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MULTI-CRITERIA DECISION MAKING FOR SEISMIC RETROFITTING OF AN UNDERDESIGNED RC STRUCTURE

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SUMMARY

Seismic retrofitting of under-designed structures is a consolidated approach to risk management. Several options are available for the achievement of the vulnerability reduction goals, each of those having peculiar performances in respect of different technical and non-structural criteria. Selection of the best solution is a non-trivial task, because criteria may conflict each other. Multi-Criteria Decision Making (MCDM) methods may be useful in the matter, allowing to rank the overall performances for the set of alternatives and, therefore, to identify the optimal one. In the study presented herein, such approach was applied to the seismic upgrade of an old type RC building, hypothesizing an update of the seismic hazard at the site where the structure is supposed to be located. Four different strategies were designed to get the required seismic performance. Non-linear structural modeling, seismic risk analysis, criteria selection and MCDM results are also discussed.

1. INTRODUCTION

Once the assessment of a building reveals insufficient seismic performance and upgrade is found as a convenient option, the decision maker (DM) has to select the most appropriate retrofit strategy. Along with traditional solutions, in recent years innovative technologies became available to the engineering professionals to satisfy the structural goals of upgrade. These options are characterized by peculiar values in respect of different judgment criteria (costs, time, structural performances, architectural impact, occupancy disruption, etc.); therefore identification of the most suitable solution is not straightforward because may be no solution satisfying all criteria simultaneously.

Multi-Criteria Decision Making (MCDM) methods are commonly employed to solve similar problems occurring in several fields (i.e. resources allocation planning, natural resources management, medical treatment choices). In the following of the paper the application of the MCDM TOPSIS method [Hwang and Yoon, 1981] for the retrofit of an under-designed RC structure is discussed. The building is a real scale 3D frame tested at the European Laboratory for Structural Assessment (ELSA) of the Joint Research Center (JRC), within the SPEAR project [Fardis and Negro, 2005]. For this structure four different alternatives were designed. Three of these aim to enhance the seismic capacity of the building by different retrofit philosophies: improving deformation capacity by columns' confinement with Glass Fiber Reinforced Plastics; increasing strength (and stiffness) by adding steel bracing; enhancing both ductility and strength by concrete jacketing of selected columns. The fourth considered retrofit option reduces the seismic demand through base isolation.

Decision making procedure is made of: (1) un-retrofitted structure assessment, (2) design of interventions, (3) choice of the evaluation criteria, (4) weighting the criteria, (5) evaluation of alternatives, (6) conversion of qualitative evaluations into crisp numbers, (7) application of the TOPSIS method to identify the best retrofit solution.

2. THE SPEAR STRUCTURE

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The structure is a three-storey building designed to be representative of pre-seismic code constructions in Southern Europe [Fardis and Negro, 2005]. The standard floor plan is presented in Fig. 1. The plan irregularity shifts the centre of stiffness away from the centre of mass, causing torsion, while the structure can be considered regular in elevation. The interstorey height is 3.0 m.

