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An investigation on the value-based evaluation: optimum rehabilitation process of the unreinforced masonry buildings

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Abstract. *Nowadays, distinctive methods are being used for evaluation of alternatives in making-decision. Among them the analytic hierarchy process (AHP) is one of the most efficient one. The study is set up for the low-rise unreinforced masonry buildings and includes classification of the most important parameters in strengthening of masonry buildings, and the factor analysis is performed to make the preferences of the alternatives. Due to the existence of the large number of unreinforced masonry buildings, and also the great importance of process duration for clients, the application of the AHP method in order to optimize the process and reach to the best alternative of the masonry buildings strengthening are developed. Effective parameters in evaluation of the alternatives are classified and suitable alternatives for rehabilitation are evaluated. Finally, based on the binary concept the model of binary approach decision-making (BADM) is utilized to analyze the decision parameters. Therefore, each criterion is simulated by question texts which appraiser faces two possible answers; yes and no. The results illustrate preference of the strengthening the masonry walls with interior shear wall, compared to the other alternatives. Also, effectiveness of the method is compared to the expert judgment.*

1 INTRODUCTION

Earthquake is an unpredictable phenomenon that the probability of the occurrence can be sensed at any moment. Hence, the study of suitable techniques in earthquake management will be influential in keeping the society safe and declining the losses of this mortal event. The consideration has shown that most of the masonry buildings are vulnerable so in recent years the seismic rehabilitation of the existing buildings has been gained more careful attention. The duration of the theoretical phase is a key point for the decision makers; that is, long process will cause severe economical losses for the clients. That the procedure evaluates the alternatives in the shortened time will decrease the further losses. In this area, different methods as a multi-criteria decision making methods (MCDM), have been used by the decision makers: such as analytic hierarchy process (AHP) a quantitative decision model by using pair-wise comparison, analytic network process (ANP) which is a general form of the AHP method but the elements are not independent and have interaction as a network, multi-attribute utility theory (MAUT) used to combine dissimilar measures of costs, risks, and benefits along with stakeholder preferences, cost-benefit analysis (CBA) a systematic quantitative method of assessing the desirability of government projects or policies, Kepner-Tregoe (K-T decision analysis) in which a team of experts numerically score criteria and alternatives based on individual judgment/assessment [1]. As a matter of the applicability, efficiency, and uniqueness, the analytic hierarchy process (AHP) is used to depict an operative procedure for the decision makers in the optimum alternative selection of the rehabilitation a vulnerable masonry building.

The method has been the subject of many researchers who have tried to optimize the selection process. Among them, the establishment measurement for intangible properties [3], the benefits, opportunities, costs, and risks of a decision [4], the application of the method in risk management [5], a novel approach of cotton fiber selection [6], the result consolidation of the large nominal group of dispersed decision makers [7], the prioritization of road maintenance project [8], structuring remedial decision at contaminated site [9], making decision by using dynamic criteria [10] are appreciative studies in recent years. On the other hand, some papers are discussed about the disadvantages of the applied method [11, 12].

2 THE METHODOLOGY

Decision analysis is a logical process of the ideas, experiences, and information so that the justified decision is resulted from the reasonable procedure. In general, results are described in the qualified appraisal so that an AHP hierarchy provides a comprehensive and rational framework to organize a decision problem, for quantifying its elements. The method includes three main parts, the overall *goal*, a group of options as the *alternatives* for reaching the goal, and the *criteria* that relate the alternatives to the goal which in some cases the criteria can be further broken down into the *sub-criteria* and so on. The design of the hierarchical process depends on the nature of the problem and the appropriate model should be presented. The model consists of five steps which are illustrated in the figure 1. In the first step, based on the nature of the problem, the project objective is defined. The next step deals with the limited assumptions, interfaces, ambiguities, organizational boundaries, and any stakeholders’ issues. Therefore, the policy of decision analysis with the circumstances is adopted. In the third step, the appropriate criteria and alternatives are identified. In this regard, the discriminating criteria are introduced and the associated ones are classified in the specific categories. Similarly, those alternatives that cover the principles are eligible for further consideration. Basically, alternatives vary in their ability to meet the requirements and goal and offer different approaches for changing the initial condition into the desired condition [1]. The next phase includes analyzing criteria and alternatives by using the systematic method in order to handle the information. This part is the main body of the assessment and within this part the weight is assigned to each criteria and alternatives. The optimum option is elicited from the accurate analysis and the level of the accuracy is related to the level of the experience which in this study the consistency ratio is used to restrict the deviation of the preciseness. Finally, the most efficient alternative is chosen with the highest score compared to the others, in the grading process.

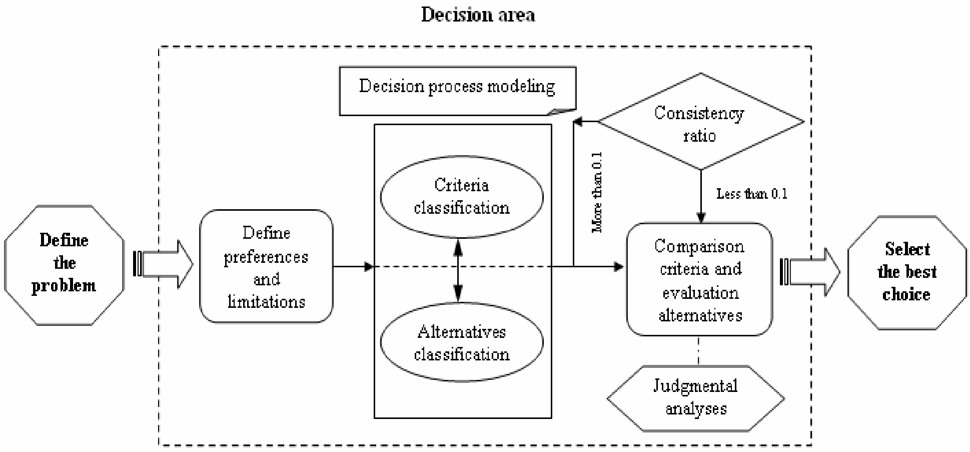

Figure 1: procedure of the decision optimization

2.1 The decision process

Once the hierarchy has been constructed, the pair-wise matrices are configured for each node of the process. The participants establish the two-by-two comparison of the priorities for all nodes, so that the intensity of the relative importance (table 1) is utilized to perform rational analysis of the decision elements. In the completion of each matrix, the array a_{ij} signifies the determinate priority of i-th item over the j-th item. By definition, the array a_{ji} points out the inverse preference of the compared item $(a_{ij} = \frac{w_i}{w_j} \Rightarrow a_{ij} = \frac{1}{a_{ji}})$. In this manner, if the group has N items then the decision-makers need to fulfill the $\frac{N(N-1)}{2}$ comparisons.

