Seismic vulnerability assessment and mechanical – based fragility analysis of a masonry clustered building in South Italy

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Abstract. The paper discusses the seismic behaviour assessment of a masonry clustered building, which is a prevalent typology in historical centres, particularly focusing on a case study located in a small town in Southern Italy. Following the introduction about the historical centre, the main architectural and structural features of the selected aggregate are outlined, based on the CARTIS Form, which was developed as part of the DPC – ReLUIS Italian research project. After establishing the characteristics of the building, its seismic assessment is conducted. Non-linear analyses reveal inadequate seismic behaviour in both longitudinal and transverse directions. A consolidating intervention which foresees the application of a seismic coating system is proposed. This integrated approach aims to improve both the seismic and energy performance of the aggregate. In the final part of the work, a comparison is made between the results obtained before and after the intervention. This includes the evaluation of the seismic safety index, as well as the examination of the fragility curves. The objective is to assess the effectiveness of the coating system on the structural units of the aggregate, thereby determining the overall improvement in seismic performance following the intervention.

1 Introduction

The paper provides insight into the significance of clustered buildings in Italian architectural heritage, emphasizing their prevalence in historical centres and their representation of ancient construction methods.

These buildings, characterized by multiple adjacent structural units, often lack connections among walls, leaving individual units susceptible to local failure mechanisms, such as partial or global overturning, as well as horizontal or vertical bending phenomena, which could be due to several factors, such as the increase of the weight on the slabs, the thrust derived from the shape of the roof and so on [1 – 4].

Since these constructions were constructed without any seismic design considerations, relying solely on workers' knowledge and experience to withstand gravity loads, they are very vulnerable to seismic events, as evidenced by the past earthquakes that resulted in significant damage and loss of life [5].

Recognizing the urgent need to preserve this architectural heritage, the work emphasizes the importance of assessing and retrofitting clustered buildings to reduce their seismic vulnerability. Despite the challenging nature of this task, the DPC-ReLUIS project has developed the CARTIS form to characterize clustered buildings in Italy, providing valuable data for assessing their structural characteristics and seismic behaviour. However, research on clustered buildings remains limited due to difficulties in obtaining information about their materials, age, and past interventions, as well as the complexity of modelling their behaviour accurately [6 - 9].

Therefore, the paper aims to contribute to this field by investigating the interaction effects among structural cells resulting from seismic interventions, specifically focusing on an innovative integrated seismic - energy coating applied to the facades of one structural unit of a case study aggregate.

2 The centre of Castelpoto and the case study

The seismic investigation focuses on a clustered building placed in the small historical centre of Castelpoto, located in the district of Benevento, within the Campania region in the Southern part of Italy.

Castelpoto is a hillside village with medieval origins, positioned on the outskirts of Benevento, as depicted in Fig. 1.

Fig. 1. Placement of the centre of Castelpoto

Like many historical centres, the study of Castelpoto's historical evolution has been challenging due to the disorganized and poorly documented nature of its construction and alterations occurred over the centuries. However, the paper provides an evolutionary framework detailing the village's development, including identification of major construction epochs.

Castelpoto was founded, according to some archaeological evidences, during the Roman era. Its current location dates back to the medieval period, around the year 598, when the Longobardi, a Germanic population, occupied the territory of Benevento and its environs. The village experienced a period of prosperity during Norman rule, after which there was the succession of several families in power.

Nowadays, Castelpoto's urban layout is structured around two main road axes. The first one features requalified or newly constructed buildings, while the second axis is characterized by the presence of ancient and damaged structures requiring consolidating interventions.

The masonry aggregate under examination is placed in Dietro La Torre Street, slightly detached from the ancient medieval nucleus of Castelpoto. This area has been targeted by the local administration for redevelopment, aiming to revitalize the historical centre, which, thanks to the presence of the old medieval Castle, holds potential as a tourist destination.

The location of the case study is depicted in **Fig. 2**.