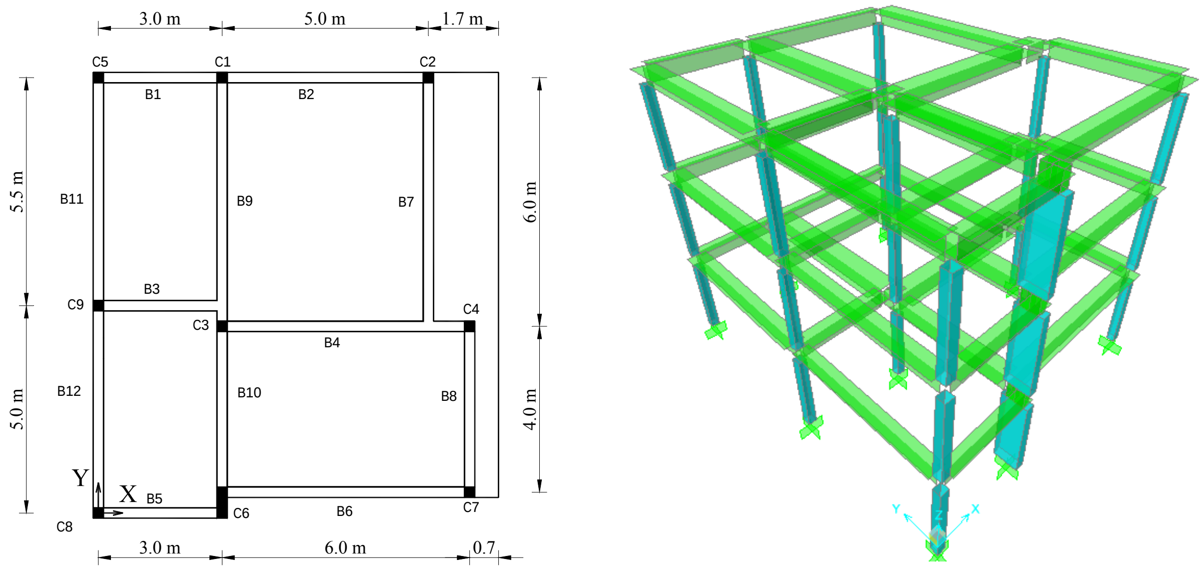


Figure 1: Standard floor plan and 3D view of the three-storey building

All the columns have square cross section of 250x250 mm, except for column C6 which is 750×250 mm. The beams' depth is 500 mm; the slab thickness is 150 mm. The frame can be defined as a weak column-strong beam system, and is therefore far from the capacity design concepts. The reinforcement consists of smooth bars of 12 mm and 20 mm in diameter. Stirrups are smooth 8 mm diameter bars and are spaced by 200 mm in the beams, 250 mm in the columns. They are not continue in the joints. The confinement provided by this arrangement is very low [Jeong and Elnashai, 2004].

2.1 Assessment of the un-retrofitted structure

The building is assumed to be located in Pomigliano d'Arco (Naples, Italy). This site was classified as a seismic zone in 2003. The code's peak ground acceleration is 0.25g [OPCM 3431, 2005]. In order to assess the seismic performances, a nonlinear static analysis of a lumped plasticity model of the building was performed considering the rotational properties of the plastic hinges according to the mentioned code. The concrete's stress-strain behavior was modeled according to Mander et al. [1988]. The ultimate strain is assumed to be 0.004. The lateral force pattern corresponds to the first oscillation mode in each direction. Pushover curves along the four directions and the comparison between capacity of the building and required seismic performances are given in Fig. 2.

The building does not satisfy the Significant Damage (SD) and barely withstand the Damage Limitation (DL) limit state. (DL is attained when the Maximum Interstorey Drift Ratio (MIDR) is 0.005; SD corresponds to the attainment of 3/4 of the ultimate rotation of an element. In the following the Near Collapse (NC) limit state will be not considered.)

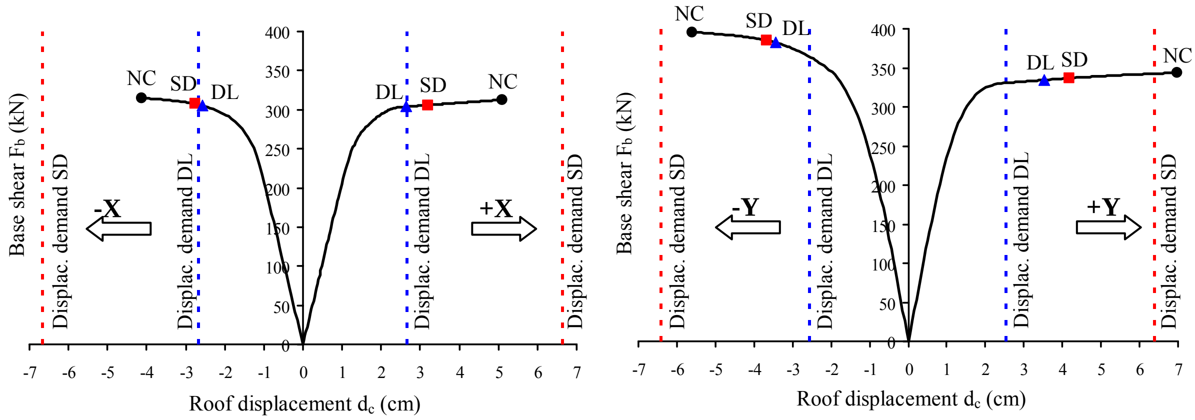


Figure 2: SPEAR building: pushover curves. Comparison between displacement capacity and code's demand at each limit state, for each of the four directions –X, +X, –Y, +Y.

3. RETROFIT STRATEGIES

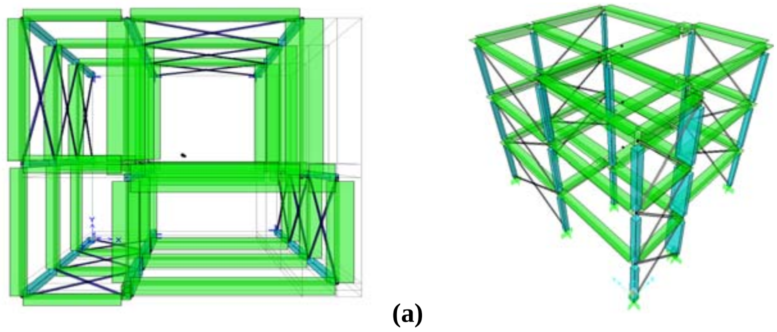
A total of four retrofit options are considered, three of those aiming at a seismic capacity enhancement, the last one providing a seismic demand reduction. In the following there will be indicated as alternatives A_1, A_2, A_3 and A_4 respectively. In particular, A_1 consists of confinement by Glass Fiber Reinforced Plastics (GFRP) of columns and joints and results in an increase of the building deformation capacity; A_2 provides a global strength (and stiffness) enhancement by add steel braces; A_3 is the concrete jacketing of selected columns, which provides a partial but simultaneous enhancement of strength and ductility; finally, the base isolation of the structure is referred to as alternative A_4.

