Selection of optimal seismic retrofitting strategy for existing RC building

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Abstract: The selection of the retrofitting strategies has a fundamental technical and social role. Nevertheless, the adopted strategies have often been devoid of objective criteria. Because of the number of buildings that require seismic retrofitting and the reduced economic availability, researchers, professional engineers, and administrators must prepare interventions that represent the best solution to avoid waste. The paper would to introduce some objective tools for professional practice; it highlights several topics (as disruption of use, safety conditions and operational step in construction site) usually neglected in the retrofitting strategies. The retrofitting strategy has been defined through a global vision based on strongly different topics that should be considered. In the paper the main phases of the procedure to define the optimal retrofitting strategy of existing RC buildings are described. The structures under examination were designed and constructed in the ‘80s, in according to the old Italian seismic code. They have showed a general good condition but the assessment has revealed a generalized deficiency of the structures with regard to the required seismic resistance in the new code; thus a retrofitting is necessary. The main design phases have been: (i) structural assessment against seismic and gravity loads, (ii) definition and comparison of some retrofit strategies, (iii) selection of a retrofit strategy based on the results of the structural assessment, architectural and economic considerations, functional strategies defined by owner of the buildings, and quantitative assessment of the workplace health and safety. Different strategies have been considered and compared with Multi Criteria Decision Making (MCDM) in order to select the optimal solution. On the basis the current use of the buildings, the problem of disruption of occupancy has been a fundamental topic. The remarkable importance of the utilization requirements have been considered and particular attention has been devoted to the operational steps.

Keywords: Seismic vulnerability assessment, Existing RC Buildings, Retrofitting Strategies selection, Multi-Criteria Decision Making.

1. Introduction

In the paper, the main phases of the design of the structural intervention on existing RC buildings are described. Generally, in retrofitting strategy a fundamental role is played by different approach to model and analyse the existing structures. Instead, in this work, attention is focused on comparing between different retrofitting strategies and different operational strategies.

In recent years, several studies have been carried out; the core of these works is the vulnerability of buildings and its main problems. Significant questions are considered as different structural details (on the bases of seismic code), materials, degrading parameters and so on (for example Masi and Vona, 2012; Vona, 2014). Moreover, significant efforts have been carried out in order to define the optimal procedure for the assessment of buildings performance (Calvi, 2013). These topics have been investigated in more works. This is an interesting question in earthquake engineering and a fundamental part of the current research. In particular, attention has been devoted to the following topics:

- degradation of the material properties, due to the effects of time and earthquakes;
- details and poor quality of construction;

- structural weakness;
- knowledge of the structure;
- accuracy and reliability of the capacity models;
- seismic retrofitting;
- conventional and innovative materials and construction techniques;
- Ect....

In a simplified way, the retrofitting strategies are generally carried out considering only the priority based on the seismic assessment. Several important topics are often neglected (about the social and economical convenience related to the seismic retrofit of existing building). Moreover, no degree of freedom is given to the decision maker (generally the owner of the building). This procedure should be considered incorrect. In fact, it is highlighted that the retrofitting strategies should be carried out taking into account various aspects: probabilistic risk analysis, environmental impact, socio-economic loss assessment, public safety, sustainability, social and natural environment. Certainly, the selection of better strategies could not be based only on technical parameters (as seismic capacity, hazard and so on). In this study the authors have been investigated in order to analyse possible application of different multi-criteria decision-making (MCDM) methods.

The main phases for retrofitting of the analysed existing building have been: (i) structural assessment against seismic and gravity loads, (ii) definition and comparison of some retrofit strategies, (iii) selection of a retrofit strategy based on Multi Criteria Decision Making (MCDM) analysis (according to results of the structural assessment, architectural and economic considerations, and functional strategies defined by owner of the buildings and users).

A number of retrofit strategies have been considered, critically analysed, and compared with the other elements, to select the best intervention solution in terms of structural safety, costs, as well as architectural, functional, and operational requirements. Further, it has to be underlined that problem of disruption of occupancy there was, on the basis of the current use of the buildings. After a specific solution has been selected, a redesign process has been carried out taking into account the new characteristics of the buildings. In the work, the safety conditions in construction site have been also considered. Building retrofit design has been designed using the criteria in the recent Italian (NTC, 2008) and European codes (EC, 2005).

Obviously, three main phases above said are all equally important. In this paper, significant efforts have been made in order to apply a rational and objective criteria to detect the better solution. Really, this approach is not novel. These methods have been used in most fields (scientific, economic and industrial) and interesting applications are possible in seismic risk mitigation (for example Vona and Murgante, 2014; Opricovic, 1998). Other applications have been carried out in order to compare different strategies of natural risks mitigation (Opricovic and Tzeng, 2004; Shohet and Perelstein, 2004). Some interesting works have been carried out in (Caterino et al. 2008, Caterino et al. 2009) in order to study the applicability and effectiveness of MCDM methods for the seismic retrofitting decision problem regarding single building. Unfortunately, the real applications are not yet frequent. In particular, in the paper remarkable importance has been given to the definition of the operational steps.

