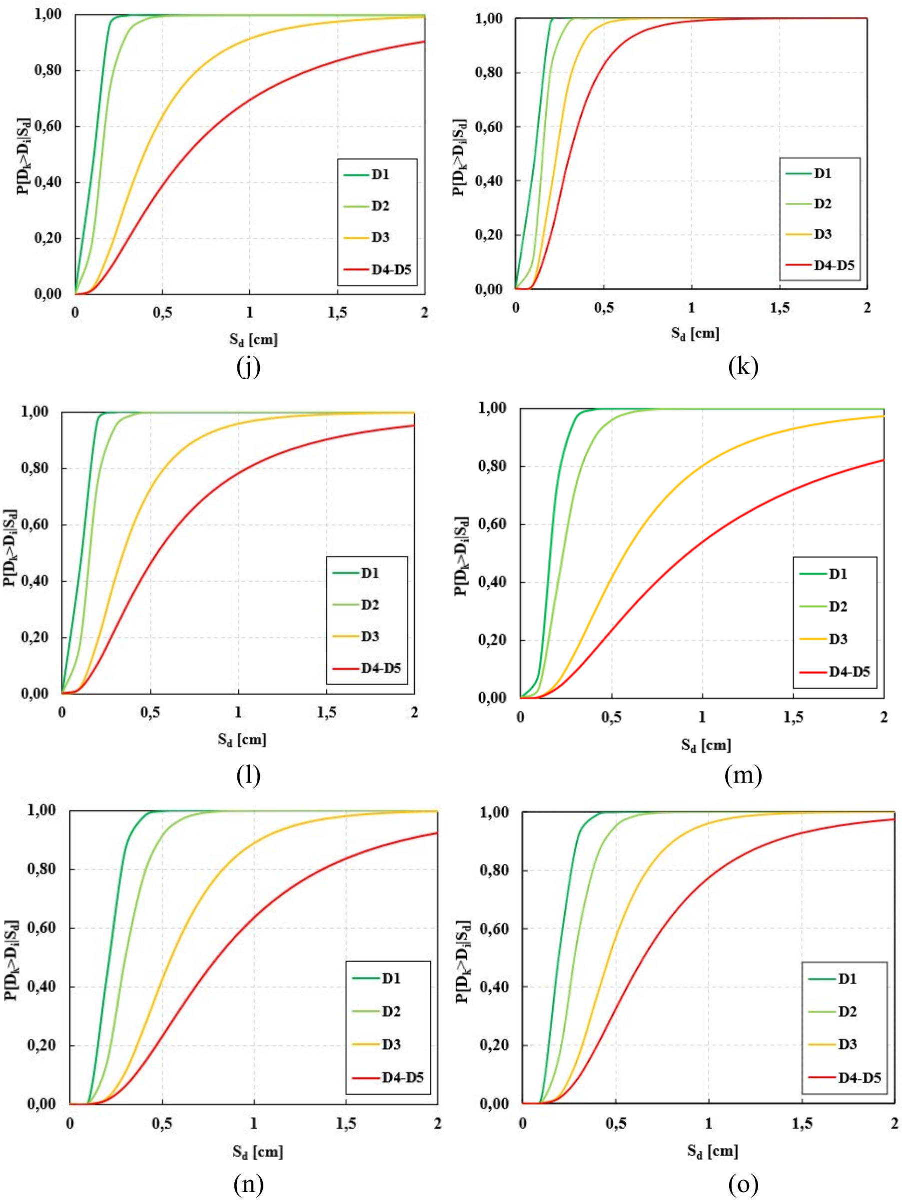


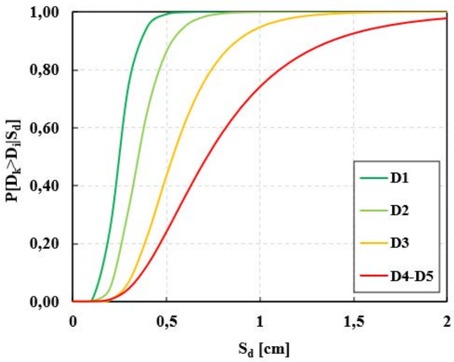
Figure 17: Fragility curves before (left) and after (right) intervention in x direction: (a) – (b) Unit 1; (c) – (d) Unit 2; (e) – (f) Unit 3; (g) – (h) Unit 4; (i) – (k) Unit 5; (l) – (m) Unit 6; (n) – (o) Unit 7.

