Condition Ranking and Rating of Bridges Using Fuzzy Logic

Saptarshi Sasmal, K. Ramanjaneyulu and Nagesh R. Iyer
*CSIR-Structural Engineering Research Centre,
CSIR Complex, TTTI Post, Taramani,
India*

1. Introduction

Bridges are the crucial components of highway networks. In recent years, there has been growing awareness about the problems associated with the existing old bridges. Many of the existing bridges in service today were designed for less traffic, smaller vehicles, slower speeds and lighter traffic. Hence, they have become inadequate according to the current loading standards/codes of practice for design of highway bridges. Even in the case of newer bridges, deterioration caused by unforeseen service condition, adverse environmental actions and inadequate maintenance is causing great concern to bridge engineers. Bridge authority has the responsibility to maintain its bridges in a safe condition. To ensure safe and durable service, it is usual to perform periodic in-situ inspections. These inspections involve visual observations, non-destructive testing and partial destructive testing. The data collected from site and processed in laboratory, would be used to decide about suitable repair, strengthening or demolition of existing bridges. It is also evident that engineers and decision makers have to deal with large number of deficient bridges in years to come and it will be extremely demanding to decide the most deserving one to allot fund for timely retrofitting. Further, it is necessary to formulate a systematic method to assess the present and future needs of the existing bridges which would help the decision makers in identifying the most deserving bridges for improvement during a given period.

In view of this, several countries have initiated development of bridge management systems for assisting their decision makers in finding optimal strategies for maintenance, rehabilitation and replacement of bridges. Furthermore, it also has to ensure value for money by carrying out preventive work at appropriate time so that future maintenance needs are also kept at a minimum level. In a broader sense, the funding body has to consider the justification and priority for money to be spent on a multitude of expenditure areas. Decision makers and/or society at large should be able to choose whether to spend money on rehabilitating a bridge or to demolish it. The bridge engineers and the policy makers are being increasingly pressed to justify the funding order proposed to maintain the bridges. It shows the importance of an exclusive bridge management system. Bridge management is a rational and systematic approach for organising and carrying out the activities related to planning, design, construction, maintenance, rehabilitation and replacement of bridges.

To decide upon all these matters, a systematic and logical way for prioritization of the bridges under consideration and rating of the most deserved one is needed (as shown in Fig. 1). The bridge condition rating is the datum for any bridge management system. The usefulness of a bridge management system and the accuracy of bridge rating rely upon the bridge condition data which constitute subjective judgment and intuition of the bridge inspector. So, a procedure like fuzzy logic would be useful to handle the uncertainty, imprecision and subjective judgment.

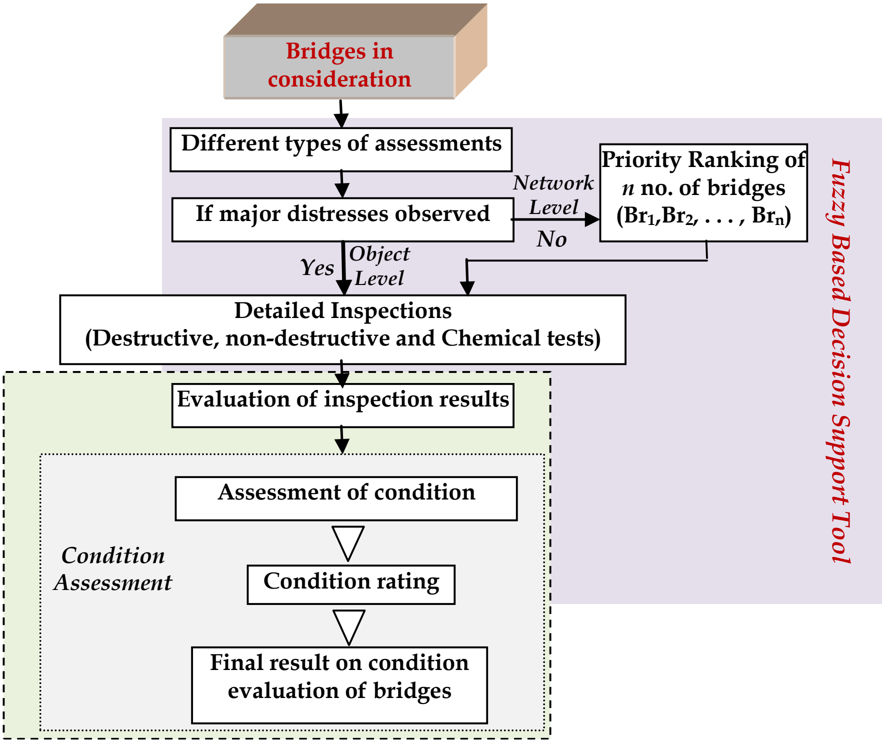


Fig. 1. Schematic representation of condition assessment of bridges

Before proceeding further, it is important to know the decision making tools useful for this type of problem. To provide the ready reference to the readers, few of the mostly used and appropriate models are discussed below.

2. Different decision making methods

One of the most crucial problems in many decision making methods is the precise evaluation of data. Very often, in real-life decision making applications, data are imprecise and fuzzy [Ben-Arieh and Triantaphyllou (1992), Tseng and Klein (1992)]. A decision maker may encounter difficulty in quantifying and processing linguistic statements. Therefore, it is desirable to develop decision making methods which can handle fuzzy data. It is equally important to evaluate the performance of the following decision making methods. Among the decision making methods, the Weighted Sum Model (WSM) is probably the best known and most widely used method of decision making, especially in single dimensional problem. If there are M alternatives and N criteria in a decision making problem, then the best alternative, A^*, is the one which satisfies (in the maximisation case) the following expression (Fishburn, 1967)

$$A^*_{WSM} = \max_i \sum_{j=1}^{N} a_{ij} W_j \quad \text{for } i = 1,2,\ldots,M \tag{1}$$

where, a_{ij} is the measure of performance of the i^{th} alternative in terms of the j^{th} decision criterion, and W_j is the weight of importance of the j^{th} criterion. Further, Weighted Product Model (WPM) is very similar to WSM. The main difference is that it uses multiplication, instead of addition, to rank alternatives. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power of the related weight of the corresponding criterion. Generally, in order to compare the two alternatives A_K and A_L, the following formula (Bridgman, 1922; Miller and Starr, 1969; Chen and Hwang, 1992) can be used.

$$R\left(\frac{A_K}{A_L}\right) = \prod_{j=1}^{N} \left(\frac{a_{Kj}}{a_{Lj}}\right)^{W_j} \tag{2}$$

where, N is number of criteria, a_{ij} is actual value (performance) of i^{th} alternative in terms of j^{th} criterion and W_j is weight of importance of the j^{th} criterion. The analytic hierarchy process (AHP) was developed by Saaty (1980), based on an axiomatic foundation that has established its mathematical viability (Harker and Vargas 1990; Saaty, 1994). The diverse applications of the technique are due to its simplicity and ability to cope with complex decision making problems. The AHP methodology has been widely used for solving problems where definite quantitative measures are not available to support correct decisions. Zahedi (1986) provided an exhaustive survey of AHP methodology and its applications. The AHP attracted the interest of many researchers for long because of its easy applicability and interesting mathematical properties. In this chapter also, AHP, the well-proven technique, is used as a decision making tool because of its inherent strength in tackling complex problems.

2.1 Formation of Analytic Hierarchy Model (AHM) for AHP

The AHP deals with the construction of an M × N matrix (where M is the number of alternatives and N is the number of criteria) using the relative importance (weights) of the alternatives in terms of each criterion. The vector $X_i = (a_{i1}, a_{i2}, a_{i3}, \ldots, a_{iN})$ for the i^{th} alternative ($i=1,2,3,\ldots,M$) is the eigenvector of an N × N reciprocal matrix which is determined through a sequence of pair-wise comparisons. Also, the elements in such a vector add-up to one. The AHP uses relative values instead of actual ones. Therefore, the AHP can be used in single- and multi-dimensional decision making problems. The analytic hierarchy model (AHM) begins with representing a complex problem as a hierarchy. At the top level of the hierarchy, the goal (objective) upon which the best decision should be made is placed. The next level of the hierarchy contains attributes or criteria that contribute to the quality of the decisions. Each attribute may be decomposed into more detailed attributes (indices). After the hierarchical network is constructed, one can determine the weights (importance measures) of the elements at each level of the decision hierarchy, and synthesize the weights to determine the relative importance (weights) of decision alternatives. First, a comparison matrix, which includes first (lowest) level elements of the hierarchy, is constructed. Then, a ratio scale through pair-wise comparison of each pair of criteria with respect to the overall goal is performed. The relative importance (weight) of each criterion is estimated using an eigenvector approach or other methods. Then, the relative importance (weight) of each alternative with respect to each criterion is determined using similar pair-wise comparisons. Here, it is important to note that the efficiency of AHP greatly depends on the accuracy with which pair-wise weights of items are assigned during the formation of comparison matrix. For pair-wise assignment of weights for items, there is a need for a scale for relative quantification of items.

