Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2019) 889-901

ECCOMAS
Proceedia

COMPDYN 2019
7th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Crete, Greece, 24–26 June 2019

POST-EARTHQUAKE REHABILITATION OF HEALTHCARE BUILDINGS: THE CASE STUDY OF THE MIRANDOLA HOSPITAL

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Abstract

Recent earthquakes in Italy and other countries have shown the fragility of hospital complexes which resulted in many cases unusable due to structural and non-structural damage. Depending on the extent of damage, unusable hospitals were reopened after some weeks/months, or affected by long rehabilitation intervention or demolished. In order to allow for a prompt resumption of the social activities of the local communities, the usability evaluation carried out in the immediate aftermath of a seismic event is a crucial step to address the short-term countermeasures and to obtain a gross estimate of the economic losses. After the first weeks, it is often necessary a more detailed assessment which allows for a more accurate evaluation of damage and, more importantly, about the reparability of the structure along with the study of feasible intervention strategies. This latter activity needs detailed analyses based on increased knowledge of the structure. Keeping in mind the objectives of detailed post-earthquake assessment and reparability evaluations, the Santa Maria Bianca hospital of Mirandola, damaged by the Emilia 2012 earthquake, has been analyzed as a case study. Analyses were devoted to defining an upgrading strategy to match the code serviceability limit states (damage limitation and occupancy). The selected strategy included solutions to carry out most of the work from outside, to limit the downtime of the building as well as reconstruction of demolished non-structural elements. Further analyses were made in order to check the effects of the upgrading strategy under the seismic actions recorded during the 2012 Emilia earthquake. These analyses highlighted that even the upgraded hospital building could not be able to remain operational after a new seismic event having the same intensity as the 2012 event, underlining the need of more stringent design criteria for strategic structures like hospitals that are requested to provide healthcare services even more when strong earthquakes occur.

Keywords: Hospitals, upgrading strategy, seismic damage, post-earthquake assessment, serviceability limit states.

Peer-review under responsibility of the organizing committee of COMPDYN 2019.
doi: 10.7712/120119.6966.18628

1 INTRODUCTION

Hospitals and health facilities should provide adequate care for the victims of any type of natural or man-made event also assuring the continuity of the services needed by the community they serve (WHO 2006). Unfortunately, even in recent years, health facilities as well as other strategic and sensible buildings (e.g. schools, [1]), demonstrated their high vulnerability to earthquakes, showing huge earthquake-induced losses estimated along with the loss of functionality. Surveys carried out in the aftermath of recent medium-to-high magnitude earthquakes have clearly shown the poor seismic performance of existing hospital buildings, e.g. after: the 2009 L'Aquila, Italy (Mw 6.3, [2]); the 2010-2011 Darfield-Christchurch, New Zealand, (Mw 7.1, [3]); and the 2012 Emilia-Romagna, Italy, (Mw 6.1, [4]). Severe losses have been observed also in occasion of the 2016-2017 Central Italy seismic sequence which affected a total of eleven hospital complexes distributed in four different regions (Umbria, Marche, Lazio and Abruzzo), even though the most damaged were located in Marche and Lazio. For example, the Amatrice (Lazio) hospital was almost destroyed by the Mw 6.1 earthquake occurred on August 24, 2016 [5], that caused extensive damage to the masonry portion of the structure, needing to be demolished a few months after [6]. In most cases, the observed damage was primarily caused by the inadequate performance of non-structural components and building contents with particular regard to specific medical equipment. In other cases, damage to structural elements made unusable the hospital buildings.

A long-lasting seismic sequence, as that of 2016-2017, demonstrated also that rapid repair works made just after the main shock can increase the losses since they can be cancelled by the aftershocks as in the case of the Amandola hospital (province of Fermo) reported in [6]. A similar case is represented by the Santa Maria Bianca hospital of Mirandola (province of Modena) affected by the 2012 Emilia (Italy) earthquakes. After the first event (on May 20, 2012), hospital's managers promptly started repair works on nonstructural components (e.g., plasterboard partition panels) but they were damaged once again by the aftershock occurred on May 29. This also demonstrates that repair works are often made by managers in the absence of a comprehensive understanding of the seismic vulnerability of buildings entrusted to them. Repair works in these cases were started on the basis of the post-earthquake survey response that revealed no or negligible structural damage, but without considering the opportunity of making a detailed assessment and eventual upgrading works.

