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APPLYING THE DECISION ALGORITHM IN SELECTING THE OPTIMUM METHOD FOR STRENGTHENING THE HISTORICAL DOMES

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Abstract. *Most of the strengthening methods of historical buildings such as Shotcrete and retaining structure usually change the stiffness and mass of the building which may affect the dynamic behavior of the building while in most cases, the purpose of strengthening is to increase the ultimate strength of the building elements without altering its dynamic behavior. Some of the strengthening methods change the facade of the buildings which do not satisfy the aesthetic restoration needs. In the present investigation, after studying the results obtained from analyzing the seismic model of the domes of Imam Reza Shrine, Isfahan Imam Mosque and Yazd Mosque in their current condition and the use of three different methods of strengthening (Shotcrete, FRP strips and FRP rods), it was observed that each of the strengthening methods depending on the type of the dome, exhibited a specific behavior in the strength increase rate indicating that the criterion of strength increase depends on the characteristics of the dome while the other sub-criteria such as the facade of the dome, faster execution, no need for specialized labor and lower cost only depend on the method of strengthening. Adhering to the cultural values of the building as well as reaching an acceptable level of strength against probable damages is another challenge that should be faced in strengthening the domes. In order to choose the most appropriate method for strengthening the domes, the advantages and disadvantages of each method should be assessed by scientifically hierarchical techniques. In this research, scientific method of decision algorithm is employed. The procedure is to evaluate the advantages and disadvantages of each strengthening method by applying both the Analytic Hierarchy Process (AHP) and Concordance analysis. Thereafter, the appropriate method in terms of most improvement of seismic behavior, least extent of interference, the reliability of the applied method, etc., is extracted and then applied to the model. Seismic behavior of the dome after applying the proposed strengthening method concludes with acceptable results about its seismic strengthening. The difference in proposed decision algorithm methods for strengthening the domes means that the distinction between facade, origin and the extent of damages of each dome, results in choosing a different method of strengthening for each dome. Consequently, presenting a general method for strengthening all the masonry domes is impossible.*

1 INTRODUCTION

Multi-criterion decision making is used where a single decision should be resolved in situations with divergent objectives and criteria. It means that achieving all the objectives is not viable and the way the criteria are balanced should be considered. Criteria comprise a collection of values and bases which results in differences between the options and hence, the selections. In such situations, some of the criteria that should be considered in decision making sometimes oppose each other. For instance, price, comfort, safety, speed and fuel consumption are the criteria to be considered in selecting an appropriate car. It is obvious that the price criterion opposes the comfort and safety criteria because it is not possible to reduce the price and increase the comfort and safety at the same time.

Increasing the lifetime and maintenance of the domes is recognized as an important concern in preserving the cultural heritage of each country. There are several methods for improving the preservation of the domes such as shotcrete, FRP strips and FRP rods. Shotcrete method which is spraying the concrete mixture with high speed caused by compressed air flow, is used for repairing some of the damages of the structure. This method affects the façade of the building. FRP methods are based on using a composite material consisted of a reinforcing fiber surrounded by a resin matrix made of polymer for reinforce the structure against lateral loads.

Opposing criteria present in shotcrete, FRP strips and FRP rods methods make selection of appropriate method of restoration difficult. For example, shotcrete method with changing the façade of the dome results in more strengthening of the structure against earthquake comparing with FRP methods which preserve the façade of the dome.

Another factor which affects the selection of restoration method is the differences in the will of the people. For example, from viewpoint of some experts, increasing the lifetime of a historical dome is more important than preserving its façade, while some may pay more attention to keeping the appearance of the building intact. Regarding all these different will simultaneously, makes the decision making process more complicated. Because the problem of "selecting the domes restoration method" has limited and countable solutions and the decision making process is carried out only between three methods of shotcrete, FRP strips and FRP rods, it belongs to the category of multi-criterion evaluation problems so the solutions applicable to these type of problems can be used to select the appropriate method.

