Fuzzy Analytical Hierarchy Damage Assessment in Old Reinforced Concrete Buildings: Case Study

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Abstract. *This study uses a fuzzy analytical hierarchy method to help people make decisions about how to plan maintenance for older reinforced concrete buildings (ORCB). Visual inspections, in addition to a variety of criteria and sub-criteria, will be used to accomplish the goal of classifying the level of deterioration that has occurred to the administrative building that serves the city of El Malah. The historical context of the building, environmental circumstances, structural capability, and professional participation are the key aspects that were evaluated in this study. After that, these components are broken down further into a number of other sub-factors. The calculation of weights (Wi) using Buckley's fuzzy geometric mean approach is what determines the relevance of each component and sub-factor individually. After that, scores from experts are allotted to each criterion and sub-criterion, and these ratings are then used to compute the comprehensive score (CS), which represents the ORCB's level of deterioration. The EMS-98 rating system is used to assign an overall rating to reinforced concrete structures based on the overall ratings. In general, this methodology offers a way that is both organised and objective to evaluate the deteriorating condition of ORCBs. As a result, it enables informed decision-making in the process of planning maintenance.*

Keywords

Degradation factors and classification of ORCB, Fuzzy geometric mean, Old reinforced concrete buildings (ORCB), Multicriteria decision-making method.

1. Introduction

In today's world, protecting both people and property involves guaranteeing the structural integrity and optimal performance of existing structures. Nevertheless, due to natural disasters, neglect, environmental effects, and poor design and construction practices, many existing reinforced concrete buildings require major renovation or destruction [1]. However, the way these tasks are done now depends heavily on the knowledge and judgement of trained engineers and experts who rate building damage based only on what they can see. Due to the subjective nature of expert judgements, which can be affected by things like the level of knowledge, technical skills, human bias, and personal ethics, these methods have turned out to be insufficient and unsatisfactory [2]. The fuzzy Analytical Hierarchy Process (FAHP) method, which was created by Zadeh in 1965, can help experts solve choice problems by putting things in order of importance and breaking down complicated problems into smaller ones [3]. In fact, this theory has been used successfully in the area of assessing damage caused by earthquake vulnerability [4]. It has been done to find out how flexible it is during growth and how well it can handle uncertainty. Also, the FAHP method has gotten a lot of attention in academic writing as a useful tool for making decisions based on multiple factors when assessing structural damage. This makes it possible to figure out the best ways to take care of these structures in the future [5] and [6]. This study uses the FAHP method to figure out how damaged old reinforced concrete buildings are. In the evaluation process, trained experts look at each building and give it an overall damage grade based on what they see. After that, the experts make a final decision by giving the building a class based on the amount of damage according to the European macro- seismic intensity scale (EMS-98) and labelling it with the right colour to show its safety status [7].

2. Methodology for the Procedure of Assessing Degradation

The primary objective of this paper is to develop a numerical representation using the FAHP approach to assess the condition of ORCBs. The flowchart illustrated in Fig. 1 delineates the five distinct steps of the model. The first step involves identifying deterioration causes directly impacting the structural state of the building. These identified elements will later contribute to the overall state evaluation. Moving to the second step, a hierarchical structure is established for the model. This framework organizes and assesses numerous elements and sub-factors relevant to evaluating the state of ORCBs. Once the hierarchical structure is in place, the FAHP technique is applied. This method computes weights for both overarching elements and subordinate factors. Further details on this computation will be presented in subsequent sections of the text. The subsequent step involves creating an overall CS Condition Score index to carry out a thorough evaluation of the ORCBs' condition. This index considers weighted variables and sub-factors, offering a holistic assessment. In the final step, the ORCBs are evaluated and ranked based on their level of deterioration using the computed CS scores. This rating system aids in prioritising maintenance activities and informs decision-making processes related to these buildings.