In this paper, the case study of the Santa Maria Bianca hospital is analyzed starting from the post-earthquake assessment reported in [4]. In particular, based on the damage observed in the aftermath of the 2012 Emilia earthquake, a rehabilitation strategy has been defined in order to ensure the serviceability limit states. In fact, excessive interstory drift values caused extensive damage to partition and infills and, consequently, the building resulted unusable. An upgrading technique acting only from outside is applied to the building, taking into account the advantages related to avoiding the disruption of healthcare activities.

2 THE BUILDING UNDER STUDY

The Mirandola hospital has 200 beds and serves, along with another hospital (i.e. Finale Emilia), about 87.000 inhabitants. It consists of seven main buildings, most of them built between 1990 and 2000 with reinforced concrete (RC) structure. Although seismic design became mandatory in the territory of Mirandola in 2003, RC structures were designed considering low seismic actions without ductility details.

The hospital under study is located near to the epicentral area of both seismic events (about 27 km for the May 20 shock and 2 km for the May 29 one) and it was fully evacuated after the first event due to severe non-structural damage. Further, during the repair interventions, the second shock increased both the level and extension of damage to non-structural components.

The building under study is named Service Centre whose infill panels, as a consequence of high vulnerability due to the outside position from the surrounding frame members and/or excessive slenderness [7], suffered out-of-plane collapse (Fig. 1a). In some cases, external failure of infills was also promoted by prior in-plane damage [8,9].

The same building also suffered significant damage in partitions made up of hollow clay bricks (Fig. 1b), while negligible damage to the structural components was observed. More details on building damage are reported in [4].

a) b)

Figure 1: Example of damage to Service Centre: a) collapsed infills and b) cracked partitions .

The Service Centre building consists of three separate RC structures, two of them (named A and C in Fig. 2) have “L” shape in plan (total dimensions about 32 × 35 m) and 4 storeys in elevation (inter-storey height ranging from 3.35 to 4.10 m). An underground floor is also present (3.2 m high).

Regarding structural resisting members, each level is characterized by flat beams 25 cm depth and square columns with constant dimensions equal to 40 × 40 cm. Both staircase and elevator sub-structures are 25 cm thick concrete walls.

Masonry infills are light hollow concrete blocks 27 cm thick, placed partially outside from the surrounding frame members.

After the May 20 earthquake, two accelerometric stations, one near the building (free field) and one at the upper (third) storey of the C structural unit, were installed in order to monitor the hospital's Service Centre. Data recorded by the accelerometric stations allowed to evaluate the fundamental period of vibration and their variations due to building damage. In particular, after the May 20 event (Ml=5.9), the fundamental period values were 0.40s along E-W direction and 0.36s in N-S one. As a consequence of the damage increase after the second event (Ml=5.8, May 29), higher values of the fundamental period were evaluated, that are about 0.42s and 0.38s, respectively for the E-W and N-S directions.

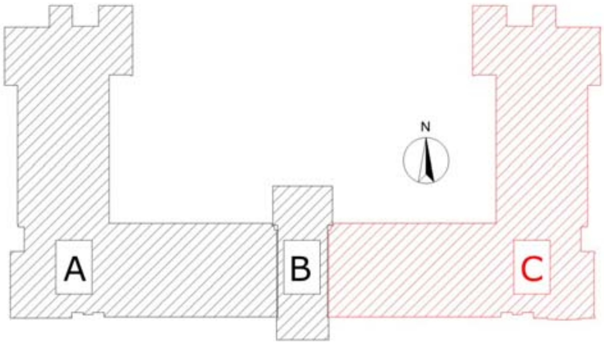

Figure 2: Sketch of the Service Centre building.

In order to better understand the building response during the main phases of seismic sequence, an analytical model was defined [4], whose dynamic characteristics were calibrated on the basis of experimental values obtained from the data recorded during the seismic events.

A good agreement with respect to the experimental values was found. Further, starting from the information evaluated on damaged configurations (i.e. after both the May 20 and 29 shocks), the unknown dynamic properties of the as-built undamaged building (i.e. before May 20 shock) were also estimated. They are T_1=0.37s and T_2=0.33s for the E-W and N-S directions, respectively.

Therefore, going from the undamage configuration (as-built) to the damaged one (i.e. after the May 20 event), the global stiffness reduction is about 30%, and it also increases to 40% after the second event (i.e. the May 29 shock). Results confirm that infills have a remarkable role in the lateral stiffness of the building under study.