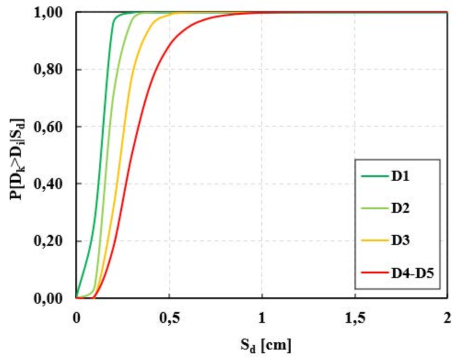
From these fragility curves provided for the x direction, it is possible to evidence that for the structural unit n.1, considering a same value of spectral displacement S_d, the probability to attain the highest damage level is reduced when the seismic coat has been applied. The same could be said for the structural units n. 2, 3 and 4, which have improved their performance thanks to the placement of the MIL 15.s on the facades of the heading building.

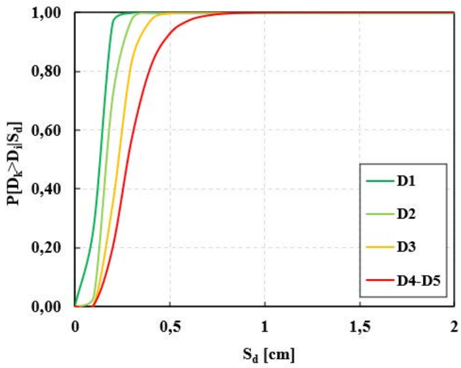
The fragility curves displayed for structural units n. 5 and 7 have pointed out a worse behaviour of these structures after the consolidating operation. This is due to the fact that the reinforcement and stiffening of the heading unit produces much more torsion effects in the building aggregate, which are detrimental for the units far from reinforced unit.

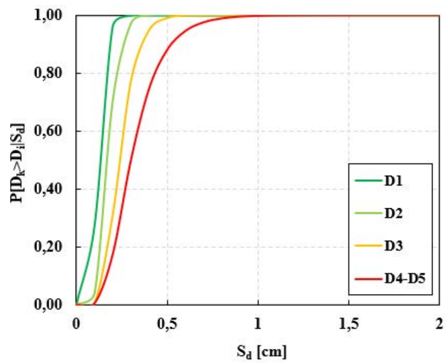
Finally, the structural unit n. 6, occupying another heading position in the aggregate, has reached a benefit from the consolidation intervention, since a decrease of exceeding the damage probability has been observed.

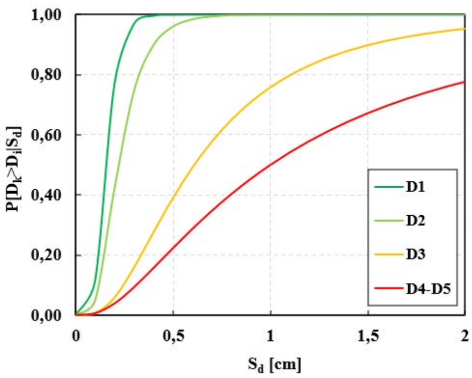
Figure 18 shows the fragility curves of all structural cells in the transverse (y) direction.