Considering the main topic of the work and the above considerations, in the following of the paper, primary importance has been given to MCDM approach. In this way, in the section 2 the case study has been briefly described. In the section 3, numerical analyses and their results has been briefly reported. Finally, MCDM application and results have been reported and discussed as the main topic. In the work, a Building Information Model (BIM) has been also considered in order to study the safety conditions in the workplace and so to support decision process. It has to be highlighted that BIM is not just a software. In this way, in last years this method has been discussed about its capability to assist the assessment and mitigation of seismic risk of buildings (Welch et al., 2014).

The paper could be a reference for professional practice. It does not say any novel analytical procedures or methods but it want to introduce some objective tools and highlight several topics (as disruption of use, safety conditions and operational step in construction site). In this way, the retrofitting strategy can be to define as a global vision of strongly different topics that should be considered.

2. Case study: School Building in Sulmona

After 2002 L'Aquila earthquake 2009 (Dolce, 2010; Masi et al., 2011; Vona et al., 2015), a wide evaluation campaign about seismic vulnerability of strategic buildings (hospitals and schools) has been setup and carried out. The case study is located in Sulmona (L'Aquila), a town about 50km far from epicentre. In the city, low damage levels have generally occurred on reinforced concrete (RC) buildings. Therefore the National Department of Civil Protection has defined some activities to mitigate the seismic risk of the city.

The case study is a school complex of RC buildings. The first step of the present investigation has been a visual survey on the structure, aimed at identifying the structural system and its dimensions as well as the damage state. The global and local damage state due to L'Aquila earthquake 2009 both on the structure and on the non-structural elements is shortly described in the following. The global damage state can be defined as low structural damage and moderate non-structural damage. As for damage location, both on structural and non structural elements, it appears not uniformly distributed along the two principal horizontal directions.

The buildings under study were designed and constructed in the '80s, in accordance to enforced Italian Code (D.M. 27.5.1985). Original design took into account the seismic actions, since the Sulmona territory was already classified as seismic zone at the time of construction.

The structural complex under examination (Figure 1) is made up of six main buildings having RC frame structure plus four smaller and less important buildings. The four main buildings (A1, A2, A3, A4, classrooms) have a Reinforced Concrete (RC) framed structure with four storeys. Number of bays in main two directions is variable. Interstorey height is equal to 3,75 m. The buildings can be considered as having approximately regular shape in plan and elevation (Figure 2). The four buildings are separated by means of expansion joints (A1-A2 e A2-A3 20cm, A3-A4 17 cm, A4 -AM 14 cm). No significant structural damage has been detected in buildings except that for PAL building. Further, the structures showed a general good condition without significant deterioration. It is worth underlining that original design of the building, though took into account the seismic actions, was not performed in according with currently suggested concepts of modern seismic design, such as bi-directional resistance and stiffness, capacity design procedures, structural symmetry.

In fact, the beams only in the longitudinal direction are rigid (i.e. where they are needed to support the gravity loads due to the one-way slabs), except for the two external transversal frames having rigid beams to carry infill panels. In transversal direction, columns are weakly connected through very flexible embedded beams (50x25 cm).

The internal beams loaded by the floor slabs have section 40x60cm. In the external frames the beams have 40x60cm section. The staircase, uncommonly placed eccentrically in the building plan, is made up of inclined beams with section 40x60 cm supporting the stair-inclined slabs. Infills are made up of two layers of hollow brick masonry (cavity walls) having a total thickness of about 23 cm (15 + 8 cm) and they show poor mechanical characteristics. The floors (including the saddle roof) are RC slabs with thickness 25 cm, thus they can be considered rigid in their own plane.

Column sizes are variable at each storey. At the basement, the columns have 60x60 cm dimensions, decreasing to 60x40 and 40x40 cm at the first two and last two storey, respectively. Reinforcement is placed mainly along the shorter side. As for the foundation system, it is placed at 1,65 m under the first floor (Figure 3). It is made up of shallow foundations (Figure 4).

