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SEISMIC RISK ANALYSIS FOR THE NATIONAL GEOLOGY MUSEUM

Research report no. 3

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INTRODUCTION: FRAGILTY ANALYSIS FOR BUILDINGS FROM THE EDUCATIONS SECTOR

The building stock from the education sector (kindergartens, schools, high schools, colleges, dormitories or children's clubs) consists of unreinforced or confined masonry buildings in a proportion of approximately 60%, according to data collected nationwide in the database from the Integrated Informatics of Education in Romania (SIIIR). Only about 20% are unreinforced masonry buildings, but more than half were built before 1920. Masonry structures with columns and reinforced concrete tie beams are the most common structural system and more than two-thirds of these buildings have been built. built before 1977.

These statistics justify the concern for a typological analysis of masonry buildings, while also considering the peculiarities of buildings classified as historical monuments. The approximately 550 buildings analyzed below are established based on the List of Historical Monuments (2015), where they were marked as having functions of kindergarten, school, high school or college. University buildings have been excluded from this analysis. A communiqué of ICOMOS Romania from 2013 (Nistor 2013) mentioned that there are 605 buildings belonging to the education sector, being included here also faculties, university headquarters and libraries.

The map in Fig. 22 illustrates the distribution of buildings classified as historical monuments, used in the education sector. The symbols represent the values normalized to the maximum number of buildings in Bacău County, so that comparisons between counties are possible. The counties with the most buildings are located mainly in the south (Teleorman, Dâmbovița), northeast (Vaslui, Iași, Bacău, Neamț) and northwest (Maramureș, Cluj).

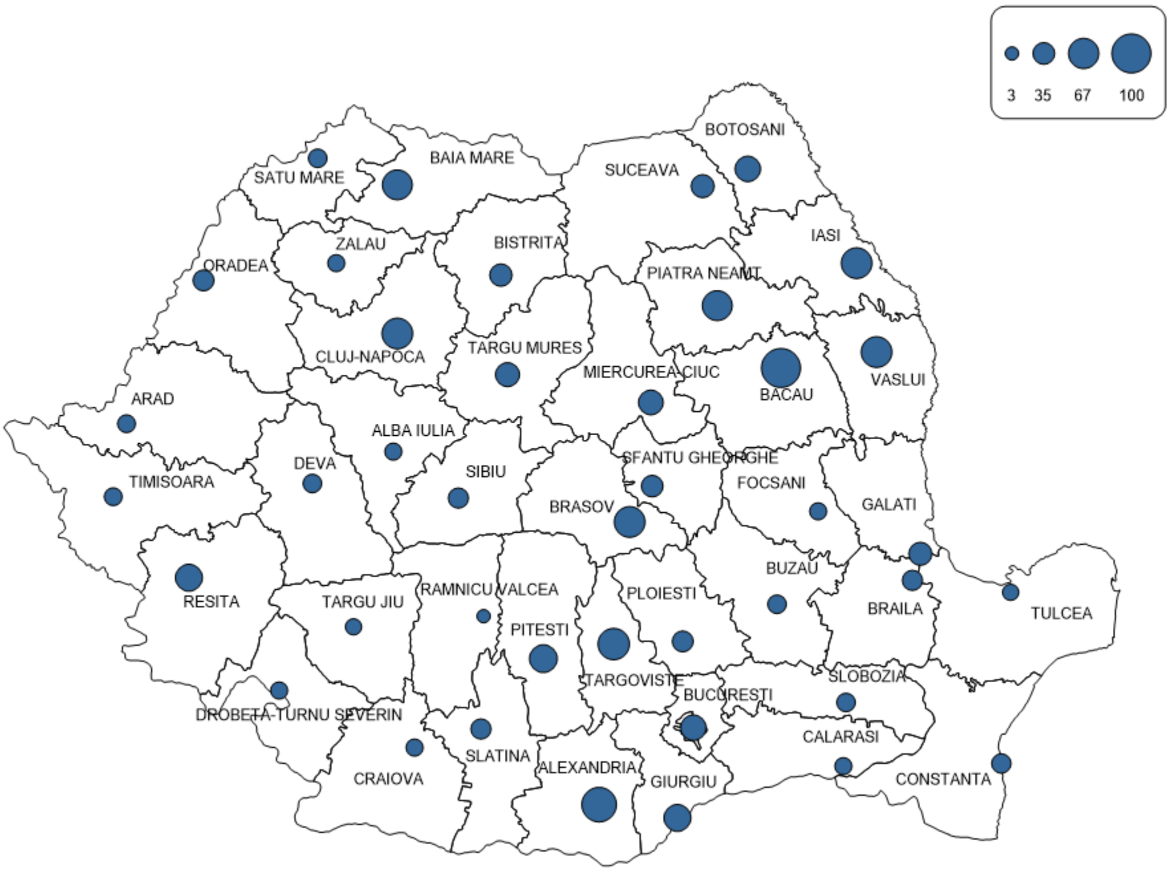


Fig. 1 The number of heritage buildings from the education sector

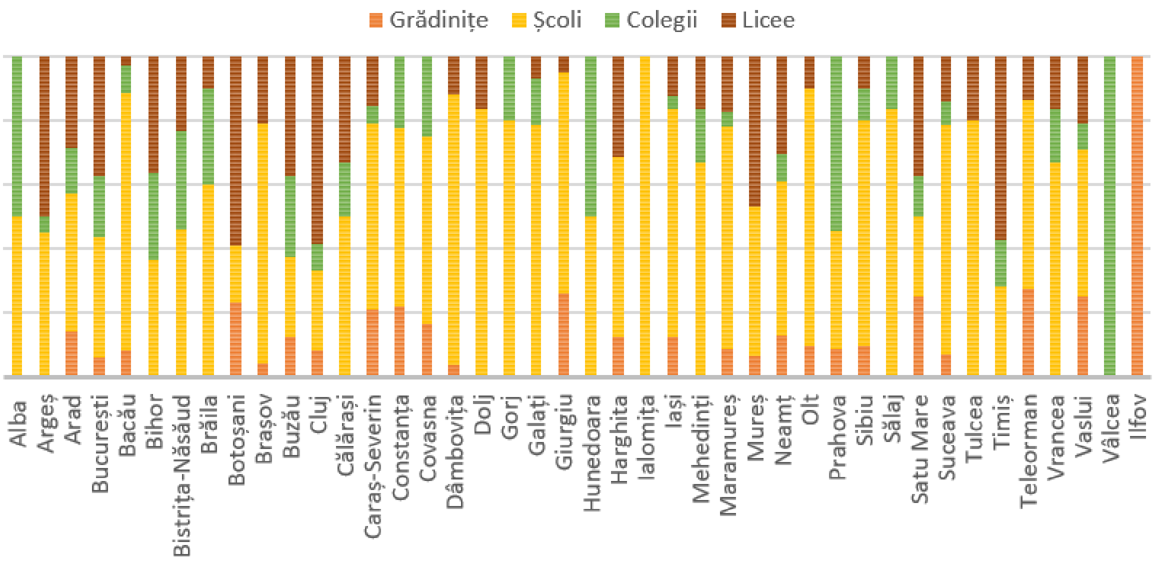


Fig. 2 The typologies of historic buildings in the education sector, at county level

Fig. 2 presents the distribution of the four types of buildings analyzed, at country level. It can be observed that most of them are schools, followed by high schools and few colleges and kindergartens. For the types of schools, ICOMOS presents some architectural typologies, which are representative for the education building stock, mentioning “Spiru Haret school type”. These are buildings constructed at the end of the XIXth century – beginning of the XXth century, predominantly in the southern part of the country and in Bacau, where there are also located most of the buildings from the map. Taking into account the historical context in which they were built, national colleges from cities like Bucharest or primary schools previously mentions represent “construction references” because they capture the identity and the abilities of the modern world (Nistor 2013).

Considering the value of the buildings that are part of the education sector, given their historical and architectural importance, but also their age, it is necessary to analyze the seismic risk associated with them. The recommended approach involves establishing structural typologies that allow the initial filtering of a large number of buildings through objective criteria in order to estimate the expected structural response.

Measures to reduce seismic risk for monumental buildings in the education sector will be analyzed through a case study of a school whose structural upgrades are representative for retrofitting interventions on masonry buildings in Romania. The results will be compared with studies in the literature and later on, fragility characteristics will be established for three types of masonry buildings: unreinforced masonry, confined masonry and reinforced masonry (invasive retrofitting measures).

BUILDING STOCK CHARACTERISTICS FOR THE EDUCATION SECTOR

Seismic risk analyses for the entire building stock require information on exposure, in the form of inventories on buildings and people exposed. For the public schools in the pre-university education sector, an Integrated Information System of Education in Romania (SIIR) has been implemented, which contains also data relevant for the analysis of the schools buildings. They were further used to assess the exposure and vulnerability of buildings.

The main attributes required for the analysis include: the structural system (as well as the type of floor systems for masonry buildings), the year of construction, the location, the built-up area, the height regime, the number of students enrolled and information on the existence of retrofitting works.

The analyzed sample for which sufficient attributes were available is 29.284 buildings from over 15.900 educational units, distributed throughout the country, as shown in Fig. 3. Out of these, 2% are buildings listed as historical monuments (2015) (National Heritage Institute 2015) from 315 school units that could be correlated with the data from the initial list of 546 monuments. The difference is represented by buildings classified as historical monuments in the education sector, but later transformed into administrative buildings, museums or housing units (Commercial School, Giurgiu – currently used as Design Institute, Normal Boys School, Vaslui - today working as a hospital), schools that were demolished (Obedeanu School, Craiova) or which could not be identified in the SIIR database (Bulbucata Kindergarten, Giurgiu).

They way the dots are placed on each county is random, but the map from Fig. 3 allows the comparison among absolute values in terms of number of buildings. Thus, it can be observed that the eastern part of the country (Iasi and Vaslui) contains the largest numbers of buildings and the highest density of such buildings in related to the surface of the county, except Bucharest area. Ilfov, Prahova, Dambovita and Botosani also have large densities of analyzed buildings, while Tulcea, Caras-Severin, Arad and Hunedoara are on the opposite side. If there are more than 4 heritage buildings/km^2 in Bucharest, in those counties the average is below 0.08 heritage education bluidings/km^2, compared to the national average of 0.22.

There are about 2395000 students enrolled in the 15929 school units which were analyzed, according to the data from 2018-2019 school year. Their distribution at county level is shown in Fig.4, where each point corresponds to 1000 enrolled students. The data shows the same as was highlighted in the case of buildings, namely that maximum values are concentrated in the Bucharest area, where there are more than 1000 students/km^2, while the national average is 35/ km^2. Tulcea and Covasna are the counties with the lowest number of students from the sample, unlike Iasi and Suceava, both counties having more than 100000s students. The southern-central region of the country (Bucharest, Ilfov, Prahova and Dambovita) and the eastern part (Iasi) seem to be the densest ones. Comparing the number of students from the sample with the demographic data from the latest Census from 2011 (INS, 2011), the counties having less than 10% children out of the total population are Giurgiu and Sibiu, while Bistrita-Nasaud, Harghita, Iasi, Suceava and Satu-Mare have more than 15%.