2.2 Scales for quantifying pair-wise comparisons

One of the most vital and crucial steps in decision-making methods is the accurate estimation of the pertinent data. Very often, these data are not known in terms of absolute values. Therefore, many decision-making methods attempt to determine the relative importance (weight) of each alternative involved in a given decision-making problem. Consider the case of having a single decision criterion and a set of N alternatives denoted as A_i (i = 1, 2, 3,…, N). The decision maker wants to determine the relative performance of the alternatives under each criterion. Here, one may consider the N alternatives as the members of a fuzzy set. Then, the degree of membership of element (i.e. alternative) A_i expresses the degree to which alternative A_i meets the criterion. This is also the approach considered by Federov et al. (1982) and Chen and Hwang (1992) and was also discussed by Saaty (1994). All the methods which use the pair-wise comparison approach eventually express the qualitative answers of a decision maker as some numbers. Pair-wise comparisons are quantified by using a scale. Such a scale is one-to-one mapping between the set of discrete linguistic choices available to the decision maker and a discrete set of numbers which represent the importance or weight of the previous linguistic choices. There are two major approaches in developing such scales. The first approach is based on the linear scale and the other is based on exponential scale [Roberts (1979), Lootsma (1991)]. It is easier to use linear scale to translate the weight of an item/element over the other. Therefore, in this study, the linear scale has been used to assign the importance/weight of items or elements under each decision layer.

2.3 Real Continuous Pair-wise (RCP) and Closest Discrete Pair-wise (CDP) matrices

A procedure is required for obtaining comparison matrix from the relative importance (weights) for a group of elements, using a suitable scale, based on pair-wise comparisons. It involves the formulation of real continuous pair-wise (RCP) and the closest discrete pair-wise (CDP) matrices. Reciprocal matrices with pair-wise comparisons were used for extracting all the pertinent information from a decision maker. Each entry in these matrices represents numerically the value of a pair-wise comparison between two alternatives with respect to a single criterion. For a problem that has 'p' objectives, a scale is constructed for rating these objectives as to their importance with respect to the decision as seen by the analyst. Let w_1, w_2, w_3, …………, w_p be the real membership values of a fuzzy set with p members. Comparing objective k with objective l, the ratios α_{kl} can be assigned, and the RCP matrix (p × p) is constructed as

$$RCP = A_{p\times p} = [\alpha_{kl}] = \left[\frac{w_k}{w_l}\right] \quad k,l = 1,p \tag{3}$$

The entry α_{kl} in RCP matrix represents the exact (and thus unknown) value of the comparison when the k^{th} member is compared with the l^{th} member. Each element β_{kl} ($\beta_{kl} \in \Phi$) in the CDP matrix can be determined and the matrix will be formed such that $\left|(\alpha_{kl} - \beta_{kl})\right|$ is minimum. Any other norm may also be assumed as

$$\left|\frac{\alpha_{kl}}{1+\alpha_{kl}} - \frac{\beta_{kl}}{1+\beta_{kl}}\right| \tag{4}$$

3. Condition evaluation of existing bridges through prioritization

The Analytic Hierarchy Process (AHP) is mainly applied to the decision making problem with multiple evaluation criteria and uncertainty conditions. After hierarchical decomposition from different layers and through the quantitative judgment, the AHP is thus made a synthetic evaluation to reduce risk of wrong decision making. The AHP uses eigenvalue method to find the weights of different items. The eigen equation is adopted to construct the comparison matrix (Yu and Cheng, 1994, Liang et al., 2001) for finding the relative importance (weights) and orders of multiple objectives to an objective and the concept has already been successfully used to solve different types of decision making problems. The methodology involves the following operations.

3.1 Relative importance (weights) of items

A decision-maker provides the upper triangle of the comparison matrix (as shown in Table 1), while reciprocals are placed in the lower triangle which do not need any further judgment. The diagonal elements of the matrix are always equal to one. Assuming that any item group consists of A_1, A_2, A_3, ….A_n items, the comparison matrix is constructed and then relative weights of items (A_{ij}) of the group are evaluated by comparing objective *i* with objective *j*, the ratios α_{kl} can be assigned, and the real continuous pair-wise (RCP) matrix of order $p \times p$ is constructed. It can be proved that consistent reciprocal matrix '[A]' has rank 1 with non-zero eigenvalue (λ) = n. Then, we have

$$[A]w = nw \text{ Where, w is an eigenvector} \tag{5}$$

The same equation also states that in the perfectly consistent case (i.e. $A_{ij} = A_{ik} A_{kj}$), the vector w, with the membership values of the elements 1,2,3,….,n is the principal right-eigenvector (after normalisation) of matrix [A].

3.2 Check for consistency of comparison matrices

In most of the real world problems, the pair-wise comparisons are not perfect, that is, the entry A_{ij} might deviate from the ratio of the real membership values W_i and W_j (i.e. W_i /

W_j). In a non-consistent case, the expression $A_{ij} = A_{ik} \times A_{kj}$ does not hold good for all the possible combinations. Now, the new matrix [A] can be considered as a perturbation of the previous consistent case when the entries A_{ij} change slightly, then the eigenvalues change in the similar fashion (Saaty, 1994). Moreover, the maximum eigenvalue is close to n (greater than n), while the remaining eigenvalues are close to zero. Thus, in order to find the membership values in the non-consistent cases, one should find an eigenvector that corresponds to the largest eigenvalue λ_{max}. That is to say, one must find the principal right-eigenvector W that satisfies

$$AW = \lambda_{max} W \qquad \text{where } \lambda_{max} \approx n \tag{6}$$

The consistency ratio (CR) is obtained by first estimating λ_{max} of matrix [A] Then, Saaty (1994) defined the consistency index (CI) of the matrix '[A]' as

$$CI=(\lambda_{max}-n)/(n-1) \tag{7}$$

Then, the consistency ratio (CR) is obtained by dividing CI with the random consistency index (RCI) as shown in Table 2 (proposed by Saaty, 1994). Each RCI is an average random consistency index derived from a sample of size 500 of randomly generated reciprocal matrices. If the previous approach yields a CR greater than 0.10 then a re-examination of the pair-wise judgments is recommended until a CR less than or equal to 0.10 is achieved.

B	A_1	A_2	A_3	….	A_n
A_1	A_{11}	A_{12}	A_{13}	….	A_{1n}
A_2	A_{21}	A_{22}	A_{23}	….	A_{2n}
A_3	A_{31}	A_{32}	A_{33}	….	A_{3n}
….	….	….	….	….	….
A_n	A_{n1}	A_{n2}	A_{n3}	….	A_{nn}

Table 1. Comparison Matrix

n	1	2	3	4	5	6	7	8	9	≥10
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.56

Table 2. RCI values of sets of different order 'n'

3.3 Fuzzy synthetic evaluation of estimation indices for items

Most of the decision making in the real world takes place in a situation in which the pertinent data and the sequence of possible actions are not precisely known. Therefore, it is very important to adopt fuzzy data to express such situations in decision making problems. In order to fuzzify the crisp decision making methods, it is important to know how fuzzy operations are used on fuzzy numbers. Fuzzy operation in decision making was first introduced by Dubois and Prade (1979) and Boender et al. (1989) presented a fuzzy version of the AHP. For fuzzy numbers, triangular fuzzy numbers (that is, fuzzy numbers with lower, modal and upper values) are preferred, because they are simpler than trapezoidal fuzzy numbers. A fuzzy number M on $R \in (-\infty, +\infty)$ is defined by Dubois and Prade, 1979 to be a fuzzy triangular number if its membership function $\mu_m: R \to [0,1]$ is equal to

$$\mu_m(x) = \begin{cases} \frac{1}{m-l}x - \frac{l}{m-l} & x \in [l, m] \\ \frac{1}{m-u}x - \frac{l}{m-u} & x \in [m, u] \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where, $l \le m \le u$, and l and u stand for the lower and upper values of the support for the decision of the fuzzy number M, respectively, and m for the modal value. In this study, the basic mathematical operations on fuzzy triangular numbers developed by Laarhoven and Pedrycz (1983) are followed. In decision problems, the maximum and minimum membership function suggested by Zadeh (1973) are adopted and expressed in the following form.

$$\mu(x) = \begin{cases} 1 & f(x) \le \inf(f) \\ \frac{\sup(f) - f(x)}{\sup(f) - \inf(f)} & \inf(f) < f(x) < \sup(f) \\ 0 & f(x) \ge \sup(f) \end{cases} \tag{9}$$

and

$$\mu(x) = \begin{cases} 1 & f(x) \ge \sup(f) \\ \frac{f(x) - \inf(f)}{\sup(f) - \inf(f)} & \inf(f) < f(x) < \sup(f) \\ 0 & f(x) \le \inf(f) \end{cases} \tag{10}$$

where sup(f) and inf(f) are the superior and inferior values of f(x) respectively. It is understandable that Eq. (9) is a membership function with monotonic decrease whereas Eq. (10) is a membership function with monotonic increase. The significance of Eq. (9) is that the less the value is, more requirement for repair whereas the meaning of Eq. (10) is just the opposite of Eq. (9). An evaluation method can be developed by separating bridge deterioration into D (degree), E (extent), R (relevance) and U (urgency) for assessment. A combination of visual inspection, field and laboratory testing may be employed for determining the item estimation indices of bridges considered for condition assessment. Based on inspection results of all the items, the condition index (CoI) is calculated by using

$$\text{CoI} = \frac{\sum (Ic_i \times w_i)}{\sum w_i} \tag{11}$$

Where, w_i is the weight of each bridge item and is greater than 1, and Ic_i is calculated as

$$Ic_i = \frac{\sum Ic_{ii}}{n} \tag{12}$$

in which n is the number of relevant inspection items for a particular bridge, and Ic_{ii} is the item condition estimation index for each item and is calculated as

$$Ic_{ii} = D \times E \times R^a \times U^a \tag{13}$$

3.4 Condition ranking of existing bridges

If $R_{n,m}$ (in which n= 1,2….no of criteria layers, and m=1,2,…of items in each index layer) denotes the membership degrees of estimation indices of the items under index layer and $\bar{W}_n$ stands for the relative weights of items under index layer (calculated by using Eq. 3), then the relationship between $R_{n,m}$ and $\bar{W}_n$ can be presented by

$$\bar{D}_n = \bar{W}_n R_{n.m} \tag{14}$$

where the value $\bar{D}_n$ in Eq. 14 is the fuzzy synthesis evaluation matrix. The purpose of $\bar{D}_n$ is to construct the membership function for each alternative of evaluation set. The membership degrees of estimation indices, $R_{n.m}$, can be formulated based upon the decision makers choice in using the pessimistic- or optimistic- functions as stated in Eqs. 9 and 10, respectively.