3.1 Confinement by Glass Fiber Reinforced Plastic: alternative A_1

This strategy essentially aims at enhancing the building's global deformation capacity. In general this purpose can be achieved by using composites in two different ways: the first one consists of establishing a correct hierarchy of strength by relocating the potential plastic hinges; the second one at increasing the ductility of plastic hinges without modifying their location [CNR-DT 200, 2004]. The latter approach is adopted here. Externally bonded fiber reinforced polymers are used to adding a confinement action to the columns increasing the concrete's ultimate strain and thus of the plastic hinges ultimate curvature. Mono-directional glass fiber are used for all columns, except for C6 which is strengthened by balanced four-directional glass fabric. GFRP sheets cover a partial length (related to the local plastic hinge length) of the column at each end, except for C6 which is wrapped along its full length. Two fabric layers were superimposed [Cosenza, Di Ludovico et al., 2005].
The Spoelstra and Monti [1999] model, for the stress-strain behavior of concrete confined by FRP, was adopted. Confined concrete ultimate strain ε_{ccu} was evaluated according to the CNR-DT 200 [2004] provisions as a function of the non-confined concrete ultimate strain, the concrete's strength, and the lateral confinement (ε_{ccu} = 0.007; ε_{ccu} = 0.006 for column C6). The moment-curvature curves of wrapped sections show a significant increase in ductility, especially for those with high value of axial load. The increase in strength is almost zero, as expected.

3.2 Steel bracing of some frames: alternative A_2

This intervention aims to increase the global strength of the structure without significant variation in terms of global ductility and at centering the stiffness in plan. Concentric diagonal X bracings were considered (Fig. 3). The steel used is Fe430 (strength at yield 275 MPa; ultimate strength 430 MPa). The cross section selected for all the diagonal elements was L-shaped (65x100x7 mm).
The design of the intervention was based on the following considerations: bracing of 2 parallel frames in each direction (X and Y) is needed to guarantee a sufficient regularity of stiffness in plant and thus to try to decouple the vibration modes; it is better bracing alternating bays in plant ("echelon formation" disposition) so that, when a significant earthquake happens, the large nodal actions due to the diagonals is distributed among a larger number of columns; bracing is provided in every storey of the building so that the latter remains regular in elevation.



(a) **(b)**

Figure 3: Bracing configuration: plan (a) and 3D (b).

According to the recommendations of the FIB Bulletin No.24 [2003] the diagonal braces are supplemented with a frame of horizontal and vertical steel members firmly attached to the delimiting concrete members, columns and beams. The horizontal steel elements (plates with section 250x15 mm) assist the concrete frame to resist the load effect and act as collector element for the transfer of inertia forces from the slabs to the bracing system. The vertical steel elements (2 UPN 280 for each column) assist the existing columns.

3.3 Concrete jacketing of some columns: alternative A_3

This intervention aims at centering strength in plan with consequent reduction of the harmful torsional effects in the non linear response; it consists of concrete jacketing of selected columns and results in the enhancement of both global strength and ductility of the structure. Columns C1, C3 and C4 were strengthened by a concrete jacket 75 mm thick at each storey (average concrete strength R_{cm} = 50 MPa, 8 longitudinal bars with diameter 16 mm, stirrups with diameter 8 mm and spacing 150 mm, 100 mm near the joints). The effect of the jacketing on the section's behavior is an increase of both strength and ductility. In the following will be shown that these effects also reflect on the overall response of the structure (Fig. 5).

3.4 Base isolation: alternative A_4

The designed isolation system consists of 9 (each one for each column) High Damping Rubber Bearing (HDRB) devices characterized by effective damping ratio ξ=10%. The intervention is addressed to lengthen the period of vibration of the building in order to make the seismic demand lower than the present capacity of the superstructure. The latter capacity value, 0.287g, expressed in terms of spectral acceleration S_a, was determined starting from the pushover analysis on the original building described above. By comparing this value with the demand represented by the elastic spectrum defined by the OPCM 3431 [2005] code for the seismic zone in exam (a_g=0.25g) and for ξ=10%, the minimum "isolated" period of the structure $T_{is,min}$=1.11s was determined (Fig. 4). A careful selection of two different types of devices, each of those being characterized by a different K_h lateral stiffness value (type 1: "soft" rubber, diameter 400 mm, K_h=480 kN/m; type 2: "normal" rubber, diameter 300 mm, K_h=710 kN/m), allowed to "isolate" the building by a period of vibration greater than $T_{is,min}$ (1.39 s); furthermore a rational disposition of these devices guaranteed the centering of the elastic stiffnesses in plan of the building.