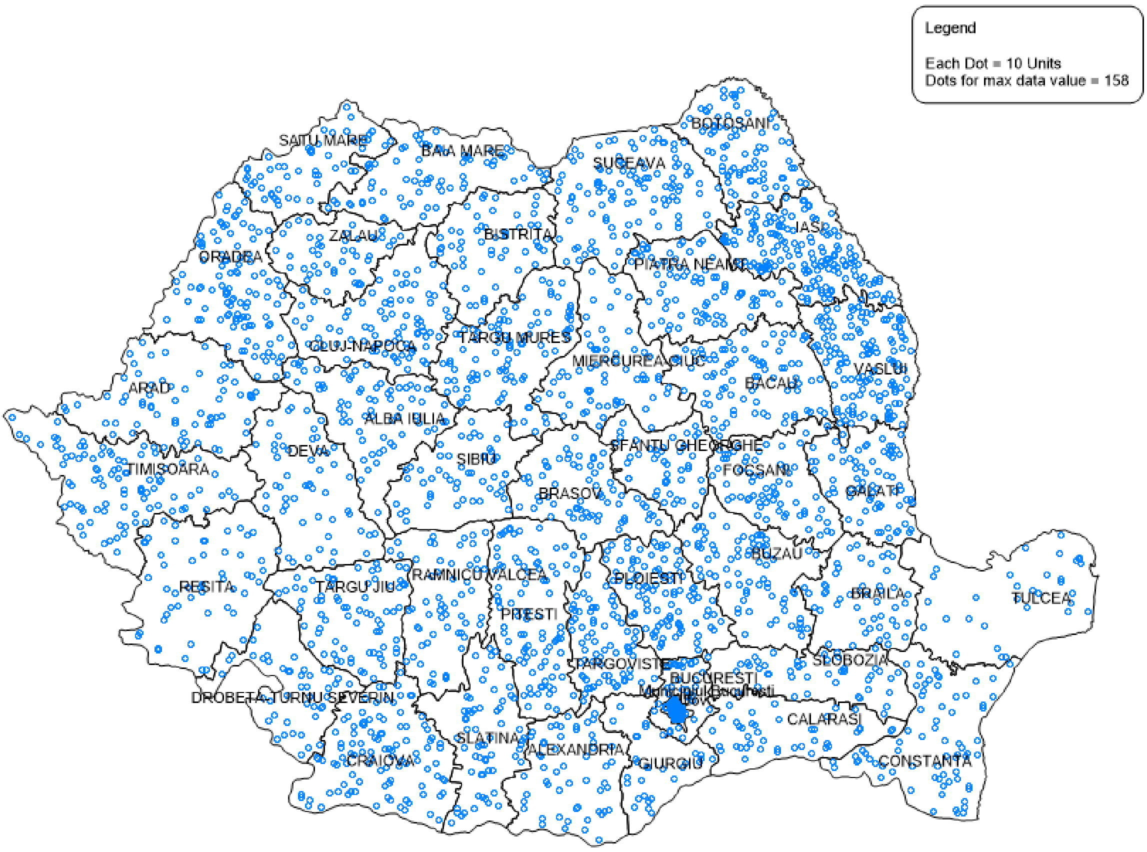


Fig. 3 Country level distribution of buildings from the considered sample

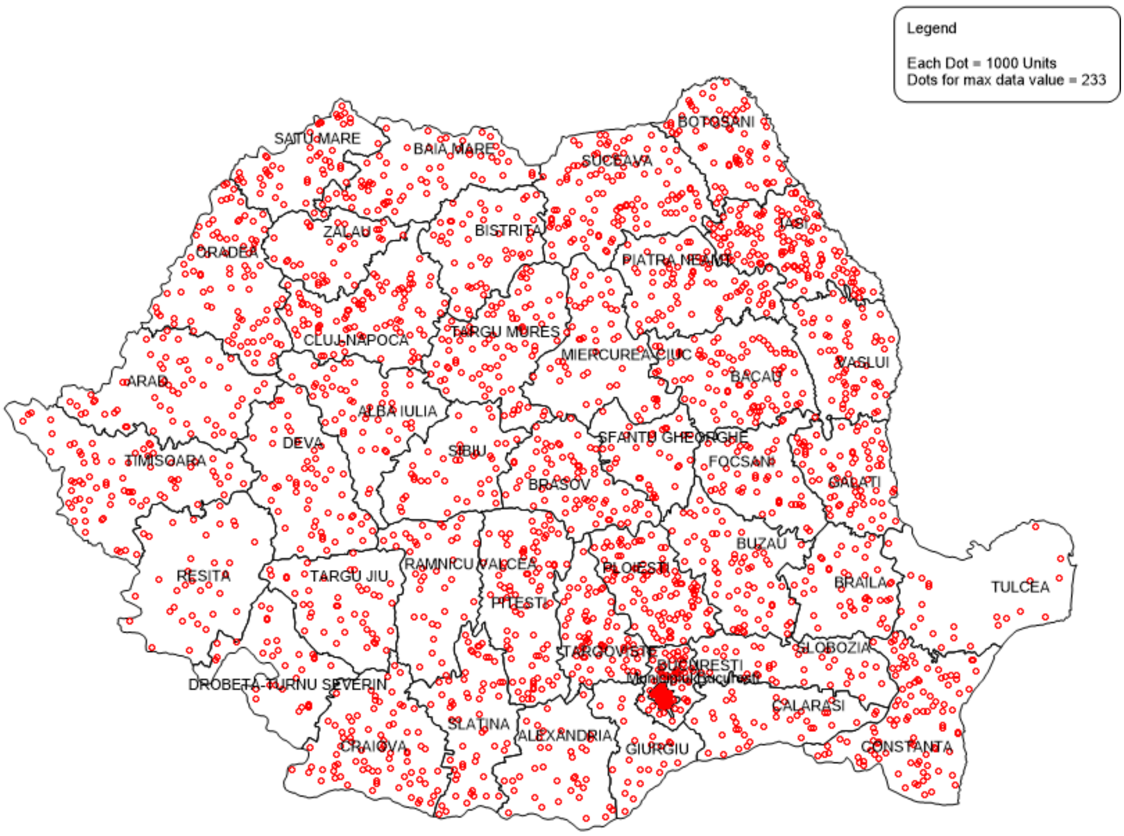


Fig. 4 Country level distribution of students enrolled from the considered sample

Starting from the list of structural systems predefined in SIIIR, the following typologies were considered:

- CM – confined masonry
- URM – unreinforced masonry
- RC_F – reinforced concrete frames
- RC_W – reinforced concrete shear walls
- W – wood
- S – steel
- RC_LP – reinforced concrete large panels

For the building having a structural system defined as "other" and for buildings having more than one structural system defined, the most probable structural system was established function of the year of construction, as shown in Fig. 5. Because the data base had contractor data in some cases, the following changes had to be done, considering the correlation between the year of construction and the construction methods adequate for that specific time:

i. For buildings built before 1920 and defined as RC (frames, shear walls or large panels), the most probable structure system was considered to be confined masonry
ii. For the buildings built before 1960 and defined as RC shear wall structures, the most probable structural system was considered to be RC frames
iii. For the buildings built before 1940 and defined as confined masonry, the most probable structural system was considered to be unreinforced masonry
iv. For the building built after 1940 and defined as unreinforced masonry, the most probable structural system was considered to be confined masonry
v. For the building built before 1920 and defined as steel structures, the most probable structural system was considered to be URM, while for the ones built in between 1920 and 1960, the most probable structural system was considered to confined masonry.

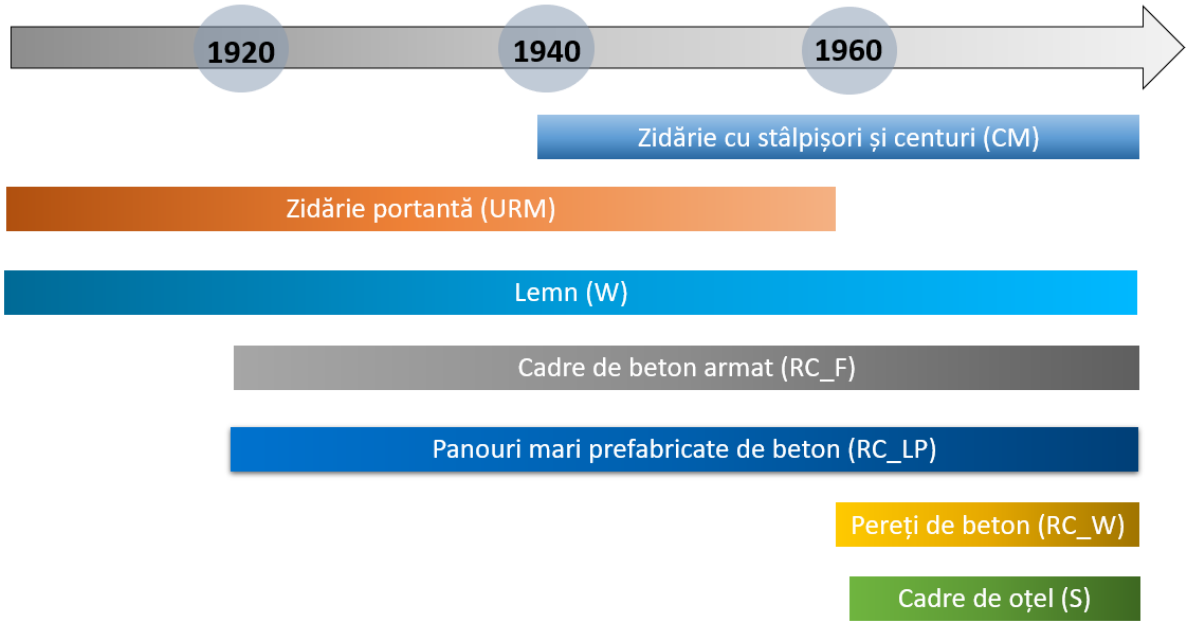


Fig. 5 Structural system evolution for buildings in the education sector

Fig. 6 shows the percentages resulted for each structural system after the changes presented above. From the entire sample of buildings, 50% of them are masonry structures (URM or CM) and about 40% are RC structures. Only 4% are RC shear wall structures or wooden frames, while less than 2% are steel structures or large RC prefabricated panels. The buildings listed as heritage structures are presented in Fig. 5 where the 445 buildings are distributed in function of their structural system. More than 40% were built before 1920 and the largest share comprises URM structures.

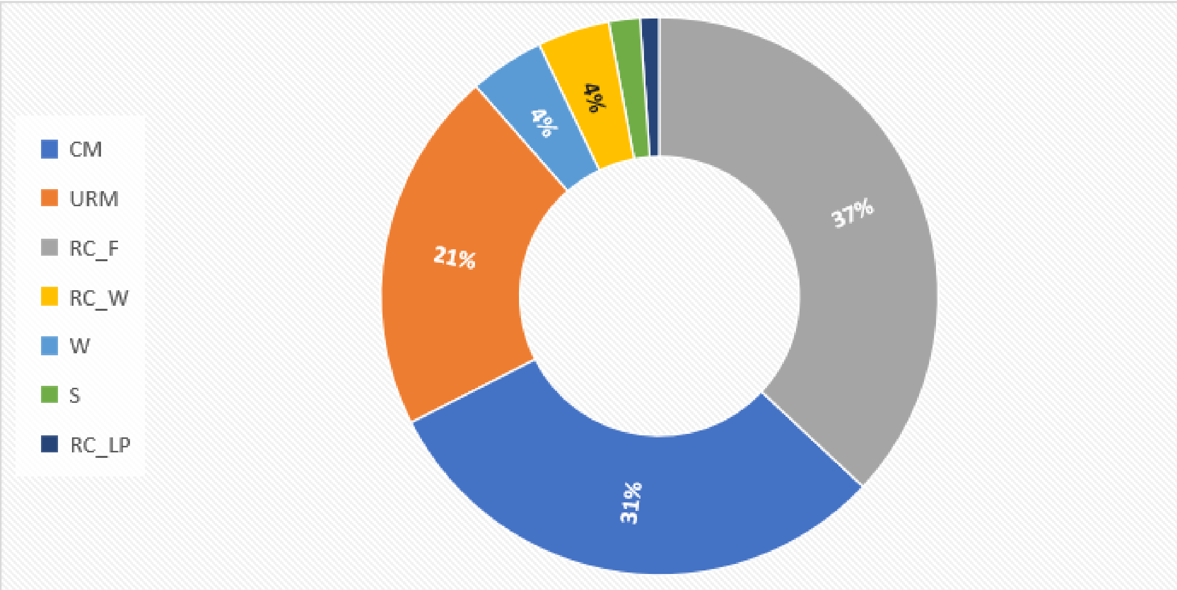


Fig. 6 Structural system distribution for the entire sample of buildings from the education sector

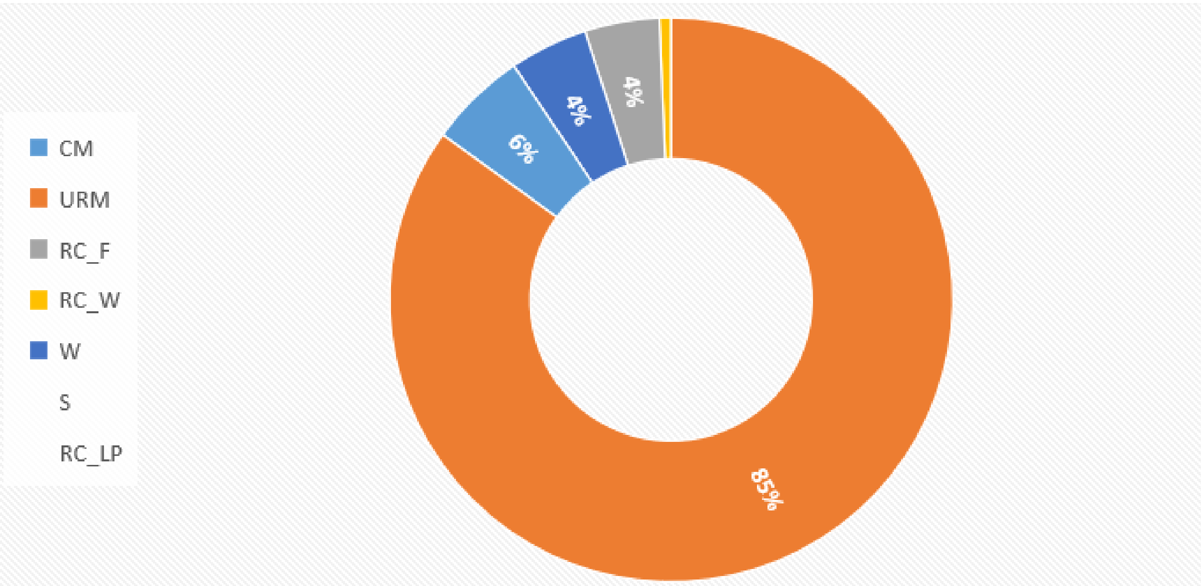


Fig. 7 Structural system distribution for the sample of heritage buildings from the education sector

The entire sample of analyzed buildings was split function of the design code level associated with the year of construction, so that the limits presented in Fig. 8 correspond to the following:

- PC: pre-code: built before 1963
- LC: low-code: built between 1964 and 1977
- MC: medium-code: built between 1978 and 1992

- HC: high-code: built after 1992

The largest share belongs to buildings built for gravitational loads only, before the seismic design code apparition (P13-63, P13-70). Only for 30% of the sample, the design was done following the codes published after the 1977 earthquake (P100-78, P100-81, P100-90, P100-92, P100-1/2006 and P100-1/2013). In between 1964 and 1992 were constructed about a quarter of the buildings included in this present analysis, 85% of them being made of RC structures and following a typified layout.

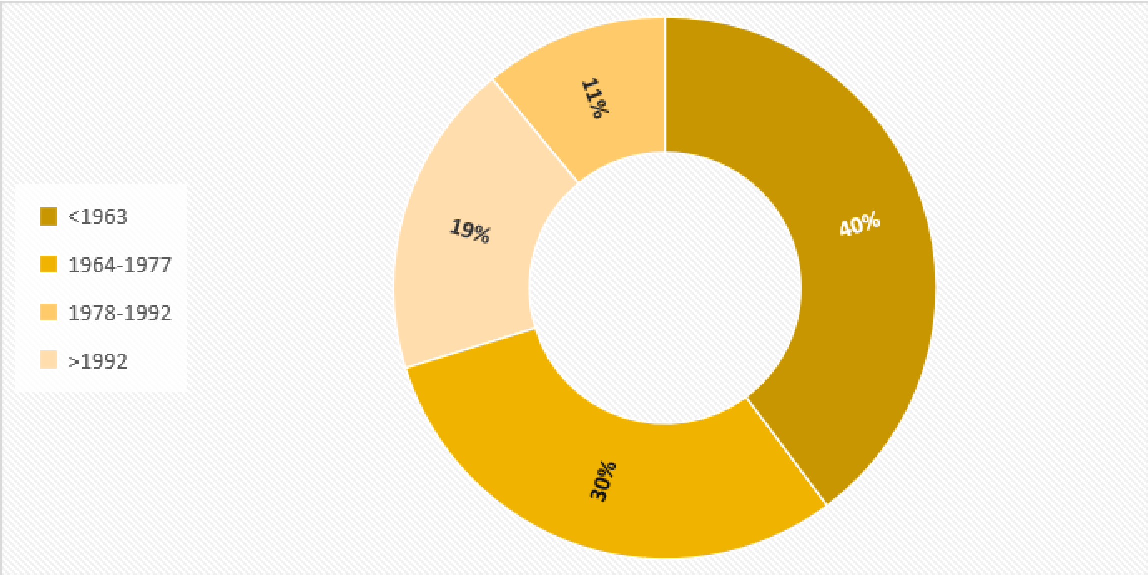


Fig. 8 Distribution of buildings from the same, function of the year of construction

The list of retrofitting works carried out within the P.R.I.S[1] project were considered together with the analyzed sample from the SIIIR database to evaluate data on strengthening interventions at national level. From the data available for 1253 units (93% of the total educational units included in the program), seismic upgrading works were carried out for about 35% of them. Fig.9 shows the distribution of the 427 education units all around the country, except Bucharest, which was not included in the project. Almost 90% of them are primary or middle schools and the remaining 10% are high schools, because kindergartens were not included in the project either.

Braila, Constanta and Timis have the largest number of retrofitted schools, unlike Brasov, Hunedoara and Ilfov. The cost estimates expressed per square meter of building are between 35 €/sqm and 1500 €/sqm, with an average of approximatively 300 €/sqm. Less than 25% of them recorded investments under 200 €/sqm or over 400 €/sqm.