Based on the fuzzy mathematics theory, the fuzzy synthesis evaluation result, $\bar{B}$, of any factor can be expressed as

$$\bar{B} = \bar{A}_n . \bar{D}_n \tag{15}$$

where, $\bar{A}_n$ is the weight vector. The prioritization or optimum repair order can be determined by using Eq. (15). The more the value of $\bar{B}$ has, the better the priority selection to decision making objective is.

4. Application of fuzzy logic for condition rating of bridges

The aim of the bridge condition rating is to evaluate the structural strength and serviceability condition of an existing bridge. Fuzzy set theory was specially defined to analyse the linguistic data within the formal mathematical framework. After the publication on fuzzy sets by Zadeh (1965), fuzzy mathematics was used extensively for numerous applications. Brown and Yao (1983) described the methodology of application of fuzzy sets in structural engineering. Tee et al. (1988) suggested a fuzzy mathematical approach for evaluation of bridges. Shiaw and Huang (1990) adopted the limit state design principle combined with fuzzy evaluation and random variable analysis to determine the bearing capacity index and degree of safety for bridges. Jwu et al. (1991) used fuzzy mathematics to determine the reliability of a wharf structure. In order to enhance the evaluation performance, the grade partition method was suggested. Tee and Bowman (1991) presented bridge condition assessment model that is based on resolution identity of fuzzy sets. Qian (1992) used the concept of fuzzy sets to evaluate the damage grade of existing bridges. Yu and Cheng (1994) presented a fuzzy based interactive comparison matrix approach for making group decision with multiple objectives. Wang (1996) provided a multi-target and multi-person evaluation method for structural durability. Melhem and Aturaliya (1996) proposed a model for condition rating of bridges using an eigenvector based priority setting. Liang et al. (2001) used fuzzy mathematics to build a damage evaluation methodology for existing reinforced concrete bridges. Liang et al. (2002) proposed grey and regression models for predicting the remaining service life of existing reinforced concrete bridges. Zhao and Chen (2002) developed a fuzzy rule-based inference system for bridge damage diagnosis and prediction which aims at providing bridge designers with valuable information about the impact of design factors on bridge deterioration. Kawamura and Miyamoto (2003) presented a new approach for developing a concrete bridge rating expert system for deteriorated concrete bridges, using multi-layer neural networks. To evaluate the condition of different structures using fuzzy logic, the proposed methods are either too simplistic [Qian (1992); Liang et al. (2001)] or very complex [Jwu et al. (1991); Kawamura and Miyamoto (2003)]. In this chapter, a systematic procedure and formulations have been proposed for condition rating of existing bridges using fuzzy mathematics combined with eigenvector based priority setting technique. From the review of literature, authors felt that the existing methodologies for condition rating of existing bridges may be difficult to follow for a practical application. In view of this, in this chapter, a methodology for condition rating of bridges is described in steps that can easily be followed for practical applications. The methodology and its application are demonstrated through a case study and the details are presented in the chapter.

4.1 Unified approach for condition rating of existing bridge

Some important issues and the methodology for the development of a systematic, fast and reliable evaluation system for rating of existing reinforced concrete bridges have been illustrated in the following sections.

4.1.1 Inspection data

Towards a systematic rating of existing bridges, the essential requirement is the input data from the bridge inspector that consist of the ratings and importance factors for the relevant elements of bridge which would reflect the overall condition of a bridge as a whole.

4.1.2 Inspector’s observation and rating of elements

Bridge inspection involves the use of various evaluation techniques in order to assess the physical condition of bridges. The Bridge Inspector’s Training manual 90 (FHWA 1991), published by the US Department of Transportation, provides the basic guidelines for bridge inspection. Bridge components and their constituent elements, different types of bridge deterioration and the common causes are discussed in this manual. It also provides procedures for rating the condition of various elements. In this study also, as specified in Bridge Inspector’s Training manual, bridge is divided into three major components, namely, ‘deck’, ‘superstructure’ and ‘substructure’. Each component is further divided into number of elements. The deck, superstructure and substructure have 13, 16 and 20 elements respectively as shown in Table 3. The bridge inspector is required to assess the condition of each element individually. The rating evaluation for that particular component is carried out based on the rating of the constituent elements. This process is repeated for all the three components towards final rating of the bridge. To a large extent, rating of the elements is based on the experience, intuition and personal judgment of the inspector. Nevertheless, although the condition assessment of each element requires the inspector’s personal judgment, general guidelines on how to assess the condition of the various elements are described in the inspector's manual. Hence, while two competent bridge inspectors may differ on the rating of a given element, but their difference in the rating would not be significant.

Deck	R	Superstructure	R	Substructure	R
1. Wearing Surface	8	1. Bearing devices	5	1. Bridge seats	6
2. Deck condition	9	2. Stringers	×	2. Wings	5
3. Kerbs	6	3. Girders	4	3. Back wall	6
4. Median	9	4. Floor beams	7	4. Footings	×
5. Sidewalks	8	5. Trusses	×	5. Piles	7
6. Parapets	9	6. Paint	5	6. Erosion	8
7. Railings	6	7. Machinery	×	7. Settlements	9
8. Paint	7	8. Rivets-Bolts	×	8. Pier-cap	2
9. Drains	8	9. Welds	2	9. Pier-column	5
10. Lighting	9	10. Rust	4	10. Pier-footing	3
11. Utilities	8	11. Timber decay	×	11. Pier-piles	6
12. Joint leakage	5	12. Concrete cracks	5	12. Pier-scour	5
13. Expansion joints	9	13. Collision damage	6	13. Pier-settlement	6
		14. Deflection	5	14. Pier-bents	4
		15. Member alignment	7	15. Concrete cracks	5
		16. Vibrations	6	16. Steel corrosion	8
				17. Timber decay	×
				18. Debris seats	5
				19. Paint	6
				20. Collision damage	5
Note: × - not applicable					

Table 3. Decomposition of a bridge into elements with observed ratings (**R**)

4.1.3 Evaluation of importance factors

In a bridge condition evaluation, rating of each element under a particular component does not influence the component's overall structural condition rating in a similar degree. A well trained inspector or the concerned expert determines the structural importance of different elements of all components of a bridge. The importance factor of element is not constant but varies with the degree of distress sustained by the element under consideration. Hence, determination of structural importance factors for various bridge elements is not an easy task. The knowledge gained by the bridge inspectors and experts through many years of design and inspection experience can not be obtained directly through structural analysis, although analysis can provide general trends of the behaviour of damaged members.

So, the importance factors for the elements at various deterioration stages should be evolved from the response of competent bridge inspectors/experts. These membership functions for structural importance were originally constructed through a survey among a number of bridge engineers and inspectors (Tee et al., 1988). Then, the collected data was statistically processed and the mean was presented by Melhem and Aturaliya (1996). As membership functions for structural importance corresponding to different ratings of elements/components is not bridge specific, membership functions for structural importance reported by Melhem and Aturaliya (1996) are used in the present study for structural importance factors of the elements under each component of the bridge. In this study, a scale of 1-9 has been considered for rating of the elements. An element with rating value of 9 signifies the best possible condition without distress and the descending rating numbers represent the increased degree of distress. The fuzzy membership values of structural importance for the elements of deck, superstructure and substructure are given in Tables 4, 5 and 6 respectively. From Tables 4 - 6, it may be noted that the mean value of the importance of an element increases as the physical condition deteriorates. For example, importance of deck concrete with rating 1 is 0.96, whereas its importance is 0.42 when the rating is 9.

4.2 Fuzzification of input data obtained from bridge inspectors

If R_n is a fuzzy set, representing rating of an element (where 'n' represents rating number i.e. n =0,1,…..9), the general form of the membership function can be formed as follows:

$$R_n = \mu_m(r_m) \mid r_m \qquad (m = 0,1,2,\ldots,9) \tag{16}$$

where, $\mu(r)$ is a membership function representing the degree of membership of any fuzzy set and $0 \le \mu \le 1$. The function as described in Eq. (16) quantifies the ambiguity associated with the rating of any element of a bridge. Any rating number can be represented using fuzzy membership function (Emami et al. 1998).

