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Seismic overall simplified strategies for vulnerability assessment of healthcare structures

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ABSTRACT

The goal of the ASSIST research project is the development of practical tools for the overall assessment of healthcare structures, in order to reach a strategic vision useful to define future financial investments.

Healthcare buildings are characterized by safety issues that concern several aspects such as the structure, the inside medical equipment, the electrical and medical gas plants, the fire safety and eventual damages due to floods. Other important issues are functionality, sustainability, adaptability and comfort level, which have also to be investigated and scored.

In the complexity of the problem, one of the main elements to be considered for the evaluation and control of healthcare facilities is related to seismic vulnerability. In seismic prone areas, local governments have the necessity of a global overview of seismic performance of their facilities to determine how to best allocate funds for structural strengthening of buildings or, in general, to prevent negative effects on the healthcare structure functionality as a whole induced by possible future earthquakes.

In the present paper, two simplified methods for the seismic assessment of reinforced concrete buildings, developed in parallel by two different research units, are presented. Both methods evolve from previous experiences: one of them was applied to school structures in the same geographic area. They have now been improved to take into account the complexity of hospital buildings. The simplified strategies allow to assess the seismic vulnerability using very few design data and through a quick analysis. The comparison of the outputs from the two different methodologies is a first way to validate the results or to point out the necessity of more detailed studies. By this way, it is possible to obtain a ranking of the buildings of the healthcare estate based on their seismic capacity. This first classification is then developed taking into account the other described aspects of safety and functionality.

The procedures are here applied to a few pilot case-studies, comparing the results with more detailed non-linear analyses. Results highlight a good reliability of the two methods.

The simplified analyses can be quickly applied in a homogeneous and coordinated way to all the buildings under control, so allowing a correct comparison among them and a ranking to properly address the financial resources.

1 INTRODUCTION

Healthcare structures are highly complex buildings, due to the presence of technological equipment and facilities, and critical scenarios can arise in case of natural events as earthquakes. The problem of deciding the possibility of immediate occupancy just after the shocks has been widely faced: in Italy, just as an example, the FAST form (Italian Civil Protection Department, 2016a) and the AEDES form (Italian Civil Protection Department, 2016b) are used for quick decisions about structural safety, and similarly FEMA P-154 (FEMA, 2015) gives indications for rapid visual screening to evaluate the seismic safety with minimum access to the buildings. In complex social systems as hospitals, however, the evaluation of exposure is still a critical issue, because of the presence of non-autonomous in-patients and the possible additional flow of injured people.

Out of the time of seismic emergency, local governments or health enterprises have the necessity of a global overview of their facilities to determine how to best allocate the nowadays often limited funds for structural strengthening of buildings or other risk reduction measures. These plans generally have to investigate not only structures in the epicentre area, but also in the surroundings, where damages caused by a seismic event may be not so relevant, but where the seismic hazard remains high.

The healthcare buildings are characterized by safety issues that concern both the structure, the inside equipment as well as the performed activities and functions. Several other basic aspects deserve to be faced as the fire safety, the electrical and medical gas plant safety, the eventual flood safety. Not less important aspects are functionality, sustainability, adaptability and comfort level, which have to be investigated and scored.

Moreover, as underlined in the European Document "Investing in hospitals of the future" (Rechel et al., 2009), hospitals have to face in the next future several other changes, as the "ageing population, the changing pattern of diseases, a mobile healthcare workforce, the introduction of new medical technologies". So, facilities will have to follow these developments of the society and several changes will have to be implemented in their internal layout, in the intended use of the areas and in the technical systems.