Importance scale	The intensity of relative importance
Equal importance	1
Significantly less importance	3
Somewhat more importance	5
Strong importance	7
Extremely importance	9
The intensity measurement of 2, 4, 6, and 8 are used to explicit the median bound of the importance	

Table 1: Relative scale for pair-wise comparison

A comparison matrix A is said to be consistent if $a_{ij}.a_{jk} = a_{ik}$ for all i, j and k. Mostly, in the multi-criteria problems, the matrices are inconsistent, so the rate which is called the consistency ratio is calculated. Consistency ratio of a matrix with the array $a_{ij} \neq \frac{w_i}{w_j}$ is a deviation that shows the variance of $(\lambda_{\max} - n)$ from the zero, and $\lambda_{\max}$ is achieved by solving the $A.W = \lambda_{\max}.W$ equation. The largest Eigen value is equal to the size of comparison matrix, or $\lambda_{\max} = n$. Following the equation 1 the consistency index and by using the equation 2 the consistency ratio is computed. If the value of consistency ratio is smaller or equal to 10%, the inconsistency is acceptable, and if the consistency ratio is greater than 10%, we need to revise the subjective judgment [14, 15].

$$C.I = \frac{\lambda_{\max} - n}{n-1} \quad (1)$$

$$C.R = \frac{I.I}{R.I} \leq 0.1 \quad (2)$$

Where
n : Number of elements
$\lambda_{\max}$: Maximum eigenvalue
$C.I$: Consistency index
$R.I$: Random consistency index (table 2)
$C.R$: Consistency ratio

The reciprocal matrix using scale, 1/9, 1/8, …,…, 8, 9 is randomly generated [3] (similar to the idea of Bootstrap) and get the random consistency index to see if it is about 10% or less. The average random consistency index of sample size 500 matrices is shown in the table below.

n	1	2	3	4	5	6	7	8	9	10
I.I.R	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.45

Table 2: random consistency index

To incorporate the results, the process is used to allocate the proportional weight factor for each item. In this regard, there are some mathematical-based methods which lead the process to the desired weight. The methods such as least logarithmic square, Eigen Values and the approximate methods which are the approaches of the Eigen Values are used to figure out the definite weights. By the way, the four approximate methods are evaluated and the result is shown (figure 2) the least deviation of the arithmetic average results; therefore, in this study the weighting factors are obtained by using this routine.

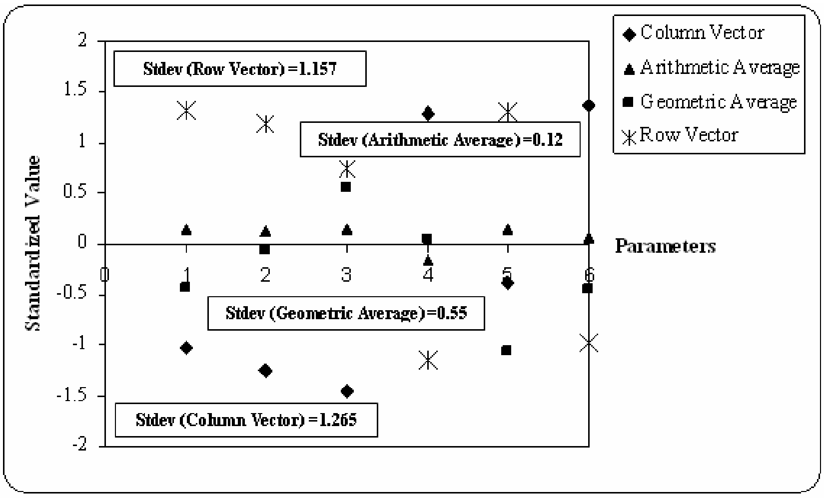

Figure 2: The comparison of approximate methods results

According to this procedure, the weight of the each criterion and also alternatives in every criterion which reveal the priority of the items is computed. Eventually, the final score of the each alternative is acquired using the following equation.

$$\Pr eferable\,(Alternative) = \max \sum_{i=1}^{n} w_{c(i)} . w_{a(i)} \tag{3}$$

Where

$w_{c(i)}$: Indicates the decisive weight of i-th criterion

$w_{c(i)}$: Indicates the decisive weight of i-th alternative

Priorities are absolute numbers between zero and one and they represent the relative weights of the nodes in any group. Due to the different number of the items in the specific groups, the value of each group is normalized to express the same value of distinctive groups. Depends on the problem nature; the final weight refers to the importance, likelihood, capability or whatever factor is being considered by the decision makers.

Beside all the facts, there is a factor that has influence on the final decision and somewhat may change the result. The decision is developed basically on the expert judgment and the decision-makers use their knowledge and experiences to decide, thus, the decision conducted by the group with the more background, more realistic outcome will be concluded. Hence, a coefficient is defined here to take this subject into the consideration which is multiplied to the final result.

	Coefficient of the background
No background	0.9
Less than 3 years	1.0
More than 3 years	1.1

Table 3: proposed coefficient of proportionate study background

3 THE APPLICATION IN THE REHABILITATION OF A MASONRY BUILDING

3.1 Objective

Every year, large amount of money is spent for developing the infrastructural projects in which the allocation of the resources in the right order is the stakeholders' concern. Researches in this area demonstrate that study the optimization methods can bring significant outcome in the time-cost management and the decision-makers are capable to utilize a proper policy to save time and expenditures. Among them the consideration of the effective parameters in seismic rehabilitation [15], assessing the benefits and costs of earthquake mitigation [16], and also the study of affecting issues in the sustainability of buildings by the optimum design [17] can be mentioned. The unreinforced masonry buildings include the large part of the urban constructions and the researches have indicated the vulnerability of the majority numbers. In order to rehabilitate the structure and increase its seismic performance the retrofitting process is conducted, but the remarkable point for the clients is the process duration and the cost of the strengthening which the undesirable management will impose some losses to the project finance. Due to the aforementioned subject, the main purpose of this study is to demonstrate the applied procedure by the comparative algorithm to designate the optimum strengthening alternative with the assessment of the all related criteria in the selection process of unreinforced masonry buildings. As been stated before, to analyze the decision process, the criteria and alternatives are necessitated, so in the following part the appropriate criteria and possible alternatives are identified.

3.2 Criteria and sub-criteria

In the strengthening process of the masonry building, there are some parameters which affect the process and these parameters are identified and classified properly. These parameters are picked out by reviewing the related methodologies, codes, and provisions [18, 19, 20, 21, and 22]. The main criteria which are selected in the procedure include: *building characteristics*, *constructional aspects*, *economical aspects*, *technical aspects*, *architectural aspects*, and *mechanical and electrical equipment*. Each category has some sub-criteria which can be observed in the table 4.