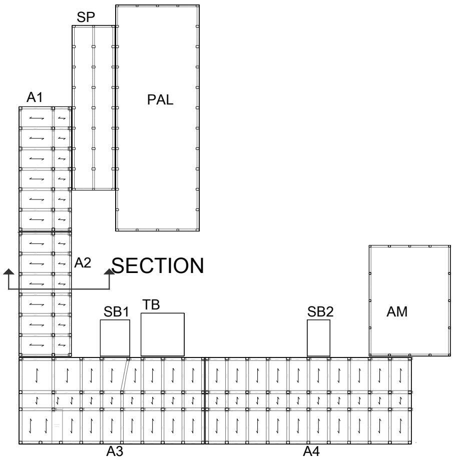

Figure 1 – Plan of framing before retrofitting

Figure 2 – Main entrance view

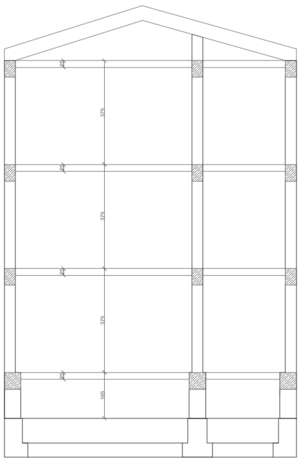

Figure 3 – Section

Figure 4 – Foundation of classrooms buildings

Concerning non-structural elements, significant damage has been found both in the external infill panels and in the internal partitions. Infill panels suffered wide cracking at the ground and first storeys along both the longitudinal and transversal frames. The most damaged areas are near the stiff stair-structure and along the longitudinal direction. Specifically, wide cracks are present along the longitudinal direction in the infill panels placed in the last bay of the ground and first storey. Along the transversal direction, lower damage has been detected, where several window openings are present. Damage mechanism is mainly in-plane. Cracking along the diagonals of the panel (due to inclined tension stress mostly concentrated within the centre region of the panel) and crushing of panel corners (due to the interaction with the surrounding frame) have been observed. Heavy damage has been found also on internal partitions, which appear frequently disconnected from the structural elements and sometimes in incipient collapse condition. Further, it is worth noting that, at the last (second) storey, during the main-shock, the weighty shelves of the historic archive were completely overturned.

3. Seismic evaluation

At the first step of the present investigation a visual survey on the structure has been carried out, aimed at identifying the structural system and its dimensions as well as the damage state. Many inspections and analyses of surveyed data have been carried out on the structural system, on the details of the building elements, and on the mechanical properties and condition of constituent materials. Moreover, dimensions and details of reinforcing steel have been detected by means of pachometric tests, radar techniques, and visual inspection on structural elements.

3.1 Study for knowledge

In the recent Italian and international codes the evaluation and retrofit activities are strongly dependent on the amount and quality of the information collected (knowledge level) for the structure under examination.

The type of analysis and the confidence factor (CF) value are dependent on the knowledge level available or achievable. Three knowledge levels are considered in the code in order to choose the admissible type of analysis and the appropriate confidence factor values: Limited Knowledge (KL1), Normal Knowledge (KL2), Full knowledge (KL3). In the case under examination, different amounts of technical documentation were available for each structure of the building complex. Thus, a visual survey on these structures has been carried out. It has shown irrelevant discrepancies from the outline construction drawings. On the contrary, no technical documentation was found for the structural parts. For this reason a full survey was preliminarily carried out aimed at identifying the overall structural geometry, while information on details were drawn from a simulated design and a subsequent limited survey.

Taking into account the amount and quality of information available or collected, in accordance with code a KL2 was achievable. As a consequence, linear and nonlinear analysis methods, either static or dynamic, could be adopted in the structural evaluation, and a confidence factor FC = 1.2 was used in the safety verifications.

3.2 Details and Materials

Due to great importance of the topic, information on details and mechanical properties of the structural materials (type, amount and detailing of reinforcement in the structural members, in-situ concrete strength) have been reported in this section. They have been obtained starting from the available original documentation and particularly from wide in situ inspections and laboratory tests. The investigation procedure is based on standard method (Masi and Vona, 2009) and application of radar technique for details.

In order to detect the amount and layout of longitudinal and transverse reinforcement in the structural members, some tests based on electromagnetic scanning were carried out, in some cases supplemented by direct visual inspection after the removal of concrete cover. 140 surveys with pachometer, 130 direct surveys on beams, columns and floors, were performed.

Pachometer tests have been carried out in order to evaluate the steel reinforcement bar position, diameters, stirrups spacing, and concrete cover.

The testing locations have been carefully selected at different points of each floor level to represent the spatial distribution of the investigated details and properties. Non-destructive tests are also useful for the assessment of critical components and systems that must be tested without damaging structural integrity. Moreover, NDT methods have been used to locate flaws in concrete (cracking, voids, honeycombing, delaminations, etc.), determine thickness of a concrete cover, locate bars, pipes, conduits, and so on.

In order to validate the results obtained from standard procedures an interesting methodology has been used. Radar techniques have been extensively employed. 120 surveys with radar technique have been carried out. The results have showed that in several cases the standard NDT procedures can lead to incorrect or partial information.

In fact, it must be highlighted that the use of the radar method has provided important information on the amount and location of the reinforcement bars. These information would not have been detected with standard techniques. Without these investigations, the capacity of the structural elements would have been underestimated. For example, in Figure 5 it is shown the comparison between the results obtained from the pachometer test and those obtained from the radar tests. Moreover, the radar survey has been also extended to other areas normally neglected (top of the columns). A greater number of reinforcement bars with respect to the sections of the centre has been identified. This configuration is common and it has been also checked with several direct survey (Figure 6).