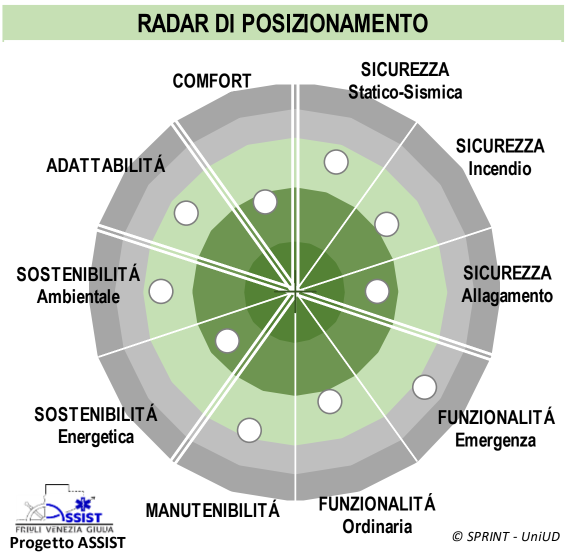

Figure 1: Global overview of hospital performances (Grimaz et al., 2018b)

Therefore, it is important to carry out integrated evaluations, to identify the key elements that can support decision-makers in the definition of organization and management strategies (Gubana et al., 2018; Grimaz et al, 2018 a).

The final goal is a global overview of the facility performances, which can be well synthetized by a radar-format indicator (Figure 1).

In the complexity of the problem, it is undoubtable that, in earthquake prone areas, one of the main elements to be considered is related to the seismic safety of buildings. This information is in fact a priority and all the other considerations cannot be done if this aspect is not reliably assessed. In Figure 2 these concepts are graphically synthetized.

Figure 2: ASSIST procedure (Grimaz et al., 2017).

Several methodologies have been developed to derive seismic vulnerability curves: they are mainly based on statistical approach, expert opinion or analytical approach (Lupoi et al., 2008; Cornell and Krawinkler, 2000). The ATC-13 methodology (ATC-13, 1985) is based on the combined use of empirical data and expert opinion. Presently the fast development and improvement of structural reliability assessment methods based on FEM structural models makes possible very detailed analyses of the response of single structures, in linear or non-linear field, but this approach is too much resource consuming for a first macroscopic estimation of large number of buildings, due to the large amount of data required and to the computational costs. The problem of functional loss due to possible damages on inside equipment has been outlined in the HAZUS methodology (NIBS, 1977), where the vulnerability functions are based on estimated fragility of structural and non-structural elements. Similarly, the World Health Organization promoted an holistic approach, taking into account structural systems, non-structural components and organization components (WHO, 2015).

Recent papers have underlined how the seismic assessment of existing buildings is subjected to many uncertainties, not only about the seismic demand, but also about the data used (i.e. information about geometry and material properties), and correctness of the implementation of the evaluation procedures in the commercial codes and, in particular, of their use made by practitioners (Choun and Elnashai, 2010; Rota et al., 2014; De Falco et al., 2017).

The present work is part of the ASSIST project, funded by the local Health Administrative Structure of Friuli Venezia Giulia Region, and it is aimed at the development of tools for the assessment and monitoring of buildings for healthcare services, with the goal to reach a framing perspective and an overall strategic vision, useful to correctly define the financial investments over several years.

In this paper the first problem, the structural safety of the buildings, is addressed: a double simplified cross checked methodology is presented for the seismic assessment, together with a case study validation.

The final goal of the methodology is to acquire a first ranking of the seismic response of the local facilities in order to put in evidence possible critical situations and to define a priority scale for eventual complete detailed analyses, where necessary. Moreover, taking into account the economically important plant content, the interaction of the response with the functionality of the plants and more generally with the other non-structural elements, has been addressed, so additional information about drifts and damage levels are the subsequent goal of the this first phase.

2 SEISMIC VULNERABILITY ASSESSMENT PROCEDURES

The evaluation of seismic safety of hospital buildings has already been faced by means of several different methodologies. In the present research project, important references were some previous Italian experiences as the ones in the Basilicata region (Dolce, 2005), the school buildings safety evaluation in Friuli Venezia-Giulia (Gattesco et al. 2012), the RE.SIS.TO® experience in Bologna (Chinni et al., 2013) and more recent safety evaluation after the 2016 earthquake in central Italy (Santarsiero et al., 2017).