2 METHODS OF PROBLEM SOLVING

Due to the complexity in classification of the problems and the various objectives, there is no specific method for solving the multi-criterion evaluation problems and therefore, different methods for solving this type of problems have been proposed. In this research, two common and practical methods of "hierarchical analysis" and "envelopment analysis" were used to solve the "selecting the domes restoration method" problem.

Hierarchical analysis method

One of the most efficient methods in decision making process is the hierarchical analysis which was introduced by Thomas L. Saaty for the first time in 1980. This method which is based on pair comparisons, gives the decision maker the opportunity to investigate different scenarios. Main steps of hierarchical analysis method are: modeling the hierarchical analysis process, designing the questionnaire, determining the weight of the criteria, pair comparing the options based on the criteria and calculating (estimating, assessing) the priorities.

3 MODELING THE HIERARCHICAL ANALYSIS PROCESS

Choosing the criteria is the first step in the hierarchical analysis. In some cases, in determining the importance of a criterion, a set of other criteria are influential which are called sub-criterion. The options are evaluated based on the criteria and the sub-criteria. In the "selecting the domes restoration method" problem, common options are shotcrete, FRP strips and FRP rods methods. For selecting the appropriate method, the importance of the criteria from viewpoints of different group of people is considered. Because of the diversity in the opinions about the domes restoration problem, the opinions of four different groups of people involved in the problem including cultural heritage experts, municipal and architectural experts, civil experts and ordinary people were acquired. Based on the studies carried out, each group specifies its own sub-criteria of increased strength, preservation of dome façade, project operation speed, unskilled labor and lower expenses.

3.1 Designing the questionnaire

In this step, in order to determine the importance of each criterion with regard to the hierarchical illustration in figure 1, the viewpoint of different groups of society were acquired by designing a questionnaire. After collecting the questionnaires, by calculating the average weight from the opinions of the experts. In the "selecting the domes restoration method" problem, for determining the importance of sub-criteria and criteria, questionnaires and scenarios were used respectively.

3.2 Determining the weight of the criteria

In this step, relative weight of each criterion is calculated. To do so, several methods have been suggested such as: least squares method, logarithmic least squares method, Eigenvector method and approximation methods. Among all the existing methods, eigenvector is the most accurate method hence in this study, this method was used.

4 CONCORDANCE ANALYSIS METHOD

The Concordance analysis method is one of the most important and frequently used methods specifically in solving the problems where the measurements cannot be converted into a same unit. For example, the criterion of increased strength is measured by N/mm^2 while the expense criterion is evaluated by Rial. It is worth mentioning that some of the criteria such as preserving the façade of the building are assessed qualitatively and quantitative measurement of these criteria are difficult. The first step of this method is similar to hierarchical analysis method. At first, the criteria and sub-criteria and the relation between them are specified. Thereafter, the weight of each criterion is calculated by opinion poll and creating different scenarios.

In this method, the set of options that works better for a specific weighing system rather than an average weighing system is called the set of dominant options. After calculating the net indices of envelopment and unenvelopment, preferable options are put into the set of dominant options. With changing the weighing system, members of the set of dominant options will also change. The options that are members of the set of dominant options in each weighing system are called competitor options and selecting each member of the set of competitor options is a proper solution for the decision making problem. [10]

In order to reach a conclusion and select the appropriate method of restoration based on the results acquired from the seismic analysis of the structural model of the domes, next step after specifying the relation between the options, criteria and sub-criteria is to determine the weight of these groups. Due to the historical importance of these domes, specifying and weighing the sub-criteria are of great importance. In designing the questionnaire, different aspects of restoration of the historical buildings have been considered. It is obvious that in designing the questionnaire the opinions of the restoration experts should be regarded.

4.1 Evaluating the Options

Regarding to the studies carried out for different domes, each method of restoration depending on the type of the dome, behaved distinctly in increasing the strength of the building. It shows that the criterion of increasing strength depends on the characteristics of the dome while the sub-criteria of preserving the façade of the building, faster operation time, unskilled labor and fewer expenses only depend on the method of restoration and do not change with the type of building.