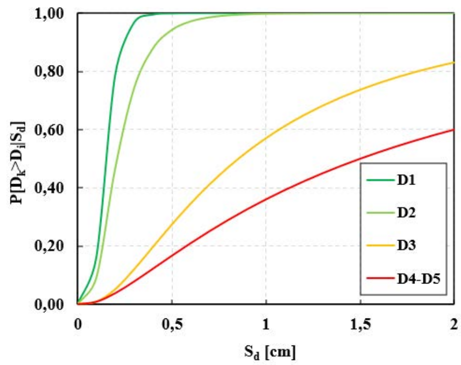

1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(a)

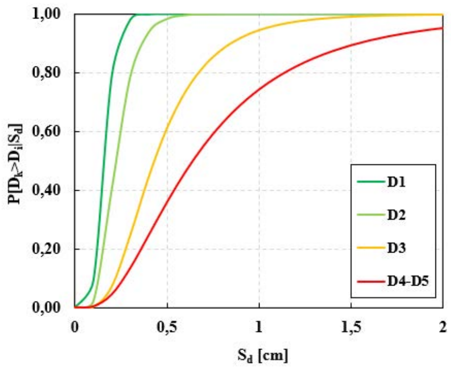

1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(b)

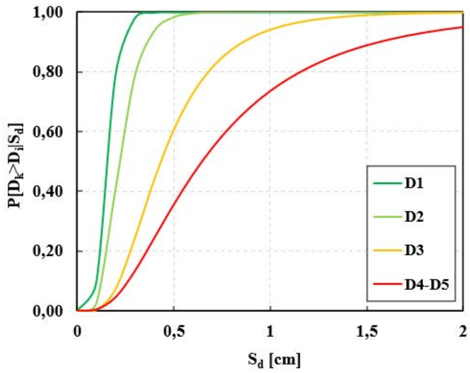

1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(c)

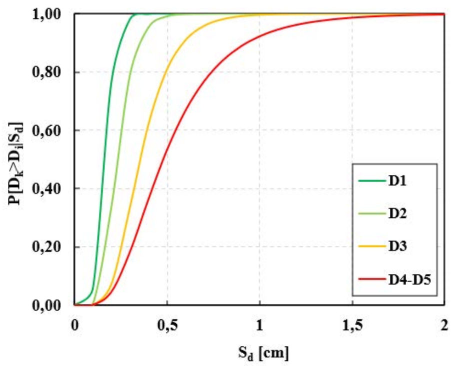

1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(d)


1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(e)

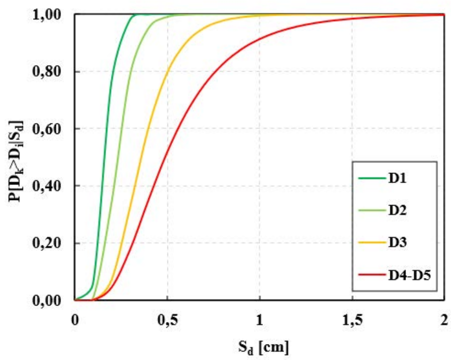

1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(f)


1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(g)

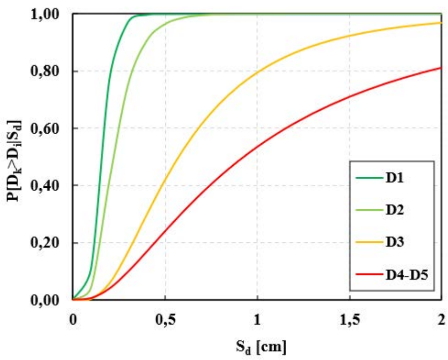

1,00
0,80
0,60
0,40
0,20
0,00
P[Dk>Di|Sd]
D1
D2
D3
D4-D5
0
0,5
1
1,5
2
Sd [cm]
(h)



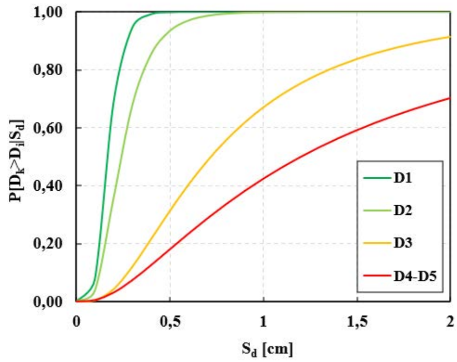
(j)