The parameter here chosen to rank the hospital facilities is the Safety Index, indicated by the Italian Ministry of Infrastructure in 2017 (DM n.58, 2017) to define the seismic capacity of the existing buildings. It represents the ratio between the seismic capacity in terms of earthquake acceleration and the code prescribed acceleration to be resisted by new buildings. The values of the index are correlated to colors to be easily comprehensible also to no technician people (Figure 3).

The two developed procedures are herein described, underlining that a prompt comparison of the two results is considered part of the procedure itself, as it represents a first check of the results.

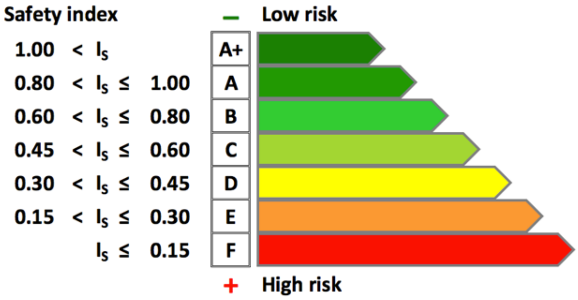

Figure 3: Safety Index and equivalent seismic risk classes as defined by Italian Ministry of Infrastructure.

2.1 *The FirStepEvo method*

The FirStepEvo method allows to evaluate in a simplified way the seismic capacity of reinforced concrete structures using few data about the geometry of the building and its material properties.

The method is an evolution of the FirStep one, developed in (Gattesco et al., 2012 and Gattesco et al., 2013). It is an analytical method, not based on expert opinions, which aims to obtain an objective result. The method is conceived to require as few data as possible, in order to reduce time only necessary to gather and elaborate the original drawings. The goal is a ranking of the facilities, with the awareness that the actual seismic resistance can be obtained only with more detailed analyses.

The procedure can be applied both to r.c. buildings with a frame structure or with shear walls resistant systems. Moreover, it can also analyse buildings with infilled masonry walls or with squat columns. The eventual brittle collapse of beam-column joints is also considered.

The main simplification consists of running the analysis only at the base level. This means that a regularity in height is needed to obtain reliable results. Anyhow the geometry of the upper structure is taken into account, by means of an algorithm which gives different levels of constraint to the analysed structural system. The reliability of this procedure has been proven by analytical and numerical studies. In the present version of the software, changes have been made on the evaluation of the shear strength of existing vertical elements (Eurocode 8-3) and on the evaluation of stiffness and strength of reinforced concrete cores.

The FirStepEvo procedure is developed to be easily used by practitioners. The geometrical data are automatically extracted from CAD drawings of the building. Other information, such as the mechanical properties of concrete, the reinforcement, the inter-storey height, the number of floors and the characteristics of the seismic site, are needed. Material properties are derived from the original design documentation, generally preserved in the hospital technical archives, due to their importance for public safety and civil protection.

The procedure first evaluates the vertical loads on each element, considering the tributary area. A first check is performed with reference to the vertical load capacity, as changes in the intended use of some areas may have taken place. In a second phase the software evaluates the distribution of the seismic forces among the vertical elements. The resulting forces are then compared with the shear or bending resistance of the elements. The capacity of the building is defined as the force that causes the collapse of the first element. A simplified ductility value is evaluated on the basis of the collapse mechanism and then it is used to calculate the capacity in terms of acceleration. A ductility factor value equal to 1.5 is used when the collapse is fragile (shear failure or beam-column joint failure), whereas a ductility value between 1.5 and 3.0 (on the basis of the axial load) is considered in case of a bending collapse.

2.2 *The ESSE method*

The ESSE method gives an assessment of the seismic capacity of the whole building from the simplified capacity curve of each storey. The method uses the same input data set of the FirStepEvo method, extended to all the storeys. Reinforced concrete framed (with or without shear walls) and masonry buildings can be considered.

The main hypotheses are: rigid floor diaphragms, elastic beams, height-wise distribution of the seismic loads proportional to floor masses and elevation, vertical elements collapse due to bending moment and axial force (ductile behaviour) or shear (fragile behaviour).