In order to study the degree of change in selected options with change in characteristics of the building, the specifications of three domes of Imam Reza Mosque, Isfahan Imam Mosque, and Yazd Mosque were acquired. Tables 1 to 4 show the results of pair comparing between the options for four sub-criteria of preserving the façade of the building, faster operation time, unskilled labor and fewer expenses (which do not depend on the characteristics of the dome) based on the hierarchical analysis method. Tables 5 to 7 show the results of pair comparing between the options for the sub-criterion of increased strength for each dome separately. It is worth mentioning that the project time of restoration in shotcrete method was shorter than the FRP methods, but since the building is closed and cannot be used during the restoration with shotcrete method, lower weight is assigned to this method compared with FRP methods for the criterion of building operating time.

Table 1: comparing the options based on the preserving the façade of the dome (Hierarchical analysis method)

restoration method	shotcrete	FRP strips	FRP rods
shotcrete	1	0.2	0.167
FRP strips	5	1	0.25
FRP rods	6	4	1

Table 2: comparing the options based on faster operation time (Hierarchical analysis method)

restoration method	shotcrete	FRP strips	FRP rods
shotcrete	1	0.167	0.143
FRP strips	6	1	0.333
FRP rods	7	3	1

Table 3: comparing the options based on unskilled labor (Hierarchical analysis method)

restoration method	shotcrete	FRP strips	FRP rods
shotcrete	1	4	5
FRP strips	0.25	1	3
FRP rods	0.2	0.333	1

Table 4: comparing the options based on fewer expenses (Hierarchical analysis method)

restoration method	shotcrete	FRP strips	FRP rods
shotcrete	1	4	5
FRP strips	0.25	1	3
FRP rods	0.2	0.333	1

Table 5: comparing the options based on increased strength in dome of Imam Reza Mosque (Hierarchical analysis method)

restoration method	shotcrete	FRP strips	FRP rods
shotcrete	1	5	6
FRP strips	0.2	1	2
FRP rods	0.167	0.5	1

Table 6: comparing the options based on increased strength in dome of Isfahan Imam Mosque (Hierarchical analysis method)

restoration method	shotcrete	FRP strips	FRP rods
shotcrete	1	4	5
FRP strips	0.25	1	2
FRP rods	0.2	0.5	1

Table 6: comparing the options based on increased strength in dome of Yazd Mosque (Hierarchical analysis method)

restoration method	shotcrete	FRP strips	FRP rods
shotcrete	1	0.333	0.333
FRP strips	3	1	1
FRP rods	3	1	1

The shotcrete method in dome of Isfahan Imam Mosque increased the strength less than the FRP methods in dome of Imam Reza Mosque. As a result, in table 6 shotcrete method had a lower weight compared with table 5. In dome of Yazd Mosque, because of considerable changes in the characteristics of the dome compared with two other domes, shotcrete method did not increased the strength and the FRP methods made only minor improvement in the behavior of the building.

Table 8 shows the results of evaluating the options based on four sub-criteria of preserving the façade of the building, faster operation time, unskilled labor and fewer expenses for the Concordance analysis method. Table 9 shows the results of evaluating the options based on the increased strength for the domes separately.

Table 8: Evaluating the options (Concordance analysis method)

sub- criterion / restoration method	preserving the façade of the building	faster operation time	unskilled labor	fewer expenses
shotcrete	5	14	16	18
FRP strips	12	16	12	15
FRP rods	20	18	10	14

Table 9: Evaluating the options based on increased strength (Concordance analysis method)

dome / restoration method	Imam Reza Mosque	Isfahan Imam Mosque	Yazd Mosque
shotcrete	16	15	1
FRP strips	13	13	5
FRP rods	12	12	5

4.2 Determining the Weight of Sub-Criteria

For determining the weight of each sub-criterion, a questionnaire is designed and is available on internet for different groups of people. This questionnaire is divided into three parts. The information provided in the first part is used for classification of the criteria and the information provided in the second and third part are used respectively for weighing the sub-criteria in hierarchical analysis and Concordance analysis method. The result of this opinion poll based on the educational degree, field of study and occupation in the cultural heritage organization is divided into four groups which are as follows:

1- Cultural heritage experts including the people working in the cultural heritage organization and the people whose field of study is restoration of monumental heritages.

