Innovative and Traditional Techniques for Seismic Retrofitting of an Existing RC School Building: Life Cycle Assessment and Performance Ranking through MCDM Methods

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Abstract. In the paper the seismic retrofitting of an existing RC school building located in the district of Naples has been faced. The school, which was designed to sustain gravity load only, is composed of seven constructions seismically jointed each to other. One of these constructions has been retrofitted with traditional (RC shear walls) and innovative (concentric braces, eccentric braces, buckling restrained braces and steel plate shear walls) intervention techniques, whose effectiveness has been evaluated in the non-linear field. Moreover, the environmental impact of these interventions has been assessed by means of an appropriate analysis program. Finally, the choice of the best intervention from economic, structural and environmental points of view has been done by using the MCDM TOPSIS method.

1. INTRODUCTION

The disastrous effects of the earthquakes occurred in Italy during the past few years do not depend on their significant seismic intensity only, but also on both the high population density of the different territory areas and the poor attention paid to build seismic-resistant buildings. In particular, more than 30% of the reinforced concrete buildings in Italy are inadequate to withstand design seismic loads prescribed by Italian current regulations. The seismic behaviour and the consolidation of existing RC buildings, with particular reference to those with public functions, is therefore an extremely important topic in the field of Earthquake Engineering. The present work fits perfectly within this context, it being developed as part of the European research project COST Action C26 *"Urban Habitat Constructions under Catastrophic Events"* with the aim of assessing the vulnerability of buildings with respect to catastrophic, both natural and artificial, actions. In particular, it was made reference to the risk scenario deriving from a possible eruption of Vesuvius. In-situ surveys were conducted for the seismic-volcanic vulnerability analysis of private, monumental and public buildings of the most populous city in the area around Vesuvius, Torre del Greco. With reference to the school buildings, ten masonry buildings (primary schools) and five reinforced concrete buildings (secondary schools) were examined. The majority of such buildings was erected without seismic requirements and, therefore, requires a seismic retrofit. In this paper the attention is focused on the "d'Assisi" secondary school, which consists of seven reinforced concrete constructions seismically-joined each to other. The case study is one of these constructions, which is developed on two-story and is herein retrofitted with both traditional (RC shear walls) and metal-based innovative (concentric braces, eccentric braces, buckling restrained braces and steel plate shear walls) techniques. The comparison among these interventions has been faced in terms of structural, economic and environmental points of views by using the Multi-Criteria Decision Making (MCDM) TOPSIS method.

2. THE CASE STUDY: THE “SAN FRANCESCO D’ASSISI”SCHOOL IN TORRE DEL GRECO (NA)

The structure under study is part of the school complex "San Francesco d'Assisi" located in Torre del Greco, district of Naples. The school, which was erected in the late eighties, is divided into seven RC buildings (two used as gyms), independent from each other by seismic joints (Fig 1a). The structural unit object of the research is the construction representing three of the seven buildings that constitute the school complex. The interiors of the modular RC structure are used as classrooms and teaching laboratories (Fig 1b). The selected structural unit has almost rectangular shape with plan dimensions of 19.70m x 23.00m and develops on two levels. The structural organization shows an eccentric arrangement of the staircase that confers to the building a plan irregularity. The seismic-resistant vertical structures are RC frames placed in the vertical direction (*y*), which withstand the loads deriving from floors (Fig 1c).

Due to the absence of the original technical drawings, the design of the structural elements in terms of geometrical dimensions and bars (longitudinal and stirrups) have been done by means of the simulated building project, which was executed under the rules used at that time of construction. The mechanical properties of the concrete were determined using the results of laboratory tests performed on buildings built in the same period within the same territorial region of the investigated construction. From the results of the experiments, it was found a C20/25type for the concrete. Instead, for reinforcing bars, considering the time of construction and the intended use of the structural module investigated (strategic building), a steel type FeB38k was considered.