The stiffness and resistance contribution of each vertical element considers the elastic stiffness of the concurrent floor beams and the wall-frame interaction in dual systems. Axial forces in wall and columns are evaluated from vertical load at each floor, also considering the effect of lateral seismic loads on the building. Both bending and shear resistance consider the effect of the axial force. Simplified capacity curves at all the levels are then computed in term of inter-storey shear vs inter-storey drift on the basis of the resistance and the ductility of each vertical element. Eccentricity between the center of mass and the center of the stiffness is considered.

Each curve is obtained imposing the inter-storey displacement to the floor control point and determining the correspondent total resisting force of all the vertical elements. Diagramming the scaled capacity curves, in term of base shear vs inter-storey drift, it is possible: a) to identify the weakest storey, b) to appraise the base shear corresponding to the collapse of the first element, c) to appraise the maximum base shear capacity of the building, d) to perform operational limit state verifications related to inter-storey drift.

Finally, an approximated appraisal of the overall pushover building behaviour can be obtained assembling all the single capacity curves.

3 CASE STUDY

An example of a case study to check the results of the different approaches is herein presented.

3.1 *Pavillon E*

The 8-storey building used as case study, built in 1981, is part of an Italian multi-pavilion hospital. The plant is rectangular (117.4 x 42.7 m) with a regular structural grid 7.2 x 7.2 m. Four of the storeys (h=3.4 m) have healthcare functions and are alternated with the others (h=2.0 m), used for plants and technical facilities. Seismic forces are mainly resisted by concrete walls. Transversal precast 2 m story-height truss beams are included in the technical storeys. A plan view of a typical storey is shown in Figure 4, whereas a scheme of the seismic resistant elements is shown in Figure 5.

The geometry of the building and the reinforced concrete sections were deduced from the original drawings. Dead loads are the ones from the original calculation report. Live loads are the ones prescribed by the actual Italian Building Code. Material properties are obtained from the original material test reports, in this particular case confirmed by recent destructive tests.

A simplified ground floor plan is drawn in AutoCAD software and then imported. Few rules are used to represent columns, walls and beams. Different layers and colours are used to define materials and reinforcement properties in the AutoCAD format input file.

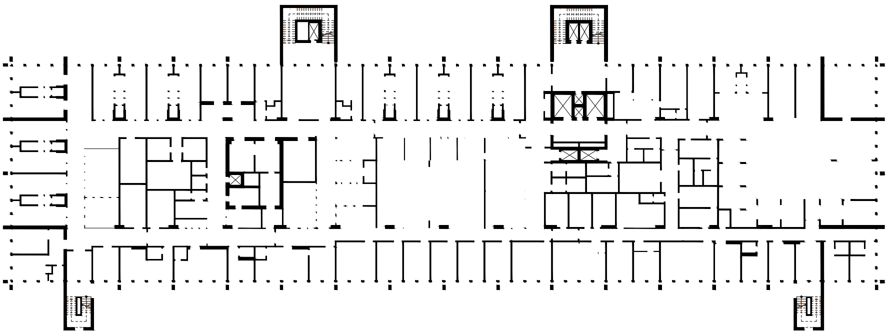

Figure 4: Typical floor plan of the building used as case study.