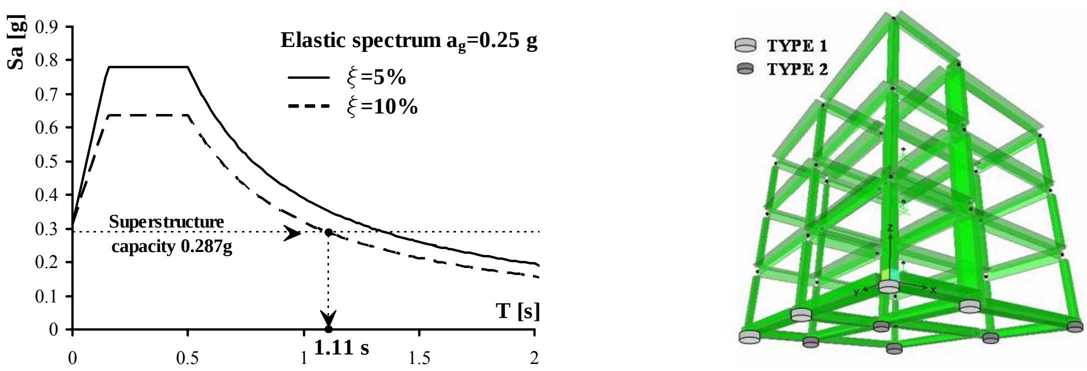


Figure 4: Minimum "isolated" period evaluation and devices (types 1 and 2) layout

4. EVALUATION CRITERIA

The criteria are different ways of evaluating the same solution and reflect specific needs of the DM. They can be distinguished in *economical/social* and *technical* criteria [Thermou and Elnashai, 2002]. The criteria depend on the destination of the structure and on the decision maker's profile. The building focused in the application is supposed to be residential, the DM is the owner; the considered criteria are those reported in Table 1.
The specific definition of each criteria and the way of measuring the alternatives' performances according to them will be discussed during the paragraph dedicated to the evaluation of the retrofit options.

Table 1: Evaluation criteria

Group	Symbol	Description
Economical / social	$\mathbf{C_1}$	Installation cost
	$\mathbf{C_2}$	Maintenance cost
	$\mathbf{C_3}$	Duration of works/disruption of use
	$\mathbf{C_4}$	Functional compatibility
Technical	$\mathbf{C_5}$	Skilled labor requirement/needed technology level
	$\mathbf{C_6}$	Significance of the needed intervention at foundations
	$\mathbf{C_7}$	Significant Damage risk
	$\mathbf{C_8}$	Damage Limitation risk

5. WEIGHTING THE CRITERIA

In order to take into account the relative importance of each criterion, the definition of the *weight* w_i referring to criteria C_i is needed. The method used herein [Saaty, 1980] is based on eigenvalue's theory and allows to calculate the weights starting from the matrix A in which each element a_{ij} is the relative importance of criteria C_i in respect to C_j expressed in a 1 to 9 grade scale (Table 2).

Table 2: Scale of relative importance [Saaty, 1980]

Intensity of Importance	Definition	Explanation
1	Equal importance.	Two activities contribute equally to the objective.
3	Moderate importance of one to another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience or judgment strongly favours one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocal of above	If criterion *i* compared to *j* gives one of the above then *j*, when compared to *i* gives its reciprocal	

The resulting A matrix is given in Eq. 1. Please note that should be $a_{ij} = 1/\, a_{ji}$ and $a_{ii} = 1$, therefore in this case the numbers to assign are $n(n\text{-}1)/2 = 28$ where n=8 is the number of criteria. As discussed, these numbers are founded on a personal judgment; for example, it is assumed that the maintenance cost (C_2) is moderately more important than installation cost (C_1) because the former may imply additional disruption of use which is undesirable. Installation cost (C_1) is considered to be as important as the duration of works (C_3) because the latter results in a loss (e.g. rent) for the owner. The functional compatibility (C_4) is considered to be important due to the residential destination of the structure. The significance of the needed intervention at foundations is also very important since it may result into large additional cost. The criteria C_7 (SD) is less relevant than C_8 (DL) because, since the design target is SD and it is satisfied by all the alternatives, the owner is more interested to reduce the expected loss related to the repair in case of DL limit state occurrence.