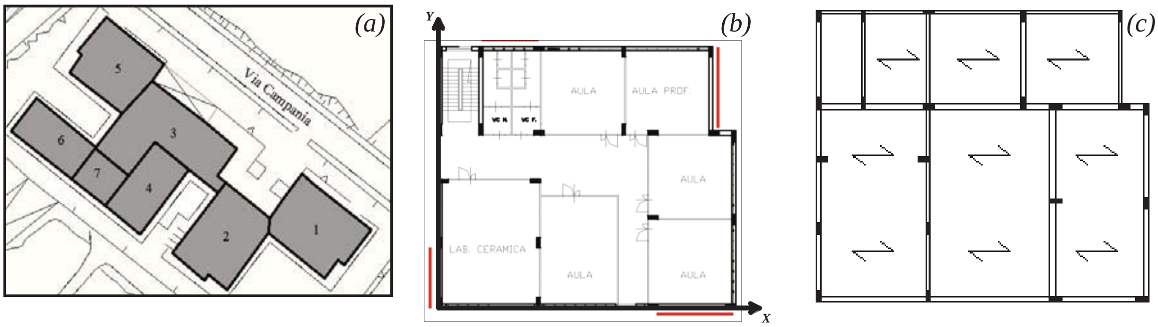

Fig 1: The school complex “D’Assisi” (a) and the structural unit under investigation: the architectural layout (b) and the structural scheme (c).

The building under investigation has been modelled by using the finite element software SAP2000 V.14.2.4 [3] (Figure 2a). It has an irregular seismic behaviour, as it appears from results of modal analysis (Figures 2b, c, d), where it is evident that the second mode is of torsion type.