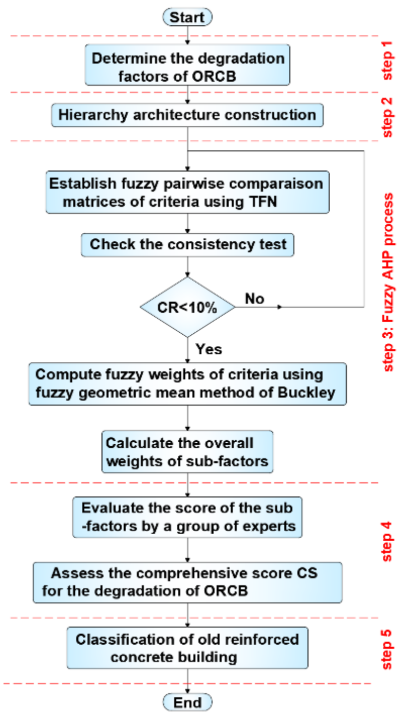

Fig 1. Flowchart illustrating ORCB degradation estimation procedure.

2.1. The Organisation in A Structure Based on Hierarchy

The utilisation of a hierarchical structure facilitates the methodical allocation of assessment components, commencing with the comprehensive delineation of the issue and advancing towards more detailed criteria and sub-criteria. This framework enables the systematic organisation and classification of several aspects that contribute to the evaluation of the degradation of aged reinforced concrete structures. The ORCB degradation evaluation has a hierarchical framework with four distinct stages, as visually depicted in Fig. 2.

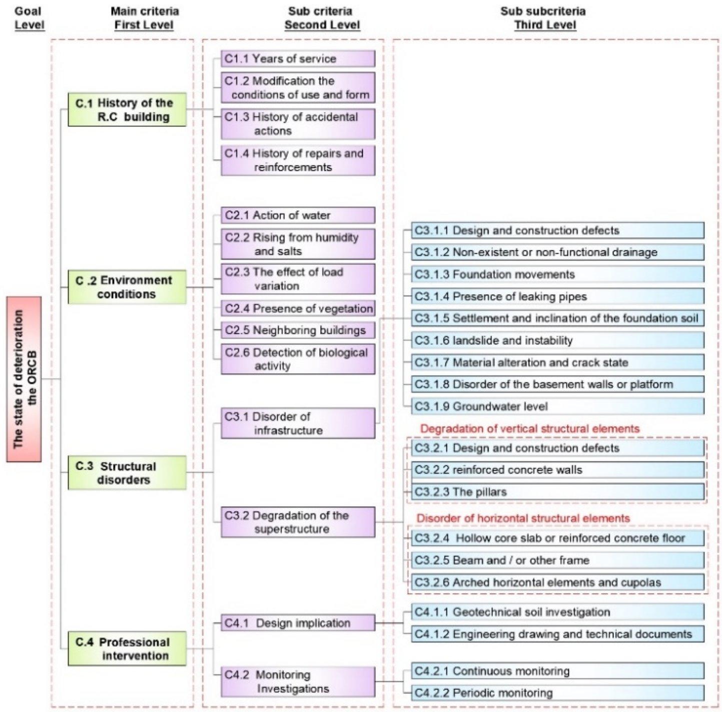

Fig 2. Hierarchical assessment criteria structure adopted.

2.2. FAHP Method For Weight Calculation

2.2.1 Weight Calculation with TFN

To deal with uncertainty and ambiguity, this work employs the triangular fuzzy number (TFN) as a fuzzy number within the FAHP approach. TFN is popular among researchers since it is simple to use on computers. A TFN is represented by the triplet (l, m, u), where the first letter stands for the lower bound, the middle binding, and the last letter stands for the upper limit of the TFN. Fig. 3 is an illustration of the membership function of a TFN.

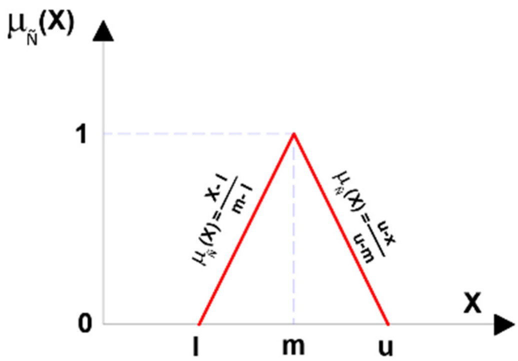

Fig 3. TFN graphic representation [5].