$$A=\begin{bmatrix} a_{11} & a_{12} & \dots & a_{18} \\ a_{21} & a_{22} & \dots & a_{28} \\ \dots & \dots & \dots & \dots \\ a_{81} & a_{82} & \dots & a_{88} \end{bmatrix}=\begin{bmatrix} 1 & 1/3 & 1 & 1/5 & 4 & 1/3 & 4 & 1/3 \\ 3 & 1 & 3 & 1/2 & 6 & 1 & 6 & 1 \\ 1 & 1/3 & 1 & 1/5 & 4 & 1/3 & 4 & 1/3 \\ 5 & 2 & 5 & 1 & 6 & 2 & 5 & 2 \\ 1/4 & 1/6 & 1/4 & 1/6 & 1 & 1/6 & 1/2 & 1/5 \\ 3 & 1 & 3 & 1/2 & 6 & 1 & 5 & 3 \\ 1/4 & 1/6 & 1/4 & 1/5 & 2 & 1/5 & 1 & 1/3 \\ 3 & 1 & 3 & 1/2 & 5 & 1/3 & 3 & 1 \end{bmatrix} \quad (1)$$

Since a_{ij} is dependent on the w_i/w_j ratio (w_i and w_j actual weights of importance of criteria C_i and C_j respectively), the eigenvector W of A is made of the sought weights w_1, w_2, …, w_8:

$$W=\{w_1, w_2, ..., w_8\}=\{0.073, 0.172, 0.073, 0.280, 0.026, 0.201, 0.035, 0.141\} \quad (2)$$

So, the more important criteria is resulted to be C_4 (functional compatibility) with weight $w_4 = 0.280$; the less important is C_5 (skilled labour requirement/needed technology level) with $w_5 = 0.026$.

Even their arbitrary nature, there is a way to check that the a_{ij} values are set consistently; the *Consistency Ratio* (CR) is $(\lambda_{max}-n)/(1.41(n-1))$; where λ_{max} (8.45) is the maximum eigenvalue of A and 1.41 is the value of the so called *Random Consistency Index RCI* (average random consistency measure obtained by numerous empirical studies) corresponding to $n = 4$. In this case CR = 4.1% (10% is the acceptable limit value).

6. EVALUATIONS OF THE ALTERNATIVES

The retrofit alternatives have to be evaluated according to each criterion defined above.

Criteria C_1 (installation cost): the total cost to be beared for the realization of each alternative, including all the required materials and labor, is evaluated (A_1: 23,096 €; A_2: 53,979 €; A_3: 11,175 € ; A_4: 74,675 €).

Criteria C_2 (maintenance cost): since the application of composite materials to structures is relatively recent, the durability and consequently the maintenance needs are still open issue [CNR-DT 200, 2004]. The unpredictability of the necessary maintenance interventions to be done during the economic life of the building (conventionally assumed to be 50 years), it is considered more realistic comparing the retrofit alternatives in terms of monitoring cost to be beared during this period. For the option involving steel bracings, it is considered necessary remaking the anticorrosive treatment every 20 years independently from the periodic inspections' results; the relative cost is then included into the evaluation of A_2 according to the criteria in exam. For the alternative A_4 (base isolation), according to the instructions of the HDRB devices' producers, it is moreover considered the substitution of a single device every 10 years in order to test it and compute its mechanical properties evolution. Finally, these costs result to be: A_1: 23,206 €; A_2: 115,037 €; A_3: 40,353 € ; A_4: 97,884 €. These values, apparently large if compared with installation costs, account for a 4% revaluation rate.

Criteria C_3 (duration of works/disruption of use): the duration of each intervention is calculated by analyzing the time required for each stage (beginning from the needed demolitions up to the finishings' realization) and considering a team of four workmen (two of those are specialized workers). By assuming that each day is composed by eight working hours, it results A_1: 33 days; A_2: 122 days; A_3: 34 days ; A_4: 119 days.

Criteria C_4 (functional compatibility) and C_5 (skilled labor requirement/needed technology level): the evaluation of each alternative according to these two criteria, due to their own nature, may be only qualitative. In the following paragraph, the needed conversion of the evaluations into crisp numbers will be done.

Criteria C_6 (significance of the needed intervention at foundations): the evaluation according to C_6 consists in calculating a "global" parameter as the maximum ratio, measured for each column at first storey, between axial load due to the seismic action plus gravity loads and that due to the gravity loads only. Each column is assumed to have its own independent plinth of foundation. (A rigorous assessment of the substructure should be performed in order to evaluate its present capacity and then to compare it with the demand due to the earthquake.) It results A_1: 2.90; A_2: 15.18; A_3: 2.97; A_4: 2.65.

Criteria C_7 (Significant Damage risk) and C_8 (Damage Limitation risk) are related to the seismic capacity of the building being defined as the earthquake intensity (measured by the peak ground acceleration, PGA) at which a certain limit state is attained [Cosenza and Iervolino, 2005]. For alternatives A_1, A_2 and A_3, a nonlinear static (pushover) analysis was performed along the 4 directions (±X, ±Y). The comparison among the corresponding pushover curves is shown in Fig. 5. The un-retrofitted building's curves coincide in strength with those relative to the building retrofitted by GFRP up to the vertical dashed lines indicating the attainment of the SD limit state (as far as the DL limit state is concerned, the original and retrofitted by GFRP building have almost the same capacity). The corresponding values of PGA of "failure" at SD and DL limit states are then obtained by applying the N2 method [Fajfar, 1999] to the capacity curves.

