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USE OF FUZZY SETS IN CONDITION RATING OF RC HIGHWAY BRIDGE STRUCTURE

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ABSTRACT: Structural evaluation of existing infrastructures becomes necessary due to deterioration, change in service, increased loading and damages due to natural disasters such as earthquakes and fires. In this paper, we present the use of fuzzy set theory for assessing the overall structural rating of RC highway bridges. Fuzzy sets are used to express the lack of precision in field observations. The system combines the experience and judgement of investigating engineer, results of field observation and if needed strength computation for individual members. A fictitious example of a simple RC highway bridge is presented.

KEYWORDS: expert system, fuzzy set theory, RC highway bridge, reinforced concrete, structural condition rating

1. INTRODUCTION

Structural evaluation of existing infrastructures becomes necessary due to deterioration, change in service, increased loading and damages incurred due to earthquakes and fires. As far as reinforced concrete structures in general are concerned, deterioration can be due to cracking, scaling, concrete spalling and reinforced corrosion. Excessive deflection of horizontal members and drift or sway of vertical members also cause serviceability problems and create inconvenience to the users. In the case of RC highway bridges, structural members including beams, girders, piers, and foundations may become deficient in their load carrying capacity. Different elements of structures have different levels of importance to the overall integrity of the whole structure. The structural condition rating of a structure is a process of assessing the overall condition and integrity of the structure as a whole, so that appropriate steps can be taken either for repair and rehabilitation or replacement. The condition rating of an existing structure involves a number of steps, which combines the different strength and serviceability parameters obtained from the structure and expert judgement of the investigating engineer. In most of the situations, the judgement cannot be estimated quantitatively, since the condition of the structure is described qualitatively. Structural condition rating of a structure depends on the type of structure and its intended service.

The concept of fuzzy sets has been applied in many structural and civil engineering problems by different researchers [1-5]. In this paper, we present the use of fuzzy set theory for assessing the overall structural rating of RC highway bridges. Fuzzy sets are used to express the lack of precision in field observations. The uncertainties involved in the qualitative judgement of the expert engineer are assigned weighting factors according to the importance of individual elements in the whole structural system. The system combines the experience and judgement of the investigating engineer, results of field observation and if needed strength computation for individual members of RC highway bridge structure. A fictitious example of a simple RC highway bridge is presented to illustrate the steps involved.

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2. OVERVIEW OF FUZZY SET THEORY

A set theory is the collection of elements that define all possibilities in a probabilistic problem. In a crisp set theory, a data either belongs to or does not belong to a particular element in the set. That means it has either a membership value of 1.0 or 0.0. Lotfi A. Zadeh stated that our ability to make precise and significant statements concerning a given system diminishes with increasing complexity of the system [1]. He concluded the closer one looks at a real world problem, the fuzzier the manner of solution becomes. In many cases, a complex real world problem can be divided into a sequence of simpler questions, which in turn can be answered by an experienced engineer with descriptive word or phrases. The theory of fuzzy sets is a tool, where these fuzzy words and phrases can be interpreted with the use of membership functions. As an example we consider a set that represents the quality of a concrete mix. An experienced engineer may express the quality as good, average, poor and bad. These words describe the concrete mix in a qualitative manner, for which precise quantification is not possible. This vagueness or fuzziness in judgement can be expressed by the use of fuzzy sets. Let A denotes the fuzzy set defining quality of concrete mix and G, A, P, and B are the elements of the set. The case, where the engineer describes the mix quality as "Good" may be expressed as **Eq. 1**.

$$A = \{1.0/G \quad 0.5/A \quad 0.1/P \quad 0.0/B\} \tag{1}$$

The above equation indicates that the most likely membership is the "Good", but there is also a possibility that it has membership in an element denoting lesser quality of concrete mix. In usual practice, the membership values are normalized so the same relation can be expressed in normalized form as in **Eq. 2**.

$$A = \{0.625/G \quad 0.3125/A \quad 0.0625/P \quad 0.0/B\} \tag{2}$$

In multilevel fuzzy composition, a complex problem is divided into a number of simpler problems, which then again subdivided into even simpler problems. The problem is divided till it reaches a case, when the question can be answered based on one's expertise or on an observed or computed value. These answers are expressed as fuzzy composition. In stepwise manner, answers are obtained for each level up to the original level of problem.