3 SEISMIC ASSESSMENT

3.1 Building modelling and seismic analysis methods

Starting from the above-mentioned results for the undamaged building (i.e. before the May 20 event), a 3D elastic finite element model was defined by adopting beam-type finite elements. A reduction factor equal to 70% was assumed for the gross values of the beam inertial moment in the undamaged structure to take into account cracking due to the effects of vertical loads. In accordance with the Italian structural code [10], the concrete elastic modulus E_c was evaluated as a function of the mean concrete strength (f_{cm}), assumed equal to 28 MPa on the basis of the original design specifications.

At each floor, a diaphragm constraint was imposed. Infill panels were modelled by using an equivalent diagonal strut. Infill stiffness was evaluated considering an elastic modulus equal to E_w =4,000MPa and a cross section area $A= t\, w$, where t is the thickness and w is the width evaluated according to [11].

As already reported in [4], a reduced thickness of the infill panels has been assumed to account the external position with respect to the surrounding frame members.

The presence of large windows in the infills forced to reduce the axial stiffness of the equivalent struts by a reduction factor ρ, as follows:

$$\rho = (1 - \frac{5}{3} \cdot \frac{A_{opening}}{A_{panels}}) \tag{1}$$

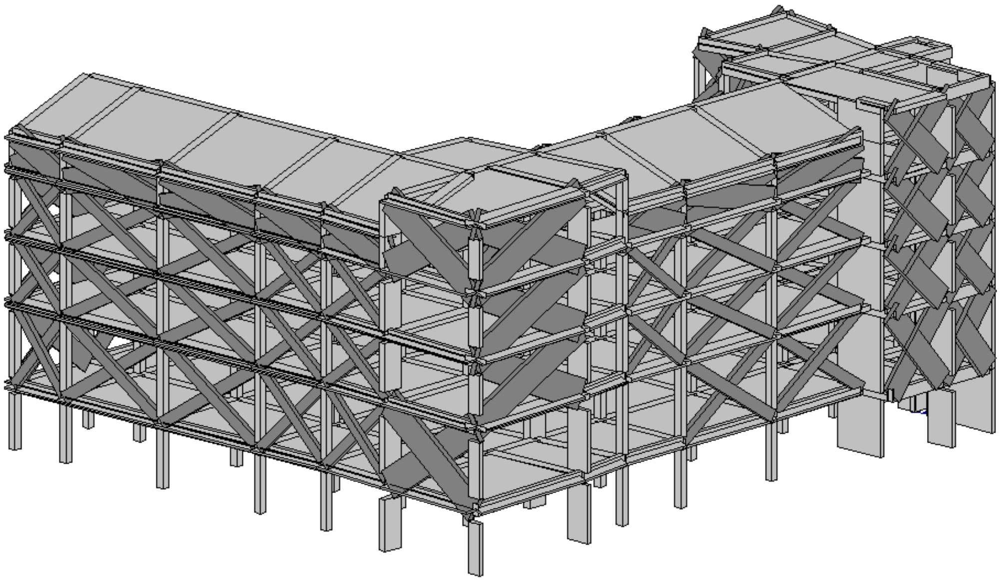

Figure 3: Model of "as-built" configuration of the C structural unit

This study is focused on the countermeasures that can be adopted for the upgrading of a hospital building in the aftermath of a seismic event, accounting that damage was mainly related to non-structural elements. For this reason, it has been assumed as advisable using a linear analysis method like the linear dynamic analysis with response spectrum for both the assessment and the upgrading phases. Moreover, linear analysis methods are most commonly used in the practice by engineers through commercial software packages [12]. In fact, the approach of designers for the definition of an upgrading intervention is generally oriented to linear analysis because it provides directly the structural details, avoiding a double step procedure: determining details with linear analysis and then assessing it suitability with non-linear pushover analysis. This can save time in a real upgrading intervention design.
To this purpose, the elastic 5% damped spectra are reported in Fig. 4 along with the indication of the vibration period of the first and second mode shapes.