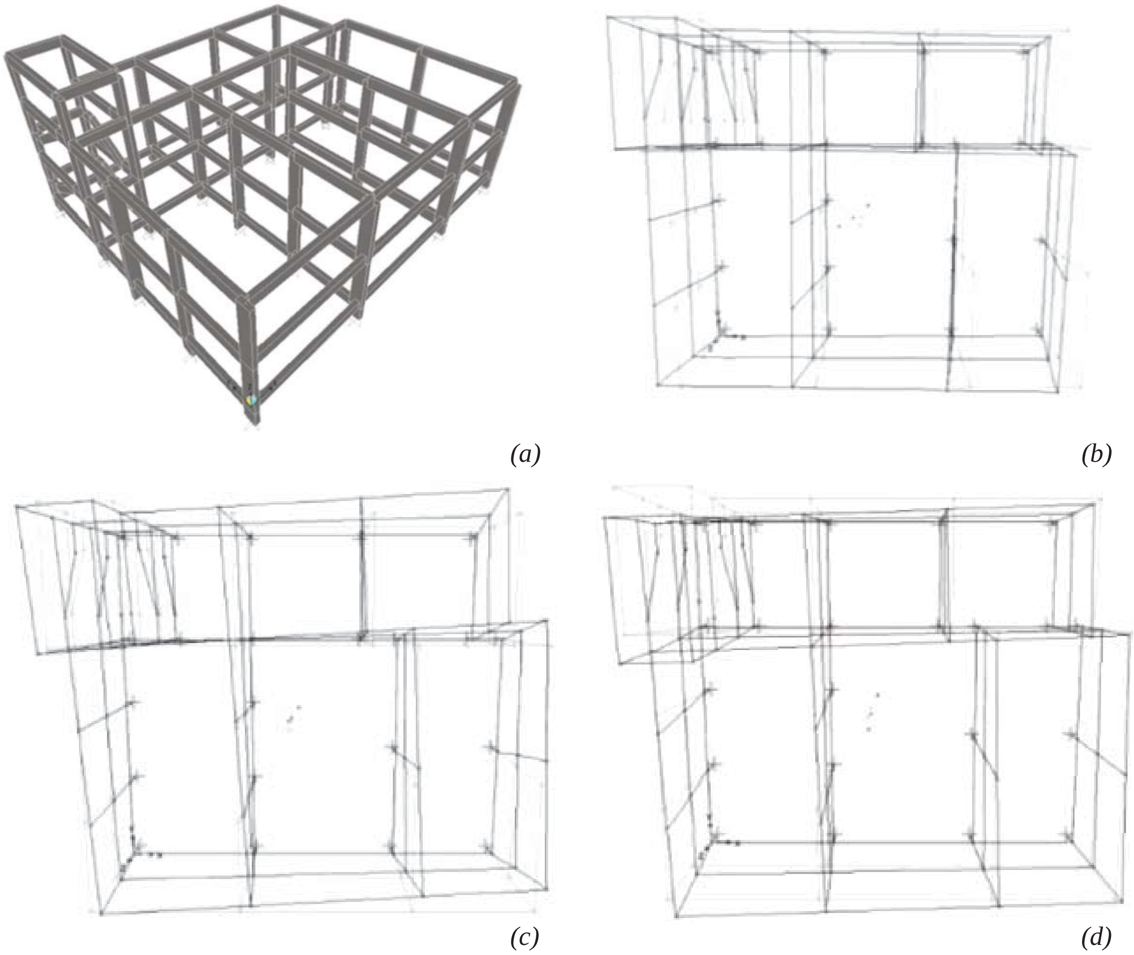

Figure 2: 3D model of the school unit under investigation (a) and modal analysis vibration shapes: first mode (T = 0,61) (b); second mode (T=0,43) (c) and third mode (T=0,34) (d).

3. DESIGN AND APPLICATION OF THE PROPOSED REHABILITATION SYSTEMS

The upgrading design herein proposed is finalized both at increasing strength and stiffness of the examined construction under seismic actions. Various upgrading systems have been applied to the proposed case study to achieve the proposed targets: Concentric Bracing Frames (CBF), Eccentric Bracing Frames (EBF), Buckling Restrained Braces (BRB), Steel Plate Shear Walls (SPSW) and seismic-resistant RC Shear Walls (RCSW). Taking into account the location of the staircase, the upgrading systems have been placed in an eccentric manner with respect to the school barycentre so as to guarantee a good regularization of its seismic behaviour. Therefore, the existing structural parts, that is the RC frames hosting the considered upgrading systems and foundations, have been verified under the new stress state deriving from insertion of new devices.

3.1. *Analysis and comparison of results*

The application of the five seismic upgrading systems has been done to improve the dynamic behaviour of the existing structure, affected by problems of torsion rotation of the floors caused by the inhomogeneous location in the plane of seismic-resistant systems. Table 1 shows values and directions of the main vibration periods for the original building and the same building retrofitted with the above mentioned techniques. From this table it is noticed that the structural performances of the retrofitted building improve in all cases. In fact, unlike the case of the bare structure, with all upgrading systems the first two modes are translational, while the third is of torsion type.

Table 1: Comparison among different retrofitting techniques

	Existing structure		**CBF**		**EBF**		**BRB**		**SPSW**		**RCSW**	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Δk(%)	-	-	106	39	170	72	91	76	124	54	57	36
ΔV (%)	-	-	35	25	17	13	51	16	74	48	23	9
ductility (times)	1	1	1,78		1,75		1,90		1,72		1,70	
T_1 [sec]	0,61 (x)		0,43 (x)		0,39 (x)		0,45 (x)		0,44 (x)		0,50 (x)	
T_2 [sec]	0,43 (φ)		0,33 (y)		0,33 (y)		0,32 (y)		0,32 (y)		0,33 (y)	
T_3 [sec]	0,34 (y)		0,31 (φ)		0,31 (φ)		0,31 (φ)		0,32 (φ)		0,31 (φ)	

Figures 3 and 4 show pushover curves of the structure upgraded with the different techniques used considering the distributions of forces proportional to the first vibration mode and those related to the structural masses, respectively.