		Mean values of Structural Importance									
SL No.	Item \ Rating	0	1	2	3	4	5	6	7	8	9
1	wearing coat	1	0.90	0.80	0.70	0.61	0.51	0.45	0.33	0.23	0.17
2	deck concrete	1	0.96	0.92	0.89	0.85	0.81	0.77	0.72	0.50	0.42
3	curbs	1	0.85	0.70	0.55	0.40	0.25	0.20	0.14	0.10	0.08
4	median	1	0.85	0.70	0.54	0.39	0.24	0.21	0.14	0.11	0.09
5	sidewalks	1	0.88	0.76	0.64	0.52	0.40	0.33	0.25	0.17	0.14
6	parapets	1	0.88	0.76	0.63	0.51	0.39	0.33	0.26	0.19	0.19
7	railing	1	0.88	0.76	0.65	0.53	0.41	0.35	0.26	0.19	0.16
8	paint	1	0.87	0.74	0.61	0.48	0.35	0.31	0.24	0.18	0.15
9	drains	1	0.90	0.80	0.70	0.61	0.51	0.45	0.35	0.29	0.22
10	lighting	1	0.86	0.72	0.57	0.43	0.29	0.27	0.20	0.16	0.15
11	utilities	1	0.85	0.70	0.55	0.40	0.25	0.23	0.17	0.13	0.11
12	joint leakage	1	0.91	0.82	0.72	0.63	0.54	0.49	0.41	0.34	0.28
13	expansion joint	1	0.92	0.85	0.77	0.70	0.62	0.55	0.47	0.38	0.30

Table 4. Mean values of the structural importance for the deck elements for different rating

		Mean values of Structural Importance									
SL No.	Item \ Rating	0	1	2	3	4	5	6	7	8	9
1	bearing device	1	0.96	0.92	0.07	0.83	0.79	0.71	0.60	0.47	0.42
2	stringers	1	0.96	0.92	0.07	0.83	0.79	0.72	0.61	0.50	0.44
3	girders	1	0.98	0.97	0.95	0.94	0.92	0.85	0.75	0.64	0.58
4	floor beams	1	0.98	0.96	0.94	0.92	0.90	0.83	0.72	0.60	0.54
5	trusses	1	0.97	0.94	0.90	0.87	0.84	0.77	0.67	0.56	0.51
6	paints	1	0.90	0.80	0.70	0.60	0.49	0.43	0.35	0.29	0.24
7	machinery	1	0.94	0.88	0.82	0.76	0.70	0.66	0.58	0.52	0.44
8	rivet or bolts	1	0.96	0.91	0.87	0.82	0.78	0.71	0.61	0.49	0.42
9	weld cracks	1	0.97	0.95	0.92	0.90	0.87	0.83	0.73	0.63	0.56
10	rusts	1	0.95	0.90	0.84	0.79	0.74	0.64	0.54	0.40	0.31
11	timber decay	1	0.97	0.93	0.90	0.86	0.83	0.75	0.65	0.51	0.43
12	concrete crack	1	0.96	0.91	0.87	0.82	0.78	0.70	0.59	0.49	0.40
13	collision damage	1	0.94	0.88	0.83	0.77	0.71	0.64	0.53	0.42	0.35
14	deflection	1	0.95	0.89	0.84	0.78	0.73	0.66	0.59	0.50	0.43
15	alignment	1	0.94	0.88	0.83	0.77	0.71	0.64	0.54	0.44	0.37
16	vibrations	1	0.95	0.88	0.81	0.75	0.69	0.63	0.54	0.43	0.36

Table 5. Mean values of the structural importance for the superstructure elements for different rating

		Mean values of Structural Importance									
SL No.	Item \ Rating	0	1	2	3	4	5	6	7	8	9
1	bridge seats	1	0.95	0.90	0.86	0.81	0.76	0.68	0.57	0.45	0.40
2	wings	1	0.92	0.73	0.75	0.66	0.58	0.51	0.41	0.33	0.29
3	backwall	1	0.85	0.86	0.80	0.73	0.66	0.58	0.48	0.40	0.35
4	footings	1	0.95	0.90	0.84	0.79	0.74	0.67	0.57	0.46	0.42
5	piles	1	0.94	0.89	0.83	0.78	0.72	0.66	0.56	0.46	0.39
6	erosion	1	0.94	0.87	0.81	0.74	0.68	0.60	0.51	0.40	0.35
7	settlement	1	0.96	0.92	0.87	0.83	0.79	0.70	0.60	0.50	0.45
8	piers, caps	1	0.95	0.89	0.84	0.73	0.78	0.65	0.56	0.46	0.41
9	piers, columns	1	0.96	0.91	0.87	0.82	0.78	0.70	0.60	0.49	0.43
10	piers, footing	1	0.95	0.90	0.84	0.79	0.74	0.67	0.57	0.47	0.42
11	piers, piles	1	0.95	0.90	0.84	0.79	0.74	0.68	0.59	0.48	0.38
12	piers, scour	1	0.95	0.89	0.84	0.78	0.73	0.65	0.53	0.43	0.45
13	Piers settlement	1	0.96	0.91	0.87	0.82	0.78	0.70	0.62	0.51	0.42
14	pile, bends	1	0.95	0.90	0.85	0.80	0.75	0.67	0.58	0.48	0.42

SL No.	Rating / Item	Mean values of Structural Importance									
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
15	concrete crack	1	0.94	0.88	0.82	0.76	0.70	0.62	0.51	0.37	0.32
16	steel corrosion	1	0.95	0.90	0.84	0.79	0.74	0.66	0.54	0.43	0.36
17	timber decay	1	0.96	0.93	0.89	0.86	0.82	0.72	0.62	0.50	0.44
18	debris, seats	1	0.89	0.78	0.68	0.57	0.46	0.40	0.33	0.25	0.21
19	paint	1	0.90	0.79	0.69	0.58	0.48	0.41	0.34	0.26	0.22
20	collision damage	1	0.94	0.87	0.81	0.74	0.68	0.59	0.48	0.34	0.28

Table 6. Mean values of the structural importance for the bridge substructure elements for

Usually, the membership values for each rating value are assumed without indication of any specific reason. If membership functions for rating values of 0 and 1 are specified, the membership functions for other rating values can be evaluated using consecutive fuzzy addition rule (Kaufmann & Gupta, 1985). In this study, the rating membership functions for '0' and '1' are assumed as follows:

R_0 = {1.00 | 0, 0.76 | 1, 0.55 | 2, 0.35 | 3, 0.16 | 4, 0.00 | 5, 0.00 | 6,………. ,0.00 | 9} and

R_1 = {0.00 | 0, 1.00 | 1, 0.45 | 2, 0.00 | 3, 0.00 | 4, 0.00 | 5, 0.00 | 6,………. ,0.00 | 9}

Using fuzzy addition, rating membership functions for '2' is calculated as

R_2 = {0.00 | 0, 0.45 | 1, 1.00 | 2, 0.70 | 3, 0.45 | 4, 0.20 | 5, 0.00 | 6,………. ,0.00 | 9}

R_9 = {0.00 | 0, 0.09 | 1, 0.18| 2, 0.28 | 3, 0.39 | 4, 0.51 | 5, 0.62 | 6, 0.74| 7, 0.87| 8, 1.00 | 9}

Fuzzy membership functions for rating values 0 - 9, as obtained above, are shown in Fig. 2.

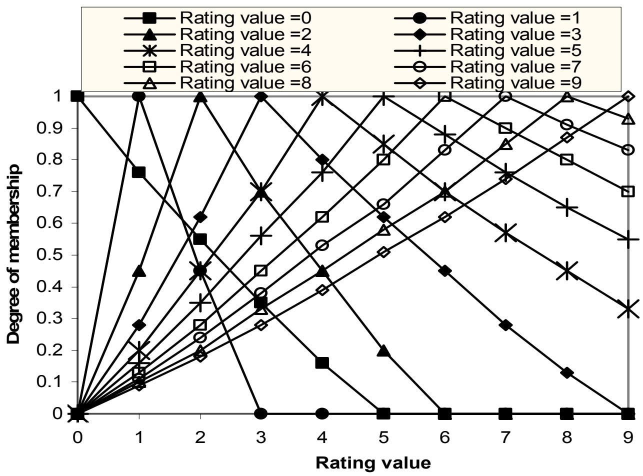


Fig. 2. Degree of membership of fuzzified rating values

4.3 Overall condition rating of a bridge

After getting the fuzzified rating and importance of all the elements, it is required to process those sets to arrive at the rating set for the components. In the similar way, the final rating for the bridge can be evaluated by processing the rating and importance sets of components. Generally, the processing of these rating and importance sets is executed using Fuzzy Weighted Average (FWA) or resolution identity technique. Brief details of these two techniques are given below:

4.3.1 Fuzzy Weighted Average (FWA) technique

Using a structural damage rating scheme according to the local, global and cumulative damage of the structure, resulting damage rating, R, can be evolved (Bertero & Bresler, 1977), using a weighted average approach, as

$$R=\frac{\sum(w_i\phi_i\Omega_i)}{\sum(w_i\delta_i\tau_i)} \tag{17}$$

where, w_i is the importance factor for the i^{th} structural element,

ϕ_i is the service history coefficient for structural response (or demand),
Ω_i is the structural response (or demand) in the i^{th} element due to load,
δ_i is the service history influence coefficient for capacity, and
τ_i is the resistance (or capacity) in the i^{th} element

For a bridge structure, Eq. (2) can be simplified for obtaining the rating as

$$R = \frac{\sum_{i=1}^{p}(w_i \times r_i)}{\sum_{i=1}^{p} w_i} \tag{18}$$

where, w_i is the importance coefficient of the i^{th} object, r_i is the local rating of the i^{th} object and R is the global or overall rating index when w_i and r_i stand for the bridge components, R is the component rating when w_i and r_i stand for the bridge elements. Detailed discussions on this methodology are given elsewhere (Sasmal et al., 2004a, 2004b).

4.3.2 Fuzzy resolution identification technique

A fuzzy set can be easily decomposed into its level sets or intervals through resolution identity as suggested by Dong and Wong (1987). If A is a fuzzy set of universe (U), then an α-level set or alpha cut of A is a non-fuzzy set denoted by A_α which comprises of all elements of U whose grade of membership in A is greater than or equal to α.

A_α can be expressed in symbolic form as:

$$A_\alpha = \{u \mid \mu_A(u) \geq \alpha\} \tag{19}$$

In mathematical form, the fuzzy set A can be decomposed into its level sets through the resolution identity such that

$$A = \sum_{\alpha=0}^{1} \alpha A_\alpha \text{ or, } A = \int_0^1 \alpha A_\alpha \tag{20}$$

where, αA_α is the product of a scalar α with the set A_α, and the symbol $\int_0^1$ (or $\sum_\alpha$) is the union of the A_α, with α ranging from 0 and 1.