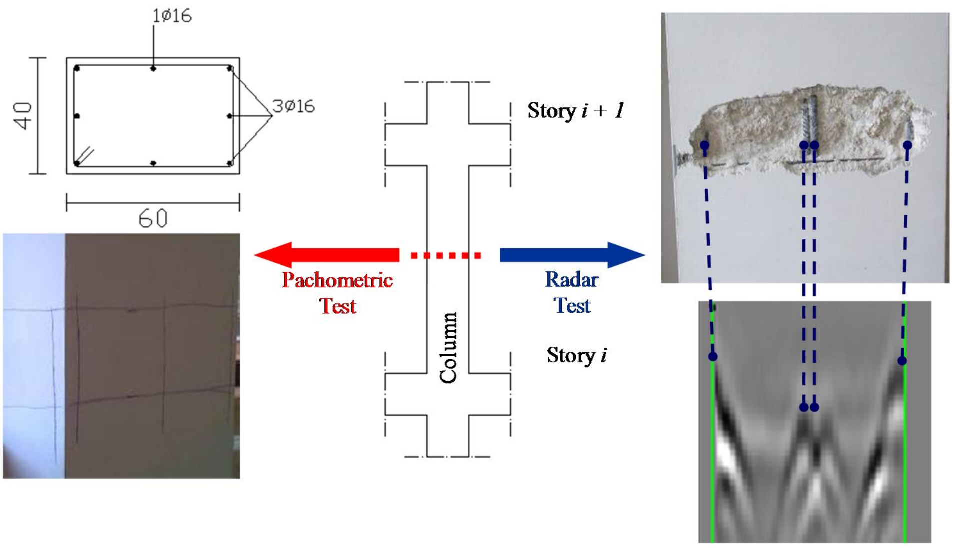

Figure 5 – Comparison between pachometer tests and radar technique result

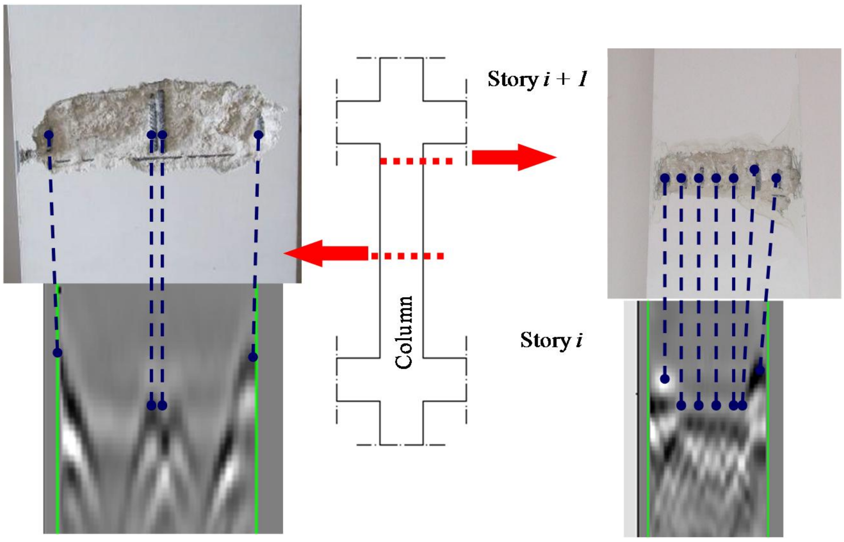

Figure 6 – Results of wide application of radar technique

In order to evaluate the mechanical properties of the structural materials (concrete and steel bars), a wide tests campaign has been carried out. In-situ concrete strength has been estimated through non-destructive (Schmidt hammer test and ultrasonic test) and destructive tests: 170 non-destructive tests, 49 destructive tests on concrete and 6 on steel bars. Concrete cores have been extracted and tested in laboratory to evaluate their cylinder compressive strength. These core test values have been converted into the equivalent in situ values (Figure 7) by a common expression (Masi and Vona, 2009).