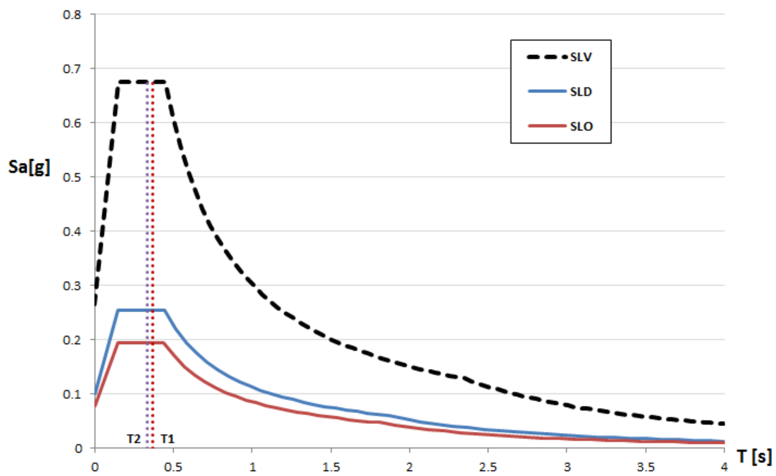

Figure 4: NTC2018 response spectra for both Life safety (SLV), damage (SLD) and operation limit states (SLO). Site of Mirandola, soil C, category T1, Class of use IV.

3.2 Analysis results for serviceability limit states

Based on the previously described model, the serviceability limit states according to the Italian seismic code [10] have been carried out, that are usability (SLO) and damage limit states (SLD).

For SLD, different interstorey drift thresholds are considered as a function of the type of infill panels. Specifically, "*for buildings having non-structural elements of brittle materials attached to the structure*" design interstorey drift must be lower (or equal) than 0,005h (*h* is the storey height). Regarding SLO, interstorey drift value equal to 2/3 of those indicated for SLD is prescribed.

It should be noted that the prescribed threshold values are provided assuming that RC buildings are generally modelled as bare frames, i.e. without considering the contribution of masonry infills. As a consequence, when assessing existing buildings, NTC2018 Commentary [13] requires that thresholds for both SLD and SLO limit states are suitably reduced if the analysis model includes infills. Therefore, for the case study under examination, threshold values are equal to 0.3% and 0.2% for SLD and SLO, respectively. In [14], the prescribed threshold values of interstorey drift are compared with some available experimental results in order to verify their effectiveness.

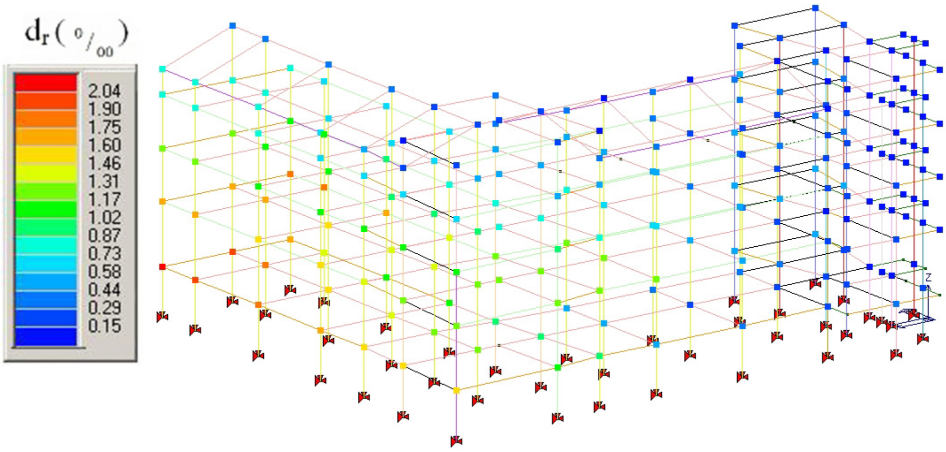

Figure 5: SLO results.

As can be seen from Figure 5, the SLO limit state is not satisfied. In particular, in some region of the structure, and consequently for the corresponding infill panels, located in the perimeter of the structure, far from the rigid staircase, drift values slightly exceed the drift threshold prescribed by the code (0.2%). As could be expected, these results have been evaluated at lowest storeys where higher values of interstorey drift are generally experimented [8,9].

Similar results have been evaluated for SLD, as plotted in Figure 6. In fact, almost the same areas of the building show points where the interstorey drift is slightly higher than the code threshold (0.3%).

For a strategic structure like a hospital, it is important the continuity of functionality, especially for medium-high intensity events. Due to this, it is also interesting to consider the Mirandola earthquake occurred on May 29, 2012 (M_l=5.8) as a seismic input for the structure's assessment at serviceability limit states. To this purpose, analyses have been carried out by using the elastic response spectra (HN1 and HN2 in Fig. 7) obtained from the accelerometric records acquired during the surveys on the Mirandola hospital [4]. In Fig. 7, the elastic design spectrum for life safety limit state (SLV) according to the Italian seismic code [10] is also plotted.