The minimum (pessimistic) and maximum (optimistic) values of the intervals for a specific level set correspond respectively to the lower and upper limits of fuzzy membership function at that α-level. The set describing the rating of a component at a particular level of α would be

$$R_\alpha = \frac{\sum_{i=1}^{n} W_{i\alpha} R_{i\alpha}}{\sum_{i=1}^{n} W_{i\alpha}} \tag{21}$$

where, $R_{i\alpha}$ is the rating value for the i^{th} element at α-level, $W_{i\alpha}$ is the importance value for the i^{th} element at α-level. Therefore, the most pessimistic and optimistic range of the resulting set at each α-level would form all possible combinations using the discretised non-fuzzy values. Hence, the resolution identity technique provides a convenient way of generalizing various concepts associated with non-fuzzy sets to fuzzy sets.

From the above mentioned techniques for processing fuzzy sets, the FWA technique is simpler and faster. As FWA technique does not require discretisation of fuzzy set, accurate result may be achieved with less computational effort provided that the sets representing the rating or importance of different elements are convex. Otherwise, adjustments have to be made to the resulting fuzzy set to ensure its convexity for making the task of transforming a computed fuzzy set into natural language expression easier. Further, another adjustment that is often made to a fuzzy set is the normalization operation to ensure that at least one of the elements of the set contains the degree of membership of one, as suggested by Mullarky and Fenves (1985). On the other hand, accuracy of resolution identity technique depends on refinement of the concerned sets through α-level which has a direct impact on computational time. Therefore, in this study, a methodology has been proposed by judiciously using the advantages of both the techniques.

4.4 Combined technique for condition rating of existing bridges

In this present approach, the results obtained from eigenvector based priority setting approach combined with FWA for rating of the bridge components are taken as the input for the resolution identity module. It is to be mentioned here that the number of alternatives increase with the increase in the objects (here, components) considered. For example, if a bridge is considered to consist of three main components, such as, 'deck', 'superstructure' and 'substructure' with different ratings and importance factors, number of alternatives produced for each α-level is $2^{3+3} = 64$ to determine the most optimistic and pessimistic values. Further, for 11 α-levels (from 0 to 1.0 in step of 0.1), total number of calculations are

704. The same increases enormously with the increase in number of objects (here, components or elements of the bridge). If the procedure mentioned above is implemented for a bridge which is assumed to be divided into 10 components, the number of calculations required to get the resultant rating fuzzy set would be $2^{10+10} \times 11 = 11534336$. In fact, the availability of high speed microcomputers has made this approach attractive and practical for actual bridge inspection, management and planning applications.

Further, question may arise that why the resolution identity technique alone can not be applied for the whole bridge rating system by avoiding FWA technique. The simple answer is that component rating can be evolved by the simple FWA technique because there is no need for tackling non-convexity of the assigned sets unless it is essential. Otherwise, for the whole rating evaluation, number of calculations would be enormous. For a bridge having 3 components with 13, 16 and 20 elements (as described in Table 3) under the components, the total number of calculations required for the final result using resolution identity alone would be in the order of 1.2×10^{13}. Hence, a combined technique is proposed in this study to get the accurate result without much increase in computing time.

In the approach proposed in this study, priority setting values of elements are calculated to evaluate the power of importance of each element in describing the condition of a particular component. The usual techniques available for condition rating combine the rating and importance of elements to arrive at the rating of each component. But, the importance factor, as mentioned earlier, is very much dependent on the prevailing condition (rating) of the particular element. Thus, a minor element with worse condition may unnecessarily reduce the rating value of that component under which the element is grouped. This problem can be tackled by the introduction of power of importance which is independent of the prevailing condition of elements. As mentioned earlier, imprecision, subjective judgment and uncertainty are associated with bridge inspection data. Because of uncertainty, the bridge inspector may not exactly know the prevailing condition (rating) of a particular element of a bridge. Moreover, importance factor for an element depends on its rating. But, decision on rating is a difficult proposition. Under these circumstances, several models were introduced for decision making in a fuzzy environment. In this study, Multi-Attributive Decision Making (MADM) model has been adopted as a decision tool.

4.5 Multi-Attributive Decision Making (MADM) model

Multi-Attributive Decision Making (MADM) model is one of the methods in decision studies where the factors towards a priority decision are many (multi-criteria). The assessment of bridge rating can be viewed as a Multi-Attributive Decision Making model because of its many components and sub-components (elements). In this study, an attempt has been made to use MADM model, to get the priority vector of elements depending on their importance over the others which would lead to a reliable decision (rating) from the bridge inspection data. The general MADM model can be expressed as follows:

Let $L = \{L_i | i = 1,2,3,\ldots,p\}$ be a set of goals and $C = \{c_j | j=1,2,3,\ldots,n\}$ be a finite set of decision alternatives from which the acceptability of the alternatives is judged. The objective is to select the one, from these alternatives, that best satisfies the set of goals, $L_1, \ldots\ldots L_p$. The objective function can be expressed in the form of fuzzy set as follows:

$$L_i = [\mu_{i,1}(c_1)|c_1, \mu_{i,2}(c_2)|c_2, \mu_{i,3}(c_3)|c_3, , \mu_{i,n}(c_n)|c_n]_{i = 1, p} \quad (22)$$

in which $\mu(c_i)$ is the membership grade corresponding to alternative c_i. The solution would be the optimal alternative which has the highest degree of acceptability with respect to all relevant goals L_i. Towards this, several models have been introduced, in recent years, for fuzzy MADM but the eigenvector based priority setting approach is considered as one of the best alternatives.

4.6 Application of priority vector in MADM model for condition rating

For the general MADM problem described using Eq. (22), a positive, non-zero number in the priority vector (W) corresponding to each object indicates the power of importance (α_i) of that object in the decision process. By applying the associated powers $\alpha_1, \alpha_2, \alpha_3, \ldots \alpha_p$ to the fuzzy objective sets $L_1, L_2, L_3, \ldots, L_p$ respectively, the following can be obtained:

$$L_i^{\alpha_i} = [\mu_{i,1}^{\alpha_i}(c_1) \mid c_1, \ [\mu_{i,2}^{\alpha_i}(c_2) \mid c_2, \ [\mu_{i,3}^{\alpha_i}(c_3) \mid c_3, \ldots \ [\mu_{i,n}^{\alpha_i}(c_n) \mid c_n]; _{i = 1, p} \quad (23)$$

The decision function D is then obtained from the intersection of the fuzzy sets representing the goals as

$$D = L_1^{\alpha_1} \cap L_2^{\alpha_2} \cap L_3^{\alpha_3} \ldots \cap L_p^{\alpha_p} \quad (24)$$

$$\text{Or, } D = [D_1(c_1)| c_1, D_2(c_2)| c_2, D_3(c_3)| c_3, \ldots, D_n(c_n)| c_n] \quad (25)$$

where, $D_1(c_1)$, $D_2(c_2)$, $D_3(c_3)$, ……………, $D_n(c_n)$ are the decision values corresponding to the alternatives $c_1, c_2, c_3, \ldots, c_n$, and are given by Aturaliya (1994) as :

$$D_j(c_j) = \min[\mu_{1,j}^{\alpha_1}(c_j) \mid c_1, \ [\mu_{2,j}^{\alpha_2}(c_j) \mid c_2, \ [\mu_{3,j}^{\alpha_3}(c_j) \mid c_3, \ldots, \ [\mu_{p,j}^{\alpha_p}(c_j) \mid c_p]; _{j = 1, n} \quad (26)$$

The final decision is the one that corresponds to maximum of all decision values. Hence, the final decision becomes

$$D_{final} = \max[D_j(c_j) \mid c_j]; \quad j = 1,n \quad (27)$$

For the bridge rating application, let $e_1, e_2, e_3, \ldots, e_p$ be the elements considered under each component of the bridge. The fuzzy set for a given condition rating r_i of element e_i can be expressed as the objective (goal) L_i, as

$$L_i = [R]_{ei} = \{\mu_{i,1} \mid r_1, \mu_{i,2} \mid r_2, \ldots, \mu_{i,9} \mid r_9\} \quad (28)$$

where i = 1 , p and $\mu_{i,n}$ is the membership value of element e_i at r_n.

Therefore, decision value (D) for rating of any element can be evaluated from Eq. 25 as

$$D = [d_1| r_1, d_2| r_2, d_3| r_3, \ldots, d_n| r_n] \quad (29)$$

The final rating of each of the major bridge components is found from the decision values as

$$D_{final} = \max \{ d_1| r_1, d_2| r_2, \ldots, d_9| r_9\}$$

$$= [d_m | r_m] \quad (30)$$

Hence, the rating of the particular component would be 'm' that represents any integer value between 1 and 9.

5. A case study for illustration of the proposed methodology

Computer programs have been developed based on the formulations presented in the preceding sections for condition evaluation of existing bridges and rating of the most deserved one. Based on the formulation discussed in the previous sections and the computer program developed in this study using the formulations, a study has been made for priority ranking of bridges. The data corresponding to five RC bridges (Br1, Br2, Br3, Br4 and Br5) has been adopted. In order to use the AHP to rank these bridges, at first an Analytic Hierarchy Model (AHM) with three layers, such as, objective layer (OL), criteria layer (CL) and index layer (IL) is constructed, as shown in Fig. 3. This hierarchy model is constructed by the authors based on the information available from FHWA (1991) and Liang et al. (2003) to demonstrate the proposed methodology. It is worthy to mention that the proposed methodology can be used for any hierarchy model. Therefore, it may be noted that the appropriate item(s) under any layer (as shown in Fig. 3) may be added or deleted depending on the requirement for assessing the condition of concerned bridges.