2.2.2 The standard comparison scale

Experts must consider the importance of two criteria simultaneously in selecting an appropriate TFN, as shown in Fig. 4.

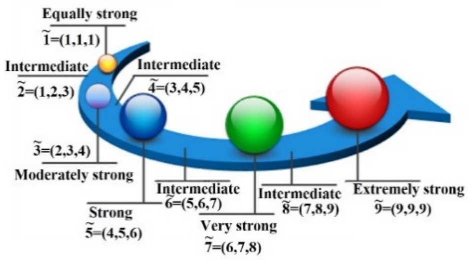

Fig 4. Scale for comparing criteria.

2.2.3 Fuzzy geometric mean method (FGMM)

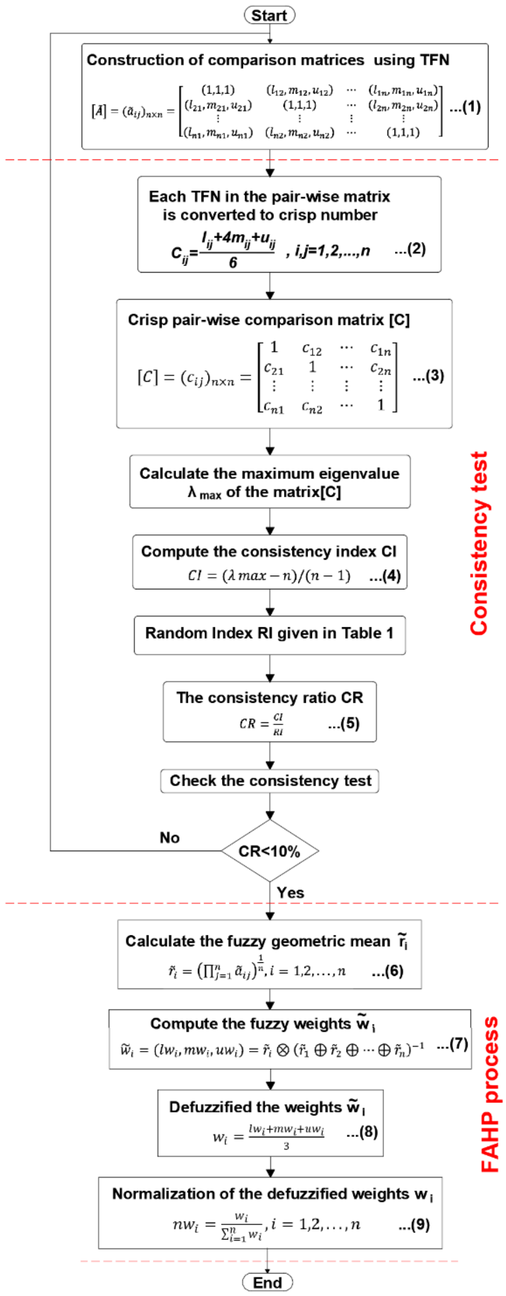

Fig 5. Flowchart illustrating weight calculation using FGMM.

Tab 1. Random Consistency Index (RI), [8].

n	3	4	5	6	7	8	9
RI	0.53	0.88	1.11	1.25	1.34	1.41	1.45

Figure 5 shows the step-by-step process for using the geometric mean method to find weights. The linked Tab. 1 that was used in the flowchart is shown above. The following paragraph will provide a more detailed explanation of the process:

- Step 1: Matrix comparison construction. The pairwise comparison matrix, denoted as $[\tilde{A}]$, is detailed in Eq. 1 of Fig. 5. Here, i and j range from 1 to n, where n represents the number of criteria under consideration. This matrix is created by gathering expert scores derived from pairwise comparisons of the relative importance of criteria, as depicted in Fig. 4.

- Step 2 : Consistency check. In order to verify the coherence of the judgement matrix, each TFN in the pairwise matrix was defuzzified by converting it into a net number c_{ij} (Eqs. 2 and 3 of Fig.5). Eq.4 is then used to compute the consistency index CI [8]. Where the symbol λ_{max} signifies the maximum eigenvalue of the matrix [C]. Subsequently, the formula to calculate the consistency ratio (CR) is provided in Eq. 5, utilising the random index (RI) specified in Table 1 for this computation. Matrices exhibiting CR values equal to or below 10% are considered acceptable, while those surpassing 10% are deemed unacceptable, according to Saaty's research [8].