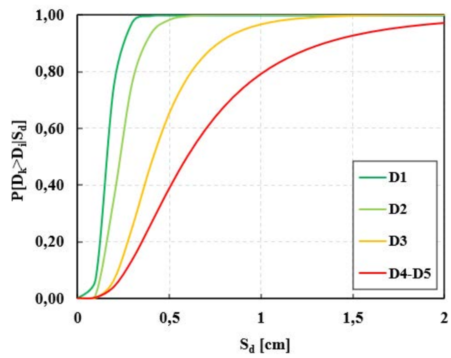
(k)



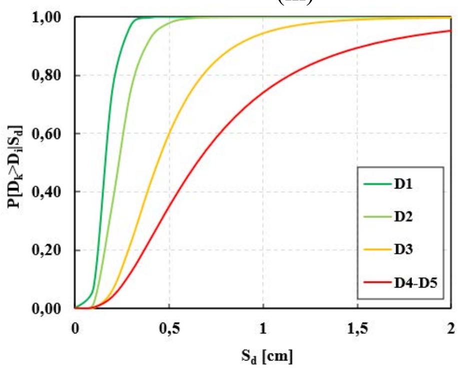
(l)



(m)



(n)



(o)

Figure 18: Fragility curves before (left) and after (right) intervention in y direction: (a) – (b) Unit 1; (c) – (d) Unit 2; (e) – (f) Unit 3; (g) – (h) Unit 4; (i) – (k) Unit 5; (l) – (m) Unit 6; (n) – (o) Unit 7.

The above fragility curves have displayed that for the structural unit n. 1 the insertion of the seismic coat has not produced a seismic benefit. The same result has been verified for the structural unit n.2, where any improvement of the seismic behaviour after intervention has been perceived. Contrary, the other structural units seem to have a light reduction of the probability of exceeding a specific damage level after insertion of the seismic coat.

6 CONCLUSIONS

The paper dealt with the evaluation of the seismic behaviour of a clustered building placed in the historical center of Castelpoto, in the district of Benevento.

Once the historical evolution and the crack pattern affecting the investigated case study building aggregate were defined and traced, in the following phases the pushover analyses, considering all the 24 load combinations foreseen by the current standard code, were carried out. Since the results pointed out a weak seismic behaviour of the clustered buildings in both analyses directions, with very low values of the seismic safety factor α_{SLV} especially for one of the heading unit (n. 1), a consolidating intervention was hypothesized. As retrofitting technique, an innovative lightweight exoskeleton made of both aluminium alloy extruded profiles and sandwich panels was applied to the structural unit n. 1.

After this intervention has been designed, the evaluation of its impact on both the reinforced unit and the other structural cells was done. This was pursued through static non - linear analyses carried out before and after the intervention by monitoring the displacements of a control node belonged, time by time, to each of the seven units. The achieved results in terms of α_{SLV} demonstrated that the structural units nearest to the reinforced one are those positively influenced by the presence of the seismic coat ,while for the other ones the intervention carried out did not provide a benefit in terms of seismic behaviour.

Contrary, different outcomes were achieved through the fragility curves, which evidenced, especially in the longitudinal direction (x) of the building aggregate, a general improvement of the seismic behaviour of the major part of structural units, with a reduction of the probability of exceeding a specific damage level. This result was in contrast with what occurred in the transverse direction (y) of the clustered buildings, where insertion of the seismic coat gave rise to almost unchanged damage probabilities. However, considering that the MIL 15.s coat did not decrease significantly the seismic behaviour of the structural cells of examined aggregate, the proposed combined seismic - energy retrofit system revealed to be helpful as effective retrofit technique of clustered buildings.

ACKNOWLEDGEMENTS

The Authors would like to acknowledge the TM Group Srl company, who patented the MIL 15.s seismic coat, for having inspired and co-financed the present research activity in the framework of a collaboration with the University of Naples Federico II.

REFERENCES

[1] M. Angiolilli, S. Lagomarsino, S. Cattari, S. Degli Abbati, Seismic fragility assessment of existing masonry buildings in aggregate. *Engineering Structures*, **247**, 2021.