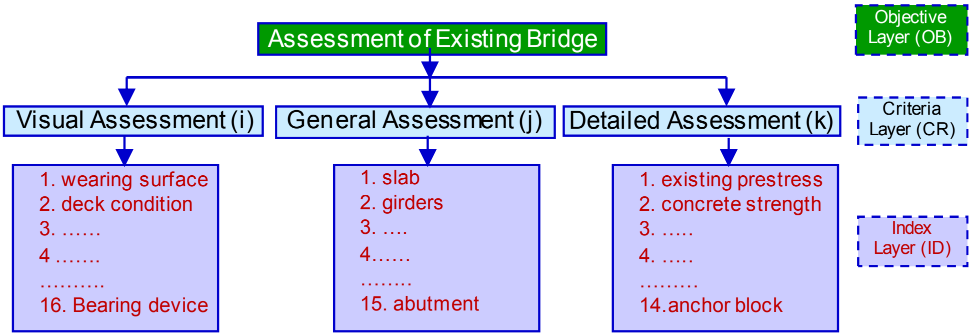


Fig. 3. Analytic Hierarchy Model (AHM) for Existing RC Bridge

After establishing the model, a set of relative importance (weights) between each single factor evaluation (item) is set-up for controlling the reliability of layer ranking. Combination of relative importance (weights) to each single item forms a comparison matrix. Condition evaluation of the considered bridges through prioritization and the rating of the most deserved bridge are arrived using the methodology described in the preceding sections. The whole procedure has been described in following sections for better illustration and understanding.

5.1 Formulation of comparison matrices for each layer and check for consistency

The first step is to carry out pair-wise comparisons of items under each layer of the AHP model as shown in Fig. 3. In this study, criteria layer is divided into three parts, namely, visual assessment, general assessment and detailed assessment. The items which can be evaluated through visual inspection are grouped under visual assessment. The items which need a detailed inspection, comprehensive observation and thorough study are grouped under general assessment. Further, the items which would require rigorous testing, both at site and in the laboratory using sophisticated instrumentation are grouped under detailed assessment. The comparison matrices for different components are formed (Triantaphyllou et al., 1997; Sasmal et al. 2006). The relative importance of any item with respect to the other, under any layer, may change depending on location, societal importance and decision objectives. The eigen solutions of the comparison matrices are carried out for different criteria layers to check for the consistency (in other words, check for acceptance of the comparison matrix) of the elements assigned for different items under criteria layer. The largest eigenvalue (λ_{max}) of the comparison matrix corresponding to each layer is obtained by solving Eq. 6 and this eigenvalue is used for calculating the consistency ratio (CR). The values for consistency index (CI) are obtained by using Eq. 7 and the consistency ratio (CR) is obtained by dividing CI with random consistency index (RCI). The values of λ_{max}, CI, RCI and CR for different items under criteria layer are presented in Table 7 and the values of CR for different items (index layers) under criteria layer are within the acceptable limit (<10%). Hence, the comparison matrix assigned for index layers are accepted for further study.

	λ_{max}	CI =(λ_{max}-n)/(n-1)	RCI	CR = (CI/RCI)100%
Visual assessment (16)	17.3951	0.0930	1.56	5.962
General assessment (15)	16.1770	0.0841	1.56	5.391
Detailed assessment (14)	15.1707	0.0901	1.56	5.776

Table 7. Check for consistency of pair-wise assigned weights

5.2 Calculation of relative weights of different index layers on criteria layer

The relative weights for components of index layers (i), (j) and (k) are established using the Eq. 3. The relative importance (weights) of items under index layers (i, j and k) obtained in this study are presented in Table 8. From the table, it is clear that there are considerable differences in relative weights of items in each index layer which signify their importance on the functionality of a bridge as a whole. It is also worthy to mention here that a large variation of relative weights of items signifies the necessity for correct, logical and realistic assignment of the weights for formation of comparison matrix using AHP.

5.3 Formulation of higher layer comparison matrix using AHP

Next step is to form the pair-wise comparison matrix for criteria layer to get the optimum goal in objective layer. Following the scheme described above, relative weights of each item of the criteria layer has to be evaluated. Table 8 shows both the comparison matrix between criteria layers and the relative weights of each criteria layer on objective layer. It signifies that the relative weight of detailed assessment on condition assessment of existing bridge is much more than that of the visual assessment. But, it may be noted that the relative weights of different assessments on condition assessment of overall bridge may change with the type of bridge, specific site condition and the degree of accuracy of different assessment procedures. Hence, the comparison matrix has to be modified accordingly.

Index layer (i) Visual assessment		Index layer (j) General assessment		Index layer (k) Detailed assessment	
Item	Relative weight	Item	Relative weight	Item	Relative weight
i1	0.0342	j1	0.0338	k1	0.0233
i2	0.0194	j2	0.0165	k2	0.0572
i3	0.0152	j3	0.0421	k3	0.0225
i4	0.0591	j4	0.0252	k4	0.1373
i5	0.0189	j5	0.0200	k5	0.0298
i6	0.0134	j6	0.0704	k6	0.0684
i7	0.0439	j7	0.0250	k7	0.1875
i8	0.0179	j8	0.0169	k8	0.1816
i9	0.1442	j9	0.0483	k9	0.0840
i10	0.0282	j10	0.0233	k10	0.0457
i11	0.0645	j11	0.1563	k11	0.0425
i12	0.2012	j12	0.0375	k12	0.0369
i13	0.1881	j13	0.0867	k13	0.0212
i14	0.0719	i14	0.2081	k14	0.0621
i15	0.0367	j15	0.1900		
i16	0.0431				

Table 8. Relative weights of items under index layer on criteria layer

5.4 Fuzzy synthesis and evaluation of membership functions

This step deals with the assessment of condition of bridge items under index layer (in this case, i, j and k). In this study, the assessment of items has been carried out by determining the estimation indices of the items as described in preceeding section. The estimation indices of the items for different bridges (Br1, Br2, Br3, Br4 and Br5) are presented in Table 9. In this table, the relative weights of components, are calculated using the procedure described above. In this study, the optimistic membership evaluation function has been used for developing membership functions. Using the estimation indices of items as tabulated in Table 9, the membership degrees, $R_{n,m}$ (n=1 to 3; m = 1 to 16/15/14) of each items are calculated for the bridges (Br1, Br2, Br3, Br4, Br5) considered for assessment.

5.5 Fuzzy synthesis evaluation matrix and priority ranking values

The relationship between the membership degrees $R_{n,m}$ (in which n= 1,2….no of criteria layers, and m=1,2,…no of items in each index layer) of each single factor (alternative) evaluation index and weight, $\overline{W}_n$, is $\overline{D}_n = \overline{W}_n R_{n.m}$ as per Eq. (14), where the value $\overline{D}_n$ in Eq. (14) is the fuzzy synthesis evaluation matrix. The proposition of $\overline{D}_n$ is to construct the membership function for each alternative of evaluation set. Based on the fuzzy mathematics theory, the fuzzy synthesis evaluation result, $\overline{B}$, of any factor can be expressed as in Eq. 15.

In this case, $\overline{B} = \begin{bmatrix} 0.456636 & 0.256391 & 0.296120 & 0.525126 & 0.43876 \end{bmatrix}$

Estimation Criterion	Subsystem weight	Item No.	Estimation items	Item weight	Estimation indices of items of bridge				
					Br1	Br2	Br3	Br4	Br5
Visual assess-ment (i)	0.126	1	wearing surface	0.0342	0	0	0	2	1
		2	deck condition	0.0194	2	0	12	9	3
		3	kerbs	0.0152	0	2	2	1	0
		4	median	0.0591	0	4	0	0	2
		5	sidewalks	0.0189	0	2	2	2	0
		6	parapets	0.0134	2	0	1	1	0
		7	railing	0.0439	4	2	0	0	0
		8	paints	0.0179	3	4	2	2	1
		9	drains	0.1442	6	6	4	6	0
		10	lighting	0.0282	9	9	0	0	0
		11	utilities	0.0645	2	2	4	4	6
		12	joint leakage	0.2012	0	0	3	9	12
		13	expansion joint	0.1881	1	4	4	6	2
		14	bearing device	0.0719	3	3	12	18	3
		15	wing masonry	0.0367	4	2	0	0	2
		16	others	0.0431	12	9	2	4	9
General assess-ment (j)	0.297	1	stringers	0.0338	×	×	×	×	×
		2	girders	0.0165	27	18	0	18	6
		3	slab beams	0.0421	×	×	×	×	×
		4	trusses	0.0252	×	×	×	×	×
		5	chloride content	0.0200	12	0	0	2	9
		6	rivet bolts	0.0704	×	×	×	×	×
		7	concrete crack	0.0250	36	12	36	2	9
		8	pier settlement	0.0169	27	27	12	18	3
		9	erosion	0.0483	12	18	2	18	3
		10	substructure protection	0.0233	18	36	0	3	27
		11	pier	0.1563	18	0	12	3	9
		12	pier shaft	0.0375	0	12	0	0	0
		13	friction layer	0.0867	0	9	0	0	0
		14	abutment	0.2081	12	6	9	3	2
		15	others	0.1900	0	2	3	12	9