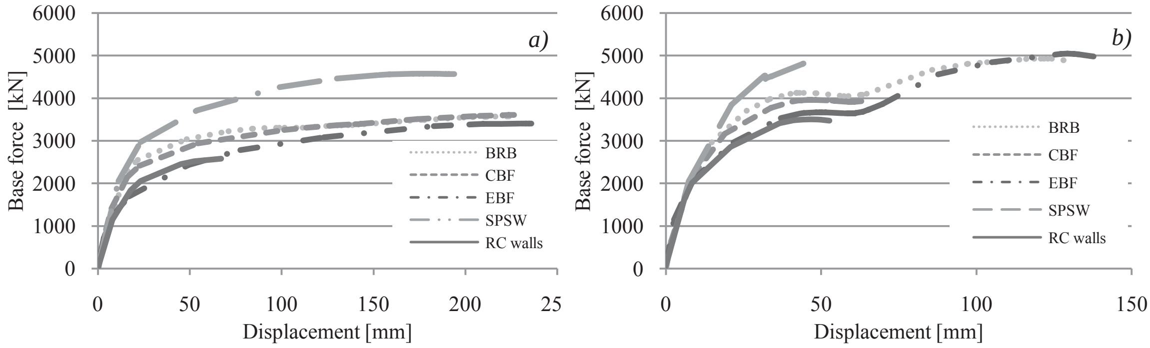

Fig 3: Pushover curves with forces proportional to the first vibration mode in directions x (a) and y (b)

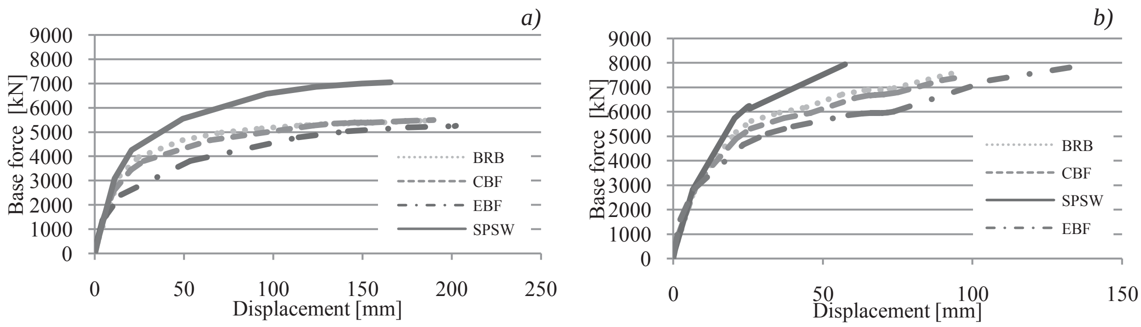

Fig 4: Pushover curves with forces proportional to the masses in directions x (a) and y (b)

Moreover, in all cases, the energy dissipation was concentrated in the sacrificial elements designed with dissipative function that, exhibiting extensive damage in the plastic field, preserve the existing structure from brittle collapse. Referring to the examined innovative retrofitting systems, the greatest increases of performance in terms of stiffness and strength in comparison to the behaviour of the bare structure are obtained respectively with EBF and SPSW. Even in terms of ductility substantial performance improvements are found, with values ranging between 1.72 (SPSW) and 1.90 (BRB).

4. LIFE CYCLE ASSESSMENT

4.1. *Foreword*

The Life Cycle Assessment is an analysis method evaluating a group of iterations that a product or service has with the environment during its entire life cycle. It includes the steps of pre-production, considering also the extraction and the production of primary materials, production of the finite element, distribution, use, taking into account also any reuse and materials used for normal maintenance, recycling and final disposal.

Therefore, LCA is an objective evaluation and quantification method of energy, environment loads and potential impacts associated with a product, considering both its fabrication process and activity along the whole life cycle, from raw material acquisition to the end of life. The criterion under question is considered as a fundamental support to the development of environmental labelling schemes with the purpose either to define reference environmental criteria for a given group of products or to represent the main tool to obtain an Environmental Statement of products. It considers the environmental impacts of the examined case in relation to the human health, the quality of the ecosystem and the impoverishment of resources, considering also the economic and social impacts. In the current study only general information on the life cycle of each product are given, that is only a partial assessment of the processes of pre-production and production of the products has been done, whereas a comprehensive study of all the processes occurred during their whole life cycle has not been performed.

4.2. *LCA of retrofitting strategies*

After the structure has been updated through different retrofitting techniques, the problem of evaluating the environmental impact of each of them arises. The main objective is not just going to assess the environmental performance of the above techniques, but also to compare them in order to evaluate that with the lowest environmental impact.