3. CONDITION RATING OF RC HIGHWAY BRIDGE

An RC highway bridge has many structural components such as foundations, abutments, piers, girders, beams, slab and connections. The condition rating involves the individual assessment of all these members and collective assessment using the multilevel fuzzy composition. A probable strategy for evaluating the structural condition of RC highways bridges is shown in **Fig. 1**. At the primary level there is the goal set which contains the states that are to be used to define all possible conditions for the bridge. In this work, we suggest four states as shown in **Table 1.**

Table 1 States and conditions of bridge in the goal set

Elements of goal set	State of bridge	Condition of bridge
u_1	Good	Bridge is sound and safe, some non–structural members may need repair
u_2	Average	Bridge as a whole is sound, some structural members may need repair
u_3	Poor	Bridge does not meet code requirements, needs repair and rehabilitation
u_4	Bad	Bridge is severely deficient and unsafe thus needs to be demolished

The overall structural condition of the bridge will correspond to the state that has the highest computed degree of membership. In goal set, we define four states, so all factor sets should also have four sets. To rate the bridge condition, factors selected must include original condition including design and construction, the present condition of all structural and non-structural members and any other pertinent data related. Each factor is divided into lower levels till the questions posed by the factor can be answered by the user. The grouping of each type of members in a group gives the user flexibility of assigning appropriate weighting factor according to the importance of each group to the whole structure.