3.3 Alternatives

The vulnerability of a building subjected to an earthquake is dependent on seismic deficiency of that building relative to a required performance objective [23]. Two possible ways are constructive, here. One is to demolish and rebuilt the building and the other one is to rehabilitate which can be the increasing the capacity of structure (add new elements, enhance existing elements; improve connections) or reduction the demand on the building. The rehabilitate techniques are used to enhance the seismic performance of the building and eliminate those deficiencies, subsequently. Different buildings types require different mitigation technique, and depend on the seismic deficiencies alternative recommendation are made to satisfy the performance objective of rehabilitation. In this study, six alternatives are proposed to improve the lateral performance of the unreinforced masonry building. The alternatives include: *strengthening with the shotcrete* (using the shotcrete overlay on the masonry wall), *strengthening with the interior shear wall* (adding the concrete shear wall inside the plan), *strengthening with the FRP* (using the FRP laminate on the masonry wall), *strengthening with the exterior steel frame* (adding the steel frame outside the plan), *strengthening with the exterior concrete frame* (adding the concrete frame outside the plan), *strengthening with the exterior shear wall* (adding the concrete shear wall outside the plan).

3.4 Concluding remarks

The parameters which affect the selection process of the masonry buildings are categorized. The sort is performed based on the different characteristic of the items and in the term which can be compared, simultaneously. More discussion is provided in detail in the subsequent parts.

3.4.1 Building characteristics

Building characteristics include: *plan dimension*, *design and construction quality*, *building area*, and *vulnerability intensity*. Due to load distribution, using the strengthening with shotcrete and FRP will be more desirable in the buildings with large-sized plan. Some buildings have low design and construction quality, so that the alternatives like the shear wall which absorb the large amount of seismic loads, is desirable.

In some projects, the client may need to increase the building area beside the retrofitting implementation, so the alternatives which are adjunct to the structure (exterior frame or shear wall) will be more effective, and like wise if the existing building has the high vulnerability index which is obtained by the defenselessness analysis, those alternatives such as added-frame or shear wall are more productive. In this case, for a poor quality building, sometimes it is better to employ a method that reduces the transferred seismic force to the building rather than designing a huge new system for it [15].

3.4.2 Constructional aspects

Constructional aspects include: *construction duration, construction difficulties, construction technology*, *availability of materials*, *automation possibility*, *availability of constructional guideline*, and *level of experience needed for contractors and labors*. Projects related to their occupancy demand a specific duration timeline. In this regard, experiences have indicated the effectiveness of the strengthening with the FRP in comparison with the other alternatives and it is more operable for those projects which have limited time.

Adding the reinforced elements to the existing building is executed with some difficulties (hard accessibility to the structural components, connections, or even foundation) and mostly, it may affect severe impact on the project fund. In execution of shear wall the most troublesome part is the strengthening the foundation and if the wall designed outer part, the excavation and also the construction of new foundation is needed, too. Those alternative in which are added from outside, the adequate connection to the storey diaphragm is so important. However, the interior shear wall and strengthening with shotcrete need some difficulties in connection to the storey diaphragm, if the diaphragm has rigid material. Therefore, the strengthening with the FRP is evaluated the more efficient one.

The mechanized scheme which the required materials and the construction technology are available is more impressive. The level of the experience for the construction team is another important item so that some schemes are more sensitive to the errors and the high-experienced team is needed. Also, the availability of constructional guideline can be useful for low-experienced contractors to be aware of the executing process.

3.4.3 Economical aspects

Economical aspects include: *effect on the loss reduction*, *cost of retrofitting*, *cost of required tools and machinery*, *cost of labors*, *current value of building*, and *presence of occupants in the time of rehabilitation*. The main goal of the rehabilitation process is to decrease the expected losses in the existing building. The losses have direct relation with the stiffness of the building, so the constant-ductile alternatives which increase the global stiffness such as shear wall will be more efficient.

One of the important parts of the evaluation is dedicated to the cost estimation, and it is among the most important parameters, specifically for the clients who should consider selecting the best retrofitting option. The cost of retrofitting comprises the destruction, strengthening, and repair cost which denote a series of items from the cost of removing some components to the cost of adding new material or elements and finally provide a new finishing. In fact, the value of retrofitting costs, including designers, labors, equipments and materials expenditure, compared with the benefit of performing the strengthening plan. The cost of the labors and tool/machinery will be added to the cost of retrofitting which are varying in different area.

According to the lifetime of the building, the retrofitting will increase the value of the building and the amount will be more significant for the older buildings. Also, those alternatives which are added from outside will increase the area and accordingly increase the building value. Some buildings have critical occupancy in which the interruption in the service will bring some losses to the occupants. In this regard, the alternatives which are adjunct to the structure will be preferable, because these approaches have no interference in the existing occupancy.

3.4.4 Technical aspects

Technical aspects include some parameters related to the structural and dynamic attributes such as: *effect on the building weight*, or increasing the global *stiffness* and *ductility*. Basically, the seismic load is received by the mass of the building. So, one way to resist the earthquake hazards is to decline the mass of building. Another way is to use an absorption mechanism of the earthquake energy by increasing the stiffness or the ductility of the building. Based on the behavior, the shear wall and frame highly increase the global stiffness of the building. Depend on the design parameters, the shear wall and frame are more ductile and can be more desirable, comparatively.

A discontinuity in the load distribution from diaphragm to the supporting soil brings about the local defect and prevents the seismic system to be effective. The irregularity (plan and vertical) feature has some negative effects on the building performance. The irregularity may place extraordinary demands on elements and the irregular building has more unknown behavior and different modes should be taking into the analysis so that codes are strongly recommended to avoid this feature. The solid movement of the building as grouped components is suggested in leading to the reliable behavior against applied loads. Some alternatives are preferable according to its effectiveness in completing the *load path*, improving the *irregularity*, increasing the overall *solidarity* and *torsional capacity*, like the shear wall, and added frame, respectively. On the contrary, the strengthening with the shotcrete and FRP are preferable in the *minimum strengthening in the foundation* and relative easiness in the *connection to the storey diaphragm*.

These two items are among the most difficult part of strengthening which the ignorance will cause increasing the costs. In supporting of the boundary conditions, the foundations of most masonry buildings are superficial and present noticeable settlements: they are far from the rigid foundations of the structural textbooks. They are unknown, and essentially unknowable, as slight changes of the soil conditions, the sudden action of loads (e.g., storms or earthquakes) could alter the response to the loads [24]. Also, the diaphragm deficiencies are described as inadequate restraints, in-plane strength, and insufficient local shear transfer to lateral-force resisting elements.

Masonry walls are the part of the lateral resisting system which is qualified to endure the seismic loads. Although, the alternatives such as shear wall and frame absorb the high rate of the earthquake energy, but they decrease the portion of masonry walls. If the *using of maximum structural capacity* is the purpose, the strengthening with the shotcrete and FRP are more operative. Diaphragm shall be designed to resist the effects of the seismic forces calculated by dynamic analysis [25]. *The rigidity of the diaphragm* is the key point in the lateral load distribution and reduces the three degree-of-freedom. In buildings with rigid diaphragm the load distribution is based on the stiffness of the elements, so the alternatives with high stiffness such as shear wall are not suitable for the building with flexible diaphragm. Moreover, due to stiffness of the shear walls, the load transmission between diaphragm and shear wall cause stress concentration and the connections are needed strengthen with the resistant materials.