In order to perform a LCA analysis of comparative type it has been made the hypothesis that the different intervention techniques are designed to achieve the same structural performance, thus defining the functional unit of the analysis. In particular, the techniques are applied to obtain the same increase of the structural capacity, such that the retrofitted structure can sustain seismic actions corresponding to a risk index equal to 100%. In addition, for each technique used, the LCA is conducted by referring to the steps from the "cradle to gate": extraction of raw materials, production, preparation of the substrate to host the reinforcement installation and seismic upgrading. For the analysis the following steps have been considered:

- Production of the material: this stage includes the extraction of raw materials and the production process of the materials used in the upgrading techniques;
- Preparation of the substrate where the reinforcement will be applied;
- Installation of the reinforcement.

About inventory analysis, both primary data and secondary ones have been used. In particular the main data have been used for modeling steel and concrete. Instead, secondary data were taken from the databases *Ecoinvent* and *Idemat* available in the program Simapro 7.

The environmental impact analysis is conducted by the method Impact 2002+, whose results are presented in terms of "End point category" or categories of damage (*Human Health, Ecosystem quality, Climate Change and Resources*) (Figure 5).

The environmental impact assessment of each intervention on the whole structure, once the environmental impacts of each reinforcement per square meter are known, is achieved with a simple multiplication operation. After conducting the LCA for the individual strategies of seismic upgrading, the next step is to perform a LCA comparison between the different strategies in order to evaluate which of those used has the best environmental performance. The results of the analysis are presented with normalized values relative to the value of maximum impact for each category of damage. Once these normalized values are known, a multi-criteria analysis considering as LCA criteria the "*Human health*" has been performed, as it will be shown in the next Section.

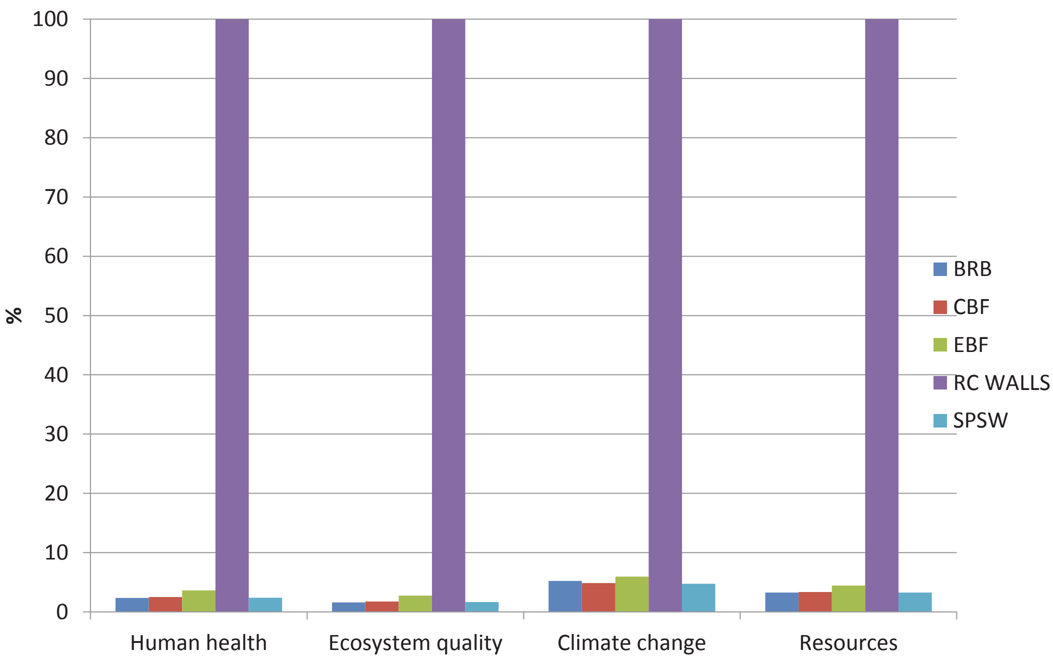

Fig 5: Results of the LCA analysis

5. MULTI-CRITERIA DECISION ANALYSIS: THE TOPSIS METHOD

The MCDM analysis methods are comparison procedures based on multiple criteria aiming at contributing to the development of a learning process which feeds the same decision-making process. In particular, they can be considered mathematical tools allowing to solve a decision problem by identifying the best alternative meeting a given number of criteria. All multi-criteria problems, regardless of their different nature, have common features, which can be summarized as follows:

- Multiple goals/attributes with the purpose to identify objectives and/or attributes relevant to the focus of the problem;
- Conflicts between criteria;
- Immeasurable measurement units;
- Selection of the most satisfying alternative.

All multi-criteria decision problems are analysed by considering the following elements:

- A "goal" or a set of "goals", which represents the general aim to be achieved.
- A Decision Maker (DM) or a group of decision makers (DMs) involved in the selection process, who are responsible of the evaluation procedure.
- A set of decisional alternatives, which are the fundamental elements of the evaluation and selection process.
- A set of evaluation criteria, used by DMs to evaluate the performance of alternatives.
- The preferences of DMs, which are typically expressed in terms of weights assigned to the evaluation criteria.
- A set of scores, expressing the value of the alternative i with respect to the criterion j.

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method is an easy MCDM technique used by a DM to find the best solution among a number of alternatives or various options considered. This method allows to represent the various alternatives as points of a vector space having dimensions equal to the number of criteria considered, so that the performances of the different solutions become the coordinates in the vector space assumed. The TOPSIS method identifies two ideal alternatives, the worst (A-) and the best (A+), with reference to the criteria investigated, so that the optimal solution of the decision problem is the alternative having the shortest distance from A+ and the maximum distance from A-. This method has been already applied from several researchers to some cases of structural modification interventions, namely vertical addition and seismic retrofitting, of existing buildings

In this case, the "alternatives" are the various retrofitting techniques applied to the structure under study (CBF, EBF, BRB, SPWS and RCSW), while the evaluation "criteria" are the vulnerability index, the continuation of the educational activity, the reversibility of the intervention, the human health (LCA) and the intervention cost. The criteria under consideration can be identified as of benefit (B) type or the cost (C) one, with the former and the latter that must be maximized and minimized, respectively. At the end of the decision-making procedure a sensitivity analysis of the solution is conducted for evaluating the reliability of values assigned to the weights of the judgment criteria. This analysis assesses the stability of the optimal solution, ensuring that it does not change when the values of the weights are modified. The stability of the results obtained is evaluated by varying the weight from 0 to 1 and checking that the final solution of the decision-making process does not modify.

In the examined case, first, among the five criteria considered, major attention has been dedicated to the structural (vulnerability index), environmental (LCA) and economic (cost) parameters, which have assumed weights greater than the others. Afterwards, three different analyses have been performed with the TOPSIS method. In the first analysis, the greatest weight has been assigned to the Vulnerability index (I_V), while in the second and third analyses the highest value of the weight has been given to the Human Health (LCA) and to the cost of the intervention (C), respectively. The weights assigned to all criteria are depicted in Table 2.

For each of the analyses carried out, the ranking of the alternatives considered are plotted under form of histograms in Figure 6, where the best consolidation technique to be used is identified.

From the analyses performed it is apparent that the best intervention for retrofitting the school structural unit under study is represented by CBF, which are immediately followed by the use of BRB. On the other side, from seismic and environmental points of views RCSW represent the worst intervention, whereas SPSW are the most expensive technique.

Table 2: Weights assigned to the criteria in the three MCDM analyses performed

	Criteria	**Weight**	**Max C_1**	**Max C_4**	**Max C_5**
C_1	Vulnerability Index (I_v)	w_1	0,36	0,25	0,24
C_2	Continuation of the Educational Activity	w_2	0,05	0,05	0,05
C_3	Reversibility of the Intervention	w_3	0,10	0,10	0,10
C_4	Human Health (LCA)	w_4	0,24	0,36	0,25
C_5	Cost (C)	w_5	0,25	0,24	0,36
	-	w_{tot}	1,00	1,00	1,00