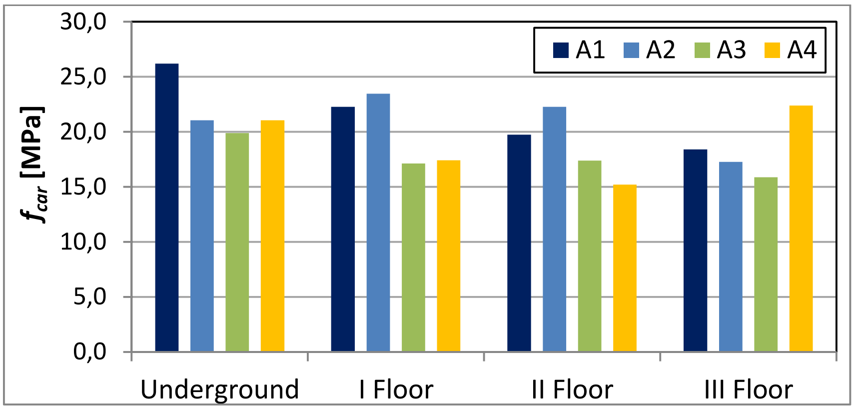

Figure 7 – In situ concrete strength values

Considering an existing procedure (Masi and Vona, 2009), the relationship between the in-situ concrete strength and the NDT measurements has been obtained. This existing procedure can be used to obtain a relationship between the in-situ strength fc and the NDT measurements, based on the following equation:

$$f_c = a \cdot RN^b \cdot V^c \tag{1}$$

where *RN* is rebound number, *V* ultrasonic velocity and the coefficients *a, b* and *c* are derived for the specific concrete under test. Using Maximum-Likelihood Estimation (MLE) method, f_c can be evaluated. In statistics, MLE is a method of estimating the parameters of a statistical model given data. MLE should accomplish this considering the mean and variance and then finding particular parametric values that make the observed results the most probable. Using the obtained relationship, the in-situ concrete strength can be also evaluated in points where only non destructive measurements have been done. Then, the concrete design strengths have been defined in a more representative and reliable way. Based on the results of destructive and non–destructive tests, for the concrete and the steel, the following strength values have been obtained and then used in the assessment and retrofit of the structure. About reinforcement, the destructive tests have been provided the yield stress f_{ym} = 420MPa.

3.3 Analyses

In this section, method of analysis, seismic scenarios, and their results are briefly reported. Firstly, it has to be noted that many professional engineers are more familiar with linear analyses. In the professional practice applications, the linear methods based on the use of the response reduction factor are still common; in particular this is an important topic for existing buildings. For this reason, in several codes (for example Italian NTC 2008 and European code, ASCE SEI/ASCE 7–05, 2005; BIS IS 1893, 2002) the reference method for seismic analysis is the modal response spectrum analysis, based on a linear-elastic model of the structure, the design spectrum and behaviour factor used to reduce the forces obtained from the elastic analysis. For design of new structures, to define a satisfactory seismic behaviour the structures are designed with ductile behaviour of its elements while brittle behaviour and/or mechanisms are inhibited. In this way, the design of new structures can be based on elastic analysis: a response spectrum is defined with respect to the elastic one by the behaviour factor q. Moreover, regarding existing buildings, it has to be highlighted that in many cases due to the lowest knowledge level and/or for irregularity building, the elastic analysis is the only allowed analysis method unless to use more complex Non Linear Dynamic Analyses. Then, coherently with main topics of the work, assessment using linear dynamic analyses has been carried out considering a modal response spectrum analysis according to the codes NTC 2008.

On the basis of the above investigation and information, 3D Finite Element models (Figure 8 and Figure 9) for each structure have been implemented using SAP2000 software (Computers and Structures Inc, 2006). The seismic action effects have been evaluated using a modal response spectrum analysis. Seismic assessment is carried out for each retrofit solution respectively.

Following the code provisions, the life-safety limit state (probability of exceedance of 10% in 50 years, return period of 712 years), and the damage-limitation limit state (probability of exceedance of 63% in 50 years, return period of 75 years) have been considered. Seismic effects have been combined with the effects of the other loads (dead loads and live loads) considering the usual (Italian building codes) load combinations. The operational limit state and ultimate limit state requested by code have been verified in terms of inter-storey drifts and ultimate strength of each element, respectively. Structural elements have been checked for ductile and fragile failure modes. About the check of the structural elements, material strengths have been defined according Italian code.

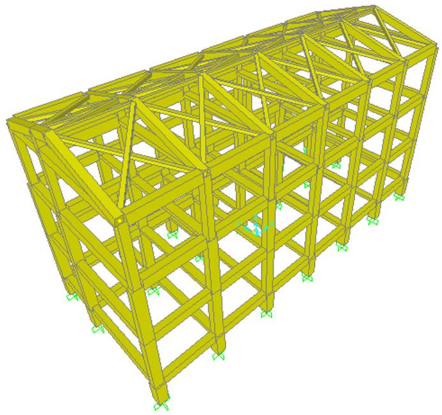

Figure 8 – 3D Finite Element models A1 building

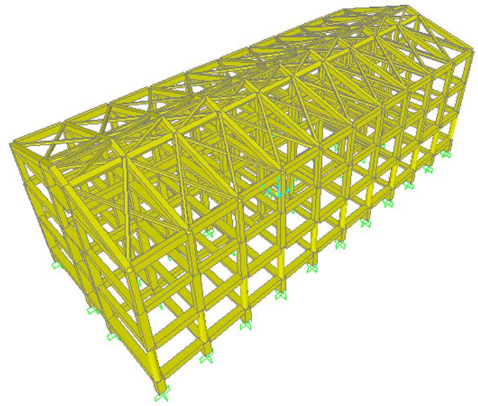

Figure 9 – 3D Finite Element models A4 building

The analysis results revealed a generalized deficiency throughout the structures. Pounding between the building A2 and the adjacent buildings A1 and A3 could be forecast even for very low values of the design ground acceleration ag, due to inadequacy of the existing joints.