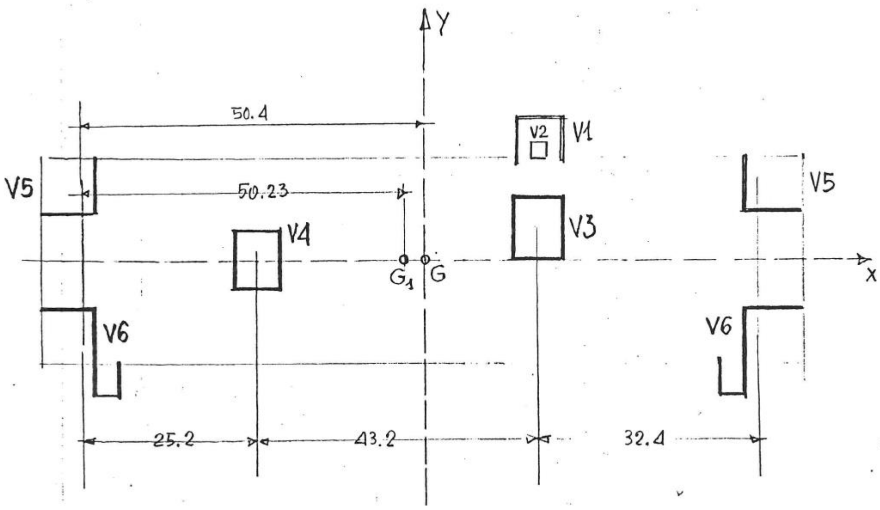

Figure 5: Scheme of the seismic resistant elements (from the 1980 original design report).

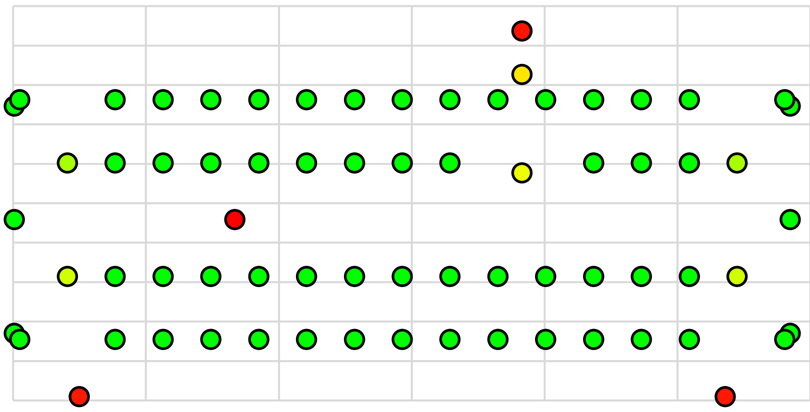

Figure 6: Ratio between seismic demand and capacity of the ground floor vertical elements in for seismic action in X direction. Red colour identifies collapsed elements.

3.1.1 FirStepEvo method results

The analysis has been performed in X and Y directions, evaluating the total shear load corresponding to the collapse of the first critical element. Numerical values are summarized in Table 1. Figure 6 shows an example of possible output in graphical form. The ratio between the seismic demand and capacity of the vertical elements at collapse for the X-direction is easily evidenced by colours. The red colour identifies the collapsed elements. For both loading directions, the critical elements are the shear walls.

3.1.2 ESSE method results

The ESSE method analyses moved from the same input data set used of FirStepEvo analysis, extended to the eight storeys. The results confirmed the first floor as the weakest in X direction. In Y direction the first collapse refers to the 2nd storey (technical), while the maximum capacity to 3rd one. The first elements to reach the collapse are always the shear walls. Numerical values are summarized in Table 1.

3.1.3 Pushover analysis (Midas GEN)

A non-linear pushover analysis has been performed via a FEM model of the entire building, with the aim to compare the results with the simplified methods. The geometry of the model, shown in Figure 7, has been obtained from the original drawings using a purposely developed code (NextFEM, 2018) that performed translation for Midas GEN. Non-linear behaviour is assigned to each element using concentrated plastic hinges at both ends, as per Eurocode 8 definitions, both for bending moments and shear forces. The lateral force pattern has uniform distribution, and it's proportional to floor masses.

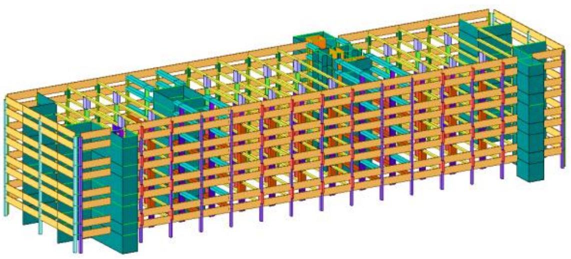

Figure 7: Model geometry for non-linear pushover analysis with the software Midas GEN.