Only 4% of the retrofitted schools have buildings listed as monuments, namely 17 units, out of which 9 are high schools or colleges and 8 are general schools. The cost values per m^2 evaluated for the monument buildings are between 70 €/sqm and 530 €/sqm, with an average of 240 €/sqm, below the estimated value for the retrofitting of the entire sample of investments through P.R.I.S. For middle schools with more than 1000 sqm, the costs per square meter are almost double (310 €/sqm) when compared to high schools with more than 2500 sqm (170 €/sqm). Fig. 10 illustrates the situation of surfaces and investment costs for the 17 education units listed as heritage buildings retrofitted during the above-mentioned project. "L" means

[1] School infrastructure rehabilitation project (2007-2019): rehabilitation and upgrading of 1329 school units from Romania and 16 student dormitories, for safety, hygiene, sanitary and comfort reasons.

high school, “CN” comes from national colleges and “SG” is the denomination of middle schools. The horizontal lines from the graph represent the average built-up areas and the average costs per square meter for the categories considered: high schools and middle schools.

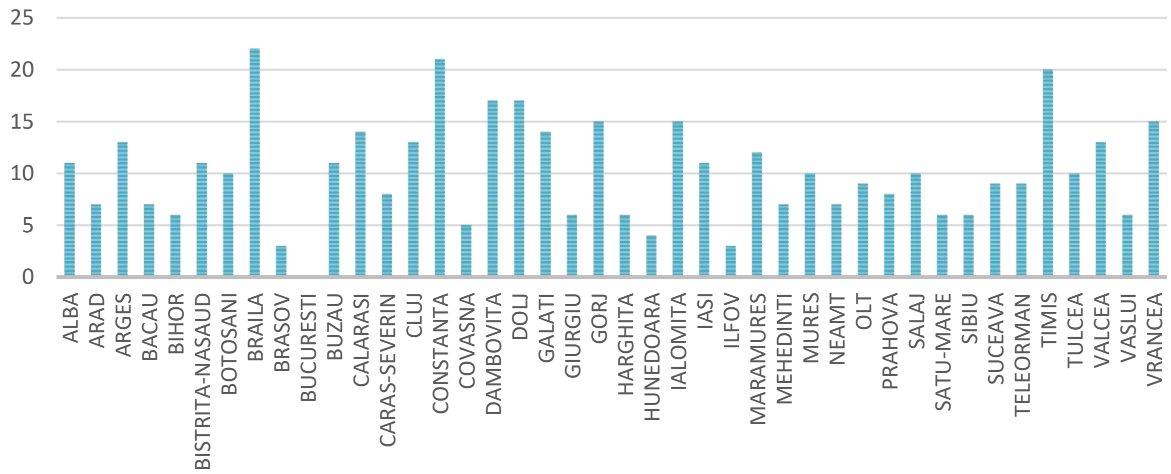


Fig. 9 Distribution of retrofitted buildings

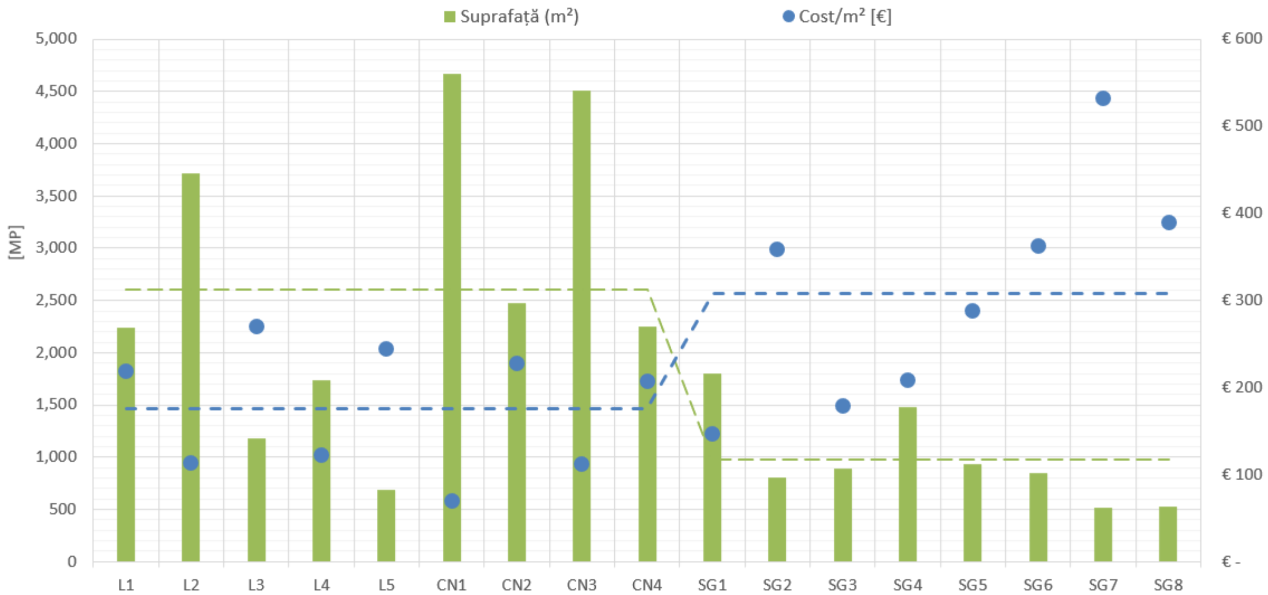


Fig. 10 Investment costs per sqm established based on retrofitted surfaces for heritage buildings

THE ANALYZED STRUCTURE

The school from Bucharest considered as case study, was built in 1884, according to the data from the seismic evaluation report. It was listed as a historical monument, being representative of the typology of heritage buildings in the education sector, built in the late nineteenth century - early twentieth century.

Currently, the school has a main building part (the old school) connected to the secondary building part by a connection part that houses the stairwell and toilets. The retrofitting project proposed in the seismic evaluation report involves strengthening interventions only for the main building part and the connecting one, as the other parts are to be rebuilt.

The structure in the initial version was made of unreinforced masonry with wooden floors, which were transformed in the 40's into rigid floors, made of reinforced concrete, 12 cm thick. After the 1977 earthquake, a small number of reinforced concrete frames (beams and columns) were added. Masonry walls have reduced thicknesses along the height (25% -30% reductions in wall areas, from one floor to another), but there are no major discontinuities in their location. The building has a basement, semi-basement, ground floor and first floor, with a wooden roof. Fig. 13 shows the three-dimensional model of the building, made in 3DMacro, where the basement was not modeled.

The school functions in two shifts, with about 250 pupils enrolled in primary and middle school grades.

The retrofitted interventions proposed in the seismic evaluation report are concentrated on local repairs and jacketing of masonry walls with reinforcement mesh ø10/15x15cm (OB37) placed on both sides and M50T mortar with 10 cm total thickness.

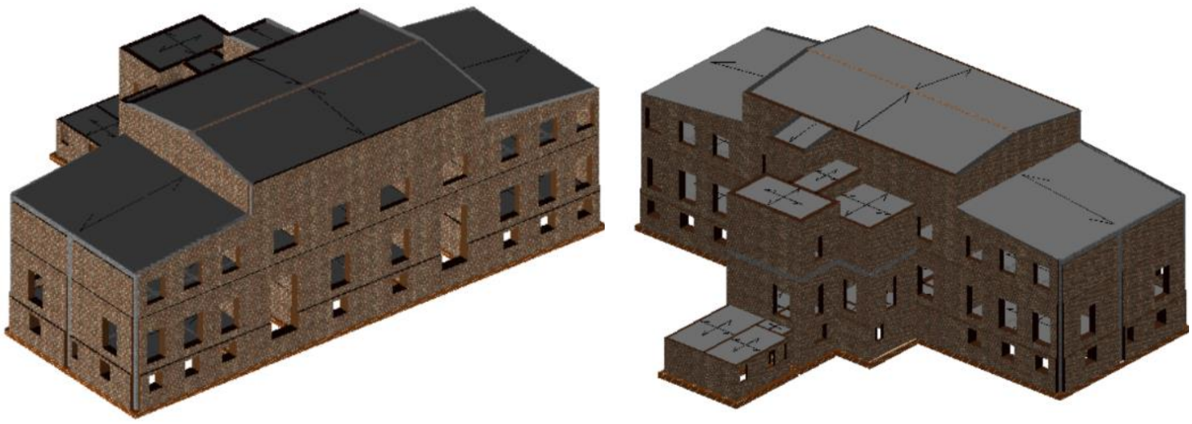


Fig. 11 3D model of the school (3dMacro): front façade of the main building part (left) and the secondary building parts (right)

Reducing the vulnerability of masonry school buildings represents a subject frequently approach in literature, as the example of schools from Italy. The study case illustrated by Formisano (Formisano, 2014) presents an Italian building, initially built in the XIXth century as a mansion and rehabilitated in 1970 in order to use it as a school. It is a protected monument, but after the 2012 Emilia-Romagna earthquake, the buildings suffered some damage. The decision related to the need of retrofitting was established by evaluating the displacement demand and the deformation capacity of the structure. Through nonlinear analyses (done in Tremuri and 3DMacro), validated by means of post-earthquake damage assessments, several retrofitting proposals were studied from the point of view of their efficiency, either using FRP strips or steel meshes. The final optimized solution implied variations in terms of layout and dimensions of steel strips, which helped obtaining an increase in strength and ductility, larger than the one resulted from FRP application, but with lower costs.

NONLINEAR STATIC ANALYSIS

3DMacro, uses two-dimensional elements discretized according to the scheme illustrated in Fig. 12. It uses springs at the interface between masonry panels (piers and spandrels), attributing to them mechanical characteristics that allow compression-bending or shear behavior (Formisano 2014). The masonry elements are also modeled by means of diagonal springs that describe the tensile and compressive behavior. Comparing the results of the experimental campaign with those obtained from numerical models, it was concluded that both softwares allow for a reasonable trust level in what concerns the evaluation of structural capacity through nonlinear static global analysis (Marques and Lourenço 2014).

Confined masonry buildings can be considered a particular type of masonry structures, although they also have features similar to RC structures. The transfer of forces from RC frames (columns and tie beams) and masonry walls generates the need for defining an interaction law between the two materials. The RC columns are modelled in 3DMacro as line elements, with concentrated plasticity and tridimensional constitutive laws N-Mx-My.

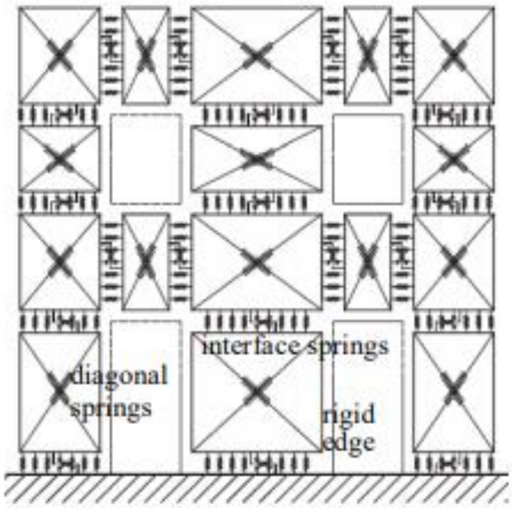


Fig. 12 Element modelling for masonry walls using 3DMacro software (Marques and Lourenço 2014)

Starting from the data regarding the analyzed structure, four numerical models of the school were made, using the 3DMacro program for some of the nonlinear static analyses. The unreinforced masonry model, hereinafter referred to as URM, has a structural conformation close to the shape in which the building was built in 1884. It keeps the unreinforced masonry walls without columns, but also contains the reinforced concrete slabs that were added in year 1947, over the original floors with wooden beams and filling.

The initial model is representative for the typology of confined masonry structures and it represents the stage in which the building was after the 1977 earthquake. The retrofitting works comprised the addition of a reduced number of RC columns and tie beams, able to form a RC frame structure for lateral loading.

The retrofitted model represents the current state of the building, after jacketing works were done (10 cm shotcrete with reinforcement mesh placed on both sides or on one side). Additional RC columns were also added (30x30 cm), different from the previous configuration, but thus following the provision from current regulations for confined masonry structures. Fig. 13 illustrates the areas in which the above strengthening measures have been applied.

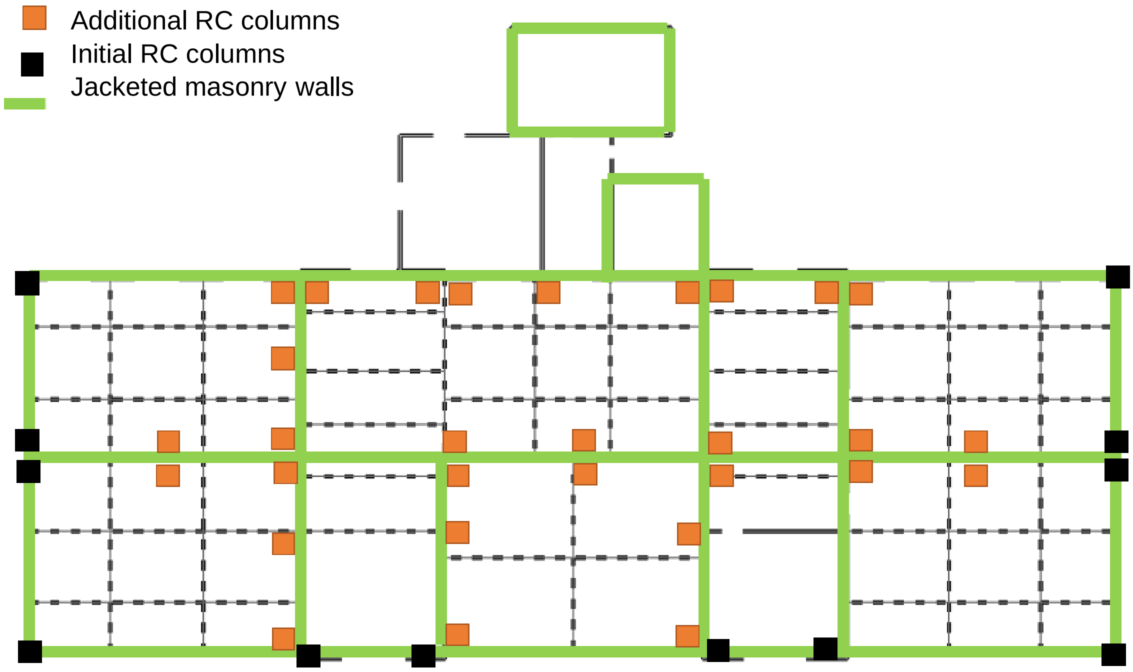


Fig. 13 Retrofitting measures (semi-basement level)

The three models will be analyzed in the next part, in order to highlight the different typologies: URM structure, CM structure and RM structure (retrofitted).