Estimation Criterion	Subsystem weight	Item No.	Estimation items	Item weight	Estimation indices of items of bridge				
					Br1	Br2	Br3	Br4	Br5
Detailed assess-ment (k)	0.577	1	existing prestress	0.0233	36	12	0	36	27
		2	concrete strength	0.0572	27	18	36	36	48
		3	foundation mat	0.0225	12	0	12	18	9
		4	vibration	0.1373	18	9	0	36	27
		5	prevention earthquake block	0.0298	18	0	0	0	18
		6	steel corrosion	0.0684	0	36	0	0	12
		7	deflection	0.1875	12	18	36	48	12
		8	footing	0.1816	18	0	3	12	6
		9	collision damage	0.0840	0	0	0	0	12
		10	piles	0.0457	×	×	×	×	×
		11	pier-column	0.0425	12	2	9	6	9
		12	pier footing	0.0369	18	3	12	3	18
		13	prestressing cable corrosion	0.0212	36	12	0	18	36
		14	anchor block	0.0621	27	12	0	36	48

× Represents the non-availability of estimation data

Table 9. Estimation indices of items of the bridges considered for condition assessment

The fuzzy synthesis evaluation result, $\overline{B}$, actually shows the relative condition of existing bridges considered. Therefore, the values under $\overline{B}$ can also be treated as the priority vector for condition assessment of the bridges. As the optimistic membership evaluation function is used in this study (given in Eq. 10), the higher value in fuzzy synthesis evaluation result for a bridge in comparison to the other ones signifies greater degree of distress. In this study, the condition of Br4 among the five bridges considered here can be treated as most deficient and similarly, Br2 would be the best. The condition priority order of the bridges considered here for illustration is shown in Fig. 4. From the figure, it may be noted that the priority order of the bridges considered is as follows:

=[Br4, Br1, Br5, Br3, Br2]

5.6 Condition rating of the most deserved bridge

Using the fuzzy mathematics, ratings of different component of the bridge, Br4, are calculated using FWA. Importance(weight) of different elements has been considered as reported in (Aturaliya, 1994). Fuzzy sets for rating of the components, i.e, deck, superstructure and substructure are shown in Table 10 and corresponding importances (weights) are shown in Table 11.

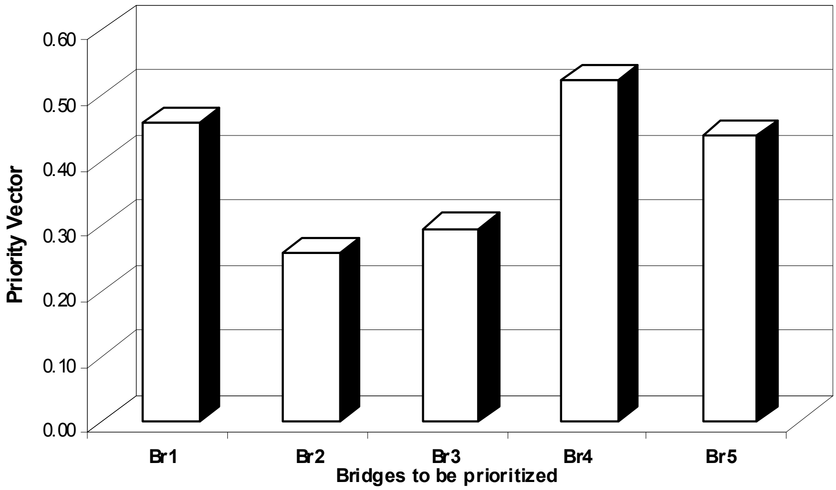


Fig. 4. Priority ranking values of the bridges considered for condition assessment

Components	Rating membership									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1. Bridge Deck	0.00	0.33	0.67	1.00	0.83	0.67	0.50	0.33	0.17	0.00
2. Superstructure	0.00	0.25	0.50	0.75	1.00	0.88	0.75	0.63	0.50	0.38
3. Substructure	0.00	0.25	0.50	0.75	1.00	0.88	0.75	0.63	0.50	0.38

Table 10. Computed fuzzified rating values for different components of the bridge

Components	Importance factors									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1. Bridge Deck	1.00	1.00	0.90	0.80	0.70	0.61	0.51	0.45	0.33	0.23
2. Superstructure	1.00	1.00	0.96	0.92	0.87	0.83	0.79	0.71	0.60	0.47
3. Substructure	1.00	1.00	0.80	0.70	0.60	0.50	0.35	0.25	0.15	0.10

Table 11. Importance membership functions of the components

As described earlier, the resolution identity technique is adopted in this study to get the final rating of the bridge when the component ratings (from the elemental values) are computed using eigenvector based priority setting technique using MADM combined with FWA method. Hence, for arriving at the final rating of the most deserved bridge, the basic data considered are the calculated ratings of the components and computed weights as shown in Tables 8 and 9. The fuzzy membership functions of rating and weights of different components (deck, superstructure and substructure) thus obtained, are discretised using resolution identity technique. Here, each set is discretised into 11 α-levels (from 0.0 to 1.0 in step of 0.1). For better illustration, the resolution identification of the fuzzy set representing the rating of the deck component of the bridge concerned is shown in Fig. 5. Further discussion can be found elsewhere [Sasmal el al. (2005)].

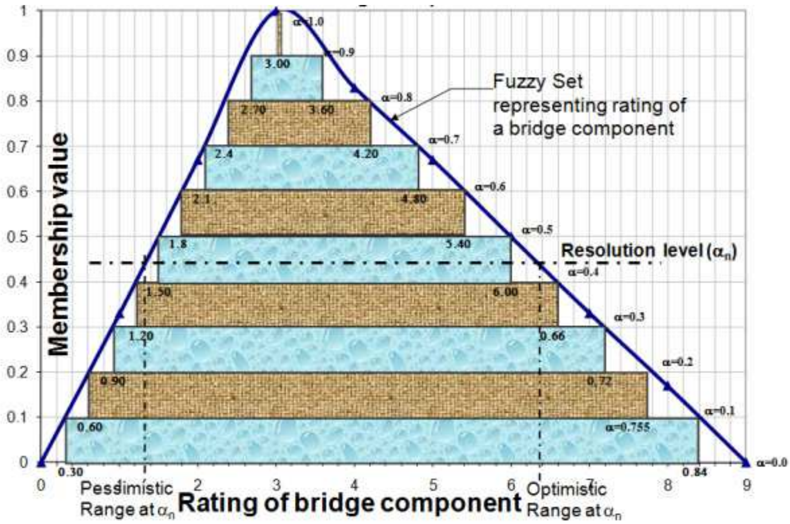


Fig. 5. Resolution identification of the fuzzy set representing rating of the deck component

At each α-level, there would be 64 combinations to get the most optimistic (maximum) and pessimistic (minimum) range of the fuzzy set at that α-level. For 11 α-levels (as considered in this study) the optimistic and pessimistic ranges of the resultant set and the membership representation of the resultant rating (RR) derived from the pessimistic and optimistic ranges using resolution identity technique is shown in Fig. 5. The resultant rating of the bridge, as a whole, has been defuzzified using MATLAB, to get the rating value of the bridge. For this particular case, the defuzzification has been executed using the centroidal method and the rating value is obtained as '**4.6668**'. From the result, it is clear that the rating of the bridge (Br4) falls in between 4 and 5 but closer to 5. It may be the decision maker's discretion in considering the rating value depending on the practical condition and other factors like the environmental condition, importance of the bridge as a whole on the societal service etc. As mentioned earlier, a scale of 0-9 has been considered in this study. So, the condition of the bridge (Br4) falls between 4 and 5 which perhaps reflect the moderate condition. Since, the condition rating of the most deserved bridge among the bridges considered in this study is in between 4 and 5, hence the other bridges are comparatively in better condition.

6. Concluding remarks

- In bridge engineering, systematic identification of the order of degree of deficiency of the bridges that are considered for their condition assessment is a usual problem. Until now, no systematic approach seems to be available for priority ranking of existing bridges.

- In view of this, a methodology based on AHP has been used, in this chapter, for ranking of the existing bridges towards their assessment of prevailing condition which would help in fixing their repair order.
- The comparison matrices for different layers of hierarchy are formulated for arriving at the relative weights of the items under each layer. An eigen solution is carried out for each comparison matrix to extract the largest eigenvalue which is further used for checking the consistency of the formulation of the comparison matrices. Estimation indices of individual bridge components have to be arrived based on the bridge inspector's observation and the results of field and laboratory testing. Thus, the estimation indices would suffer from subjective judgement and uncertainty. Hence, an optimistic fuzzy membership function has been used to scale the indices of all the components of the bridges uniformly. Based on the fuzzy synthesized evaluation matrix, the priority ranking of the bridges has been evolved.
- For evaluating the condition rating of the most deserved bridge determined from the prioritization, it is found that as the number of elements of bridge components increase the complexity in arriving at a unique rating number using Fuzzy Weighted Average (FWA) also increases. Hence, a resolution identity method is incorporated in the methodology to take care of the problems that may arise due to non-convexity and requirement of normalisation of the concerned sets.
- Further, for the component rating, the Multi-Attributive Decision Making (MADM) model based on priority vector of the constituent elements of the component is also considered because it gives a more realistic representation of the condition of the component.
- A computer programs have been developed based on the proposed methodology for condition evaluation through prioritization and rating of bridges. It is found that the methodology is capable of handling any number of bridges without any limitation on consideration of components, and elements and rating scale. Thus, the proposed methodology would certainly help the engineers and policy makers concerned with bridge management to arrive at a systematic judgment and to formulate methodical steps towards retrofitting, rehabilitation or demolition of bridge in future years.
- It is worthy to mention here that though the condition evaluation through fuzzy logic based AHP may be used as an useful tool for decision making, it should be utilised with adequate care because the whole procedure is dependent on different estimation indices of controlling parameters which have to be taken from inspector's observation and results of field and laboratory testing.