The results of safety verification showed a strength lack of columns, particular at ground and first storey. Generally, columns evidenced a poor behaviour towards the combination of axial force and bending moments.

In order to evaluate the seismic capacity of investigated structures, in this study the results have been expressed in terms of ground acceleration values able to determine either the achievement of the life safety limit state that the damage-limitation limit state ( ) according to NTC 2008. The Seismic Risk Indexes (SRI) have been defined as:

$$\alpha_{LS} = \frac{PGA_{LS}}{PGA_{code}} \quad (2)$$

Where PGA_{code} is the required value for new buildings. PGA_{LS} is defined on the basis of building seismic capacity. The values considered in this work have been obtained analysing the damage state of structural members (PGA_{ULS}) and the damage state of non-structural elements (PGA_{DLS}). Collapse of the structure is identified on the basis of the first structural elements that achieves the considered damage state. The values of the seismic risk index for the life safety limit state are reported in Table 1.

Table 1 – Seismic risk index for investigated structures

	A1	**A2**	**A3**	**A4**
α_{LS}	21,3%	21,3%	19,8%	24,3%

4. Selection of the retrofitting strategy

Main topic of the following analyses is the evaluation of the better retrofitting strategy which is consistent with above numerical results. Selection of the optimum retrofitting strategy is a hard work that involves different criteria based on the results of the assessment procedure and in agreement with the requirements of the owner. Commonly, in order to select the retrofitting strategy, the design solution that minimizes the total cost is considered. The total cost includes retrofit installation costs and (if present) damage repair costs but it completely neglects other fundamental aspects. In studied case, these repair costs have been also considered. The total cost evaluation has been performed for each investigated technical alternatives.

The structural interventions have been selected from a long and accurate design process. Several technical strategies or alternatives, based on innovative and/or traditional techniques have been considered (as reported in the following Table 2). Each of them shows different advantages and drawbacks.

Table 2 – List of Technical strategies or alternatives

ID name	Technical strategies
a_1	Base - isolation system
a_2	Flexural and shear improvement capacities of beams and columns with Carbon fiber reinforced polymer (CFRP) wrapping
a_3	Flexural and shear improvement capacities of beams and columns with steel and RC jacket
a_4	Energy dissipation bracing systems

The structural intervention based on a base - isolation system, with elastomeric (i.e. HDLRB) and sliding (i.e. steel-PTFE) bearings has been considered (a1). The isolation devices have been located at the foundation level. The obtained structural system has been completely modified in order to achieve a extremely more favourable seismic behaviour.

Retrofitting through traditional techniques (a3) and similar new techniques (a2) have been also considered; they can be effective but also very invasive and destructive (in particular for no-structural elements). Retrofitting through dissipative bracing (a4) has been also investigated and they seem very effective on the structural view point. In order to select the best intervention strategy, these techniques have been critically analysed and compared with the other aspects of the design procedures. The above investigated options are significantly different in respect of various aspects such as costs, time, structural performances, architectural impact, disruption of school activities, etc.

The selection of the retrofitting strategy involves several and non-homogeneous variables and different objectives. In several studies, the evaluation of the optimal and sustainable retrofit solution is defined on the basis of single aspects (levels of seismic demand, technical choice, and so on). Several studies have considered different seismic rehabilitation techniques, based on different approaches. Generally, in the better cases, the suitable solution has been defined on the basis of too much simple "compromise" between safety and costs. In recent years, some studies have been carried out including the life-cycle as a further point of view.

On the other side, any studies have been carried out in last years in order to explore a rational and quantitative approach to evaluate and rank different solutions for the seismic retrofit (for example, Caterino et al. 2009).

More interesting multi-criteria decision methods (MCDM) have been set up. These methods allow a quantitative evaluation of different strategies based on the relevant scores of the selected alternatives. Using these methods, significant importance is given to the Decision-Maker opinion.

The weights of the functional compatibility and the level of protection from earthquake damage have been considered predominant on all criteria

In the considered case study, the most relevant criteria for the decision about seismic retrofitting have not been only those related to structural performances and related costs. Others non-technical and/or non-quantitative criteria have been also considered. The need, strong point of the whole rehabilitation project, to minimize the impact on the original architectural characteristics and current use of the buildings has played a crucial role. The weights of the functional compatibility and the level of protection from earthquake damage have been evaluated predominant on all criteria. For the project, the requirements imposed by the owner have been fundamental; they have been considered, obtaining an overall view of the project's goals in operational phase. Although this approach seems to be the most logical, it is not yet become common in practice application.