The sensitivity of performance of each scheme *to the technical and constructional errors*, and also the availability of information on performance of such schemes in previous earthquakes is much useful. In all design codes there is a safety factor to consider the indispensable uncertainties in designing where in the rehabilitation process with limited structural information and knowledge factor is certainly much more. The error can be part of the process, but the avoidance or even reduction the errors should be taking into the consideration. The errors include design errors, constructional errors, experiments errors or even the lack of structural information. Conceptually, the shear wall and frame bear the major part of the force, so that they are more sensible to the expected errors. On the other hand, the shotcrete or FRP added-layers are linked to the masonry wall and the combination is assumed to endure the applied force, so the experiments errors and also the lack of structural information have a certain disposition towards the results. Also, in order to design each alternative and lateral capacity appraisal, a design code should be available.

Sometimes, the building under consideration has some weakness in *gravitational load-bearing* which added elements like the shear wall or frame are eligible for improving this deficiency. In using the exterior alternatives, the sufficient area is needed. Due to the strengthening with the shotcrete, interior shear wall, and FRP inside the building, they are evaluated more efficient. Beside the assessment of the structural elements, non structural components which are separated into the displacement-sensitive and acceleration-sensitive should be appraised. The alternative with more stiffness are more effective, so the shear wall, frame, shotcrete, and FRP are preferable, respectively. But the shear wall and somehow the frame increase the diaphragm acceleration, and in this manner the application are not justified.

Occasionally, the local renovation of the masonry walls is needed. In this case, the shotcrete overlay and also the FRP laminate would be preferable compared to the shear wall and frame. These renovations are enhancing the poor condition walls by removing some deteriorated masonries, repointing by using grout and epoxy injection to increase the shear strength. Thus the deformation-controlled action would be replaced with the force-controlled of the diagonal tension. Masonry wall with height-to-thickness ratio or out-of-plane stresses in excess of the permitted by codes need to be strengthen and the shotcrete and FRP can be proper. Also, the masonry walls are weak in the corner of the opening in which the shear cracks are extended, if the dimension exceeds the allowable values [26, 27, and 28]. Masonry walls with undesirable length or height can not behave properly in earthquake and the maximum value are limited in the related codes [25]. In this order, the application of the shotcrete and FRP are qualified in decreasing the length and height in using as a tie.

According to the resisting system, all connection should have the desirable anchorage. Adequate strength should be provided in the connection between walls, wall to diaphragm and wall to the partition to resist the transfer forces. For local renovations the local scheme can be made to improve the local performance, but either shotcrete overlay or FRP laminate can be applicable.

Finally, *Past experience* is relevant in proving that retrofitting URM buildings reduce damage and loss of life, but also that building configuration and the quality of the evaluation, design and construction makes a substantial difference in the degree of improvement [29].

3.4.5 Architectural aspects

Architectural aspects include: *effect on the building's façade*, *effect on the building spacing*, *effect on the building lighting*, and *changing rooms' occupancy*. In the architectural viewpoint, the optimum alternative is the one which has the least affect on the building architecture and the clients prefer an alternative which has less interference in the aesthetic. In this regard, the most efficient option is the one which does not need to change the spacing, reduce the lighting, or even cause changing some rooms' occupancy. These are some limitations that mostly the designers are faced and are requested to avoid them. Among the proposed alternatives, the adjunct components like the exterior frame or shear wall have significant impact on the façade, or even reduce the lighting. In addition, in many cases the interior shear wall cause changing in some occupancy. Thus, the strengthening with the FRP is more productive.

3.4.6 Mechanical and electrical equipment

The mechanical and electrical equipments are one of the important parts of the building which removing can impose extra costs to the project finance. The effective alternative is defined the less necessity to the equipment removal, and accessibility. The alternatives which are added from the outside, unaffectedly, do not interfere in the building equipments. Also, compared to the strengthening with the shotcrete and FRP, the less shear wall is needed to fulfill the capacity requirements.

3.4.7 Case study

As been mentioned in the prior part, some parameters are constant in comparative evaluation, but some others can be varying in different area, so that different result will be obtained. The study is localized the evaluation of the effective parameter in order to select the best alternative for the rehabilitation of the masonry buildings. The results which is illustrated in the table 4, is accomplished for a masonry building located in the Tehran city to give us a broader perspective of the procedure.