The results of the pushover analysis in X and Y direction have been used as a comparison for simplified approaches. In X direction the building exhibits a mixed shear/flexural collapse, while in Y direction a fragile failure is clearly outlined in the capacity curve. Pushover curves are reported and commented in the following.

3.1.4 Pushover analyses (Sap2000)

Other non-linear pushover analyses have been performed to validate the results using a different modelling approach and a different code (Sap2000 v.19). The mechanical non-linearities have been taken into account by applying distributed plastic hinges to column elements for bending moments, and concentrated plastic hinges for shear forces, following the NTC 2008 definitions. Three different load distribution options have been considered.

3.1.5 Pushover results

The results of the pushover analyses in longitudinal (X) and transversal (Y) directions are shown in Figures 8 and 9.

A triangular distribution of forces was used for the first model, while a triangular and a proportional to the first mode force distributions were applied to the second model.

As to the X direction, the first model of the building exhibits a mixed shear/flexural collapse, while in Y direction a fragile failure is clearly outlined in the capacity curve.

The results of the SAP analyses shows the same mixed shear/flexural collapse in direction X, while a more fragile failure is evident in the Y direction. The pushover curve stops because of numerical instability in the solver code in the unloading portion, which leads to a program halt.

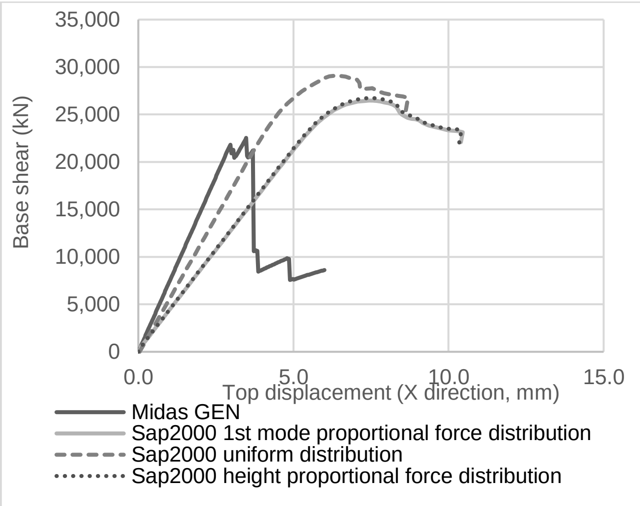

Figure 8: Pushover curves in X direction

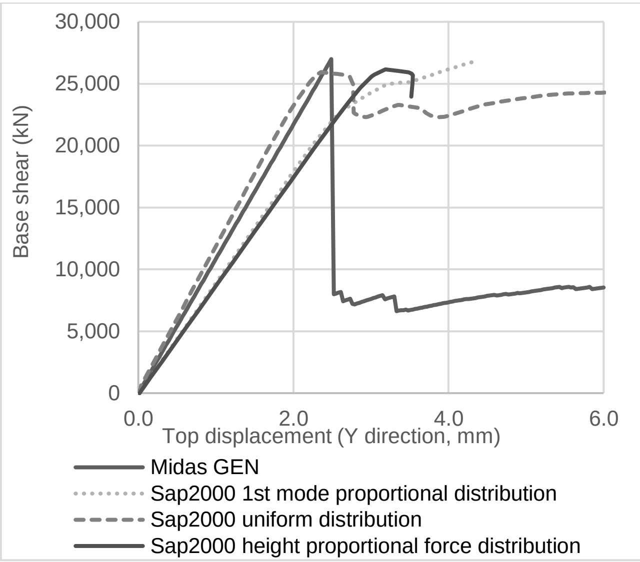

Figure 9: Pushover curves in Y direction

An initial stiffness difference is evidenced in transversal (X) direction between the two models and it is due to different modelling strategies for the technical floors large truss beams. In particular in the first model the reinforced concrete trusses were described as monolithic stiff element, while in the second model no simplifications were adopted and the deformability of the truss elements has been properly taken into account.