Moreover, in this case study, risk assessment on workplace sites is the key step to achieve adequate safety levels, particularly to support decision-making in safety programs. To give adequate answers about these questions, working procedure in the construction site have been considered in the design phase. In fact, the laws highlight that every alteration, demolition and dismantling work must be carefully planned and carried out by competent people to avoid unplanned structural collapse, injuries, and risk for people. Design, finance, and legal aspects overlap and interrelate. For this reason, in present work all aspects have been integrated into a unique framework, and many efforts have been made in the decision process.

Safety problems on construction sites seem to be largely prevailing in order to avoid injury during construction phase considering the simultaneous presence of students. A systematic mechanism to interrupt and prevent injuries on construction sites must be developed. Thus, construction site operations and associated equipment have been investigated. The main aim of the research was to investigate operations on construction sites exploring different options, their effectiveness, and their effect on safety. The factors influencing the occurrence of accident situations have been analysed. This study has examined into the working processes, the factors that have to be taken into consideration during positioning and use of equipment, the new structural components and the competent persons required when operating equipment. The research findings showed main points to improve safety in construction site operations. These are: planning; equipment and employees selection; continuous inspection and communication. Finally, Building Information Model (BIM) has been partially defined in order to study the safety workplace evaluation and so to support decision process.

For above reasons, a MCDM method has seemed the best procedure and so MCDM methods have been adopted. For more detailed analyses of the advantages and weaknesses of different possible method, several studies have been reported in scientific literature. In this work, TOPSIS method has been used. Moreover, the design phases have been partially supported by a Building Information Modeling (BIM). The selected alternatives following the Decision-Maker’s opinion have been compared using TOPSIS method (Hwang and Yoon, 1981) that allows to order of alternatives by similarity to an ideal solution. TOPSIS attempts to choose alternatives that simultaneously have the shortest distance from the positive ideal solution and the farthest distance from the negative-ideal solution. In the last years, TOPSIS is further used in infrastructure and buildings management (Vona and Murgante, 2014). Applying TOPSIS, the following phases have been considered:

phase 1 - Definition of decision matrix,

phase 2 - Definition of weighting matrix,

phase 3 - Definition of ideal solutions for each criteria,

phase 4 - Definition of Optimal solution.

In this way, a ranking of the selected alternatives has been defined. Moreover, a sensitivity analysis has been carried out in order to assess the stability of the optimal solution.

Different criteria have been considered based on Social-Economics and Technical point of view (Table 3). These criteria have been defined considering the usual professional practice, the architectural and economic considerations, the functional strategies defined by owner of the buildings, and the quantitative assessment related to health and safety at the workplace. In order to compare different criteria, different weights must be defined. This choice has a key role in the procedure and it is representative of the owner and Decision-Maker (DM) choices. The weights have been defined considering the Saaty's approach (Saaty, 1980; Saaty, 1999). This approach is based on the pairwise comparisons of criteria (3) using Saaty's scale (Table 4) and eigenvalues theory. A simple and enlightening application can be found in many existing applications (for example, Vona and Murgante, 2014; Caterino et al. 2009). In this work, it is interesting to highlight the role of DM choices and the particular key role of the C4 and C8 criteria. Obviously, an ordinary consistency measurement of the pairwise comparisons has been made in order to exclude unacceptable conflicts. In this way, the final solution is a logical solution and not a random order.

Table 3 – List of Selected Criteria

Social-Economics criteria	Technical criteria
C_1 - Installation costs	C_5 - Feasibility of the retrofitting strategy
C_2 - Maintenance Costs	C_6 - Damage limitation
C_3 - Functional and Architectural compatibility	C_7 - Next possible strength Upgrade
C_4 - Disruption of use	C_8 - Safety in construction site operations

$$C = c_{ij} = \begin{bmatrix} 1 & 4 & 1/3 & 2 & 1/2 & 1/4 & 5 & 3 \\ 1/4 & 1 & 1/7 & 1/3 & 1/6 & 1/8 & 2 & 1/2 \\ 3 & 7 & 1 & 4 & 2 & 1/2 & 8 & 5 \\ 1/2 & 3 & 1/4 & 1 & 1/3 & 1/5 & 4 & 2 \\ 2 & 6 & 1/2 & 3 & 1 & 1/3 & 7 & 4 \\ 4 & 8 & 2 & 5 & 3 & 1 & 9 & 6 \\ 1/5 & 1/2 & 1/8 & 1/4 & 1/7 & 1/9 & 1 & 1/3 \\ 1/3 & 2 & 1/5 & 1/2 & 1/4 & 1/6 & 3 & 1 \end{bmatrix} \tag{3}$$