						Strengthening with the shotcrete	Strengthening with the Interior shear wall	Strengthening with the FRP	Strengthening with the exterior steel frame	Strengthening with the exterior concrete frame	Strengthening with the exterior shear wall	I.R
Building Characteristics	0.850	Plan Dimension			1.280	3.586	1.645	3.586	0.657	0.657	0.657	0.009
		Design and Construction Quality			2.372	1.307	8.720	0.784	4.784	2.195	2.195	0.055
		Building Area			0.659	0.185	0.185	0.185	1.667	1.667	1.667	0.000
		Vulnerability Intensity			5.688	2.768	5.501	1.487	12.721	12.721	12.721	0.023
	Section scores					0.931	1.905	0.717	2.354	2.046	2.046	
Constructional Aspects	1.395	Construction Duration			2.149	1.047	2.065	11.725	6.028	4.288	4.856	0.043
		Construction Difficulties			3.379	1.714	3.648	19.023	11.711	7.650	3.441	0.051
		Construction Technology			0.366	0.471	1.870	0.191	0.862	0.862	0.862	0.058
		Availability of Materials			0.334	0.898	0.898	0.180	0.898	0.898	0.898	0.000
		Automation Possibility			1.197	1.213	6.252	0.689	3.534	3.534	1.498	0.059
		Availability of Constructional Guideline			1.924	7.093	10.155	0.857	3.560	3.560	1.649	0.048
		Level of Experience needed for Contractors and Labors			0.650	2.157	3.483	0.312	1.254	1.254	0.618	0.053
	Section scores					1.045	2.032	2.362	1.995	1.579	0.990	
Economical Aspects	2.540	Effect on Loss Reduction			2.036	3.577	16.229	2.384	6.647	6.647	16.229	0.037
		Cost of Retrofitting	3.884	Destruction Cost	2.605	65.342	34.707	116.043	16.211	16.211	8.539	0.052
				Strengthening Cost	6.333	234.659	81.691	18.887	44.604	163.434	81.691	0.068
				Repair Cost	1.062	22.669	12.679	45.164	8.172	12.679	3.389	0.084
		Cost of required tools and machinery			1.044	4.068	5.814	11.525	2.074	2.074	0.969	0.055
		Cost of Labors			0.356	3.909	0.940	2.513	0.480	0.940	0.254	0.068
		Current Value of Building			0.337	0.356	0.356	0.356	2.495	2.495	2.495	0.000
		Presence of Occupants in Time of Rehabilitation			2.343	2.049	5.856	2.049	16.523	16.523	16.523	0.048
	Section scores					2.947	1.386	1.742	0.851	1.935	1.139	
Technical Aspects	4.463	Effects on building weight			0.277	3.264	0.640	4.649	1.584	1.584	0.640	0.035
		Using Maximum Structural Capacity			0.456	7.914	1.131	7.914	1.131	1.131	1.131	0.000
		Accordance to the diaphragm rigidity			0.641	10.351	1.192	10.351	2.764	2.764	1.192	0.021
		Load path			0.159	0.236	1.653	0.236	1.653	1.653	1.653	0.000
		Effect on the regularity of the building			0.796	2.642	11.257	1.224	4.775	4.775	10.834	0.058
		Effect on the torsion of the building			0.656	2.374	3.595	1.083	5.629	5.629	10.951	0.088
		Minimum Strengthening in Foundation			0.386	4.935	1.845	8.195	0.891	0.891	0.473	0.063
		Increase the solidarity of the building			1.003	2.004	6.414	1.128	14.400	14.400	6.414	0.037
		Increase the stiffness of the building			0.230	0.652	3.400	0.255	1.802	1.027	3.127	0.069
		Increase the ductility of the building			0.138	0.280	1.399	0.280	1.399	1.399	1.399	0.000
		Connect to the storye diaphragm			1.276	12.889	7.426	28.737	4.102	1.898	1.898	0.073
		Local renovation of the walls deficincies	0.468	Conditional improvement of the walls	0.263	0.250	1.250	0.250	1.250	1.250	1.250	0.000
				Repointing	0.902	0.856	4.281	0.856	4.281	4.281	4.281	0.000
				The ratio of the height to the tickness	2.333	24.430	5.536	2.164	5.536	5.536	5.536	0.011
				Wall length	1.200	12.569	2.848	1.113	2.848	2.848	2.848	0.011
				Wall height	1.580	16.538	3.748	1.465	3.748	3.748	3.748	0.011
				Wall out-of-plane strength	3.224	33.755	7.649	2.990	7.649	7.649	7.649	0.011
				Enlarged opening	0.497	5.208	1.180	0.461	1.180	1.180	1.180	0.011
		Walls connection renovation	0.165	Connection between walls	2.828	8.116	1.159	8.116	1.159	1.159	1.159	0.000
				Connection between wall and diaphragm	6.434	18.462	2.637	18.462	2.637	2.637	2.637	0.000
				Connection between wall and partition	0.738	2.117	0.302	2.117	0.302	0.302	0.302	0.000
		Access to the building different faces			0.132	1.715	1.715	1.715	0.245	0.245	0.245	0.000
		Effect on the gravitational load-bearing			0.088	0.198	1.986	0.198	0.513	0.513	0.513	0.016
		Effect on the displacement sensitive non-structural component			0.167	0.538	2.310	0.230	1.214	0.872	2.310	0.068
		Effect on the acceleration sensitive non-structural component			0.165	1.771	0.372	3.076	0.741	1.016	0.372	0.067

						Strengthening with the shotcrete	Strengthening with the Interior shear wall	Strengthening with the FRP	Strengthening with the exterior steel frame	Strengthening with the exterior concrete frame	Strengthening with the exterior shear wall	*I.R*
Technical Aspects	*4.463*	*Sensitivity of performance to the technical and constructional errors*	*1.07*	*Design errors*	*1.219*	20.783	4.157	20.783	4.157	4.157	4.157	0.000
				Construction errors	*2.633*	37.723	12.574	37.723	12.574	12.574	12.574	0.000
				Experiments errors	*5.579*	12.109	60.543	12.109	60.543	60.543	60.543	0.000
				Structural information errors	*0.569*	2.194	1.075	9.986	4.636	4.636	4.636	0.040
		Availability of the design codes			*1.344*	5.479	12.689	3.730	12.689	12.689	12.689	0.023
		Past experiences of the performance in earthquakes			*0.149*	1.315	3.189	0.286	0.626	0.626	0.626	0.044
		Lightening possibility in the rehabilitating process			*0.235*	0.748	0.748	2.245	2.245	2.245	2.245	0.000
	Section scores					*2.251*	*1.521*	*1.717*	*1.512*	*1.485*	*1.515*	
Architectural Aspect	*0.479*	*Effect on the building's façade*			*5.579*	7.620	2.683	13.033	1.124	1.124	1.124	0.031
		Effect on the building spacing			*1.219*	2.166	0.667	2.166	0.279	0.279	0.279	0.016
		Effect on the building lighting			*2.633*	3.857	1.488	5.497	0.707	0.707	0.350	0.060
		Changing rooms occupancy			*0.569*	0.814	0.126	0.814	0.370	0.370	0.232	0.044
	Section scores					*3.020*	*1.037*	*4.493*	*0.518*	*0.518*	*0.414*	
Mechanical and Electrical Equipment					*0.279*	0.105	0.280	0.105	0.767	0.767	0.767	0.002
	Section scores					*0.378*	*1.002*	*0.378*	*2.749*	*2.749*	*2.749*	
				Total score		*628.045*	*379.840*	*453.682*	*319.031*	*431.394*	*335.115*	

Table 4: relatively weighted criteria, sub-criteria and alternatives

According to the figure.1 the problem is designed in which the model include the goal as a rehabilitation the masonry building. By reviewing the preferences and limitation in the rehabilitation process, the appropriate criteria are explained in the section 3.2, and the qualified alternatives are proposed in the section 3.3 The pair-wise comparative matrices are established and in this order the 5 matrices with different size for the criteria and 56 matrices for alternatives are set up. Using the mathematical syntax of numerical judgments in the decision problem, the absolute weight for the criteria and also for the alternatives is obtained. The consistency of the judgments is checked and the equation 3 is used to gain the final score in determination of the best alternative.

The results are summarized in the table 4 in which the proposed alternatives in the case of each classified criteria are compared and the priority is obtained for each of them. In the analysis the building characteristics, the vulnerability intensity serve the highest rank so the application of those schemes like the shear wall or the frame which can absorb the high rate of the earthquake energy is evaluated more desirable. The assessment of the constructional aspects denotes the importance of the construction duration and the construction difficulties among the other criteria. Based on the experience in this area, the strengthening of the masonry walls with the FRP is judged as a preferable alternative. In proceeding the economical aspects, the cost of the retrofitting and also the presence of the occupants in the time of rehabilitation acquire more effectiveness and the strengthening of the masonry walls with the shotcrete overlay is deserved higher priority. Among all the designated criteria in introducing the technical aspect of the process, the availability of the design codes and then connecting to the storey diaphragm are evaluated the most influential one. In this regard, the outcome indicates the efficiency of the strengthening of the masonry walls with the shotcrete overlay. The analysis of the architectural aspects signifies the precedence of the effect on the building's façade and the strengthening of the masonry walls with the FRP is the privileged alternative. Finally, the three exterior alternatives include strengthening with the steel frame; concrete frame and the shear wall are tending to be more useful in the mechanical and electrical equipment aspect. Whereas, the study of the effectiveness of different alternatives needs to have the acceptable level of knowledge and experiences in leading to the authentic judgment, the presented study endeavors to be performed precisely. The results illustrate the preference of the strengthening the masonry walls with the shotcrete, compared to the other alternatives.