Fig. 2. Individuation of the masonry compound under study

Comprising seven structural units positioned on a slope with varying altitudes due to their hillside placement, the masonry aggregate exhibits distinct characteristics influenced by the materials used for vertical walls and by past interventions aimed at improving their condition after seismic events. **Fig. 3** illustrates the plan configuration of the clustered buildings under study. Structural units nr. 2, 4, and 5 (depicted in grey in **Fig. 3**) underwent consolidating operations dating back to the 1940s.

Structural unit nr. 7 (highlighted in pink in the same figure) experienced local collapses, while units 1, 3, and 6 were never subjected to repair interventions.

Photographic documentation depicting the decay state of the entire aggregate is provided.

Fig. 4 reveals erosion phenomena affecting the mortar due to exposure to environmental agents, which led to its pulverization.

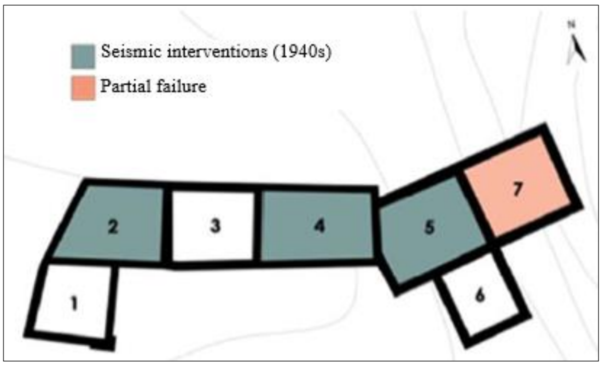

Fig. 3. Layout of the aggregate with the seven structural cells

Fig. 4. Erosion phenomena on vertical masonry walls

Additionally, partial collapses are evident in correspondence to wooden beams of intermediate floors (**Fig. 5**).

Fig. 5. Injured and deformed wooden beams

In the end, **Fig. 6** evidences the collapse of some sections of roofs.

Fig. 6. Collapses of the roofs

3 Evaluation of the seismic behaviour of the masonry compound

The seismic behaviour of the aggregate was assessed using the 3Muri computer program, developed by S.T.A.DATA company, which employs the frame by macro - elements (FME) technique. In this approach, masonry panels are divided into three macro - elements: masonry piers, spandrels, and rigid nodes. These elements are depicted in orange, green, and light blue, respectively, in **Fig. 7**.

Considering a window, the masonry piers are located next to the opening, the spandrel are above and under it, while the rigid node could be considered as the intersection of the two previous elements. It is assumed having an infinitely rigid behaviour [10].

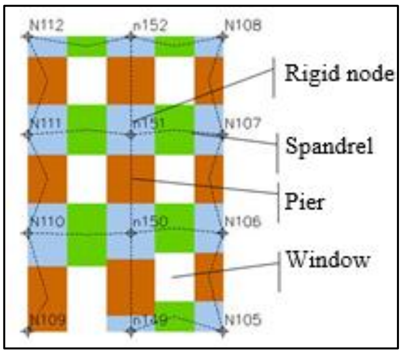

Fig. 7. The three macro - elements

The view of the meshed structure with the individuation of the three above mentioned macro – elements is represented in **Fig. 8**.

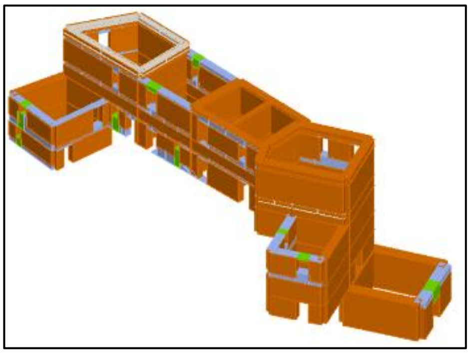

Fig. 8. A view of the meshed entire aggregate

The non - linear behaviour of the clustered building was evaluated, and the results were represented by capacity curves plotted in base shear – top displacement diagrams.