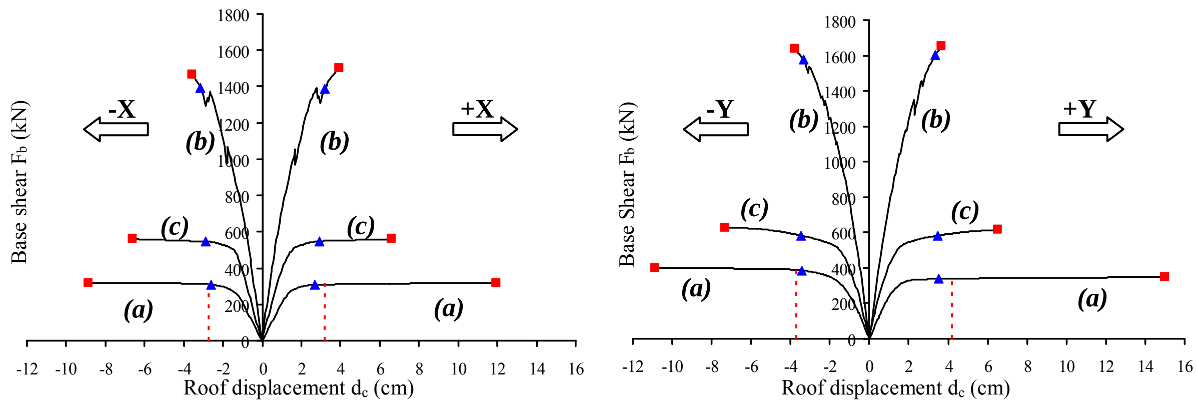


Fig. 5: Pushover curves for the interventions A_1 (a), A_2 (b) and A_3 (c), along each direction (±X, ±Y). Triangles and squares indicate the DL and SD limit states attainment respectively.

For alternative A_4 (base isolation), the capacity at SD and DL limit state in terms of PGA is, instead, obtained by a modal response spectrum analysis.

The probability of exceeding the PGA capacity in 50 years is calculated by means of the hazard curve of Pomigliano d'Arco[2]. The capacity values at SD and DL limit state (the minimum PGA value between the four direction ±X, ±Y is considered) for each alternative and the corresponding probability values of exceeding in 50 years are summarized in Table 3.

Table 3: Capacity in terms of PGA at Significant Damage (SD) and Damage Limitation (DL) limit states and probability of exceeding in 50 years ($P_{50\ years}$)

			ALTERNATIVES			
		As built	**A_1 GFRP**	**A_2 Steel braces**	**A_3 RC jackets**	**A_4 Base isolation**
SD	**PGA (g)**	0.10	0.33	0.32	0.25	0.35
	$P_{50\ years}$	0.284	**0.022**	**0.024**	**0.040**	**0.020**
DL	**PGA (g)**	0.10	0.10	0.31	0.12	0.35
	$P_{50\ years}$	0.324	0.324	0.026	0.211	0.020

The performance of each alternative according to the criteria C_7 is measured just by these $P_{50\ years}$ values, written in bold type in Table 3 (A_1: 0.022; A_2: 0.024; A_3: 0.040; A_4: 0.020).

Evaluations of the four options in respect of Criteria C_8 (Damage Limitation risk), instead, is not interpreted as the probability of exceeding the capacity at DL limit state in 50 years, but as the probability of sustain repair cost in 50 years, therefore the evaluation in respect of the it is done by calculating the probability in 50 years that the seismic capacity at the DL limit state is exceeded and at SD is not (otherwise the building is likely to be uneconomic to repair). Therefore these values are calculated as the maximum difference (among all the 4 directions) between the probability of exceeding the DL and SD limit states respectively. It results A_1: 0.311; A_2: 0.002; A_3: 0.172; A_4: 0.000. With reference to the base isolation retrofit option, since the very low lateral displacement seismic demand to the superstructure, it is interesting to observe that the capacity at SD and DL

[2] The hazard curve at the site can be approximated by the relationship $p=0.002\ PGA^{-2.18}$

limit states are both related to the attainment of the ultimate horizontal displacement of the HDRB devices, according to the OPCM 3431 code [2005]; thus these capacities have the same value and the zero value of the A_4 evaluation according to criteria C_8 is a direct consequence.