Fig. 14 and Fig. 15. Present the results of nonlinear static analyses for both loading directions. The Pushover curves from the graphs presented below illustrate the relation between the lateral displacement and the base shear force (Vb), divided to the weight of the structure (W).

The ultimate limit state considered in 3DMacro software for stopping the analysis is established for the following cases: reaching the limit of ultimate rotations in one of the beams, the decrease of base shear force up to 80% and reaching the rotation limit or the shear capacity of all piers belonging to a wall, for a certain level.

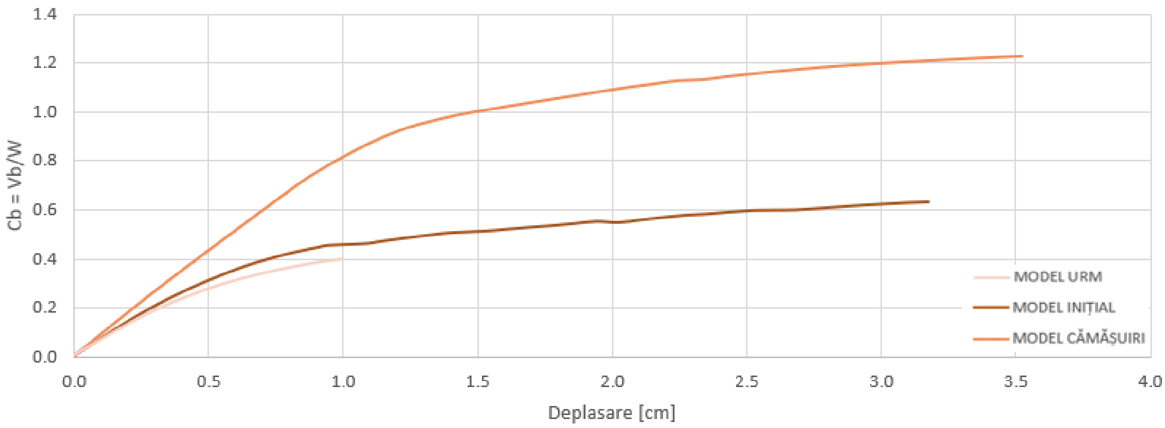


Fig. 14 Comparations between Pushover curves – longitudinal direction (X)

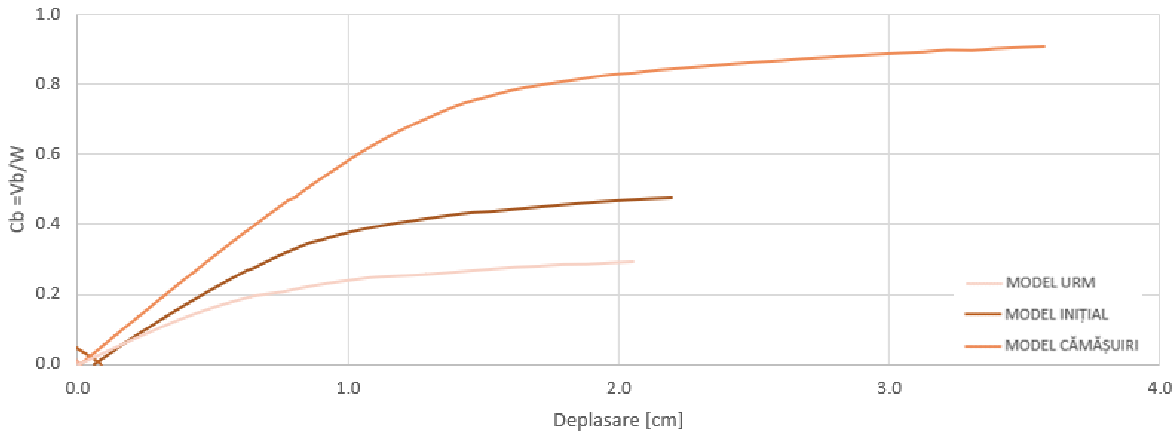
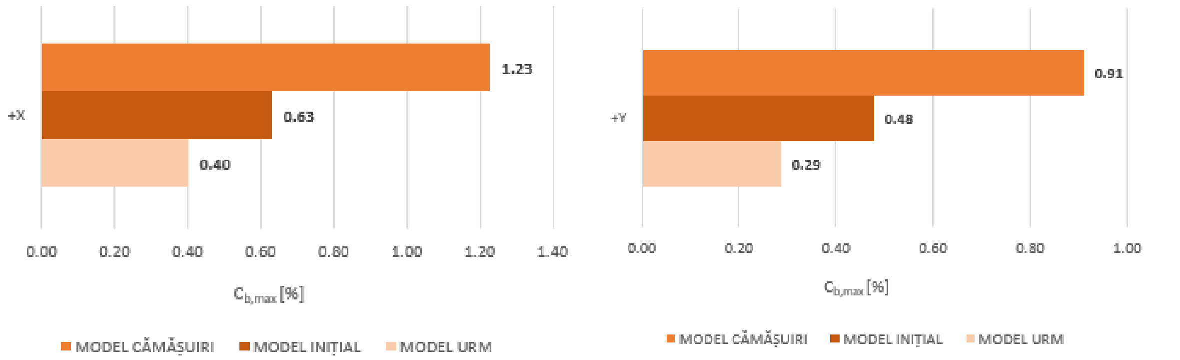
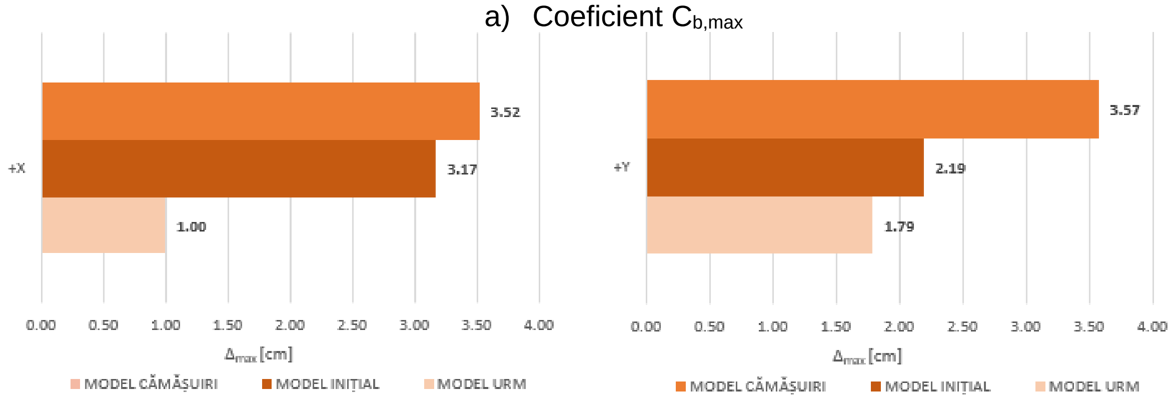


Fig. 15 Comparations between Pushover curves – transversal direction (X)

The graphs from Fig.16 show the maximum values recorded on the Pushover curves for the analysese, only for the positive direction. It can be observed that gradual increments of the lateral force capacity and displacement capacity is recorded, starting from the minimum values of the URM and increasing towards the retrofitted model. The premature failure of the URM model implies significant changes in the graph of maximum displacement on the longitudinal direction, when compared to the values from the initial model. The strength capacity increases up to 50%-60% in the initial model and up to 200% in case of the retrofitted model, with obvious improvements on X direction, where most of the jacketed walls are placed, along with the RC columns. The coefficient denominated Cb,max has values higher than unity in some of the analyses, which can be considered an indicator of excessive retrofitting. Takin into account that the initial model (with RC slabs and a few RC frames) provides increases in the strength capacity, but measures which are less invasive or local interventions could lead to more efficient and optimized results.



a) Coeficient $C_{b,max}$

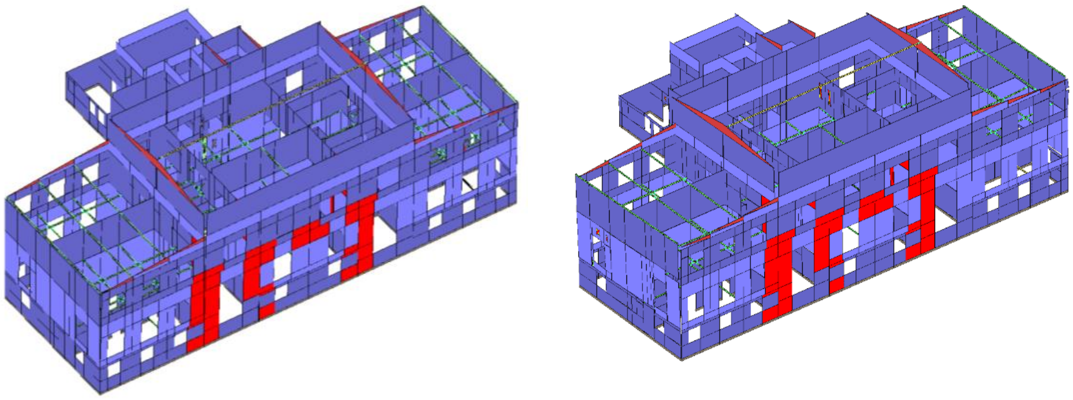


b) deplasare maximă

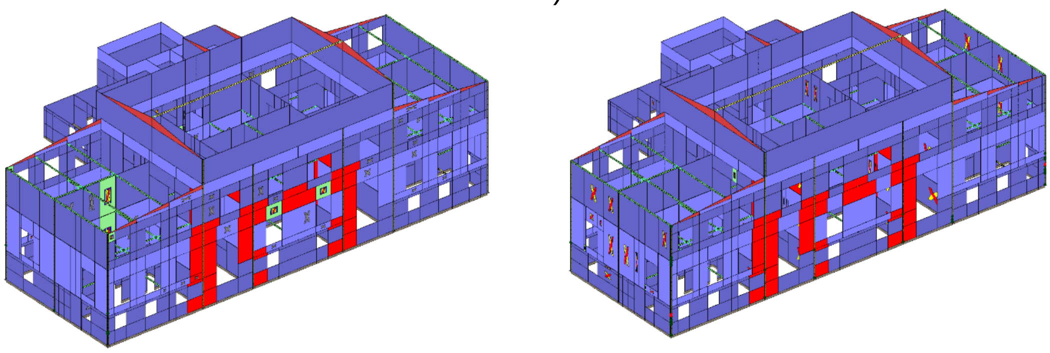
Fig. 16 Comparisons for the three models: +X (left) and +Y (right)

FAILURE MODES

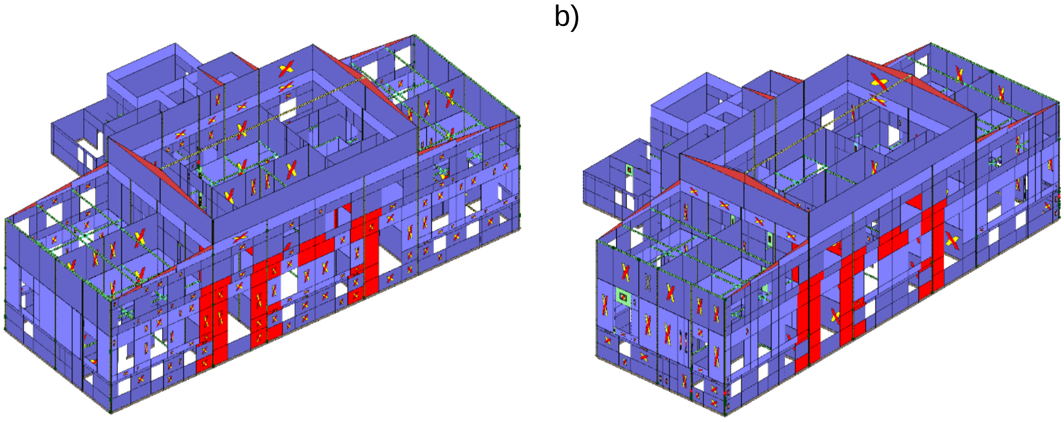
The predominant failure modes are represented by inclined cracks in the masonry panels, which appeared in the case of the + X analysis from the first steps, at a relative displacement of 0.007%. Subsequently, for a relative displacement of 0.08% and PGA of 0.204 g, the first shear failure appears, in the wall no. 2 of the façade. As can be seen in Figs. 17, the masonry panels suffer extensive damage, but controlled in the case of the jacketed model, where the final displacement reaches values higher than those in the URM model. The structural conformation of the initial model, where reinforced concrete columns are present, contributes to the redistribution of efforts between the elements and thus prevents the local collapse, specific to the unreinforced masonry buildings. The presence of confinement elements generates failure mechanisms presenting diagonal cracks in the walls, subsequently contributing to the formation of plastic joints in the reinforced concrete elements. Similar analyses in the literature indicate similar behaviors of confined masonry buildings, where for 1 cm displacements the confined masonry has extensive but controlled damage (Marques and Lourenço 2014).



a)



b)



c)

Fig. 17 Damage states for structural elements for: a) URM model, b) Initial model, c) retrofitted model

However, both sets of results illustrate the major differences between the responses obtained for the two directions. For the transverse direction, the first cracks and the first yields appear at values 50% lower than those in the longitudinal direction, given the asymmetrical layout of the building. Coating and thickening of the pillars are focused on the longitudinal direction of the building, the direction in which most of the masonry walls are located. Thus, the effectiveness of the interventions is better highlighted by the comparative results from the X direction.

Differences in between the URM model and the initial one are more obvious for thresholds corresponding to the initiation of failures from Fig. 19, where PGA values are doubled. Analyzing the drifts recorded for first failures of masonry elements, it can be observed that in case of the URM and the initial mode, both directions show values between 0.04% and 0.06%, values that corresponds also to the immediate occupancy limits for masonry buildings. It can be concluded that displacements associated to a relative displacement of 0.06% that causes first failures marks the initiation of the damage control limit state.