The assessment followed the current Italian technical code, considering 24 load combinations obtained from two inertial force distribution methods [11, 12]:

- Distribution proportional to static forces (Group 1);
- Uniform distribution of forces derived from a uniform distribution of accelerations over the construction height (Group 2).

In order to construct the model, a precise procedure was followed. Firstly, wall axes were plotted using CAD files imported into the 3Muri software. Secondly, mechanical characteristics of structural materials were defined based on the lowest level of knowledge (KL1) due to limited mechanical investigations, assuming minimum strength and average elastic modulus values for masonry.

Intermediate floors and roof structures were modelled over the masonry structure, recognizing three types of floors: one with wooden beams (Units 1, 3, and 6), and another made up of steel beams and masonry vaults (Units 2, 4, and 5). Unit 7 did not have any intermediate horizontal floor, as it consists of a single story.

After implementing the three - dimensional model, pushover analyses were conducted on the building aggregate.

The results of the two worst analyses for the internal structural unit nr. 4 are provided in **Table 1**, showing the seismic safety factor at the Life Safety Limit State for each analysis direction. The safety factor derived from the ratio of capacity and demand peak ground acceleration (PGA).

Table 1. Results of non-linear analyses

Nr.	Seismic direction	Seismic load	Eccentri city cm]	α_{SLV}
1	+X	Static Forces	67,76	0,574
19	+Y	Static Forces	173,86	0,359

4 The integrated coating system

4.1 An overview of the MIL15.s system and modelling on the software

The pushover analyses conducted by monitoring the displacement of a node belonging to Structural Unit Nr. 4 of the clustered building revealed its vulnerability under seismic actions in both longitudinal (X) and transverse (Y) directions.

As a result, a consolidation intervention was proposed. Among various existing seismic - energy integrated retrofitting techniques, a light metal exoskeleton connected to the external facades of the building was chosen. This innovative and minimally invasive technique not only improves the seismic performance, but also enhances energy efficiency by incorporating insulating panels within the exoskeleton frame.

Seismic coating systems, though modern retrofitting solutions, have evolved over the years with different versions introduced to the construction market [13, 14].

In this case, the chosen solution is the MIL15.s seismic coat, as illustrated in **Fig. 9**. It was developed and patented by the Italian company TM Group S.r.l. in 2022. This system uses aluminium alloy extruded profiles (labelled Nr. 1 and 2) attached to the masonry walls using chemical anchors (Nr. 6). Sandwich panels (Nr. 8) are inserted between two consecutive vertical profiles and connected to the aluminium elements with self-drilling screws (Nr. 7). Thermal insulators (Nr. 3) and EPDM tape (Nr. 5) are used so to reduce any thermal dispersions between different elements of the coating system.

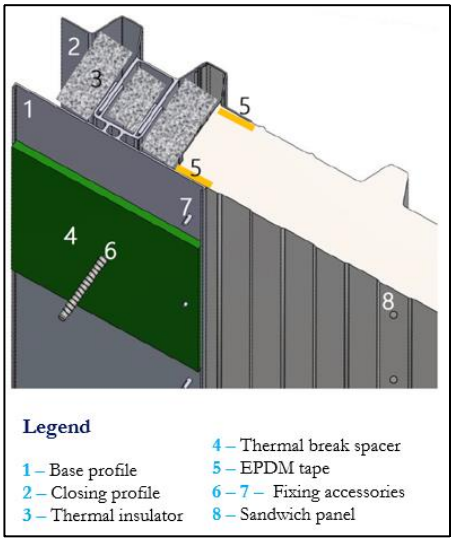

Fig. 9. The retrofitting integrated system for the aggregate

This technique not only reinforces the building against seismic forces, but also enhances its energy efficiency, allowing to have a comprehensive solution for retrofitting historical masonry structures, like the clustered building in Castelpoto.

The dimensioning and Finite Element Method (FEM) modelling phases of the seismic coating system involved introducing an equivalent diagonal system corresponding to each masonry pier at every level.