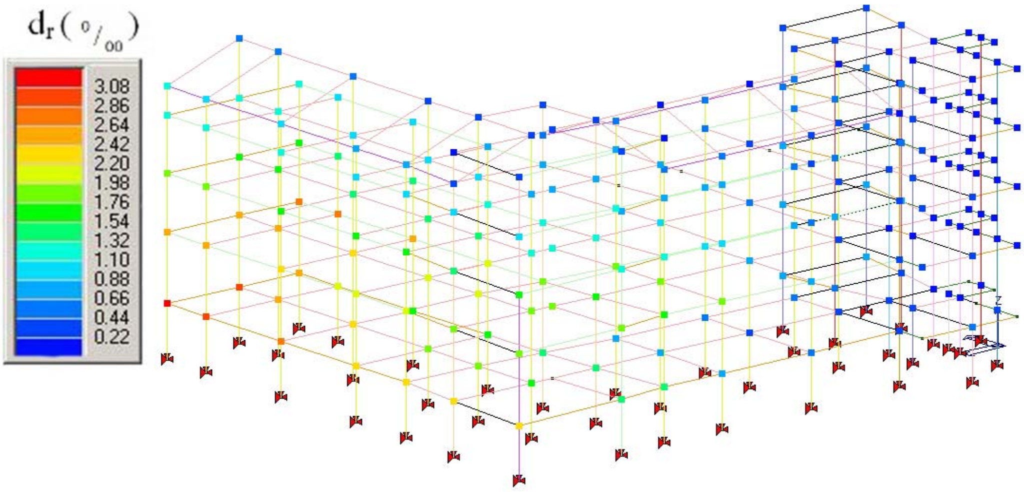

Figure 6: SLD results.

Considering the vibration period of the structure, the pseudo-spectral acceleration provided by HN2 record is almost the same as the SLV code spectrum. It can also be noted that, for lower vibration periods related to higher modes, the pseudo-spectral accelerations are lower.
Both the HN1 and HN2 components of the recorded accelerations are far higher than the code spectra for serviceability limit states (SLD, SLO). This means that the assessment under this earthquake could be representative of the building response to earthquakes with intensity higher than that provided by the code for serviceability limit states.

Figure 8 shows the results in terms of interstorey drift values under the May 29 Mirandola earthquake. As can be noted, the maximum drift (equal to 0.65%) is achieved at the peripheral area of the building plan opposite to the staircase (the stiffest zone of the building).
This is in accordance with the results of the survey that revealed the wide presence of damage to non-structural components like partition and infills.

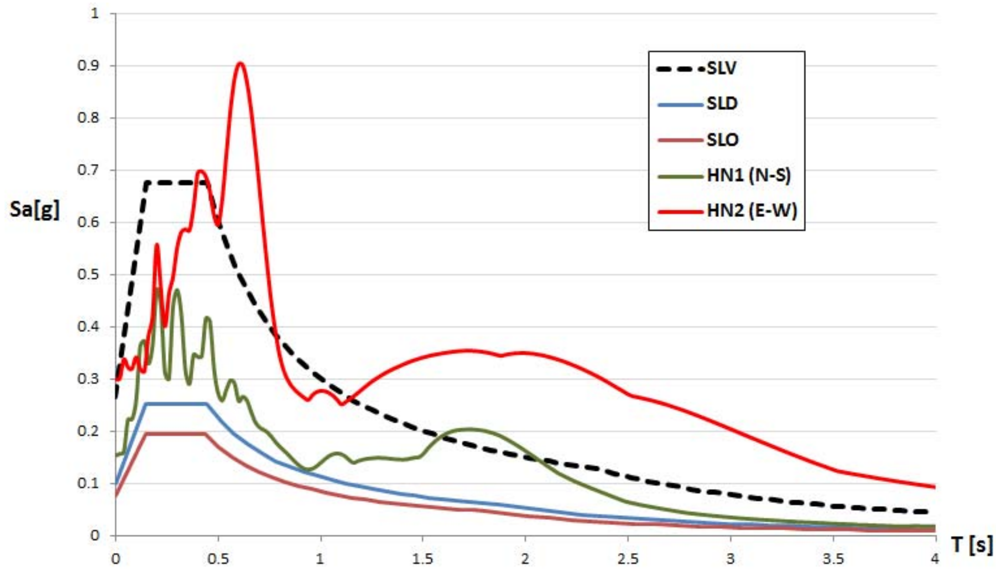

Figure 7: Response spectra of May 29 earthquake recorded and NTC elastic response spectra.