[2] M. Valente, G. Milani, E. Grande, A. Formisano, Historical masonry building aggregates: advanced numerical insight for an effective seismic assessment on two row housing compounds, *Engineering Structures*, **190**, 360-379, 2019.

[3] A. Greco, G. Lombardo, B. Pantò, A. Famà, Seismic vulnerability of historical masonry aggregate buildings in Oriental Sicily, *International Journal of Architectural Heritage,* **14:4**, 514-540, 2018.

[4] A. Formisano, A. Massimilla, A novel procedure for simpliefied nonlinear numerical modeling of structural units in masonry aggregates, *International Journal of Architectural Heritage,* **11:7-8**, 1162-1170, 2018.

[5] M. Mosoarca, I. Onescu, E. Onescu, B. Azap, N. Chieffo, M. Szitar-Sirbu, Seismic vulnerability assessment for the historical areas of the Timisoara city, Romania. *Engineering Failure Analysis*, **101**, 86-112, 2019.

[6] E. Giordano, F. Clementi, A. Nespeca, S. Lenci, Damage assessment by numerical modeling of Sant'Agostino sanctuary in Offida during the Central Italy 2016-2017 seismic sequence. *Frontiers in Built Environment*, **4:87**, 2019.

[7] F. Clementi, A. Ferrante, E. Giordano, F. Dubois, S. Lenci, Damage assessment of ancient masonry churches stroked by the Central Italy earthquakes of 206 by the non – smooth contact dynamics method. *Bulletin of Earthquake Engineering*, **18**, 455 – 486, 2020.

[8] A. Miano, D. de Silva, G. Chiumento, M.L. Capasso, Seismic and fire assessment and upgrading process for historical buildings: the case study of Palanno Colonna in Caggiano. *Frontiers in Built Environment*, **6**, 22, 2019.

[9] PCM-DPC: Manual for the compilation of the form for the damage and post-seismic usability assessment for precast and large dimensions buildings (GL-AeDES), Rome (2014).

[10] A. Davino, G. Longobardi, E. Meglio, A. Dallari, A. Formisano, Seismic energy upgrading of an existing brick masonry building by a cold-formed steel envelopre system. *Buildings*, **12**, 11, 2022.

[11] G. Longobardi, A. Formisano, Seismic vulnerability assessment and consolidation techniques of ancient masonry buildings: the case study of a Neapolitan Masseria. *Engineering Failure Analysis*, **138**, 1, 2022.

[12] A. Penna, S. Bracchi, C. Salvatori, C. Morandini, M. Rota, Extending analysis capabilities of equivalent frame models for masonry structures, *European Conference on Earthquake Engineering and Seismology (ECEES 2022)*, Bucharest, Romania, 4 – 9 September, 2022.

[13] Ministry of Infrastructure and Transport. Technical Standards for Construction; Official Gazette (nr. 42 of 20-2-2018): Rome, Italy, 2018 (In Italian). [23] Ministerial Circular n.7/2019 (M. C., 02/01/2019).

[14] Instructions for the application of the "Upgrading of Technical Codes for Constructions" (M. D: 17/01/ 2018). Official Gazette of the Italian Republic published on 2019 January 2nd

[15] https://www.ecosism.com/moduli/geniale/, last accessed 08/03/2023.

[16] https://duosystem.eu/, last accessed 08/03/2023.

[17] https://www.ecosism.com/moduli/karma/ , last accessed 08/03/2023.

[18] https://www.sismacoat.it/, last accessed 08/03/2023.

[19] https://www.progettosisma.it/resisto-cappotto-antisismico, last accessed 08/03/2023.

[20] N. Chieffo, A. Formisano, P.B. Lourenço, Seismic vulnerability procedures for historical masonry structures aggregates: Analysis of the historical centre of Castelpoto (South Italy), *Structures*, **48**, 852-866, 2023.

[21] S. Lagomarsino, S. Cattari, D. Ottonelli, The heuristic vulnerability model: fragility curves for masonry buildings. *Bulletin of Earthquake Engineering*, **19:31**, 29 – 63, 2021.