Since the MIL15.s system comprises several modules placed on each pier, represented by sandwich panels acting as seismic devices, these panels needed to be replaced with an equivalent diagonal system with a full circular cross-section for modelling purposes.

Fig. 10 depicts the three - dimensional model of the clustered buildings with the seismic coat (schematized with equivalent diagonals and represented in blue) installed on the two free facades of the internal structural unit nr. 4.

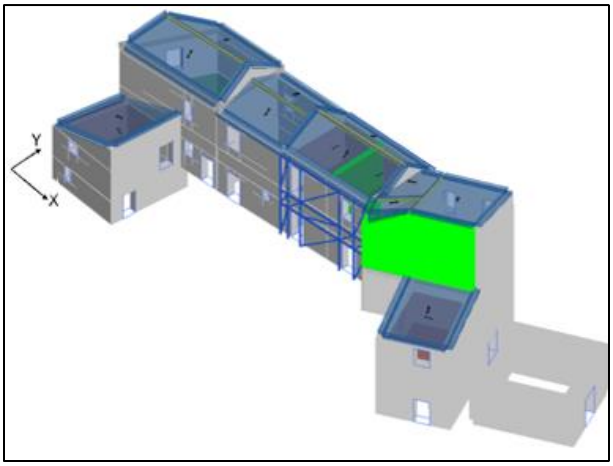

Fig. 10. The SU4 retrofitted with the seismic - energy coat

4.2 Results

The MIL15.s seismic coat was applied to the two free facades of SU4. This choice was made to investigate not only the effects of the coating system on the reinforced building, but also its impact on the other six structural cells.

In fact, it is important to consider that, within an aggregate, the behaviour of a single structural unit is strongly influenced by the others during a seismic event. Therefore, the intervention on a single structural, to be considered as an effective procedure, should not penalise the seismic behaviour of other constructions.

To evaluate the influence and effects of the seismic coat on all the other structural units, pushover analyses were conducted. These analyses were performed by monitoring the displacement of a control node belonging to each of the cells composing the clustered buildings. By checking the displacement of these nodes, the response of each structural unit when the seismic coat is applied could be assessed.

The final results are contained in **Table 2**.

Table 2. Results after consolidation intervention

SU	Seismic direction	α_{SLV} Before Seismic Coat	α_{SLV} After Seismic Coat
1	X	0,267	0,254
	Y	0,313	0,359
2	X	0,581	0,577
	Y	0,290	0,318
3	X	0,574	0,567
	Y	0,435	0,450
4 Retro-fitted	X	0,573	0,581
	Y	0,359	0,371
5	X	0,619	0,542
	Y	0,345	0,368
6	X	0,643	0,652
	Y	0,436	0,490
7	X	0,585	0,595
	Y	0,479	0,488

Regarding the retrofitted unit nr. 4, it is possible to highlight a light increase of the coefficient α_{SLV} in both directions, with a greater benefit along the transversal axis (y).

Regarding the other structural cells, the results in terms of α_{SLV} pointed out that the SUs nr. 5, 6 and 7 are those positively influenced by the presence of the seismic – energy coat, while for the other ones the intervention did not provoke a benefit in terms of seismic behaviour: indeed, their coefficients remain stable or slightly decreases.

5 Mechanical – based fragility study

In addition to the seismic verifications, a fragility study was conducted to assess the seismic behaviour of the retrofitted structural unit. This analysis was expressed in terms of fragility curves, which were derived based on the displacements obtained from the pushover analyses.

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:

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

The damage thresholds were determined according to [15] and were evaluated based on yielding and ultimate displacements. The utilized damage levels and corresponding standard deviations are presented in **Table 3**.