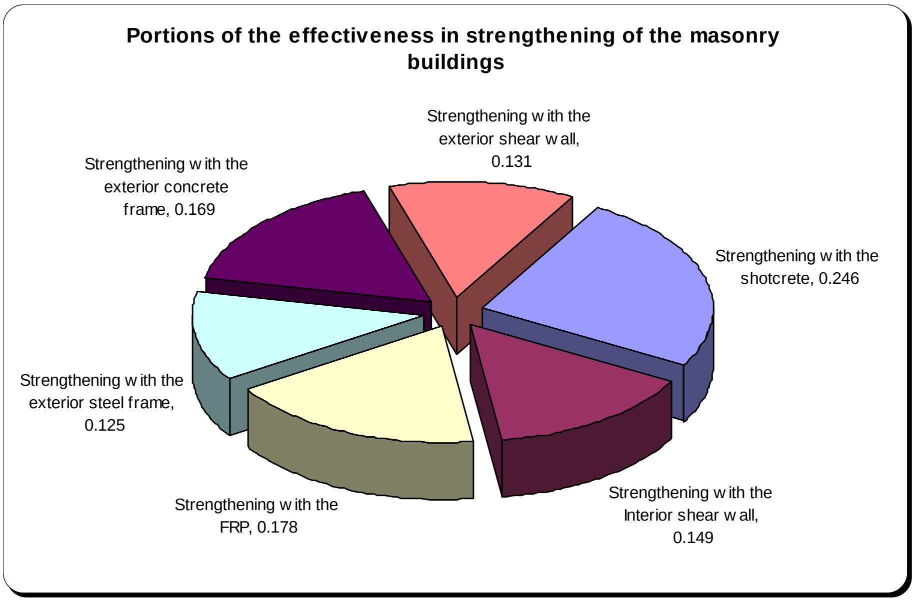

Figure 3: Final results of the proposed evaluation of the masonry buildings

4 VERIFICATION OF THE PREVIOUS STUDY

Several methods have been proposed in making-decision and in recent years various studies have been developed to analyze the decision problems. The authors presented a procedure to quantify the process for selecting the most advantageous technique, and also a practical method for specifying and prioritizing a criteria and goals for seismic retrofitting of a building [15]. A survey was conducted and some expert's opinions are gathered from some leading authorities, both from academia and profession, to calibrate the method. The aforementioned study was based on the experts' judgment and the criteria and alternatives were compared entirely in a group which it needed more concentration of its larger domain. The comparison of criteria and alternatives in this study is performed with this method again in consideration the final results. In spite of that the evaluation by the experts' judgment is expected to have divergent results but the result which is illustrated in figure 4, has shown the admissible level of outcomes. Due to close assessment, the variance of the combined results is calculated based on the equation 4.

$$\text{If } \mu = E(x) \text{ then } VAR(x) = E\left[(x-\mu)^2\right] \text{ or } VAR(x) = E\left(x^2\right) - \left[E(x)\right]^2 \qquad (4)$$

Where
x: Random variable
$p(x)$: The probability of the random variable (x_i)
$E(x)$: The expected value of the random variable (x_i)

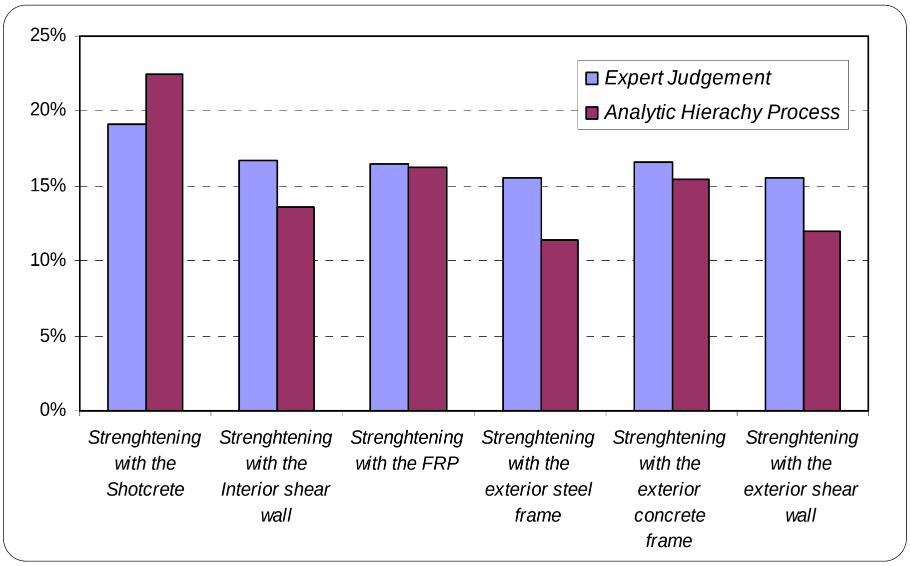

Figure 4: The results comparison of the AHP technique with the expert judgment procedure

x	p(x)	E(x)=xp(x)	x^2	$E(x^2)=x^2p(x)$
628.045	0.247	154.86	394440.76	97258.06
379.840	0.149	56.64	144278.12	21515.61
453.682	0.178	80.81	205827.04	36661.19
319.031	0.125	39.96	101781.05	12748.33
431.394	0.169	73.06	186100.67	31519.17
335.115	0.132	44.09	112301.77	14775.18
2547.106	1	449.42	1144729.40	214477.55
$Var(x)=E(x^2)-[E(x)]^2$		12496.073		

Table 5: the expected value and variance for the method-AHP

x	p(x)	xp(x)	x^2	$x^2p(x)$
402.890	0.192	77.17	162320.35	31092.83
350.540	0.167	58.42	122878.29	20479.23
346.610	0.165	57.12	120138.49	19798.13
327.290	0.156	50.93	107118.74	16668.60
349.130	0.166	57.95	121891.76	20233.10
326.830	0.155	50.79	106817.85	16598.41
2103.290	1	352.38	741165.49	124870.30
$Var(x)=E(x^2)-[E(x)]^2$		695.899		

Table 6: the expected value and variance for the method-Judgmental

The results presented in the figure 4 and the table 5 and 6 implicate the effectiveness of the experts' judgment and the variance of this method here is less than the AHP method, but the sequence of the priorities is changed. As been mentioned before, the accuracy of decision-makers in analyzing the process and making comparison has a direct relationship with the final result.