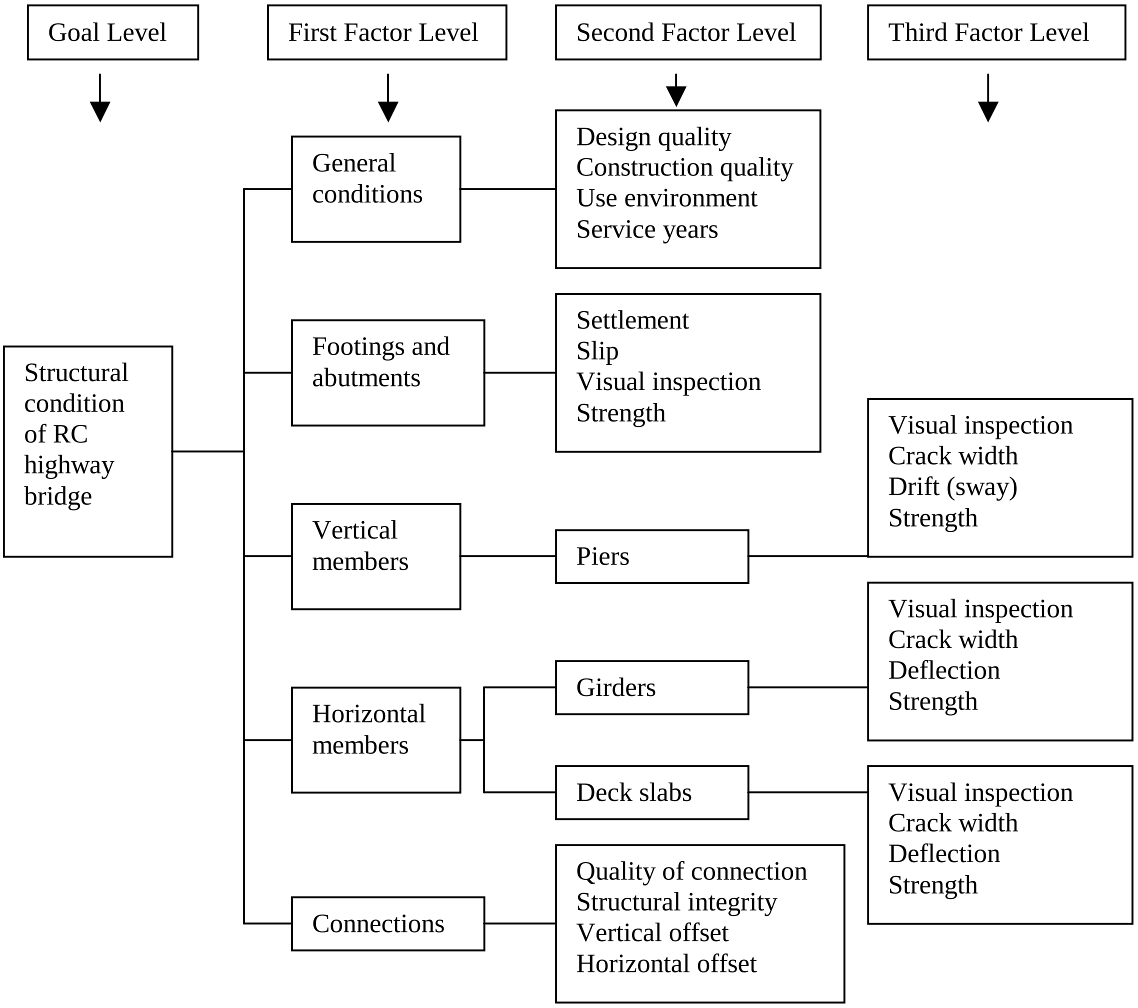

Fig. 1 Multilevel factor sets for structural rating of RC highway bridge

For demonstration purpose, we consider the case of a pier, where the condition is assessed by four factors. For factor related to visual inspection, four categories can be defined as G: no cracks or only shrinkage cracks, A: micro cracks width less than 0.3 mm, P: moderate cracking with minor spalling and B: severe cracking and possible reinforcement exposure (**Table 2**). Choosing the suitable category requires a careful judgement and there is fuzziness in selecting the categories even by the same engineer for different piers. Similarly, the membership functions are defined for maximum cracks widths, drifts, deflection and strength as shown in **Fig. 2** adopted form Luo and Simmonds [4]. Strength can be input in ratio of provided to required strengths. Regardless of condition of a pier, membership values are assigned to each of the factors considered, which results in a matrix of membership values that have as many rows as there are factors and as many columns as there are states in the goal sub-set. To arrive at the goal sub-set representing the condition of that pier, it is necessary to combine these factors taking into account of their relative importance, which is done by pre-multiplying the matrix by a vector representing the different weighting factor. For footings plus abutments, vertical members and horizontal members, this weighting factor set may be taken as **Eq. 3**.

$$W_{f/v/h} = (0.2 \quad 0.2 \quad 0.2 \quad 0.4) \tag{3}$$

For general conditions, the weighing factors set is as given by **Eq. 4** and for connections, it can be taken as given by **Eq. 5**.

$$W_g = (0.3 \quad 0.3 \quad 0.25 \quad 0.15) \tag{4}$$

$$W_c = (0.4 \quad 0.3 \quad 0.2 \quad 0.1) \tag{5}$$

Table 2 Degree of membership for visual inspection (Normalized values)

Categories	Cracking condition	States of goal sub-set			
		V_1	V_2	V_3	V_4
G	Shrinkage cracking	1.0 (0.625)	0.5 (0.313)	0.1 (0.062)	0.0 (0.0)
A	Micro cracking	0.5 (0.313)	1.0 (0.476)	0.5 (0.238)	0.1 (0.048)
P	Moderate cracking	0.1 (0.048)	0.5 (0.238)	1.0 (0.476)	0.5 (0.238)
B	Severe cracking+spalling	0.0 (0.0)	0.1 (0.062)	0.5 (0.313)	1.0 (0.625)

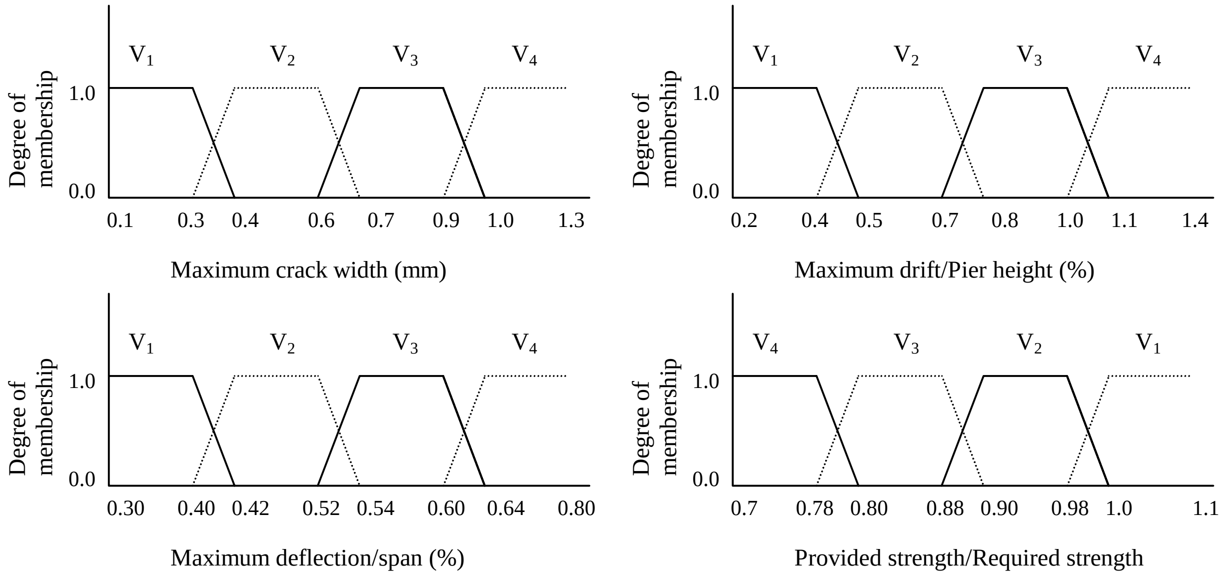

Fig. 2 Membership functions

The matrix product is the goal sub-set for a particular pier. Similarly, fuzzy sets are also obtained for each pier in the structure. While combining all piers, different or same weighing factors can be assigned according to the importance of a particular pier in the whole structure. Similarly, fuzzy sets can be obtained for all horizontal members, footings, and rest of the structural elements. For general condition of the structure, appropriate weighting factors may be assigned. At the last stage, when all the factors in the first level sets have been determined, they are combined to obtain the goal set or single fuzzy set that describes the structural rating of bridge. At this stage the weighting factors can be taken as **Eq. 6**.