Table 3. Damage thresholds for the derivation of mechanical – based fragility curves

Damage Level	Limit displacement	Damage type	Standard deviation β_i
D1	0,7 d_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	0,10+0,40ln(μ)
D4 – D5	d_u	Collapse	0,15+0,50ln(μ)

Fig. 11 and **Fig. 12** illustrate the fragility curves before and after the intervention in the x direction for the structural cell nr. 4 object of the retrofitting intervention.

These curves provide valuable insights into the probability of different damage levels occurring in each structural unit as a function of spectral displacement, offering a comprehensive understanding of the seismic performance improvements achieved with the implementation of the MIL15.s system.

Along x axis, considering a same value of spectral displacement S_d, it is possible to note that the probability to attain the highest damage level is reduced when the seismic coat has been applied.

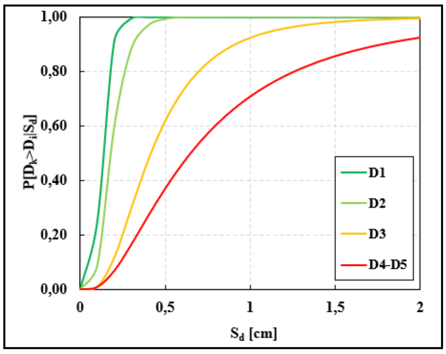

Fig. 11. Fragility curves for SU4 - Before Consolidation – x Direction

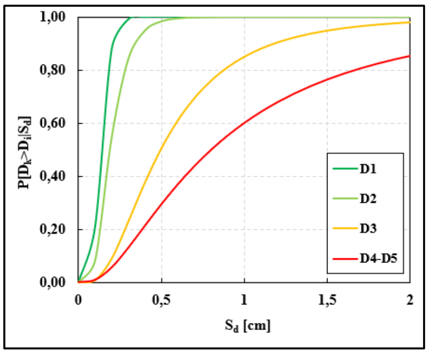

Fig. 12. Fragility curves for SU4 - After Consolidation - x Direction

Fig. 13 and **Fig. 14** show the fragility curves of the same strengthened structural unit in the transverse (y) direction.

In this direction, the insertion of the seismic coat has produced a light seismic benefit also in terms of fragility curves as occurred by considering the safety seismic index.

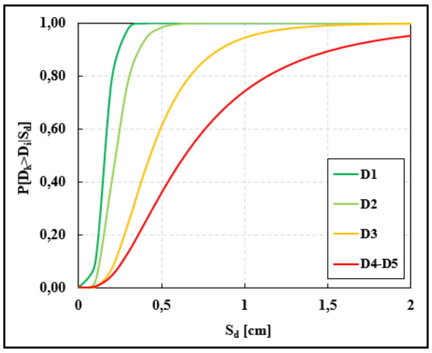

Fig. 13. Fragility curves for SU4 - Before Consolidation - y Direction

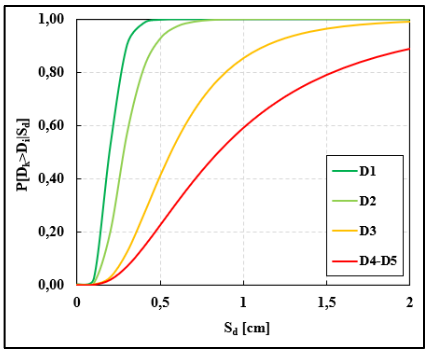

Fig. 14. Fragility curves for SU4 - After Consolidation - y Direction

The mechanical – based fragility curves were provided also for other two structural cells: the heading unit nr. 1 and another internal unit (SU5) next to the examined one.

In the first case, regarding the heading unit nr. 1, as occurred for the safety index also in terms of fragility curves, there was not a great benefit derived from the arrangement of the envelope system.

In x direction, the fragility curves appear slightly worse with an increase of the probability to attain the highest damage level when the seismic coat was applied. These curves are plotted in **Fig. 15** and **Fig. 16** before and after the intervention for the longitudinal direction, respectively.