5 THE BINARY PROCESS

The productive criteria identified and properly classified and also according to the aforementioned process in the prior section, the relative weight is assigned to each criterion and also the method is used to compare the alternatives to make the preferences in each criterion. In this step, each criterion is simulated by a question tag which covers the intelligible concept of those criteria. In this regard, the only two possible answers are drawn here: “Yes” or “No” which *yes* points the 1 and *no* refers to 0 (eq.5). The main purpose of this study is to draw a simplified flexible procedure in optimization the proposed rehabilitation alternative with consideration the interaction of criteria and alternatives; hence a binary approach decision-making (BADM) is established in this regard. The applied model tries to make a rational conclusion based on the judgmental analysis and its binary utilization authorizes the decision-makers to omit those criteria that are irrelevant to the building under consideration by giving the *no* answer. Finally, the quick survey of building with considering the structural and non-structural components, gathering comprehensive information, limitations and also clients’ objective the alternatives are evaluated by completing the survey.

$$\textit{The}\ \text{most efficient alternative} = \max \sum_{i=1}^{n} CW_i \times \varphi_{bi} \begin{Bmatrix} 0 \\ 1 \end{Bmatrix} \qquad (5)$$

Where

CW_i : Indicates the relative weight of i-th criterion

φ_{bi} : The binary coefficient of i-th alternative

The filled cells are those considered as the preferred alternative in the specific criteria, therefore each answer will be evaluated just for these alternatives and the final result will be achieved by summing up the grades. The applied form is presented in table 7 and the result is obtained for a particular building which is considered vulnerable.

Building name	Adab high school
Appraiser name	B.M.Azmoodeh
Survey date	September 17, 2009
Occupancy	Educational
Number of story	2
Number of occupants	350 persons
Year of built	1982
Building area	910 square meter
Objective performance level	Life safety for the BSE-1
Adjucent building	Not any hazards will impact the performance
Address	
N.33-Vahdati St.-Tehran	

Zone seismicity	Very High Risk ☑	High risk ❑	Moderate risk ❑	Low risk ❑
Type of diaphragm	One-way masonry slab ❑		Concrete slab ☑	Plywood ❑
Soil classification	Type I ❑	Type II ❑	Type III ☑	Type IV ❑
Type of foundation	Wall footing ☑	Single footing ❑	Strip footing ❑	Mat footing ❑
Bearing wall material	Solid brick ☑	Clay or shale brick ❑	Hollow brick ❑	Concrete block ❑
Regularity condition	Regular ☑		Irregular ❑	

Additional comment

It has many wide large openings-windows- which areas are more than 0.33 area of the walls

there were some partitin walls which the ratio of the height/thickness exceed the allowable ratio

there were some walls with the length of more than 5 meters

it is reqular in both plan and elevation with rigid floors with no discontinuty in load path

The quality of the mortar seems not in competent condition

Building photo

	main criteria weight				sub-criteria weight	cummulative weight			Strengthening with the shotcrete	Strengthening with the Interior shear wall	Strengthening with the FRP	Strengthening with the exterior steel frame	Strengthening with the exterior concrete frame	Strengthening with the exterior shear wall
Building Characteristics	0.846	**Plan Dimension**			1.280	1.083	whether the ratio of length/width of the building is more than 3?	Yes	1.0833					
		Design and Construction Quality			2.372	2.007	whether the quality of the construction is undesirable?	Yes		2.0068				
		Building Area			0.659	0.558	whether the increasing the building area is clients' objective?	No				0.0000	0.0000	0.0000
		Vulnerability Intensity			5.688	4.812	whether the vulnerability intensity of the building is more than 50 percent?	Yes				4.8120	4.8120	4.8120
Constructional Aspects	1.395	**Construction Duration**			2.149	2.998	whether the project has limited time for construct?	No			0.0000			
		Construction Difficulties			3.379	4.714	whether scheme with less difficulty in construction is preferable?	Yes			4.7135			
		Construction Technology			0.366	0.511	whether scheme with the available construction technology is needed?	Yes		0.5112				
		Availability of the Materials			0.334	0.466	whether scheme with available material is requested?	No	0.0000	0.0000		0.0000	0.0000	0.0000
		Automation Possibility			1.197	1.670	whether construction with the automation possibilities is required?	Yes		1.6700				
		Availability of the Constructional Guideline			1.924	2.685	whether the availability of the construction guidelines is necessary?	Yes		2.6845				
		Level of the Experience needed for the Contractors and Labors			0.650	0.907	whether the level of the contractors' experience is important?	Yes		0.9067				
Economical Aspects	2.538	**Effect on the Loss Reduction**			2.036	5.167	whether the expected loss reduction is important?	Yes		5.1667				5.1667
		Cost of the Retrofitting	3.884	**Destruction Cost**	1.011	2.565	whether scheme with the less destruction cost is preferable?	No			0.0000			
				Strengthening Cost	2.457	6.237	whether scheme with the less strengthening cost is preferable?	Yes	6.2368					
				Repair Cost	0.412	1.045	whether scheme with the less repair cost is preferable?	Yes			1.0454			
		Cost of the required tools and machinery			1.044	2.650	whether cost of the required tools and machinery is important?	No			0.0000			
		Cost of the Labors			0.356	0.903	whether cost of the labors is important?	No	0.0000					
		Current Value of the Building			0.337	0.855	whether increasing the current value of the building is requested?	No				0.0000	0.0000	0.0000
		Presence of the Occupants in the Time of Rehabilitation			2.343	5.947	whether the presence of the occupants in the time of rehabilitation is necessary?	No				0.0000	0.0000	0.0000