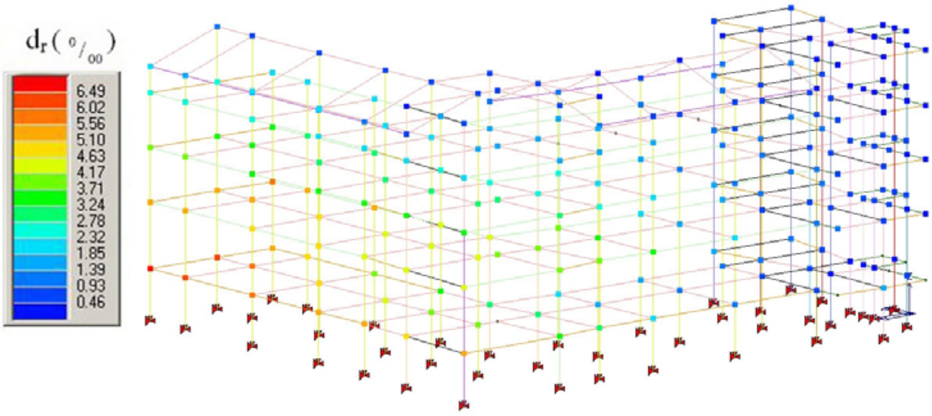

Figure 8:Interstorey drift results using the May 29 Mirandola earthquake

4 UPGRADING STRATEGY

4.1 Design of seismic intervention

Given that the upgrading strategy to be selected for the building under study should be carried out in a post-earthquake emergency management condition, it makes sense to choose it based on characteristics of rapidity and low invasiveness. These two properties are directly related each other. In fact, similarly to what found for school buildings in the post-earthquake emergency of Central Italy (2016) [1], the rapidity of intervention for public buildings (especially schools and hospitals) is a crucial issue of the recovery phase after a seismic event. Intervening only from outside saves most of the non-structural components, whose demolition and reconstruction implies high costs and take usually more time than the structural interventions works.

Due to these aspects, the upgrading system is made of RC frames located along the perimeter of the existing structure [15,16] and rigidly connected to it (Figure 9).

This intervention strategy comprises works to be carried out only from the outside with a strong reduction of demolitions and related reconstruction works. If the additional RC frame (auxiliary) structure is prefabricated, the time needed to perform works as well as disturbance to the occupancy are furtherly reduced.

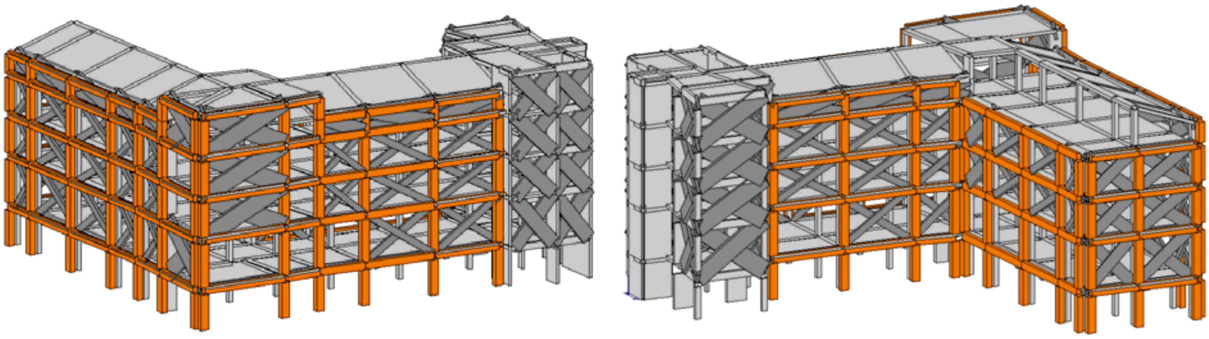

Figure 9: Building model with the upgrading system (orange colored members).

Considering the irregular shape in-plan of the structure and the eccentric location of the stairs and lift cases, auxiliary frames are placed along the perimeter excepted the staircase in order to somehow reduce the eccentricity between centres of masses and stiffness. Further, sizes of the new structural elements are limited by the aesthetic issues as well as by functional problems related to the indoor lighting. In fact, hospitals usually have large windows which must not be excessively obstructed by new structural elements.

Keeping in mind these objectives, RC members of the auxiliary frames have been designed gradually increasing their sizes in order to get a capacity/demand ratio at least equal to C/D=1 concerning the serviceability limit states.