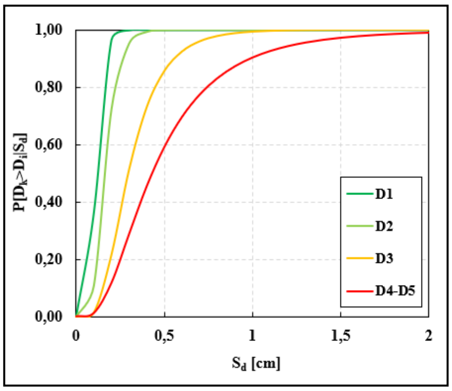

Fig. 15. Fragility curves for SU1 - Before Consolidation – x Direction

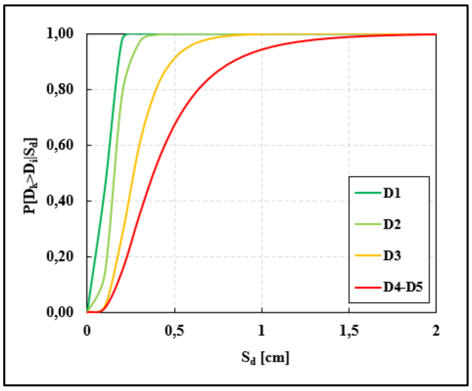

Fig. 16. Fragility curves for SU1 - After Consolidation – x Direction

On contrary, along y axis, the insertion of the seismic coat has produced some seismic benefit in terms of fragility curves, since the behaviour appears improved, as evidenced in **Fig. 17** and **Fig. 18**.

Concerning the structural unit nr. 5 placed next to the consolidated one, fragility curves highlighted a moderate improvement in the behaviour with a slight reduction in the probability of attain the highest level of damage in both directions.

The curves are illustrated for the longitudinal direction before and after the consolidation in **Fig. 19** and **Fig. 20**.