7. References

Aturaliya, S.P. (1994). *Bridge condition rating based on fuzzy set theory and Eigenvector approach*, Masters thesis, Department of Civil Engineering, Kansas State University, Manhattan, Kansas.

Ben-Arieh, D. & Triantaphyllou, E. (1992). Quantifying data for group technology with weighted fuzzy features, *Int. J. of Production Research*, Vol. 30, pp. 1285-1299.

Bertero, V.V. & Bresler, B. (1977). Design and engineering decisions: Failure criteria (Limit State): Developing methodologies for Evaluating the earth quake safety of Existing

Buildings, *Report No. UCB-EERC-77/06*, Earthquake Engineering Research Centre, University of California at Berkeley, February, 114-142.

Boender, C.G.E, de Graan, J.G. & Lootsma, F.A. (1989). Multi-criteria decision analysis with fuzzy pair-wise comparisons, *Fuzzy Sets and Systems*, Vol. 29, pp. 133-143.

Bridgman, P. W. (1922). Dimensional analysis. New Haven, CT: Yale University Press.

Brown, C.B., & Yao J.T.P. (1983). Fuzzy sets and structural engineering, *J. Structural Engineering ASCE*, Vol. 109, No. 5, pp. 1211-1235.

Chen, S.J. & Hwang, C.L. (1992). Fuzzy multiple attribute decision making: methods and applications, *Lecture Notes in Economics and Mathematical Systems*, No. 375, Berlin: Springer.

Dong W.M. & Wong F.S. (1987). Fuzzy weighted average and implementation of the extension principle, *Fuzzy sets and systems*, Vol. 21, No. 2, pp. 183-199.

Dubois, D. & Prade, H. (1979). Fuzzy real algebra: Some results, *Fuzzy Sets and Systems*, Vol. 2, pp. 327-348.

Emami, M.R. Turksen, I.B. & Goldenberg, A.A. (1998). Development of a systematic methodology of fuzzy logic modelling, *IEEE Transactions on Fuzzy Systems*, Vol. 6, No. 3, pp. 346-361.

Federal Highway Administration (FHWA). *Bridge inspectors training manual 90*, U.S. Department of Transportation, Bureau of Public Road, Washington, D.C., 1991.

Federov, V.V., Kuz'min, V.B. & Vereskov, A.I. (1982). Membership degrees determination from Saaty matrix totalities, edited by M.M. Gupta and E. Sanchez, *Approximate Reasoning in Decision Analysis*, Amsterdam: North-Holland.

Fishburn, P.C. (1967). Additive utilities with incomplete product set: *Applications to priorities and assignments*. Baltimore, MD: ORSA Publication.

Harker, D.T. & Vargas, L.G. (1990). Theory of ratio scale estimation: Saaty's Analytic Hierarchy Process, *Management Science*, Vol. 36, pp. 269-273.

Jwu, T.H., Harn, Y. & Liou, W.M, (1991). Fuzzy Evaluation of Wharf Structures at Harbour, Report of *Investigation of Corrosion Failure and Its Protection Strategy for Harbour Wharf*, Institute of Engineering and Technology of Ten-Jin Waterway, Department of Transportation, China.

Kawamura, K. & Miyamoto, A. (2003). Condition state evaluation of existing reinforced concrete bridges using neuro-fuzzy hybrid system, *Computers and Structures,* Vol. 81, pp. 1931-1940.

Kaufmann, A. & Gupta, M.M. (1985). *Introduction to fuzzy arithmetic, Theory and Applications*, New York: Van Nostrand Reinhold.

Laarhoven, P.J. M. & Pedrycz, W.A. (1983). A fuzzy extension of Saaty's priority theory, *Fuzzy Sets and Systems*, Vol. 11, pp. 229-241.

Liang M.T., Wu J.H. & Liang C.H. (2001). Multiple layer fuzzy evaluation for existing reinforced concrete bridges, *J Infrastructure System*, Vol. 7, No. 4, pp. 144-159.

Liang, M.T, Chang, J.W. & Li, Q.F. (2002). "Grey and regression models predicting the remaining service life of existing reinforced concrete bridges", *J. Grey System*, Vol. 14, No. 4, pp. 291-310.

Liang, M.T., Lin, C.M. & Yeh, C.J. (2003). Comparison matrix method and its applications to damage evaluation for existing reinforced concrete bridges, *J. Marine Science & Technology*, Vol. 11, No. 2, pp. 70-82.

Lootsma, F.A. (1991), *Scale sensitivity and rank preservation in a multiplicative variant of the AHP and SMART*, Report 91-67, Faculty of Technical Mathematics and Informatics, Delft University of Technology.

Melhem, H.G. & Aturaliya, S. (1996). Bridge condition rating using an Eigenvector of priority setting, *J. Microcomputers in Civil Engineering*, Vol. 11, No. 6, pp. 421-432.

Miller, D.W. & Starr, M.K. (1969). Executive decisions and operations research. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Mullarky, P.W. & Fenves, S.J. (1985). Fuzzy logic in a geotechnical knowledge-based system: cone, Proc., *NSF workshop on civil engineering applications of fuzzy sets*, Purdue University, Indiana.

Qian, Y.J. (1992). *Evaluation and diagnosis of existing reinforced concrete bridges*, Ph. D. Dissertation, Southwest Chiaotung University, Xian, China.

Roberts, F.S., Measurement theory, reading, MA, 1979 (Addison-Wesley).

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

Saaty, T.L. (1994). Fundamentals of decision making and priority theory with the AHP, RWS Publications, Pittsburgh.

Sasmal, S., Ramanjaneyulu, K., Gopalakrishnan, S. & Lakshmanan, N. (2004a). *Condition assessment of existing bridges through prioritization in a fuzzy environment*, SERC Research Report No. RCS-MLP10741-RR-2004-2, May 2004.

Sasmal, S., Ramanjaneyulu, K., Gopalakrishnan, S. & Lakshmanan, N. (2004b). Condition ranking of existing bridges using analytic hierarchy approach, in Proceedings of International Conference on *World of Innovations in Structural Engineering* (WISE-2004), organised by ACCE at Hyderabad during December 1^{th} to 3^{rd}, 2004, 344-352.

Sasmal, S., Ramanjaneyulu, K., Gopalakrishnan, S. & Lakshmanan, N. (2005). Condition rating of bridges using fuzzy mathematics, Proc., Int. Conf. on *Advances in Concrete Composites and Structures* (ICACS-2005), India, 943-952.

Sasmal, S., Ramanjaneyulu, K., Gopalakrishnan, S. & Lakshmanan, N. (2006). Fuzzy logic Based condition rating of existing reinforced concrete bridges, *J. Performance of Constructed Facilities- ASCE*, l 20(3), 2006, 261-273.

Shiaw, S.S. & Huang, W.D (1990). Synthesis evaluation of fuzzy and random Properties for bridge bearing capacity, *J of Chiaotung Institute* at Chung Ching, 1, 64-71.

Tee. A.B., Bowman, M.D. & Sinha, K.C. (1988). A fuzzy mathematical approach for bridge condition evaluation, *J. Civil Engineering systems*, Vol. 5, No. 1, pp. 17-25.

Tee. A.B. & Bowman, M.D. (1991). Bridge condition assessment using fuzzy weighted averages, *Journal of Civil Engineering systems*, Vol. 8, No. 1, pp. 49-57.

Tseng, T.Y., & Klein, C.M. (1992). A new algorithm for fuzzy multi-criteria decision making, *Approx. Reasoning*, Vol. 6, pp. 45-66.

Triantaphyllou, E., Kovalerchuk, B., Mann jr. L. & Knapp G.M. (1997). Determining the most important criteria in maintenance decision making, *J. Quality in Maintenance Engg.*, Vol. 3, No. 1, pp. 16-28.

Wang, H.D. (1996). Basic Study on Durability Evaluation of Reinforced Concrete Structure, Ph. D. Dissertation, Department of Civil Engineering, Dalian University of Technology, China.

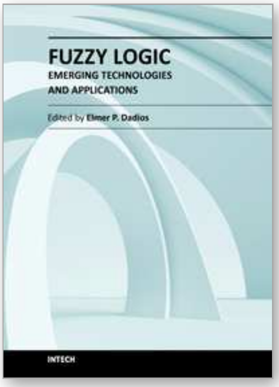
Yu, L. & Cheng, M. (1994). A new method to group decision making with multiple objectives-interactive comparison matrix approach, *J. System Engineering*, Vol. 9, No. 2, pp. 28-35.

Zadeh, L.A. (1973). The concept of a linguistic variable and its application in approximate reasoning, *Information Science, part I*: Vol. 8, No. 3, pp. 199-249.

Zadeh L.A. (1965). Fuzzy sets, *Information & Control*, Vol. 8, pp. 338-353.

Zhao, Z. & Chen C. (2002). A Fuzzy system for concrete bridge damage diagnosis, *Computers and Structures*, Vol. 80, pp. 629-641.

Zahedi, F. (1986). The analytic hierarchy process – a survey of the method and its applications, *Interfaces*, Vol. 16, No. 4, pp. 96-108.



Fuzzy Logic - Emerging Technologies and Applications
Edited by Prof. Elmer Dadios

ISBN 978-953-51-0337-0
Hard cover, 348 pages
Publisher InTech
Published online 16, March, 2012
Published in print edition March, 2012

The capability of Fuzzy Logic in the development of emerging technologies is introduced in this book. The book consists of sixteen chapters showing various applications in the field of Bioinformatics, Health, Security, Communications, Transportations, Financial Management, Energy and Environment Systems. This book is a major reference source for all those concerned with applied intelligent systems. The intended readers are researchers, engineers, medical practitioners, and graduate students interested in fuzzy logic systems.