- Step 3 : Application of the fuzzy geometric mean approach. Buckley specifies that the matrix $[\tilde{A}]$, is formulated through an aggregation process using the fuzzy geometric mean $\tilde{r}_i$, detailed in Eq. 6. The fuzzy weights $\tilde{w}_i$ are computed using the method outlined in Eq.7. This involves multiplying each fuzzy geometric mean $\tilde{r}_i$ by the summation of a vector. Subsequently, the fuzzy weights $\tilde{w}_i$ must undergo defuzzification using the centre of area approach [5], as illustrated in Eq. 8. The ensuing procedure includes normalising the defuzzied weights according to Eq. 9, as portrayed in Fig. 5.

2.2.4 Assessing degradation score

The FAHP approach is utilised in this part of the study to establish the overall weights for each element. Then, on a scale of 0 to 10, each factor is assigned an expert score known as an "ESC". Tab. 2. shows the relationship between the ESC and the appropriate scale.

Tab 2. Status of risk grading [5]

ESC	State condition of scaling
[0,2]	no risk grade noticed
[2,4]	low- grade risk
[4,6]	moderate risk
[6,8]	high risk
[8,10]	super high risk

The average score (ACS) is then calculated using the following formula: $ACS = \frac{\sum_{i=1}^{m} ESC_i}{m}$ (10)

Let m denote the total number of experts engaged in the task. Finally, Eq.11 mathematically describes the comprehensive score (CS), also known as the overall score for the degradation of ORCB.

$$CS = \sum_{i=1}^{k} W_i \times ACS_i \quad (11)$$

Here k is the number of selected sub-criteria.

2.2.5 The classification of degradation in ORCB

The present study employs the EMS98 [7] (European Macro-seismic Scale 1998) to categorise the extent of deterioration seen in ORCBs. The criteria for assessing the degree of degradation in ancient structures are outlined in Tab. 3, with consideration given to the aggregate score. The total level of deterioration is correlated with a certain hue that signifies the structural integrity of the entity. It is of significance to acknowledge that the designated levels of damage are categorised into five distinct classes, spanning from class 1 denoting no damage to class 5 indicating a collapsed structure. The classification system proposed by Allali et al [4] facilitates the categorization of structures into three distinct colour groups: green, orange, and red. This classification scheme appears in Tab. 3.

Tab 3. ORCB damage classification according to EMS-98

Class	CS	Tag Color	Damage Intensity
1	[0,2]	Light green	Negligible to slight damage
2	[2,4]	Dark Green	Moderate damage
3	[4,6]	Light Orange	Substantial to heavy damage
4	[6,8]	Dark Orange	Very heavy damage
5	[8,10]	Red	Destruction

3. Interpretation Of Results

The comparison matrices between the criteria and sub-criteria of the hierarchical structure presented in this study are depicted in Tab. A.1. of the App. A. Moreover, it is apparent that the computed coherence rates CR are below 10%, suggesting that the consistency of the evaluations of the fuzzy decision matrices is satisfactory. The local and global weights estimated using the FAHP approach may be seen in Tab. B.1. of the App. B. The data unequivocally demonstrates that the group labelled "structural disorders" holds paramount importance, constituting 56.51% of the overall weight. The category of "environmental conditions" closely trails behind, accounting for 22.51% of the total weight. In contrast, the degradation of the ORCB has a much lower degree of susceptibility to factors such as the historical condition of the ORCB and professional intervention, as seen by their respective weights of 12.46% and 8.52%.

4. Administration of EL Malah Case Study

The subject of our case study is the administration of EL Malah, situated in the northwestern region of Algeria, specifically in the town of EL Malah. The structure, erected in the period of colonialism, consists of a ground floor, a first floor, and a basement. It is important to note that the construction of this edifice occurred in the context of French colonial power. The primary factor contributing to the observed deterioration is the significantly advanced age of the structure, coupled with the inherent degradation of the constituent materials. The probable cause of this issue might be attributed to a deficiency in regular maintenance, which is often necessary for reinforced concrete structures. The images depicted in Fig. 6.a through 6.d exhibit a diverse range of indications of degradation.