In the case of Y direction the results for the same uniform load distribution, in terms of initial stiffness, maximum resistant force and displacement are closer.

The capacity curve of the SAP2000 model with 1st mode proportional load distribution has been evaluated following the N2 method, determining the target displacement of the building as shown in Figure 10.

The capacity curve is then compared with the Acceleration-Displacement Response Spectrum (ADRS) in Figure 11.

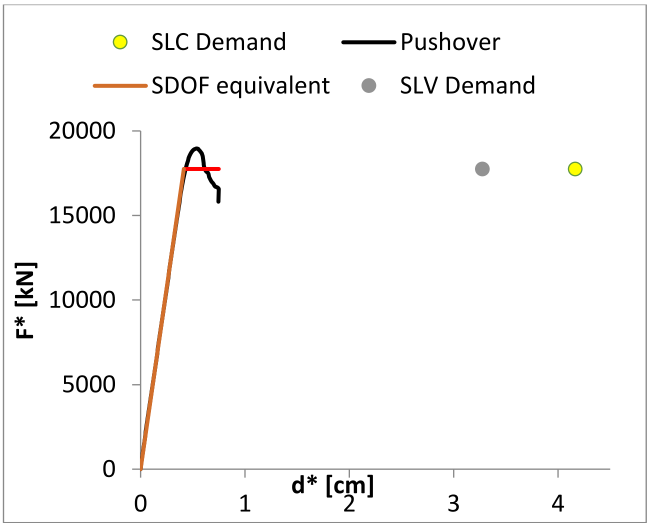

Figure 10: SDOF capacity curve, X direction

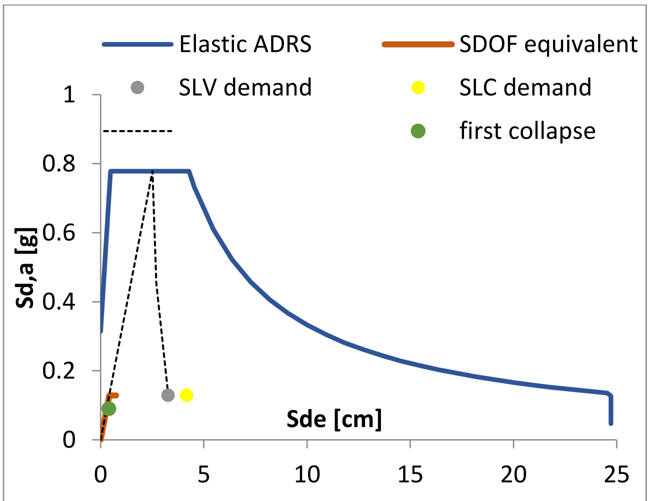

Figure 11: ADRS X direction, capacity curve and target displacement

The non-linear analysis identifies the behaviour factor of the structure q equal to 1.22 for the X direction 1.36 for the Y direction. This value has been validated also with a dynamic non-linear analysis using the same SAP2000 model (Pascolat S., 2018).

3.1.6 *Comparison of the results of the different methods*

Both the simplified methods correctly identify the critical elements during the seismic action. Table 1 shows a good agreement between the first collapse load levels obtained by the two simplified approaches. The approximated pushover curve given by the ESSE method puts in evidence a lack of global ductility in the behaviour in Y direction, as confirmed by all the FEM pushover analysis.

Method	X direction	Y direction
FirStepEvo	first collapse: 18520 kN	first collapse: 21850 kN
ESSE	first collapse: 19213 kN maximum capacity: 27390 kN	first collapse: 19608 kN maximum capacity: 29897 kN
Pushover analysis (MidasGEN)	first collapse: 21600 kN maximum capacity: 22500 kN	first collapse: 26800 kN maximum capacity: 26800 kN
Pushover analysis (Sap2000 1st mode distribution)	first collapse: 17440 kN maximum capacity: 26470 kN	first collapse: 18600 kN maximum capacity: 26780 kN

Table 1: Base shear capacity of the building, evaluated with four different methods.