7. CONVERSION OF CRITERIA C_2, C_4, C_5 EVALUATIONS INTO CRISP NUMBERS

In order to apply any MCDM methods (TOPSIS herein) the conversion of qualitative variables into crisp numbers is needed. It consists of making pairwise linguistic comparisons among the performance of each alternative with reference to the criteria C_4 (functional compatibility) and C_5 (skilled labor requirement/needed technology level) and then quantifying these statements by using the linear scale proposed by Saaty [1980], as done for evaluating the weights of the criteria. After composing these values into a 4x4 matrix, the eigenvalue approach is adopted in order to calculate the 4 numbers representing the numerical performance (*priority*) of each retrofit option according to the criteria C_i. The results are shown in Table 4. The Consistency Ratio values are acceptable (CR < 9%, limit value given by Saaty [1999] for a 4x4 matrix). Finally, the numerical evaluation of the alternatives according to C_4 criteria are A_1: 0.538; A_2: 0.074; A_3: 0.274; A_4: 0.114, while in respect of C_5 criteria are A_1: 0.414; A_2: 0.120; A_3: 0.052; A_4: 0.414.

Table 4: Quantitative evaluation of alternatives according to criteria C_4 and C_5.

C_4	A_1	A_2	A_3	A_4	Priority
A_1	1	7	2	5	**0.538**
A_2	1/7	1	1/3	1/2	**0.074**
A_3	1/2	3	1	3	**0.274**
A_4	1/5	2	1/3	1	**0.114**

C_5	A_1	A_2	A_3	A_4	Priority
A_1	1	4	7	1	**0.414**
A_2	1/4	1	3	1/4	**0.120**
A_3	1/7	1/3	1	1/7	**0.052**
A_4	1	4	7	1	**0.414**

8. RANKING OF THE ALTERNATIVES

The adopted TOPSIS method (*Technique for Order Preference by Similarity to Ideal Solution*) was developed by Hwang and Yoon [1981]. Since the performance measures x_{ij} of the *i-th* alternative (i =1, 2, 3, 4) in terms of the *j-th* criteria (j = 1, 2, …, 8) are evaluated so far, the so called *Decision Matrix* D = $[x_{ij}]$ is known (Table 5).
The first step of the ranking procedure consists in normalizing all the x_{ij} values (each of those has a different dimension) according to the expression (3). The next step is weighting this R matrix by multiplying each value of the i-th column by the weight w_i of the i-th criterion, obtaining the matrix (4).

Table 5: Decision Matrix.

	C_1 (€)	**C_2** (€)	**C_3** (days)	**C_4**	**C_5**	**C_6**	**C_7**	**C_8**
A_1	23,096	23,206	33	0.538	0.414	2.90	0.022	0.311
A_2	53,979	115,037	122	0.074	0.120	15.18	0.024	0.002
A_3	11,175	40,353	34	0.274	0.052	2.97	0.040	0.172
A_3	74,675	97,884	119	0,114	0.414	2.65	0.020	0.000

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{3} x_{kj}^2}} \qquad (3)$$

$$V = [v_{ij}] = [w_j r_{ij}] = \begin{bmatrix} 0.018 & 0.025 & 0.014 & 0.243 & 0.018 & 0.037 & 0.014 & 0.123 \\ 0.041 & 0.125 & 0.050 & 0.033 & 0.005 & 0.191 & 0.015 & 0.001 \\ 0.009 & 0.044 & 0.014 & 0.124 & 0.002 & 0.037 & 0.025 & 0.068 \\ 0.057 & 0.107 & 0.049 & 0.052 & 0.018 & 0.033 & 0.013 & 0.000 \end{bmatrix} \qquad (4)$$

The TOPSIS method identifies the *best* alternative as the one having the shortest distance from the *ideal solution* A^* and the largest distance from the *negative-ideal solution* A^-. These two solutions are fictitious; A^* is obtained by taking for each criterion the *best* performance value among A_1, A_2, A_3 and A_4; the negative-ideal solution A^- is composed by the *worst* performances. (The *best* value in terms of a criterion has to be interpreted has the *maximum* value if that in exam is a *benefit* criteria for which the decision maker wants to maximize the performance values; it is the *minimum* value if the criterion is a *cost* criteria.) In the case under exam all the criteria are cost criteria, except for the criteria C_4 (functional compatibility, to be maximized), so the ideal and negative-ideal solutions are the following:

$$\begin{aligned} \boldsymbol{A}^* &= \left\{ \left(\mathbf{min}_i \, v_{ij} \mid \boldsymbol{j} \in 1, 2, 3, 5, 6, 7, 8 \right), \left(\mathbf{max}_i \, v_{ij} \mid \boldsymbol{j} = 4 \right), \boldsymbol{i} = 1,2,3,4 \right\} = \\ &= \left\{ 0.009, 0.025, 0.014, 0.243, 0.002, 0.033, 0.013, 0.000 \right\} \end{aligned} \tag{5}$$

$$\begin{aligned} \boldsymbol{A}^- &= \left\{ \left(\mathbf{max}_i \, v_{ij} \mid \boldsymbol{j} \in 1, 2, 3, 5, 6, 7, 8 \right), \left(\mathbf{min}_i \, v_{ij} \mid \boldsymbol{j} = 4 \right), \boldsymbol{i} = 1,2,3,4 \right\} = \\ &= \left\{ 0.057, 0.125, 0.050, 0.033, 0.018, 0.191, 0.025, 0.123 \right\} \end{aligned} \tag{6}$$