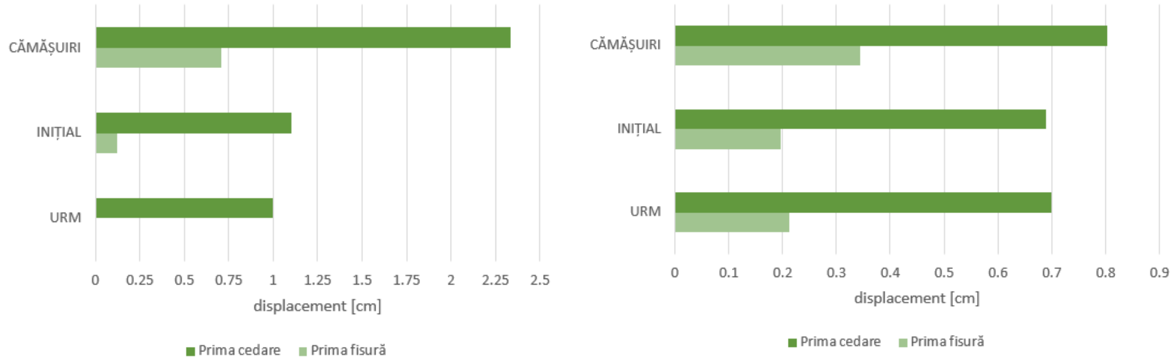


Fig. 18 Failure mechanism evolution based on lateral displacements: X direction (left) and Y direction (right)

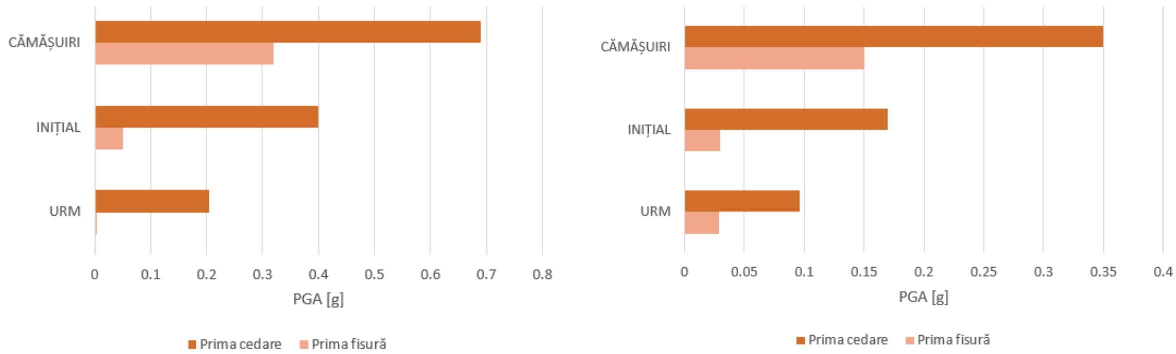


Fig. 19 Failure mechanism evolution based on PGA values: X direction (left) and Y direction (right)

GLOBAL RELATIVE DISPLACEMENTS

Using the global relative displacement limits presented in the literature, the color code indicated in Tab. 1 was overlapped with the Pushover curves of the URM model, to indicate the thresholds corresponding to each performance criteria (D0 - D3). The last recorded movements indicate that the safety limit (D2) has been exceeded for all cases, except for the analysis in the longitudinal direction, positive direction, for which the damage control state (D1) is reached.

Most masonry structures in Romania, especially those made of confined masonry and those with rigid reinforced concrete floors, are made of interlocked brick walls at intersections. For this reason, the results of the study by Vatteri and D'Ayala (Parammal and Dina 2021) on the limits of global relative displacement for confined masonry buildings yielding to the plan were used. The authors present a collection of studies in the field and finally ranges of values for the global relative displacements established on their basis. The three limit states considered correspond to the occurrence of the first crack (performance criterion: immediate occupation), significant damage and detachment of masonry walls from confinement elements (performance criterion: safety of life) and pre-collapse (performance criterion: prevention of collapse). The proposed average intervals are noted in Tab. 1 for the category of confined masonry buildings.

In order to evaluate the global performance of the building based on the displacement demand, target displacements were estimated according to the coefficient method presented in FEMA 356 (FEMA, 2000) and FEMA 440 (FEMA, 2015). The target displacement is an equivalent concept for the performance point, indicating the maximum lateral displacement that the structure is able to reach, when subjected to seismic actions. The values from Tab.2 were obtained and then transformed in relative displacements to be able to compare them with the limits presented previously. For the URM model, the target displacements are in accordance with the ones proposed in literature, with the exception of the immediate occupancy limit on Y direction that reaches 0.15% drift.

Both the initial and the retrofitted model reach final displacements that exceed the collapse prevention limit, thus having a higher capacity than the displacement requirement associated with the collapse prevention state. The unreinforced masonry model, on the other hand, reaches values even lower than the requirement for immediate occupation, which indicates the need for strengthening measures.

Tab. 1 Relative displacement limits at global level for URM and CM

		URM (Derakhshan and Griffith 2018), (Cattari et al. 2015))	CM (Parammal and Dina 2021)
D0	Immediate Occupancy (**IO**)	0% - 0.06%	0% – 0.125%
D1	Damage Control (**DC**)	0.06% - 0.1%	0.125% – 0.4%
D2	Life safety (**LS**)	0.1% - 0.2%	0.3% – 1.39%
D3	Collapse Prevention (**CP**)	≥ 0.2 %	1.54% – 4%

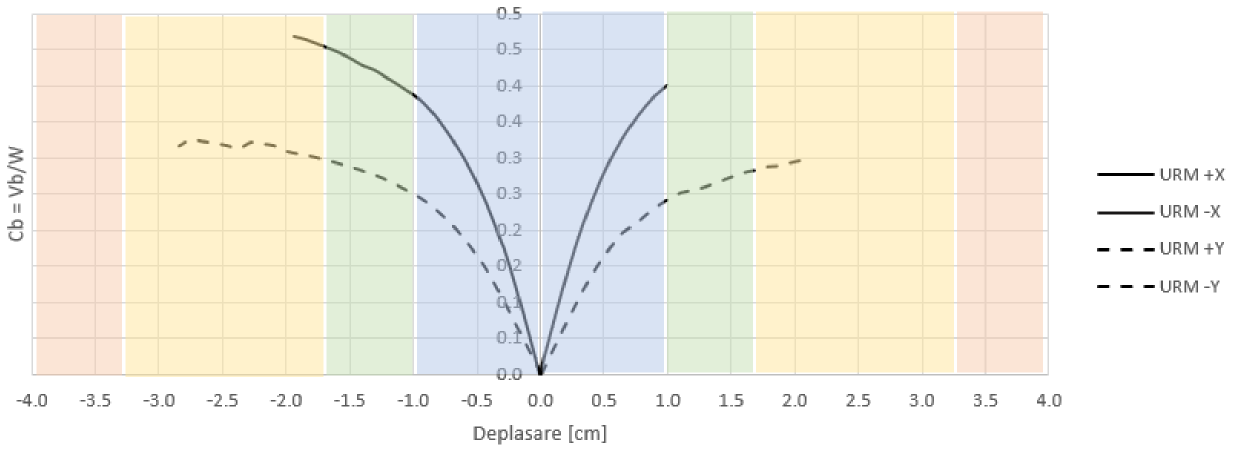


Fig. 20 Performance criteria limits – URM model

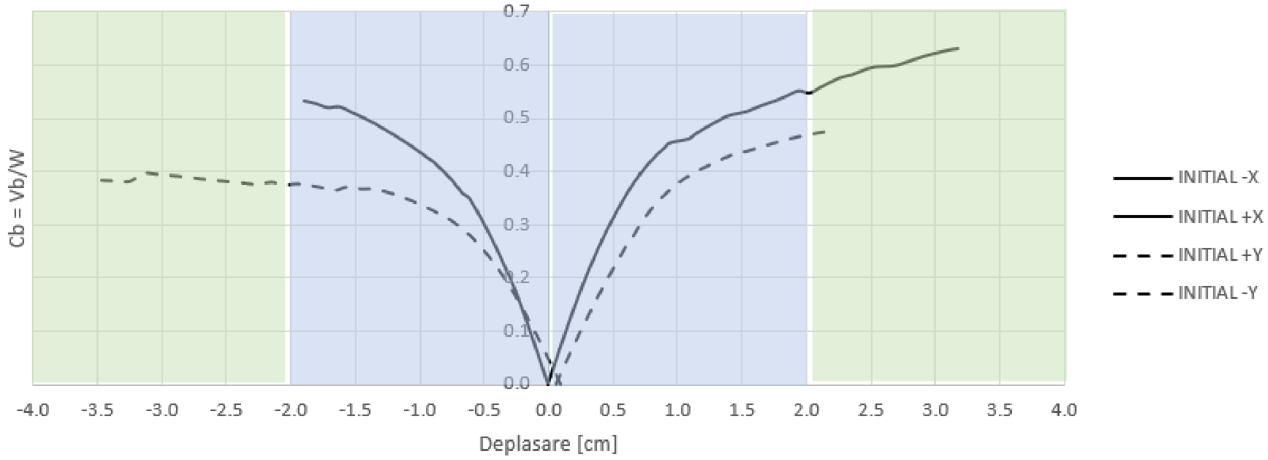


Fig. 21 Performance criteria limits – initial model

The limit states overlapped on the Pushover curves are established in accordance with the Italian norms (Ministero delle Infrastrutture e dei Trasporti, 2018), based on the following criteria:

- SLD (IO) – damages that do not threaten the life safety and do not produce significant changes for the structural strength and stiffness, allowing the immediate use of the building after the earthquake. The limit is represented by the elastic limit on the bilinearized capacity curve.
- SLV (LS) – structural and nonstructural damage that do not threaten the overall structural integrity of the building. The criterion is exceeded for displacements larger than ¾ of the displacement corresponding to SLC.
- SLC (CP) – major damages that might cause partial or complete collapse. The threshold for exceeding SLC in case of masonry elements is equal to 1% for bending deformation and 0.5% for shear failures, taking into account that this check might be skipped if the structure has rigid floors.

Tab. 2 Target displacements – coefficient method

					IO	LS	CP			IO	LS	CP	
		T_e [s]	C_0	C_1	C_2			C_3	$S_{a(BUC)}$ [m/s^2]	δt – target displ. [cm]			du – ultimate displ.
URM model	+X	0,216	1,20	1,46	1	1,28	1,48	1	5,702	1,18	1,52	1,75	**1,00**
	+Y	0,289	1,20	1,44	1	1,27	1,46	1	6,806	2,48	3,17	3,63	**2,05**
Initial model	+X	0,177	1,20	1,47	1	1,28	1,48	1	5,426	0,76	0,98	1,13	3,17
	+Y	0,241	1,20	1,45	1	1,28	1,47	1	6,254	1,60	2,06	2,36	2,52
Retrofitted model	+X	0,180	1,20	1,47	1	1,28	1,48	1	5,426	0,79	1,02	1,17	3,52
	+Y	0,124	1,20	1,49	1	1,30	1,50	1	4,874	0,34	0,44	0,51	3,57

For the initial model on +X loading direction, the limit state thresholds are marked in Fig. 22, where on the bottom are noted the events that happened during the analysis. The yellow masonry panels that fail are marked with red color and the ones that are only cracked are shown in yellow. The red color is also used for RC elements that fail, while in the cases of rotation exceeding the yielding limit, green color is used. Displamcents corresponding to the three limit states are the following: 0.35 cm = 0.02% drift (SDL), 2.43 cm = 0.14% drift (SLV) and 3.18 cm = 0.19% drift (SLC). Even if the target displacement limits presented previously indicate lower thresholds for limit states, the pre-established criteria from the software lead to a different structural behavior than the one estimated using the coefficient method.

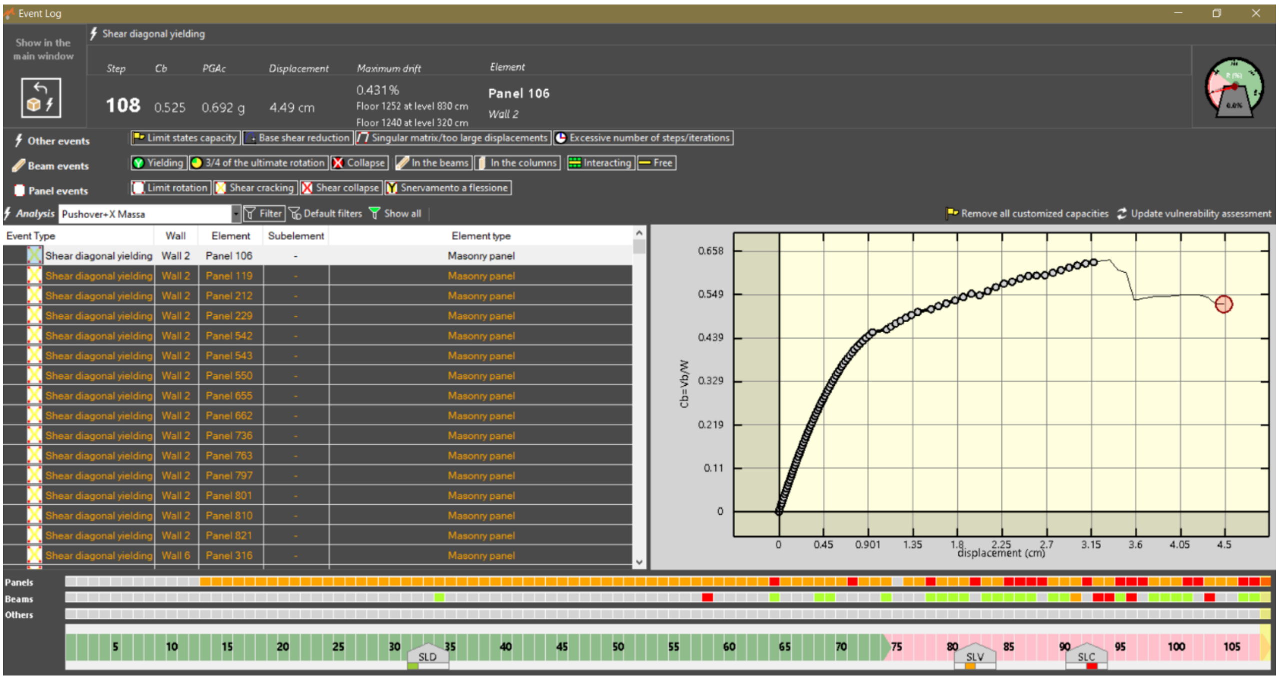


Fig. 22 Damage evolution for the initial model, +X direction

RELATIVE FLOOR LEVEL DISPLACEMENTS

Local failure modes can not be captured only by analysing the ultimate displacements from the Pushover curves presented previously. Therefore, to have a clear picture of the failure modes and the damage pattern evolution, results obtained at floor level will be studied. From the analyses done in 3DMacro, Pushover curves at wall level were obtained, where the base shear force is normalized to the total weight of the building and the lateral displacement is evaluated in a control node placed at the top level.