The total base shear resistances are converted to ground acceleration capacity values and compared to the ground acceleration demand, so obtaining the Safety Index previously defined.

Despite the differences, the values of all the four approaches refer to the E Safety Index class (Table 2 - Pavillon E).

3.2 *Applications to other buildings*

The results of other similar validation tests performed confirmed that the ranking obtained by these simplified methods is similar to the one obtainable with more accurate analysis procedures.

The simplified methods were then applied to the facilities of one hospital complex, to obtain a ranking useful to decision-makers. In Table 2 the ranking of 7 pavilions is reported as an example.

It is worth notice that the area was declared as seismic prone only after the Friuli 1976 earthquake and all the facilities built or planned just before were designed to resist only to gravity loads.

Pavillon A was designed in 1971, the structural system was conceived only for gravity loads, with frames and shear walls in correspondence of the stair and lift cores. At the time of Friuli 1976 earthquake a greater part of the structure was already completed. A seismic joint is present between the already built part and the completion of the building afterwards. A check of the building seismic resistance was performed, but the earthquake force values prescribed were very low if compared with the current code.

Pavilion B is the oldest one, built in 1936. It has a total floor surface of about 1500 m^2 and 6 storeys. The last two ones were added in 1959, with very few modifications to the original structure to support the new gravity loads. The reinforced concrete frame, with masonry infills along the perimeter, is made by slender columns, designed with very low transversal reinforcement.

Pavillon C was built in 1955, the bearing structure is made of concrete frames in only one direction with masonry infill along the perimeter. Each one of the 7 floors has a surface of about 1900 m^2 and 7 storeys. Also in this case the frame is characterized by slender columns with very low transversal reinforcement.

Pavillon D is a 10 storey high building with a slender frame only in one direction. No seismic provisions at all are present, as it was completed in 1964. Each storey has a surface of 1250 m^2. The perimeter walls are made of hollow bricks and windows of large sizes characterize the facades.

Pavilion E is the case study already described .

Pavillon F is constituted by 3 separate structural blocks of 7 floors each. The structure of each block is made by a longitudinal frame and slender shear walls in the transversal direction. The structure was completed in 1984. The total surface is 2700 m^2. It was completed in 1982.

Pavilion G is the most recent one. It was built in 2001, it has three rectangular floors of 50 m x 30 m. The structure is made by reinforced concrete frames and walls in both principal directions as seismic bearing elements.

These results are consistent with the provisions of the different codes in force at time for the structural design.

	Seismic class X direction	**Seismic class Y direction**
Pavilion A (1971)	D	E
Pavilion B (1936)	F	F
Pavilion C (1955)	F	F
Pavilion D (1964)	F	F
Pavilion E (1981)	E	E
Pavilion F (1984)	D	E
Pavilion G (2001)	D	B

Table 2: Safety Index of seven pavilions of one hospital complex.

4 CONCLUSIONS

The parallel application of the methods here proposed shows good potentiality for its spread use on the hospital facilities. The use in parallel of two simple software-based procedures, on the basis of the same input data, let to have an immediate check of the reliability of the results. These values are intended to be used to rank facilities seismic capacity and to have a first idea of their resistance. Only successive non simplified pushover analyses can better assess the ductility resources of the buildings.

The structural capacity is only one aspect of the complex problem of the evaluation of facilities performance and it has to be interfaced with results linked to the other safety aspects, as fire safety, electrical and medical gas plant safety, eventual flood safety. functionality in emergency situations, sustainability, adaptability and comfort levels. All these indicators together can give to the management and the stakeholders the possibility to decide, on objective basis, where more accurate analyses have to be performed and how to best allocate the funds for structural strengthening and seismic resistance upgrade of buildings or other risk reduction measures.

ACKNOWLEDGMENTS

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