2- Architectural and municipal experts including the graduates of architecture and municipal at the level of undergraduate, graduate and doctoral.

3- Civil experts including the graduates of civil engineering at the level of graduate and doctoral.

4- Ordinary people which were not included in the three previous groups.

As it was mentioned earlier, these four groups organize the criteria for the problem of "selecting the domes restoration method" and for choosing between three methods of shotcrete, FRP strips and FRP rods, the opinions of these groups will be considered. The degree of participation of each group is shown in table 10.

Table 10: Degree of participation

group	degree of participation (person)
Cultural heritage experts	35
Architectural and municipal experts	54
Civil experts	38
Ordinary people	113

After acquiring the information and averaging over the opinions of each group, the weight for each sub-criterion was determined. The results of this opinion poll in the hierarchical analysis method for the four groups are presented in tables 11 -14. Each cell in the table is the result of relative comparison between two sub-criteria.

Table 11: Comparing the sub-criteria based on the opinions of cultural heritage experts (Hierarchical analysis method)

sub-criterion	increased strength	preserving the façade of the building	faster operation time	unskilled labor	fewer expenses
increased strength	1	3	6.2	6.64	5.06
preserving the façade of the building	0.333	1	6.58	6.22	5.58
faster operation time	0.161	0.152	1	1.9	0.595
unskilled labor	0.151	0.161	0.526	1	0.327
fewer expenses	0.198	0.179	1.681	3.058	1

Table 12: Comparing the sub-criteria based on the opinions of architectural and municipal experts (Hierarchical analysis method)

sub-criterion	increased strength	preserving the façade of the building	faster operation time	unskilled labor	fewer expenses
increased strength	1	1.8	7.08	5.7	6.02
preserving the façade of the building	0.555	1	7.46	6.3	6.88
faster operation time	0.141	0.134	1	1.72	0.704
unskilled labor	0.175	0.159	0.581	1	0.714
fewer expenses	0.166	0.145	1.42	1.4	1

Table 13: Comparing the sub-criteria based on the opinions of civil experts (Hierarchical analysis method)

sub-criterion	increased strength	preserving the façade of the building	faster operation time	unskilled labor	fewer expenses
increased strength	1	0.704	7.48	6.24	6
preserving the façade of the building	1.42	1	6.84	7	6.64
faster operation time	0.134	0.146	1	2.38	0.5
unskilled labor	0.16	0.143	0.42	1	0.397
fewer expenses	0.167	0.151	2	2.512	1

Table 14: Comparing the sub-criteria based on the opinions of ordinary people (Hierarchical analysis method)

sub-criterion	increased strength	preserving the façade of the building	faster operation time	unskilled labor	fewer expenses
increased strength	1	0.694	6.3	6.46	4.74
preserving the façade of the building	1.441	1	6.32	6.96	5.4
faster operation time	0.159	0.158	1	3.42	0.617
unskilled labor	0.155	0.144	0.292	1	0.347
fewer expenses	0.211	0.185	1.621	2.882	1

Table 15: The weight of sub-criteria based on the opinions of different groups (Concordance analysis method)

group / sub-criterion	group 1	group 2	group 3	group 4
increased strength	18.16	18.58	17.39	17.30
preserving the façade of the building	18.59	18.65	18.55	18.21
faster operation time	13.19	11.79	11.03	11.82
unskilled labor	10.26	9.60	7.76	8.12
fewer expenses	11.03	10.62	10.89	12.16

4.3 Data Analysis

For solving the problem and finding the appropriate method for restoration of the domes, weighing the criteria was necessary. As it was mentioned earlier, in order to determine the weight of criteria, different scenarios were created. By creating each scenario, criteria are mixed together with specific percentages. In this project, thirteen scenarios were created which are presented separately in the upper section of table 16. As it is shown in table 16, in the first four scenarios only the opinions of a single criterion were considered and in the other nine scenarios, a combination of criteria with different percentages was used. It should be noted that in each scenario, the share of each color is proportionate to the degree of participation of that specific criterion in the final selection.