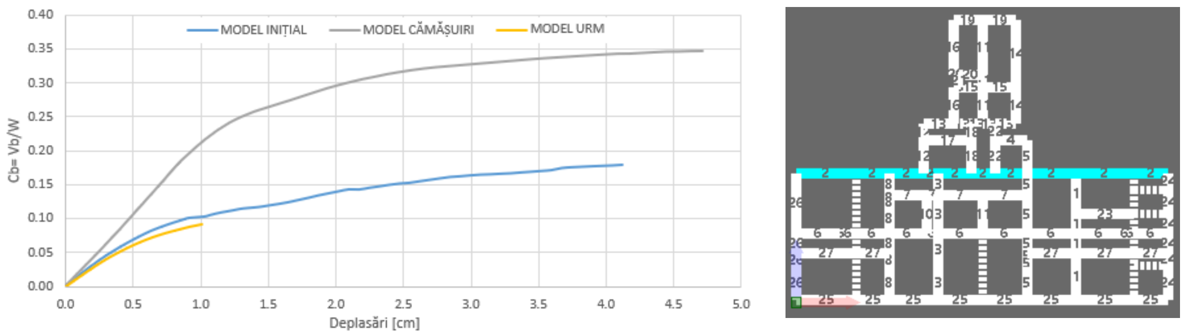
In order to be able to estimate the efficiency of the partial retrofitting works (initial model) and final (jacketed model), four walls were chosen for a more detailed analysis. They were compared in terms of damage level, the direction in which they are placed and the differences in between jacketed and not jacketed walls. The two retrofitted walls considered below are: P2 (west facade, longitudinal direction) and P24 (north facade, transverse direction), and the not retrofitted ones are: P27 (inner wall, longitudinal direction) and P12 (connecting body wall, direction transversal).

Fig. 23 shows the results of the four walls, together with sketches that illustrate their position. The transversal walls reach half the capacity level of the longitudinal walls, but they have ultimate displacements 1.5 times larger. The differences between the URM and the initial model are more obvious in the case of walls placed on X direction, having more than 70% increase of base shear force and 4 times larger lateral displacements.

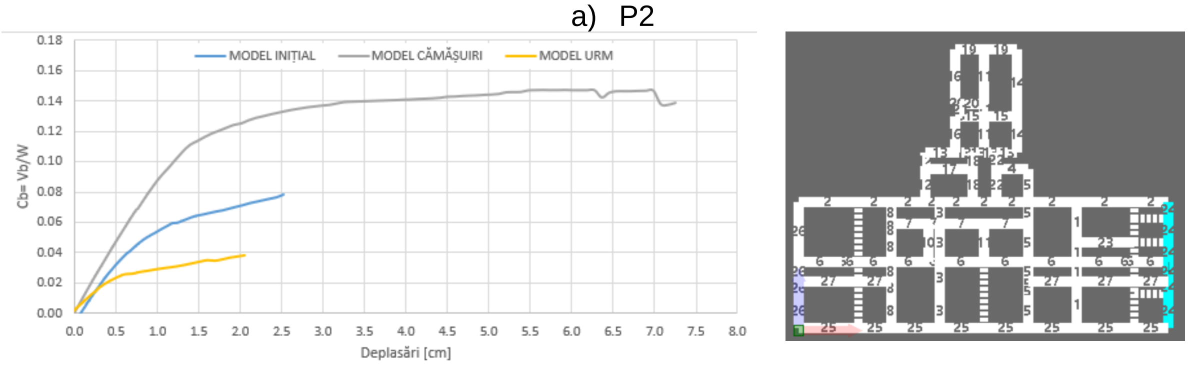
It can be observed that the most loaded wall is P2, as indicated also by the damage pattern discussed above and considering also the large number of masonry elements able to take over the seismic load. Wall 27 is placed only at the semi-basement level and this is why its base shear force normalized to the weight of the building is much lower. On the other hand, transversal wall no. 12 is continuous along the entire height of the building, but since it has reduced dimensions, it is also not capable to take over a large part of the seismic loading.

Comparing the results obtained for the jacketed walls with those that have not been retrofitted, major differences can be observed. Wall 27 and wall 12 show no increases in the lateral force capacity for the evolving models. Moreover, in the case of the retrofitted model, the P27 shows local failures marked on the Pushover curve by sudden decreases, which occur for smaller displacements than in the case of the initial model. The walls chosen to be retrofitted, such as P2 and P24, contribute significantly to the improvement of the structural capacity, but it should be emphasized that most of the walls have benefited from such strengthening interventions, as illustrated in Fig. 13.

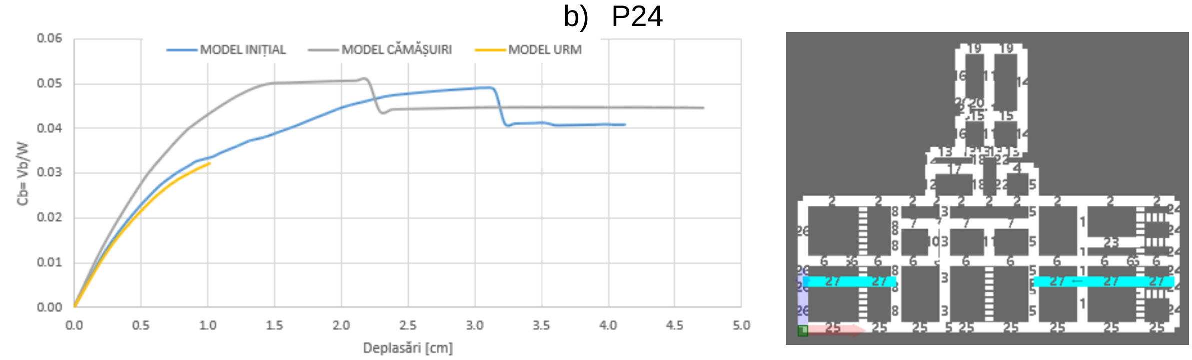
Ultimate displacements from the individual Pushover curves are equal for all walls placed on the same direction since the value represents the displacement recorded on the control node from 17.3 m height.



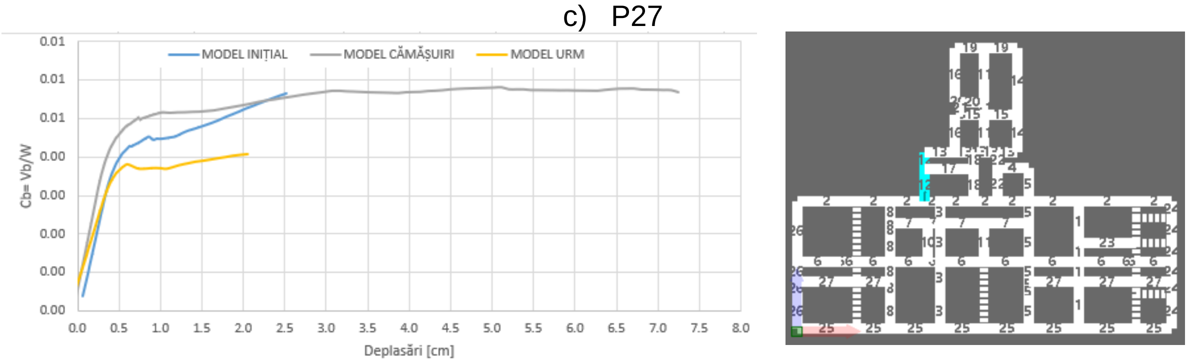
a) P2



b) P24



c) P27



d) P12

Fig. 23 Individual Pushover curves for the retrofitted walls (a, b) and not retrofitted walls (c, d

Relative displacement values indicated in FEMA 356 establish a connection between structural response of vertical structural elements and performance levels or damage associated to them, without being imposed as code limits or replacing the deformability checks for individual elements. The values presented in the US code have to be used only for comparison and not for evaluation of the seismic behavior of structures.

To evaluate the performance criteria corresponding to the three models based on the values proposed in FEMA 356, it is necessary to use the wall level relative displacements. For the URM model the limits indicated for URM structures will be employed and for the initial model, the ones for reinforced masonry structures. A reinforced masonry wall is defined in the US code as having a minimum percentage of reinforcement on the vertical and horizontal direction, properly connected with other horizontal elements. Since there is no other category that could correspond to the confined masonry structures from Romania that have RC columns and tie beams and because the reinforced masonry from FEMA has a better behaviour than the URM one, it is proposed to make use of this category. Taking into account that the retrofitted model has most of the walls jacketed on both sides with reinforcement meshes placed along their entire height and that even more RC columns were added, the proposal is to use the limits corresponding to shear wall structures in FEMA. For masonry walls retrofitted by shotcrete, FEMA 356 mentions the fact that for compound sections, performance criteria related to stiffness, strength and deformability of RC elements can be used.

Therefore, Tab. 3 summarized the limits proposed for performance estimates, corresponding to each of the three models. The building subjected to a lateral action gradually increasing up to the target displacement causes structural damages. Floor level displacements are obtained in nonlinear analyses to be further on compared with the damage degrees of the structural elements, where damage is estimated based on failure criteria implemented in the software. To check the relative displacement values proposed in FEMA 356, the damage level of walls will be studied and proposed to be ranked in one of the performance criteria described for each structural typology (unreinforced masonry wall, reinforced masonry wall and RC shear wall). Then, function of the performance level estimated, the floor drift from FEMA 356 will be compared to the relative displacement from the numerical model. The walls with the most significant damage will be chosen from both directions (P2, P6, P25 and P1, P3, p26), as shown in the layout from Fig. 24. For analyzing the damage pattern of masonry panels, the symbols from 3DMacro illustrated in Tab. 4 will be used.

The longitudinal wall no. 2 was included in the analysis because it has some of the most severe failure that led to the stop of the nonlinear analysis. It is the back façade connecting the main building part with the connection area with the staircase and it continuous along the entire height, with uneven placement of openings. Wall no. 26 is also a façade wall, located on the lateral side, on the transversal direction of the building. There are window openings only at the semi-basement level, which generates a significant stiffness difference in between this level and the ones above. Wall no. 2 and also wall no.25 and no.26 were jacketed only on the inner side, since they are façade walls. The inner walls 1, 3 and 6 were jacketed on both sides.

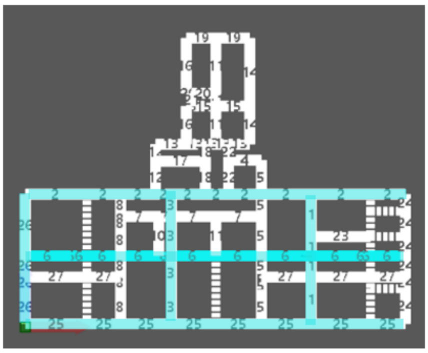
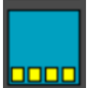


Fig. 24 Layout of walls

	Relative floor displacement limits: unreinforced	Relative floor displacement limits: reinforced	Relative floor displacement limits: RC shear wall

		masonry structures (URM model)	masonry structures (initial model)	structures (retrofitted model)
D0	Immediate Occupancy (**IO**)	0 – 0.3%	0 – 0.2%	0 – 0.5%
D1	Damage Control (**DC**)	0.3% - 0.6%	0.2% - 0.6%	0.5% - 1%
D2	Life safety (**LS**)	0.6% - 1%	0.6% - 1.5%	1% - 2%
D3	Collapse Prevention (**CP**)	≥ 1%	≥ 1.5%	≥ 2%

Tab. 3 Level drift limits and performance criteria

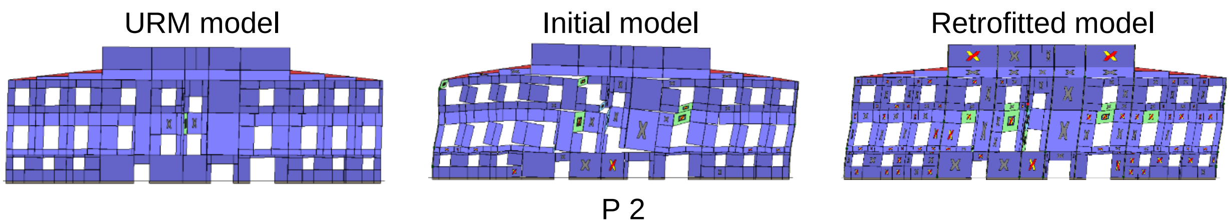
Symbol	Damage state
	Shear cracks
	Closed crack
	Shear failure
	Crushing
	Craking

Tab. 4 Symbol legend for damage states (3DMacro)

Comparing the damage patterns from the three models presented in Fig. 25, it can be observed that there is no crushing nor cracking caused by spring failure placed at the interface of panels, but only shear failures. Moreover, damage is gradually extended from the URM model to the initial model and then to the retrofitted one. Local panel detachments can be observed for the initial model, but the retrofitted one works rather as a global structure in taking over the lateral forces, therefore the cracking is extended to more elements, even is some are closed cracks. Some of the RC columns from the retrofitted model have plastic joints at their ends, marked with green circles in the model.

The panels that reach shear failure are colored in green, in this way highlighting the large number of failures for wall. 2. In the case of wall 6, the failure mechanisms shown at ground floor level and first floor are prevented in the retrofitted model, where new confinement elements are placed near central openings.

The same is valid for the walls placed along the longitudinal direcgtion, while there is a single transversal wall in the UMR model that fails in shear. All observations previously done for the longitudinal direction are the same in the case of walls placed along Y direction. Unlike the other walls analyzed before, the transversal ones have less openings for doors and windows, which ensured a better behavior of the masonry panels.