$$W_s = (0.1 \quad 0.2 \quad 0.4 \quad 0.2 \quad 0.1) \tag{6}$$

4. ILLUSTRTIVE EXAMPLE

A fictitious two-span RC highway bridge (**Fig. 3)** is considered to illustrate the process involved. The bridge is 50 years old and visible large cracks are seen on deck slab as well as the pier. Girder deflections are very large and there is some drift of pier too. Deck slab has several reinforcements exposed with some spalling of concrete visible. All other parameters as well as strengths for individual elements are assumed accordingly in the computations.

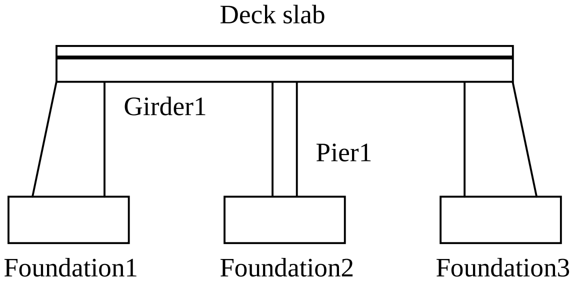

Fig. 3 Profile of fictitious bridge structure

To start with, we go to each level and construct the fuzzy matrix sets. For example, if we take general conditions, the observations are as follows: the design quality is average, construction quality is average, use environment is poor and the service year is 50 years. From these observations, we make the fuzzy relation matrix R_1 as shown in **Eq. 7**. All the matrices are formed by using the membership values as shown in Table 2. To obtain the evaluation matrix E_1, we pre multiply **Eq. 7** with weighing factor as given by **Eq. 4** and then we have the evaluation matrix for general conditions (E_1) as given by **Eq. 8**.

$$R_1 = \begin{bmatrix} 0.238 & 0.476 & 0.238 & 0.048 \\ 0.238 & 0.476 & 0.238 & 0.048 \\ 0.048 & 0.238 & 0.476 & 0.238 \\ 0.0 & 0.062 & 0.313 & 0.625 \end{bmatrix} \tag{7}$$

$$E_1 = \{0.1548 \;\; 0.3544 \;\; 0.3087 \;\; 0.1820\} \tag{8}$$

Similarly, the evaluation matrices (E_2 to E_5) are computed from the observations as well as the computations of the strengths for footing and abutments, vertical members, horizontal members and connections respectively. For footings, abutments, girders and piers, individual fuzzy relation matrices are formed for each member and averaged to get final relation matrices. Then the fuzzy relation matrices are pre-multiplied with the corresponding weighting factor matrices to get evaluation matrices. While combining fuzzy relation matrices to get average relation matrix for horizontal members, relative importance of girders and slabs must be taken into account. For this purpose, weighting factor matrix given by **Eq. 9** is used.

$$W_{gs} = (0.6 \quad 0.4) \tag{9}$$

$$R = \begin{bmatrix} 0.1548 & 0.3544 & 0.3087 & 0.1820 \\ 0.2326 & 0.2318 & 0.2338 & 0.3018 \\ 0.2096 & 0.0476 & 0.4952 & 0.2476 \\ 0.0114 & 0.0360 & 0.6261 & 0.3264 \\ 0.3000 & 0.0434 & 0.2191 & 0.4375 \end{bmatrix} \tag{10}$$

$$E = \{0.1781 \ 0.1124 \ 0.4228 \ 0.2866\} \tag{11}$$

For overall structural condition rating of the bridge, fuzzy relation matrix is composed of all E_1 to E_5 as given by **Eq. 10**. The final evaluation matrix for overall structure (E) is obtained as shown in **Eq. 11** by pre-multiplying R with structure weighting factor set W_s as given by **Eq. 6**. The final set E, E = $\{e_1, e_2, e_3, e_4\}$ is a fuzzy sub-set in goal set U, U = $\{u_1, u_2, u_3, u_4\}$. The numerical values in set E are the degree of membership of bridge corresponding to different states respectively. Here, the maximum value in set E is $e_3 = 0.4228$, thus the overall condition of the bridge is u_3. This means that the bridge is in poor condition and must be repaired and rehabilitated immediately to ensure safe and risk free operation.

5. CONCLUSIONS

A methodology for structural condition rating of an existing RC highway bridge structure based on fuzzy set theory is presented. The vagueness of qualitative expression of the condition of structural members are expressed by use of fuzzy sets and the relative importance of each members to the overall structure are expressed by the use of weighting factors. A fictitious example of a two span simple RC highway bridge is presented to illustrate the process involved.

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