The problem of selecting the restoration method for each dome of Imam Reza Mosque, Isfahan Imam Mosque and Yazd Mosque was solved separately by hierarchical analysis and Concordance analysis method for each scenario and the results are presented in the lower section of table 16. Because there were numerous possible situations along with too many calculations, MATLAB programming environment was used to analyze the scenarios. Since the condition in which, the preferable option is selected is different in hierarchical analysis and Concordance analysis, in many cases, the answers of these two methods despite the similarity, have significant differences.

In the method of hierarchical analysis, the option that has the highest weight is selected and since there is always a method with relative weight among three options, this method always has an answer. But in the Concordance analysis, the selected option should have both positive net index of envelopment and negative net index of unenvelopment. So it is possible that several methods are selected as the answer or none.

Table 16: The results of scenarios analysis for different domes

legend		scenario description												
Cultural heritage experts		1	2	3	4	5	6	7	8	9	10	11	12	13
Architectural and municipal experts														
Civil experts														
Ordinary people														
dome	analysis method	selected restoration method												
Imam Reza Mosque	hierarchical													
	Concordance													
Isfahan Imam Mosque	hierarchical													
	Concordance													
Yazd Mosque	hierarchical													
	Concordance													

* The numbers 1, 2, 3 represent the methods of shotcrete, FRP strips, FRP rods respectively. The sign (-) shows that none of the methods have been selected.

5 SELECTING THE APPROPRIATE METHOD OF RESTORATION OF BRICK DOMES

The results showed that for Imam Reza Mosque and Isfahan Imam Mosque except in the situations that the Concordance analysis was unable to select between the options, the answers of both methods of analyzing were the same. The selected method for these two domes is shotcrete and only when the criterion for selection is the opinions of civil experts and ordinary people, using FRP rods method is suggested. The only disparity of analyzing methods is in Imam Reza Mosque when the opinion of civil experts is used. In this situation, hierarchical analysis and Concordance analysis respectively suggest the use of shotcrete and FRP rods. In the dome of Yazd Mosque, due to the considerable differences in methods of restoration for strengthening the building compared with other domes, neither of the analysis methods suggests the use of shotcrete method as an appropriate selection. For this dome, the Concordance analysis method recommends the use of FRP strips and FRP rods while the hierarchical analysis method finds the FRP rods method more appropriate and the only preferable option.

6 CONCLUSION

Receiving different answers from decision making algorithm for selecting the restoration methods of the domes means that façade dissimilarity, standing and the extent of the damages caused by the applied forces on each dome result in selecting a distinctive method of restoration for each dome. The distinction of selected method in different situations, is firstly due to the distinction in the characteristics of the dome which yields to distinctive performance of restoration methods for strengthening the buildings and secondly, because of the disparity in the opinions of cultural heritage experts and architectural and municipal experts with those of civil experts and ordinary people. Considering the opinions of the ordinary people as one of the groups involved in answering the designed questionnaire and the non-conformity of their answers to expectations from restored historical building shows that although aesthetic expectations and originality preservation of the building from an inexpert viewpoint should be considered in restoration of historical buildings, in such cases since the ordinary people are not familiar with the basics and the rules of strengthening and restoration, their opinions are not functional in selecting the appropriate method of strengthening. Regarding the acquired information, it can be concluded that using Concordance analysis method for these types of problems which an absolute answer should be found for each scenario, is not appropriate and it is better to employ hierarchical analysis method.

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