Technical Aspects	4.463	Effects on building weight			0.277	1.236	whether weight of the building is more than the usual?	No			0.0000			
		Using Maximum Structural Capacity			0.456	2.035	whether using maximum structural capacity is the purpose?	Yes	2.0352		2.0352			
		Accordance to the diaphragm rigidity			0.641	2.861	whether the storey diaphragm is rigid?	Yes	0.0000		0.0000			
		Load path			0.159	0.709	whether the load path is complete?	Yes		0.0000		0.0000	0.0000	0.0000
		Effect on the regularity of the building			0.796	3.551	whether the building is evaluated regular (in plan and height)?	Yes		0.0000				
		Effect on the torsion of the building			0.656	2.926	whether the building needs to increase its torsional strength?	No						0.0000
		Minimum Strengthening in Foundation			0.386	1.723	whether the amount of strengthening in foundation is important?	No			0.0000			
		Increase the solidarity of the building			1.003	4.476	whether the building fulfills the solidarity criteria? (Does it have masonry tie?)	Yes				0.0000	0.0000	
		Increase the stiffness of the building			0.230	1.026	whether the building need to be more stiffened?	Yes		1.0263				
		Increase the ductility of the building			0.138	0.615	whether the building needs to increase its ductility?	No		0.0000		0.0000	0.0000	0.0000
		Connect to the storey diaphragm			1.276	5.695	whether the easiness of connecting the added components to the storey diaphragm is important?	Yes			5.6952			
		Local renovation of the walls deficincies	0.468	Conditional improvement of the walls	0.012	0.055	whether the construction of the walls is evaluated in acceptable condition?	No		0.0550		0.0550	0.0550	0.0550
				Repointing	0.042	0.188	whether the walls are needs to be repointed with new mortar?	No		0.1883		0.1883	0.1883	0.1883
				The ratio of the height to the tickness	0.109	0.487	whether the ratio of the height to the tickness of the structural walls is more than 10?	Yes	0.4874					
				Wall length	0.056	0.251	whether length of structural walls is more than 5 meters?	Yes	0.2507					
				Wall height	0.074	0.330	whethe height of walls is more than 4 meters?	No	0.0000					
				Wall out-of-plane strength	0.151	0.673	whether the out-of-plane strength of the walls is adequate?	No	0.6734					
				Enlarged opening	0.023	0.104	whether the building has enlarged openings? (The area of the opening is more than 0.33 area of wall?)	Yes	0.1039					
		Walls connection renovation	0.165	Connection between walls	0.047	0.208	whether the connection between structural walls is appraised in fine condition?	No	0.2083		0.2083			
				Connection between wall and diaphragm	0.106	0.474	whether the connection between wall and diaphragm is appraised in fine condition?	No	0.4738		0.4738			
				Connection between wall and partition	0.012	0.054	whether the connection between wall and partition is appraised in fine condition?	No	0.0543		0.0543			
		Access to the building different faces			0.132	0.588	whether the building has enough space in each its four faces to add strengthened components?	Yes				0.5881	0.5881	0.5881
		Effect on the gravitational load-bearing			0.088	0.392	whether the building has deficiency in bearing the gravitational load?	No		0.0000				
		Effect on the displacement-sensitive non structural component			0.167	0.747	whether the building has displacement-sensitive non structural component?	Yes		0.7473				0.7473
		Effect on the acceleration-sensitive non structural component			0.165	0.735	whether the building has acceleration-sensitive non structural component?	No			0.0000			
		Sensitivity of performance to the technical and constructional errors	1.07	Design errors	0.130	0.582	whether the expected design errors is consequential?	Yes	0.5820		0.5820			
				Construction errors	0.282	1.258	whether the expected construction errors is consequential?	Yes	1.2576		1.2576			
				Experiments errors	0.597	2.664	whether the expected experiments errors is consequential?	Yes		2.6642		2.6642	2.6642	2.6642
				Structural information errors	0.061	0.272	whether the expected structural information errors is consequential?	No			0.0000			
		Availability of the design codes			1.344	5.997	whether the availability of the design codes is necessary?	Yes		5.9967		5.9967	5.9967	5.9967
		Past experiences of the performance in earthquakes			0.149	0.667	whether the past experiences of the alternative performance in earthquakes is important?	Yes		0.6668				
		Lightening possibility in the rehabilitating process			0.235	1.048	whether lightening the weight of the building in the rehabilitating process is needed?	No			0.0000	0.0000	0.0000	0.0000
Architectural Aspect	0.479	Effect on the building's façade			5.579	2.672	whether the functional interaction of the alternatives with the building's façade is authorized?	Yes			2.6723			
		Effect on the building spacing			1.219	0.584	whether the functional interaction of the alternatives with the building spacing is authorized?	No	0.0000		0.0000			
		Effect on the building lighting			2.633	1.261	whether the effect of the alternatives on the buildings' lighting is permitted?	Yes			1.2614			
		Changing the occupancy of rooms			0.569	0.273	whether the occupancy of rooms are changeable?	No	0.0000		0.0000			
Mechanical and Electrical Equipment					0.279	2.791	whether the functional interaction of the alternatives with the mechanical and electrical equipment is allowable?	No				2.7912	2.7912	2.7912
							(The most efficient alternative)= **Strengthening with the Interior shear wall**		**13.45**	**24.29**	**20.00**	**17.10**	**17.10**	**23.01**

Table 7: the applied criteria and evaluated alternatives

The consistency of the judgments is checked and the eq.5 is used to gain the final score in determination of the best alternative. The binary procedure is used as a complementary tool to cover the decision-making process. Depends on what is concluded from the classified criteria analyses by using the AHP method, the high ranked alternatives in each criterion are spotted (blue cells). The relative weights which are assigned in previous evaluation elicited and applied in this table. Based on client's circumstances and project's demand, provided questions; whether it is relevant and needed to consider or not; make a simplified point of view of the most appropriate alternative. Due to the distinctive specifications of different projects, the binary process is added to the decision analysis in order to help the decision makers to come up with their projects with an applicable tool incorporated with the basic concept of the masonry rehabilitation.

6 CONCLUSION

- Unreinforced masonry (URM) bearing wall buildings have shown poor performance in the past earthquakes and the reasons are the inherent brittleness, lack of tensile strength, and lack of ductility. Therefore, the rehabilitation is conducted for those buildings with inadequate capacity in order to improve its seismic performance. Whereas, the high amount of money that spend in this regard, stakeholders are so eager to complete the process in much less timeline and whatever the time duration of decision-making is less, the benefit of the process will be increase. Similar study was conducted by the authors in optimizing the selection process, but the method has a disadvantage that process was rigid model and can not be changeable for different projects in minimum time, so this study brings out the best usage of the model as a flexible model for different projects in a very simple way.
- The presented study helps decision-makers face complex problem with multiple conflicting and subjective criteria. However, explicit comparison of technical characteristics of the retrofitting options is usually conducted by performing linear or nonlinear analyses of the retrofitted building to check the acceptance criteria for structural, non structural and equipments, but the application will be useful in the preliminary evaluation of the alternatives and for buildings with less importance can be appropriate approach to decrease the process timeline.
- Based on the presented study, the method is developed to evaluate the optimum rehabilitation process of the unreinforced masonry buildings. The effective criteria and alternatives for the rehabilitation of these building are introduced and classified and according to the procedure they are evaluated comparatively. The final result indicates the effectiveness of the strengthening of the unreinforced masonry buildings with the shotcrete overlay.
- This paper presents a procedure in leading to select the best rehabilitation alternative of the unreinforced masonry (URM) buildings. The proposed method is carried out in three steps in which the effective criteria are classified and the hierarchical process is used to allot the weight to each criterion. Based on this process the proposed alternatives are compared to make the preferences of each one in different criteria. By using the binary concept the model is developed to select the optimum rehabilitation alternative of the specific unreinforced masonry buildings. The most remarkable characteristic of the applied model is its tendency to be done in minimum time and its simplified structure that will be useful for the decision-makers in this area to choose the optimum option by doing quick survey. The final result

indicates the effectiveness of the strengthening of the unreinforced masonry buildings with adding the interior shear wall.

7 ACKNOWLEDGEMENT

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