Table 4 – Saaty's scale

Intensity	Definition
1	Equal importance
3	Moderate importance of one to another
5	Essential or strong importance
7	Demonstrated importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgements
Reciprocal (1/2, 1/3, …)	If criterion i compared to j gives one of the above, then j, when compared to i, gives its reciprocal

As well known, the vector W of relative weights $w_1, w_2, ..., w_8$ is the principal right eigenvector. In this work, the eigenvector has been evaluated as:

$$W = \{0.103, 0.030, 0.234, 0.069, 0.160, 0.335, 0.022, 0.047\} \quad (4)$$

In order to define the decision matrix, for each criterion an evaluation of the selected alternatives must be carried out. For this purpose, the above criteria have been considered. C_1, C_2 and C_8 criteria have been analyzed as quantitative criteria. For each technical solution have been provided different values as reported in the following.

For C_1 and C_2 criteria, the values have defined the total cost for each alternatives and the cost for maintenance on the basis of retrofitting design.

In order to define the values of C_8 criterion, a complete risk analysis has been carried out. In the procedure, risk assessment has been made on the basis of Decreto Legislativo 81/08 (in Italian). For C_8 criterion, all technical strategies have been compared on the basis of the level of risk [R], defined as:

$$R = \sum_{i=1}^{n} R_i = \sum_{i=1}^{n} M_i \cdot P_i \quad (5)$$

List of risks has been provided by code. In this list, for each step of construction phase the risk has been defined. M is the magnitude (1 to 4), P is related to probability of occurrence (1 to 4). In Table 5, the three quantitative criteria have been reported.

Table 5 – Quantitative criteria

Alternatives	Installation costs (€)	Maintenance costs (€)	Risk Level
a_1	1.900.000	70.000	674
a_2	1.520.000	57.500	280
a_3	1.450.000	38.500	223
a_4	1.550.000	77.000	325

Based on the above described procedure (Saaty's approach applied by pairwise comparisons of criteria and eigenvalues theory), others qualitative criteria have been investigated and the results are summarized in Table 6.

Table 6 – Final Normalized Decision Matrix

Alternatives	Criteria							
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
a_1	0,061	0,017	0,208	0,015	0,018	0,316	0,021	0,038
a_2	0,048	0,014	0,096	0,036	0,018	0,022	0,003	0,016
a_3	0,046	0,009	0,043	0,057	0,145	0,045	0,001	0,013
a_4	0,049	0,019	0,020	0,007	0,063	0,098	0,007	0,018

Finally, the selected alternatives have been compared using TOPSIS method. The ideal solution A^* has the best performance for each criterion. The solution A^- is achieved combining the worst performance of the alternatives for each criterion. For qualitative criteria (C_3, C_4, C_5, C_6, and C_7), the best performance is that has the maximum value for the alternatives; for quantitative criteria (C_1, C_2 and C_8), the best performance is that has the minimum value for the alternatives (Table 7).

Table 7 – Ideal solutions

Alternatives	Criteria							
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A^*	0,046	0,009	0,208	0,007	0,145	0,316	0,021	0,013
A^-	0,061	0,019	0,020	0,057	0,018	0,022	0,001	0,038

The ideal solution is chosen considering the alternative that simultaneously has the shortest distance from the positive ideal solution and the farthest distance from the negative-ideal solution. Finally, the ranking of the selected alternatives has been defined (Table 8). Moreover, the sensitivity analysis has been carried out in order to assess the stability of the optimal solution; the solution has been satisfactory. According to the results of the TOPSIS method, the alternative a_1 is the ideal solution ($C_1^* = 0.729$).

Table 8 – Raking of alternatives

Alternatives	S_{i*}	S_{i-}	C_{i*}
a_1	0,131	0,352	0,729
a_2	0,341	0,083	0,196
a_3	0,322	0,135	0,295
a_4	0,300	0,104	0,257

5. Conclusions

On the basis of the case study reported in this work and in many others papers, it is evident that the seismic retrofitting of existing RC buildings requires a dynamic management procedure both for the design and for monitoring of its phases. This topic plays a fundamental role. The paper would be a reference for professional practice. In this way, new analytical procedures or methods are reported but some unusual tools have been analysed and several important topics have been considered (as disruption of use, safety conditions and operational step in construction site). The remarkable importance of the utilization requirements have been considered and particular attention has been devoted to the operational steps.

In this way, the retrofitting strategy has been defined as a global vision of strongly different topics. MCDM application and results have been reported and discussed as main topic. Moreover in the work, a Building Information Model (BIM) has been also considered in order to study the safety evaluation at workplace and so to support decision process. The used procedure may be considered as an ideal solution and an innovative opportunity in professional practice and as multidisciplinary approach in research. This approach may be a useful tool in simplifying and supporting the administrative processes.

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