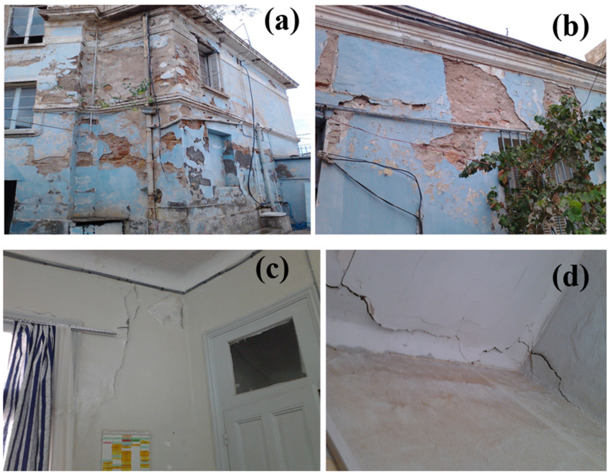

Fig 6. Photos showing a variety of signs of degradation in the ORCB in El Malah.

At this stage, it is imperative to engage the expertise of a professional to provide an ESC score for the purpose of assessing the extent of degradation of the previous reinforced concrete edifice. The ESC score of each sub-criterion is thereafter multiplied by the total relative weight. The ultimate phase of this case study is the computation of the comprehensive score in accordance with Eq. 11. According to the data presented in Tab. B.1. of the App. B, the observed outcome yielded a value of CS = 5.448, measured on a scale that spans from 0 to 10. Based on the EMS98 standard, the classification of this location assigns it to class 3, denoted by the colour bright orange. The aforementioned categorization denotes a state of susceptibility accompanied by significant harm, underscoring the pressing necessity for prompt action.

5. Conclusion

The study utilised a fuzzy hierarchic analytical technique (FAHP) to assess the structural integrity of ageing reinforced concrete structures. The FAHP methodology demonstrated its efficacy in addressing ambiguities and identifying key criteria that impact the final choice. The most prominent element identified was structural problems, accounting for 56.51% of the overall weight, followed by environmental circumstances. The influence of "historic state of the ORCB" and "intervention circumstances" on the degrading process was comparatively lower, accounting for 12.46% and 8.52%, respectively. The full score index (CS) was used to conduct a comprehensive condition assessment of the administrative building in El Malah, resulting in a CS value of 5.548, which is within the specified range of [4,6]. The construction is classified as class 3, denoted by a light orange colour, indicating vulnerability and moderate levels of harm and emphasising the need for prompt action.

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Appendix A

Tab A.1. Pairwise comparison matrices and their consistency tests

Factors	C1	C2	C3	C4	Consistency test
C1	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{6}^{-1}$	$\tilde{2}^{-1}$	λmax=4.106, CI=0.035, RI=0.882, CR=4.00%< 10%
C2	$\tilde{2}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}$	
C3	$\tilde{6}$	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$	
C4	$\tilde{2}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$	

	C1.1	C1.2	C1.3	C1.4	Consistency test
C1.1	$\tilde{1}$	$\tilde{3}$	$\tilde{1}$	$\tilde{2}$	λmax=4.030, CI=0.010, RI=0.882, CR=1.14%< 10%
C1.2	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	
C1.3	$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{2}$	
C1.4	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	

	C2.1	C2.2	C2.3	C2.4	C2.5	C2.6	Consistency test
C2.1	$\tilde{1}$	$\tilde{2}$	$\tilde{2}$	$\tilde{2}$	$\tilde{2}$	$\tilde{3}$	λmax=6.438, CI=0.088, RI=1.248, CR=7.023%< 10%
C2.2	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	
C2.3	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{4}$	$\tilde{4}$	
C2.4	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	
C2.5	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{4}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	
C2.6	$\tilde{3}^{-1}$	$\tilde{2}^{-1}$	$\tilde{4}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	

	C3.1	C3.2	Consistency test
C3.1	$\tilde{1}$	$\tilde{1}$	CR not verified for comparison between two criteria
C3.2	$\tilde{1}$	$\tilde{1}$	