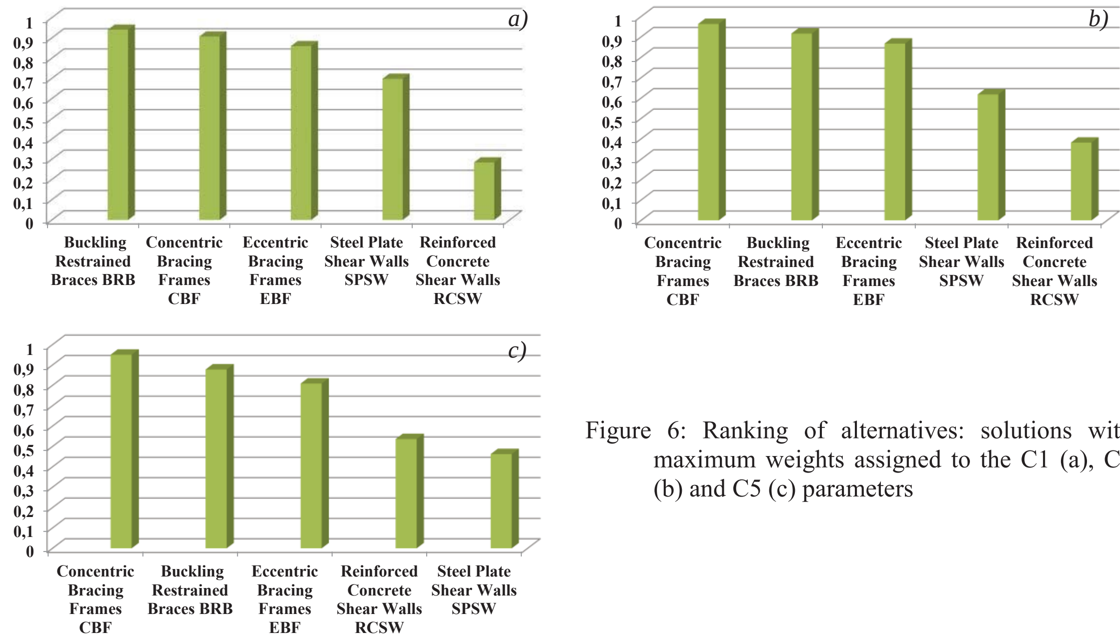

Figure 6: Ranking of alternatives: solutions with maximum weights assigned to the C1 (a), C4 (b) and C5 (c) parameters

6. CONCLUDING REMARKS

In the present paper the problem of seismic upgrading of a RC school building by means of innovative and traditional techniques has been treated. Nonlinear static analyses have shown that the seismic upgrading systems designed allow to increase stiffness and strength of the existing building, providing also an improvement of its dynamic behaviour. These purposes have been achieved by recording a decrease of periods of vibration and a regularization of the structure dynamic behaviour, with a third vibration period of torsion type.

In all analysis cases, the energy dissipation has been always concentrated in the upgrading dissipative systems, which have preserved the existing structure from damage. The comparison between the bare structure behaviour and the upgraded structures one has shown that the greatest performance increases in terms of stiffness and strength have been achieved respectively with EBF and SPSW. Noteworthy performance improvements have been found even in terms of ductility, with values ranging between 1.72 (SPSW) and 1.90 (BRB). As a conclusion, the results obtained from the analyses conducted show the effectiveness of all the devices tested for the upgrading of RC school building investigated.

Moreover, a LCA analysis has been performed with the method Impact 2002+, implemented within the Simapro 7 software,to evaluate the environmental impact analysis of different techniques used.

Finally, in order to detect the best retrofitting solution, the MCDM TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method has been used. Three different analyses have been performed by assigning the highest weight value before to the seismic (vulnerability index) parameter and after to the environmental (LCA) parameter and to the economic (cost) one.

From these analyses it is apparent that the best intervention for retrofitting the school structural unit under study is represented by CBF, which are immediately followed by the use of BRB. On the other side, from seismic and environmental points of views, RC shear walls represent the worst intervention, whereas SPSW are the most expensive technique.

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