If S_{i*} and S_{i-} are the Euclidean distances of the i-th alternative A_i from the ideal and negative-ideal solutions A^* and A^- respectively, the relative closeness C_{i*} ($0 \leq C_{i*} \leq 1$) of A_i with respect to the A^* is defined as:

$$\boldsymbol{C}_{i*} = \frac{\boldsymbol{S}_{i-}}{\boldsymbol{S}_{i*} + \boldsymbol{S}_{i-}} \tag{7}$$

The results are reported in Table 6. According to the TOPSIS method the best alternative is the one with the largest C_{i*} (i =1, 2, 3) value and then with the shortest relative distance from the ideal solution.

Table 6: Distances S_{i*}, S_{i-} and relative closeness C_{i*} of each alternative

		S_{i*}	S_{i-}	C_{i*}
GFRP	$\mathbf{A_1}$	0.125	0.285	**0.70**
Steel bracing	$\mathbf{A_2}$	0.285	0.125	**0.30**
Concrete jackets	$\mathbf{A_3}$	0.139	0.213	**0.60**
Base isolation	$\mathbf{A_4}$	0.217	0.217	**0.48**

9. CONCLUSIONS

The study briefly presented is an application showing how MCDM methods may support the decision maker to make the selection of the optimal retrofit strategies among a set of 4 designed alternatives. The applied TOPSIS method allows to take into account, in a very simple and concise manner, all the different features of each alternative by measuring their performances according to 8 significant criteria; the latters regarding not only the structural performances achieved, but also the other factors influencing the final choice, such as the costs, the installation time, that is proportional to the disruption to the occupants and their normal activities, other non-quantitative judgements regarding the functional compatibility of the building's configuration after the retrofit operations as well as the required technology level and the degree of workers' specialization needed for the labour corresponding to each alternative.

Among those considered, the best solution resulted to be the confinement of elements by GFRP, steel bracing the worst. The composites' solution has the best performance in respect to the compatibility with the destination of the structure which resulted to be one of the most important criteria. The installation time is also short comparatively to the other interventions. Moreover it requires a comparatively little foundation's upgrade which is large for steel bracing. It has to be finally noted that the building chosen for the example is a small irregular RC frame and its peculiarities may affect the ranking of the alternatives, but the procedure presented remains generally applicable.

10. REFERENCES

CNR-DT 200 (2004), *Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Interventi di Consolidamento Statico mediante l'utilizzo di Compositi Fibrorinforzati*, Roma.

Cosenza, E., Di Ludovico, M., Manfredi, G. and Prota, A. (2005), Design of the FRP retrofit of the SPEAR structure, *Proceedings of the SPEAR International Workshop*, (M. Fardis and P. Negro Eds.), Ispra, Varese, Italy.

Cosenza, E. and Iervolino, I. (2005), Seismic Retrofit of a Medieval Bell Tower by FRP, *Journal of Composites for Construction ASCE*. (*under review*)

Fajfar, P. (1999), Capacity spectrum method based on inelastic demand spectra, *Earthquake Engineering and Structural Dynamics*, 28: 979-993.

Fardis, M.N. and Negro P. (2005), Seismic Performance Assessment and Rehabilitation of Existing Buildings, *Proceedings of the SPEAR International Workshop*, Ispra, Varese, Italy.

FIB bulletin No.24 (2003), *Seismic assessment and retrofit of reinforced concrete buildings*.

Hwang, C.L. and Yoon, K. (1981), Multiple Attribute Decision Making, *Lecture Notes in Economics and Mathematical Systems*, Springer-Verlag: Berlin.

Jeong, S-H. and Elnashai, A.S. (2004), Analytical assessment of an irregular RC full scale 3D test structure, *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

Mander, J.B., Priestley, M.J.N. and Park, R. (1988), Theoretical stress-strain model for confined concrete, *ASCE Journal of Structural Engineering* 114(8), 1804-1826.

OPCM 3431 (2005), Ordinanza del Presidente del Consiglio dei Ministri, *Ultime modifiche ed integrazioni all'Ordinanza n. 3274 del 20 marzo 2003*, Roma, Italy.

Saaty, T.L. (1980), The Analytic Hierarchy Process, *McGraw-Hill*, New York, NY, USA.

Saaty, T.L., (1999), Decision making for leaders: the analytic hierarchy process for decision in a complex world, *RWS Publications*, Pittsburgh, PA., 315 p.

Spoelstra, M.R. and Monti, G. (1999), FRP-confined concrete model, *ASCE Journal of Composites for Construction* 3(3), 143-150.

Thermou, G.E. and Elnashai, A.S. (2002), Report about SPEAR Project, *Performance Parameters and Criteria for Assessment and Rehabilitation*, A.S., I.C. of Science, Technology and Medicine, UK.