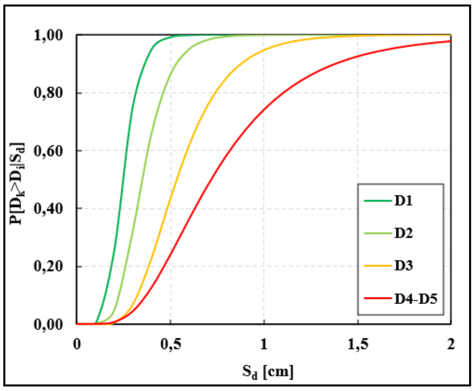

Fig. 17. Fragility curves for SU1 - Before Consolidation – y Direction

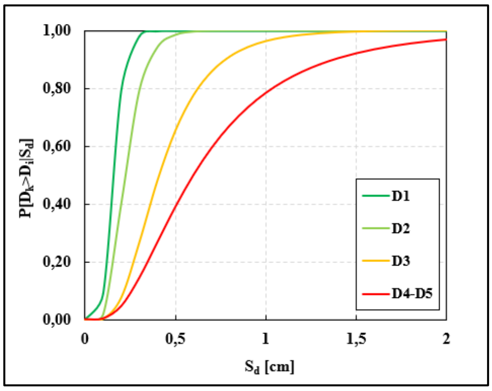

Fig. 18. Fragility curves for SU1 - After Consolidation – y Direction

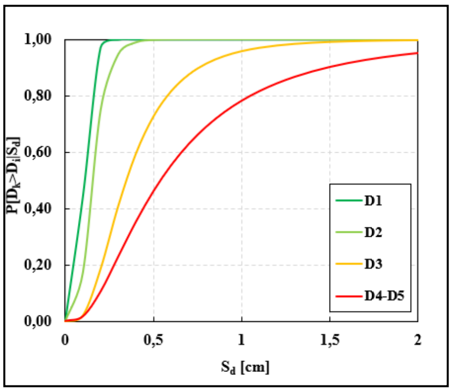

Fig. 19. Fragility curves for SU5 - Before Consolidation – x Direction

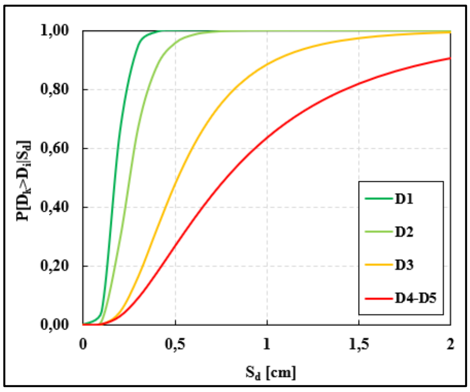

Fig. 20. Fragility curves for SU5 - After Consolidation – x Direction

In the end, **Fig.** *21* and **Fig.** *22* show the results in terms of mechanical – based fragility curves achieved in the transverse direction.

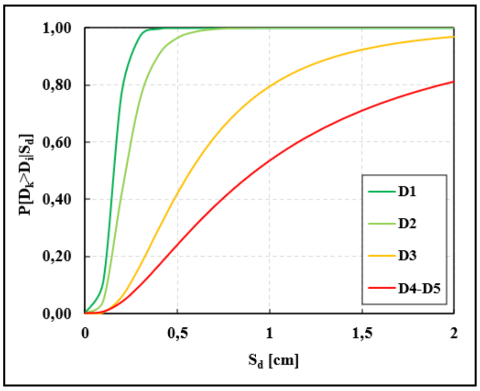

Fig. 21. Fragility curves for SU5 - Before Consolidation – y Direction

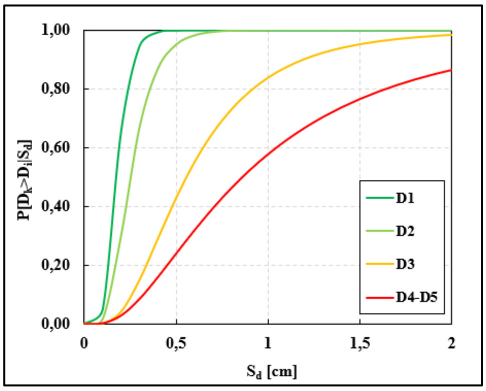

Fig. 22. Fragility curves for SU5 - After Consolidation – y Direction

6 Conclusions

The paper focuses on evaluating the seismic behaviour of a clustered building placed in the historical centre of Castelpoto, in the Benevento district. Initially, the study involved identifying the historical evolution and crack patterns affecting the aggregate under investigation. Subsequently, pushover analyses were conducted, considering all the load combinations given by the current technical code.

The results indicated a weak seismic behaviour for the clustered building in both analysis directions.

In response to this outcome, a consolidating intervention was proposed. It consisted of an innovative lightweight exoskeleton made of aluminium alloy extruded profiles and sandwich panels. It was applied to the internal structural unit nr. 4.

Following the design of this intervention, the paper evaluated its impact on both the reinforced unit and other two structural cells having different position within the aggregate. This evaluation was conducted through static non - linear analyses performed before and after the intervention, monitoring the displacements of control nodes belonging to each of the seven units. The results demonstrated that, although the seismic improvement according to the Italian technical code was not attained (since the increase of the α_{SLV} coefficient was less than 0,1), some benefits derived from the arrangement of the coating system were achieved. Particularly, the safety index pointed out that the structural units nearest to the reinforced one were positively influenced from the presence of the seismic coat, while for the other units, the intervention did not significantly improve their seismic performance.

In the end of the work, the mechanical – based fragility curves were plotted. They highlighted a general improvement in seismic behaviour for most structural units, particularly along the longitudinal direction. In contrast, the transverse direction (y) showed relatively unchanged damage probabilities after the insertion of the seismic coat.

Overall, despite not significantly improving the seismic performance of all structural cells, the proposed combined seismic - energy retrofit system is deemed effective for clustered buildings, as evidenced by its impact on fragility curves and overall enhancement of seismic response of most of the aggregated units.

7 Acknowledgements

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