	C3.1.1	C3.1.2	C3.1.3	C3.1.4	C3.1.5	C3.1.6	C3.1.7	C3.1.8	C3.1.9	Consistency test
C3.1.1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	λmax=9.141, CI=0.018, RI=1.450, CR=1.214%< 10%
C3.1.2	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	$\tilde{2}$	
C3.1.3	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	
C3.1.4	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	
C3.1.5	$\tilde{2}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	
C3.1.6	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	$\tilde{2}$	
C3.1.7	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	
C3.1.8	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	
C3.1.9	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	

	C3.2.1	C3.2.2	C3.2.3	C3.2.4	C3.2.5	C3.2.6	Consistency test
C3.2.1	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	λmax=6.070, CI=0.014, RI=1.248, CR=1.213%< 10%
C3.2.2	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{2}$	
C3.2.3	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{4}$	
C3.2.4	$\tilde{2}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	$\tilde{2}$	
C3.2.5	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	
C3.2.6	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{4}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	

	C4.1	C4.2	Consistency test
C4.1	$\tilde{1}$	$\tilde{2}$	CR not verified for comparison between two criteria
C4.2	$\tilde{2}^{-1}$	$\tilde{1}$	

	C4.1.1	C4.1.2	Consistency test
C4.1.1	$\tilde{1}$	$\tilde{1}$	CR not verified for comparison between two criteria
C4.1.2	$\tilde{1}$	$\tilde{1}$	

	C4.2.1	C4.2.2	Consistency test
C4.2.1	$\tilde{1}$	$\tilde{1}$	CR not verified for comparison between two criteria
C4.2.2	$\tilde{1}$	$\tilde{1}$	

Appendix B

Tab B.1 The weights of the criteria and classification of the investigated ancient reinforced concrete building

Level 1		Level 2		Level 3		W_i(%)	ESC	ESCxW_i
Factors	w_i (%)	Sub-Factors	w_i (%)	Sub-Factors	w_i (%)			
C1	12.46	C1.1	35.17	-	-	4.38	9.00	0.3944
		C1.2	15.40	-	-	1.92	7.00	0.1344
		C1.3	31.83	-	-	3.97	6.00	0.2379
		C1.4	21.90	-	-	2.19	9.00	0.1973
C2	22.51	C2.1	28.72	-	-	6.47	9.00	0.5819
		C2.2	16.87	-	-	3.8	8.00	0.3038
		C2.3	19.72	-	-	4.44	8.00	0.3552
		C2.4	14.81	-	-	3.34	5.00	0.1668
		C2.5	11.97	-	-	2.69	3.00	0.0808
		C2.6	7.91	-	-	1.78	2.00	0.0356
C3	56.51	C3.1	50.00	C3.1.1	10.17	2.87	6.00	0.1725
				C3.1.2	12.52	3.54	8.00	0.2829
				C3.1.3	11.62	3.28	4.00	0.1313
				C3.1.4	11.62	3.28	3.00	0.0985
				C3.1.5	12.52	3.54	3.00	0.1061
				C3.1.6	12.52	3.54	2.00	0.0707
				C3.1.7	11.62	3.28	8.00	0.2626
				C3.1.8	9.60	2.71	7.00	0.1899
				C3.1.9	7.81	2.21	2.00	0.0442
		C3.2	50.00	C3.2.1	9.59	2.71	6.00	0.1626
				C3.2.2	23.67	6.69	1.00	0.0669
				C3.2.3	26.57	7.51	6.00	0.4505
				C3.2.4	20.68	5.84	7.00	0.4090
				C3.2.5	9.59	2.71	6.00	0.1626
				C3.2.6	9.90	2.8	1.00	0.0280
C4	8.52	C4.1	64.39	C4.1.1	50.00	2.74	2.00	0.0549
				C4.1.2	50.00	2.74	2.00	0.0549
		C4.2	35.61	C4.2.1	50.00	1.52	7.00	0.1062
				C4.2.2	50.00	1.52	7.00	0.1062
$CS = \sum_{i=1}^{29} W_i \times ACS_i$=5.448; class3; tag color				Light orange	Substantial to heavy damage			