New structural members are assumed to be made of concrete of class C28/35 and reinforcing steel of class B450C according to the Italian seismic code [1]. Column members have cross-section 500x700 mm while beams 400x600 mm. The frames are provided of an RC continuous foundation with square cross section 1000 x 1000 mm, anchored on RC circular piles with 600 mm diameter, 12000 mm length and 1000 mm spacing.

4.2 Assessment of the upgraded structure

First of all, the insertion of the auxiliary frames caused the reduction of the fundamental period from T_1= 0.37s to T_1 = 0.34sec. In terms of mode shapes, a reduced predominance of rotational effects in the main modes has been noted.

Figure 10 displays the verification of the structure in the upgraded condition. For the SLO, the maximum interstorey drift is achieved on the second floor almost in the same position as happens for the as-built structure. In this case the maximum drift is $d_r = 0.0016 \cdot h < 0.0020 \cdot h$.

For the damage limit state (SLD) the maximum drift is $d_r = 0.0021 \cdot h < 0.0030 \cdot h$. Therefore, both the serviceability limit states are satisfied.

Considering the Mirandola spectrum obtained from the acceleration record of May 29, 2012, the structural response is quite different. Indeed the max interstorey drift (Figure 11) is $d_r = 0.0047 \cdot h > 0.0030 \cdot h$. This means that damage of the structure cannot be excluded in case a new earthquake (similar to that of May, 29) occurs again.

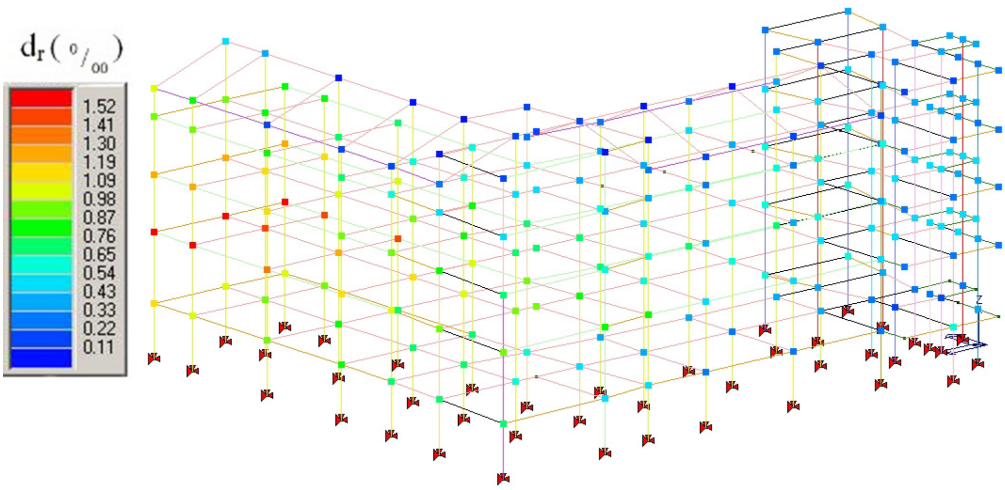

Figure 10: SLO results for the upgraded structure.

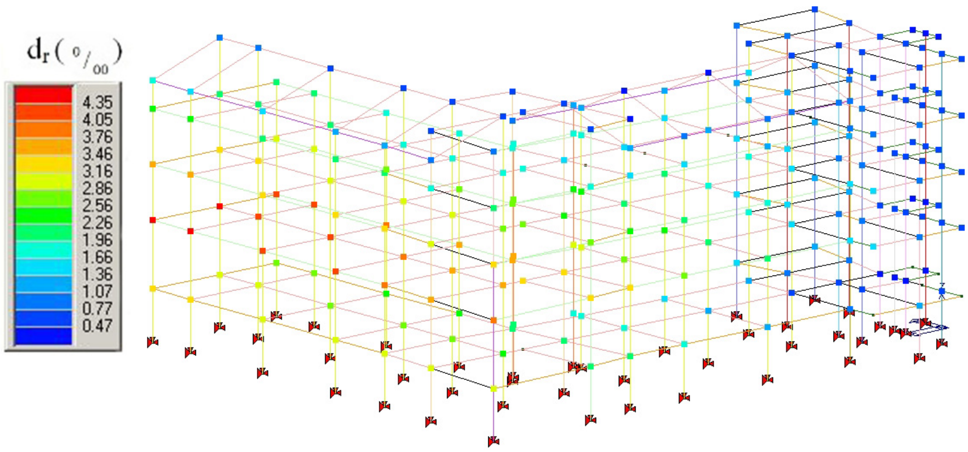

Figure 11: Interstorey drift under the Mirandola earthquake of May 29, 2012.