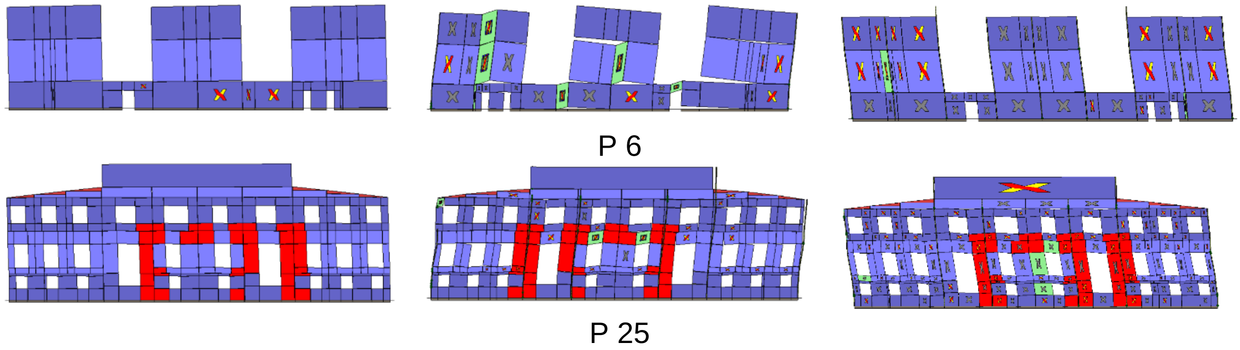


Fig. 25 Damage degree of walls, at the end of the analysis (+X direction)

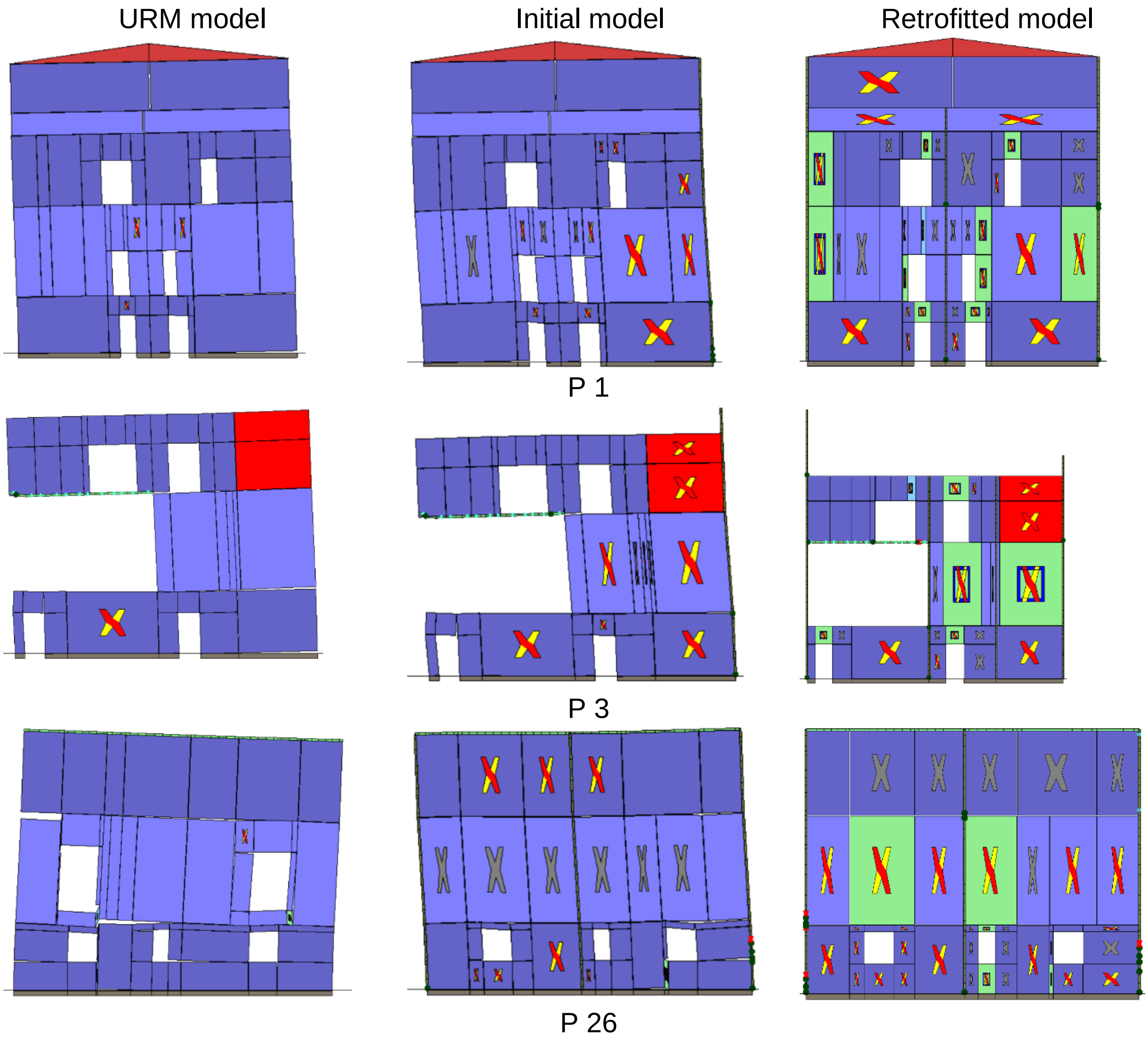


Fig. 26 Damage degree of walls, at the end of the analysis (+Y direction)

Performance criteria and associated damage also take into account the behavior of masonry walls in the out-of-plane. Numerical analyses performed in 3DMacro do not capture these aspects, but it can be considered that the reinforced concrete slabs ensure the rigid box behavior, which prevents out-of-plane failures. Taking into account that for most of the damages walls of the URM model there is no extensive cracking, but only a few cracked panels, it can be considered that the structure subjected to seismic actions reaches a damage level corresponding to the immediate occupancy criterion. In FEMA 356, the 0.3% threshold marks the immediate occupancy performance criterion, as shown in Tab. 3. Comparing this value with the maximum relative displacement of the URM model presented in Tab. 5, it can be seen that there are drifts higher than 0.3% on +Y direction, for the upper floors.

Comparing the damage to the walls of the initial model with those described for the performance levels of FEMA 356 for reinforced masonry, there is a clear exceedance of the immediate occupancy limit (minor cracks) and a possible compliance with the life safety requirements (extended cracks, distributed along the walls and some isolated failures of the main elements). The requirement for collapse presentation would involve extensive cracks and considerable damage around openings and at the corners of the building, were parts of the masonry should have collapsed. The limited amplitude of cracks and local failures does not indicate exceeding the criterion of life safety, hypothesis confirmed by the drift checks, which have values below 1.5%, the relative displacement indicated in the code as limit for collapse prevention.

For all the analyzed walls, retrofitting measures where applies, so that drift levels will be compared with the ones corresponding to RC shear walls. The damage presented in FEMA 356 for them refers to buckling and damage of the reinforcements or severe damage of coupling beams, which might not be compared with he damage patters of masonry panels from the software. The exceedance of collapse prevention limits implies important cracking from bending and shear, crushing and buckling of reinforcement. The cracking from masonry panels is quite extensive, the failing elements are more then in previous models, but shotcrete should prevent out of place failures and local collapse. For these reasons, it is considered that the relative displacement obtained for the numerical model (1.24%) is in good accordance with the code, since the drifts lower than 2% are correlated with the collapse prevention criterion.

In conclusion, the relative maximum displacements in the models correspond to the values proposed for reference in FEMA 356 for the three types of vertical structural elements, taking into account the extent of the damage of the masonry panels. In what concerns the target displacement estimates, the unreinforced masonry model fails prematurely before the performance criterion corresponding to immediate occupation.

Cotă [m]	+X, mass [%]			+Y, mass [%]		
	URM	INIȚIAL	CĂMĂȘUIRI	URM	INIȚIAL	CĂMĂȘUIRI
3.2	0.04	0.16	0.28	0.10	0.15	0.26
8.3	0.11	0.54	0.63	0.22	0.34	0.58
12.3	0.23	0.98	1.08	0.42	0.56	0.98
17.3	0.26	1.08	1.24	0.54	0.66	1.16

Tab. 5 Level drifts and performance levels

FRAGILITY ANALYSIS

Structural damage can be estimated according to the intensity of the seismic ground motion and can be expressed through damage probability matrices or through fragility functions (G. M. Calvi et al. 2006). The expression of structural fragility through the lognormal distribution model involves the use of only two parameters: the median value of a characteristic parameter for structural behavior (such as spectral displacements or spectral accelerations) and the standard deviation of logarithm, which represents the uncertainty associated with structural capacity and seismic demand. Thus, the probability of exceeding or reaching a certain damage state can be expressed, according to the formula below:

$$P[ds|SD] = \Phi\left[\frac{1}{\beta_{ds}} ln\left(\frac{SD}{\overline{SD}_{ds}}\right)\right]$$

where: $\overline{SD}_{ds}$ represents the median value of the spectral displacement, for which the structure reaches the threshold of the damage state ds, β_{ds} is the standard deviation of the natural logarithm of the spectral displacement for which the structure reaches the threshold of the damage state *ds* and ϕ is the standard normal distribution function.

The methodology further used in the fragility analysis followed the principles of the Level II procedure proposed in the RISK-EU project (Kappos et al. 2006a). This involves the generation of fragility functions expressed in terms of spectral displacements using the results of nonlinear static analyzes of numerical models performed for the case study buildings. The ultimate ductility μ_u represents the ratio between the ultimate displacement and the corresponding displacement of the inflection point on the bilinearized capacity curves. This parameter is part of the following formulas, proposed for estimating the standard deviations corresponding to each damage state (Z V Milutinovic and Trendafiloski 2003):

$$\beta_{d1} = 0{,}25 + 0{,}07 \ln(\mu_u)$$
$$\beta_{d2} = 0{,}20 + 0{,}18 \ln(\mu_u)$$
$$\beta_{d3} = 0{,}10 + 0{,}40 \ln(\mu_u)$$
$$\beta_{d4} = 0{,}15 + 0{,}50 \ln(\mu_u)$$

The calculation formulas used to establish the thresholds from one state of damage to another, depending on the relative displacement values, characteristic of each structure is presented below (Lamego et al. 2016):

$$\overline{SD}_{d1} = 0{,}7\, S_{dy}$$
$$\overline{SD}_{d2} = S_{dy}$$
$$\overline{SD}_{d3} = S_{dy} + 0{,}25 \cdot (S_{du} - S_{dy})$$
$$\overline{SD}_{d4} = S_{du}$$

The bilinearized versions of Pushover curves are shown in Fig. 27 for all the models and for both loading directions. The dotted lines represent the damage state thresholds (D1, D3 and D4), together with the yielding limit (D2). Considering the important increases of the ctrenght capacity for the retrofitted models, especially in case of jacketing, PGA values above 1g are obtained, which are common for RC structures (Lamergo et al., 2016).

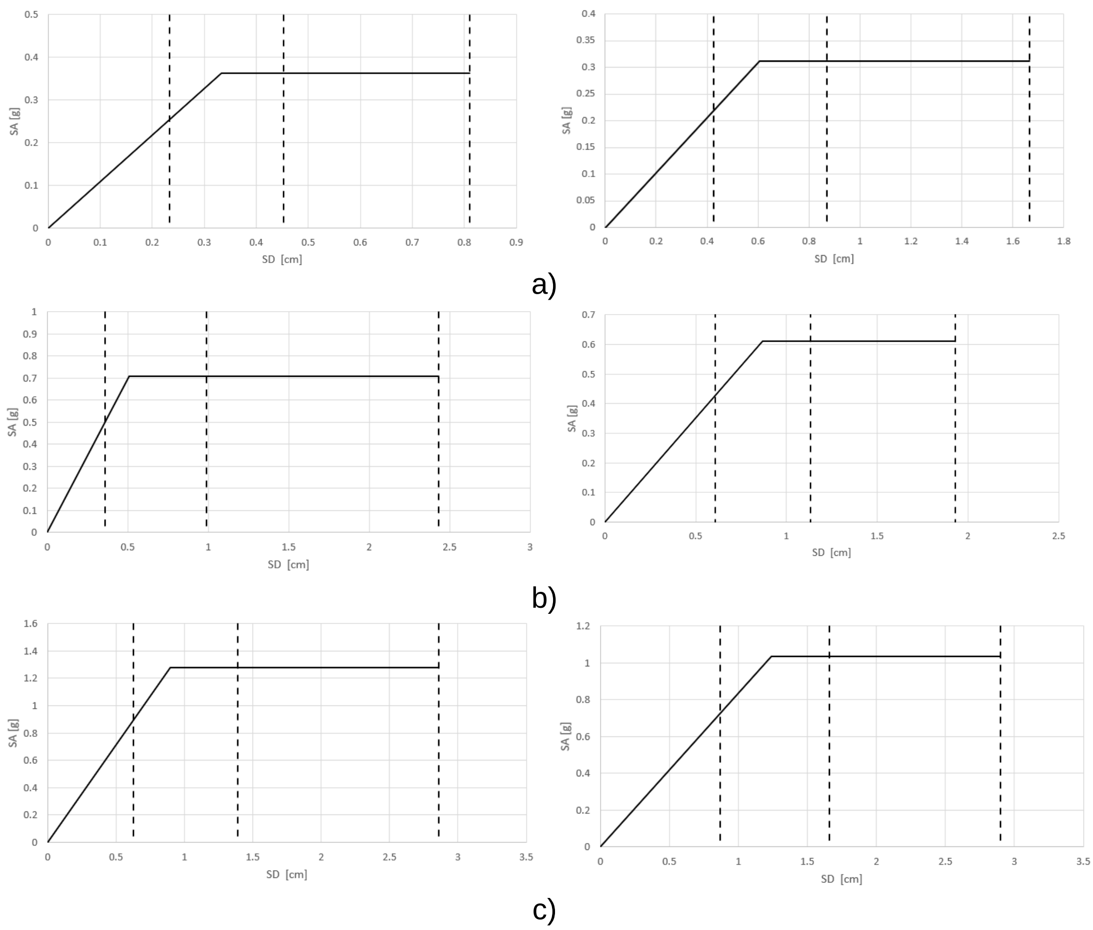
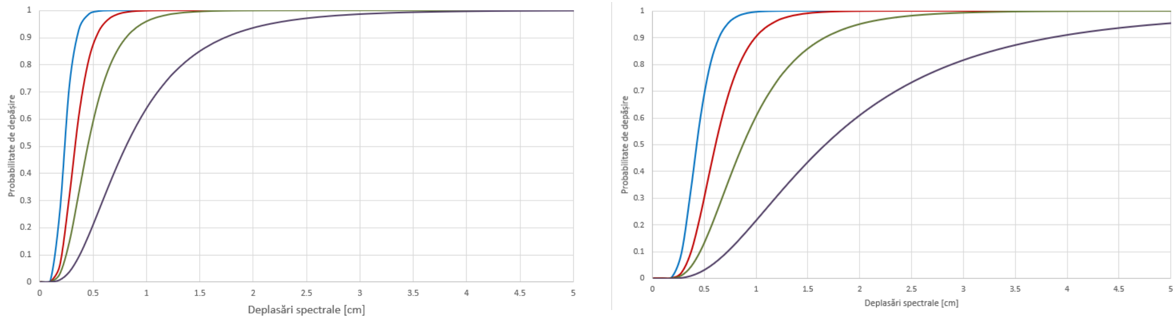


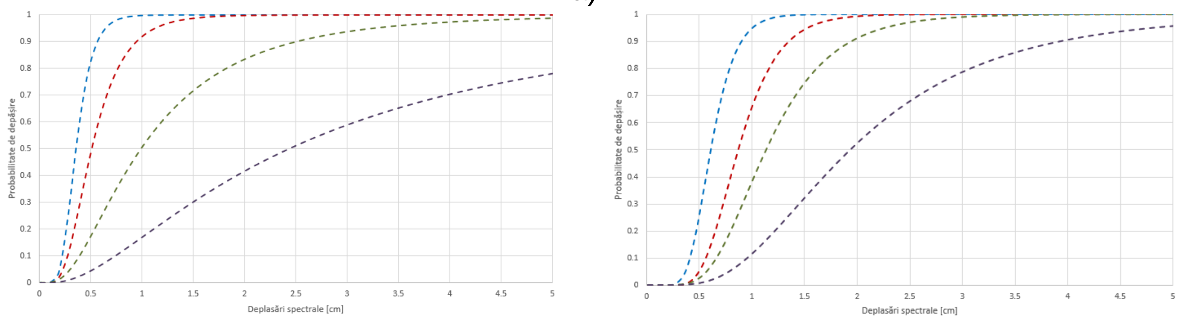
Fig. 27 Bilinearized capacity curves for X direction (left) and Y direction (right) for: a) URM model, b)initial model and c)retrofitted model

The fragility curves expressed in spectral displacements for the models are shown in the figures below, for both directions of loading. For the URM and the initial model it can be observed that there are significant differences in between the two direction, while for the retrofitted model, the results for the two orthogonal directions are more similar.

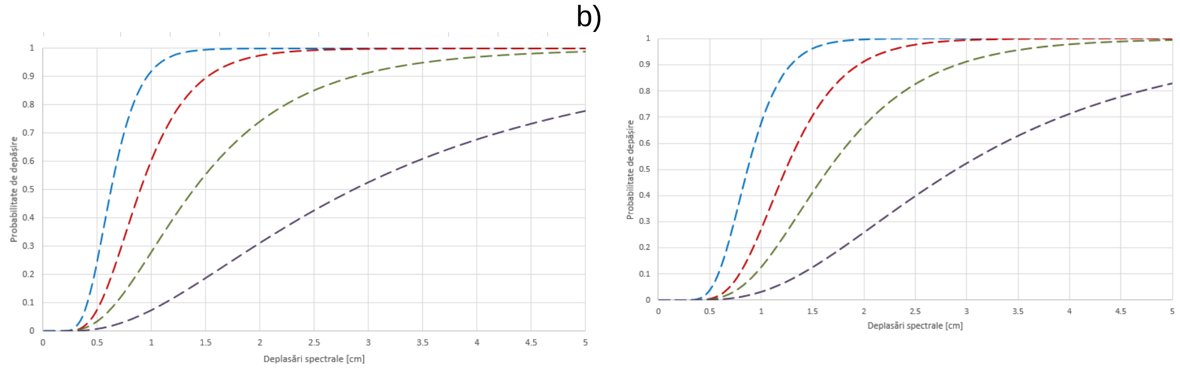
For the same level of spectral acceleration, the graphs in Fig. 28 illustrate the influence of gradual retrofitting measures applied, starting from high values for the extensive/complete damage state of the URM model and reaching probabilities below 10% of exceeding the same damage states in the case of the jacketed model. The most significant reductions are recorded for higher spectral displacements values, on X direction. In these cases, over 50% reduction of exceedance probabilities are noticed for the complete damage state. It can be noticed that there are also changes from URM to initial model, thus highlighting the importance of adding RC columns, even if they were only a few.



a)

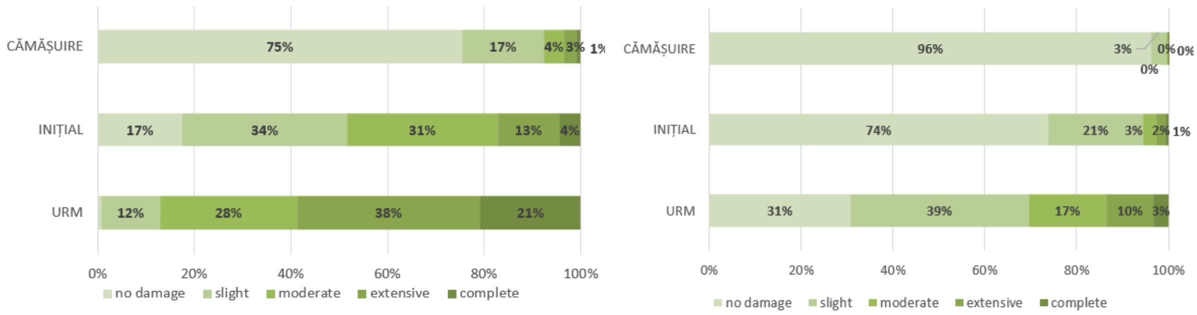


b)

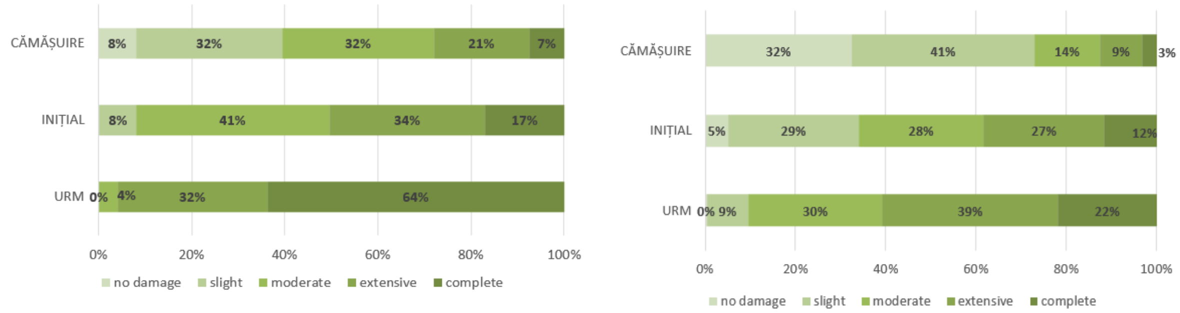


c)

Fig. 28 Fragility functions: +X direction (left) and +Y direction (right) for: a) URM model, b) initial model, c) retrofitted model



a) Sd = 0,5 cm



b) Sd = 1,0 cm

Fig. 29 Damage state probabilities for +X direction (left) and +Y direction (right)

SPECTRAL DISPLACEMENTS [CM]

		Slight damage		Moderate damage		Extensive damage		Complete damage	
		Median	β	Median	β	Median	β	Median	β
URM	+X	0.23	0.31	0.33	0.36	0.45	0.46	0.81	0.60
	+Y	0.43	0.32	0.61	0.38	0.87	0.50	1.66	0.65
INITIAL	+X	0.36	0.36	0.51	0.48	0.99	0.72	2.43	0.93
	+Y	0.61	0.31	0.87	0.34	1.13	0.42	1.93	0.55
RETROFITTED	+X	0.63	0.33	0.90	0.41	1.39	0.56	2.86	0.73
	+Y	0.87	0.31	1.24	0.35	1.66	0.44	2.90	0.57

Tab. 6 Fragility functions parameters

Comparing the fragility parameters from literature (Lamergo et al.., 2016), (Barbat et al., 2008) with the ones obtained for the models, the minimum and maximum limits are very close, as it can be observed in Tab. 7. For a more detailed comparison, it will be studied the models from (Lamergo et al.., 2016) which show similar structural characteristics, namely: Building E – URM model and building D – initial model. These correspondences where chosen taking into account the following aspects:

- Building E is the only mixed buildings (masonry and RC) that does not have columns, but only some beams and lintels, thus being quite similar to the URM model
- Both D and E buildings have RC slabs, as the URM model and the initial model have
- The masonry walls from building D are made of a material similar to fired brick without holes, even if the maximum thickness of the walls are only 40 cm on the exterior and 25 cm in the interior part.

Fragility parameters	Barcelona: mid-rise URM buildings (Barbat et al., 2008)	Lisbon: mixed « Placa » buildings (Lamergo et al.., 2016)	Bucharest: present case study
Spectral displacements [cm]	0.4 – 2.9	0.1 – 3.1	**0.23 -2.90**
Standard deviation β	0.4 – 0.7	0.3 – 1.45	**0.31 – 0.93**

Tab. 7 Fragility parameters: comparation between limits

Using the fragility parameters from Lamego et al., 2016 and the ones obtained for the model of the school building, both sets of fragility curves were overlapped on the critical direction (X) in order to observe differences in between them. The first set of curves from Fig.30 indicates good agreements for all damage states. The curves with continuous lines of the URM model suggest a higher fragility than Building E (interrupted line) for all damage state, except the extensive damage.

Fig.31 illustrates the comparisons done for the initial model and Building D, where there are more significant difference in terms of extensive damage state. Comparisons with the confined masonry and the buildings from Portugal are shown in Fig.32, where mid-rise “Placa” structures are included. These curves seems to be very similar with the ones obtained for the schools along X direction, except some differences noted for the extensive damage state.

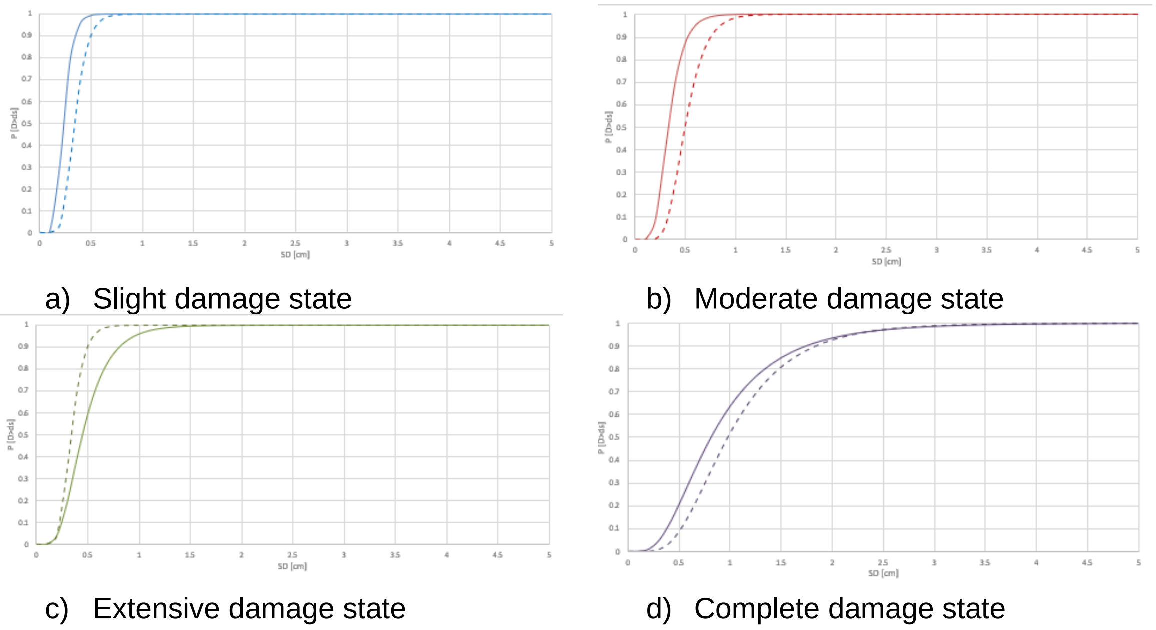


Fig. 30 Comparisons between the URM model (continuous line) and Building E (interrupted line)

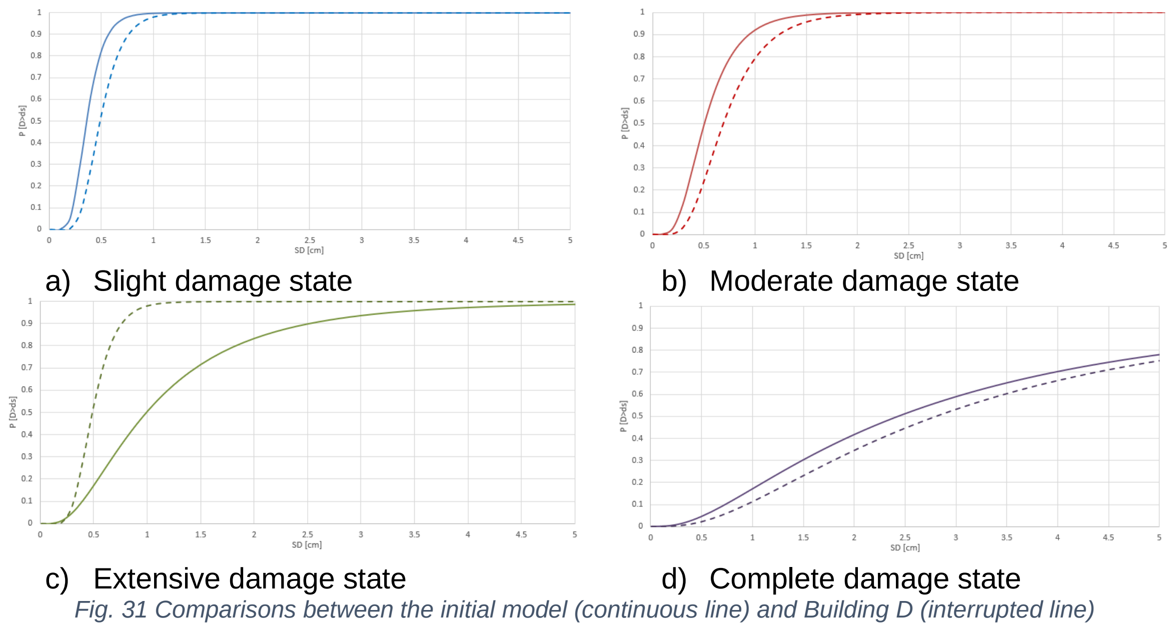
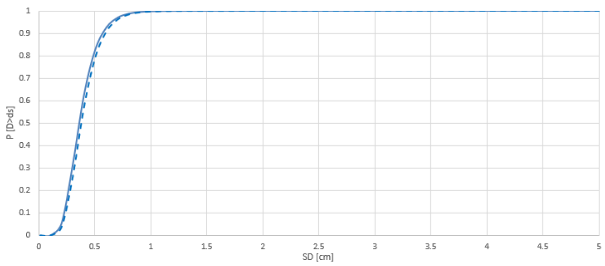
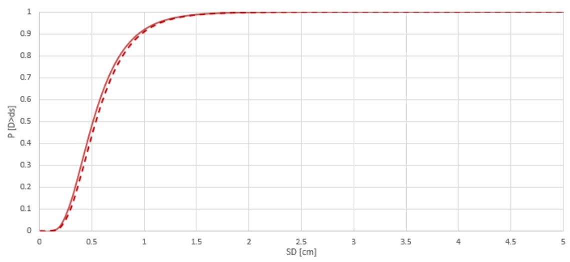


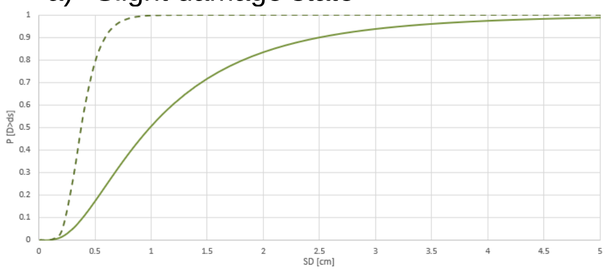
Fig. 31 Comparisons between the initial model (continuous line) and Building D (interrupted line)



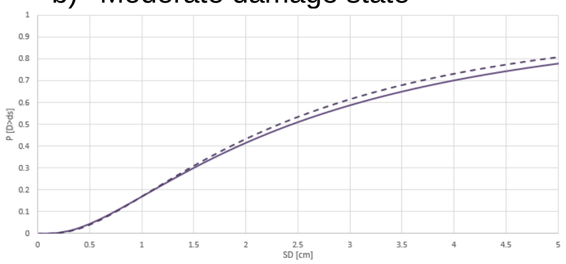
a) Slight damage state



b) Moderate damage state



c) Extensive damage state



d) Complete damage state

Fig. 32 Comparisons between the initial model (continuous line) and “Placa” buildings (interrupted line)

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