As can be seen from Table 1, the proposed upgrading technique focused on serviceability limit states, is able to obtain the full rehabilitation with respect to the code seismic input giving capacity/demand ratios higher than 1.0. The result is different considering the Mirandola earthquake as seismic input, which provides significant interstorey drift values due to high spectral pseudo-acceleration values which are similar to the life safety code seismic input.

In order to quantify the funds needed to carry out the seismic strengthening works, a cost computation has been made with respect to official price listing for public works.

The seismic strengthening needs, for foundations and auxiliary frames, a total of € 370,000. This amount is susceptible to different additional rates for VAT, security costs and general costs (total increase +40%). The total cost for the seismic strengthening amounts to about € 520,000. Considering that the total surface of the building is about 2000 m^2, a cost per unit floor area is 185 €/m^2 (only for seismic strengthening). Applying all the incremental rates, a cost of 260 €/m^2 is obtained.

		INPUT	**Drift (demand)**	**drift limit ***	**[C/D]**
SLO	**As-built**	NTC	0.0022 h	**0.002 h**	0.90
	As-built	Mirandola	0.0065 h		0.30
	Upgraded	NTC	0.0015 h		1.25
	Upgraded	Mirandola	0.0043 h		0.43
SLD	**As-built**	NTC	0.0033 h	**0.003 h**	0.90
	As-built	Mirandola	0.0065 h		0.45
	Upgraded	NTC	0.0021 h		1.43
	Upgraded	Mirandola	0.0043 h		0.64

*The code drift limit s assumed as the structural capacity at serviceability limit states

Table 1: Summary of results regarding serviceability limit states (SLO, SLD).

Applying to the Mirandola hospital a cost model referred to hospital buildings as reported in [17], the total amount obtained for the seismic upgrading is equal to 580 €/m^2. This value is more than double compared to the previous one (260 €/m^2).

A similar conclusion is reached considering the costs for the construction of the interventions on residential buildings reported in the "Libro Bianco" about the reconstruction after the 2009 Abruzzo earthquake [18] and analyzed in [19]. For RC buildings, unusable for the severe non-structural damage related, as in this case, to excessive interstorey drift values, the average cost of intervention is about 446 €/m^2. This value is about 70% higher than the cost estimated for the Mirandola hospital building that is 260 €/m^2.

5 CONCLUSIONS

A building included in the Santa Maria Bianca hospital complex, located in the town of Mirandola stricken by the 2012 Emilia earthquake, has been subjected to seismic assessment in accordance with the last version of the Italian seismic code. Particular attention has been devoted to serviceability limit states, taking into account the importance of guaranteeing functionality of strategic buildings, like hospitals, in the aftermath of a natural disaster. As it could be expected, the existing building does not match damage (SLD) and operational (SLO) limit states, nor interstorey drift limit under the seismic actions experienced during the 2012 earthquake (with reference to the May, 29 event). For this reason, an upgrading intervention has been designed, particularly addressed to overcome deformability limits. It consists of new RC frames placed along the perimeter of the existing structure and rigidly connected to it, designed to increase the lateral stiffness of the building. This solution gives some advantages as for example reduced demolition and reconstruction works on non-structural elements, like infills, finishes, etc. It is even more important the possibility of strongly reducing the downtime of the building activities in a hospital building. Keeping this in mind, the proposed intervention, exploiting additional RC frames, has been designed and verified accounting for the limits related to beam and column members' sizes, which should not excessively reduce the interior lighting.

The upgraded structure is able to fully match code seismic actions thanks to the proposed intervention but could not able to keep sufficiently low the interstorey drift values under high seismic actions like that recorded during the 2012 Emilia earthquake. Therefore, a deep discussion should be developed on design code criteria regarding strengthening interventions: current serviceability limit states could not guarantee the functionality of strategic buildings like hospitals after severe seismic events, that is exactly the situation asking for high healthcare capacity especially in the immediate aftermath of the event.

Regarding the selected intervention technique, it is worth noting that the costs related to this kind of intervention strategy (even neglecting the absence of downtime) are far lower than other more traditional techniques involving invasive interventions also inside the building.

ACKNOWLEDGEMENTS

The work reported in this paper was carried out within the framework of the DPC-ReLUIS 2018 Project, Research Line "Reinforced Concrete Structures", WP3-"Upgrading and Retrofitting of RC Existing Structures".

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