Application of Fuzzy Logic to Condition Assessment of Concrete Slab Bridges

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There is presently no well-established procedure for a bridge inspector to follow when assessing the combined effects of multiple flaws or imperfections on a bridge. Consequently, the evaluation of an existing bridge is based on a highly subjective procedure, and usually suffers from imprecision and personal bias. Different bridge inspectors may assess a given bridge differently. The purpose of this article is to examine the application of fuzzy logic for assessing the condition of concrete slab bridges. A number of factors that affect the condition of a bridge deck are examined. An example problem is presented to illustrate use of the proposed methodology.

Bridge structures of today reflect the engineering experience and research developments that have evolved over many centuries. An impressive amount of research has been conducted in the development of new technology and materials for the design and construction of bridges during the last five decades. The use of welding, high strength structural bolts, epoxy-coated reinforcing bars, and prestressed concrete are examples of recent technological advances in the field of bridge engineering (*1*). Nevertheless, these technological advances have not precluded a number of tragic bridge failures.

After a bridge has been built, it must be kept in a serviceable state through regular inspection and maintenance. Unfortunately, it took the collapse of the Silver Bridge in Ohio in 1967, which claimed 46 lives, to arouse public interest and awareness of the importance of inspection and maintenance of bridges (*2*).

Unlike the design and construction stages, bridge inspection is usually performed by a much smaller team; commonly by a single bridge inspector. The problems encountered in this type of work are numerous and often complex. The inspector must be thoroughly familiar with the various bridge design and construction features to be able to recognize and properly interpret any structural deficiencies and evaluate their seriousness before making any appropriate improvement recommendation (*3*).

During a bridge inspection, information collected and perceived by the inspector can be divided into objective and subjective parts, respectively (*4*). The objective portion involves measurable information such as the remaining diameter of corroded reinforcement bars or the width of cracks at specific locations, whereas the subjective portion involves the wisdom and experience of the inspector, who must evaluate the severity of the deficiencies and their combined impact on the overall structural integrity. Although the importance of the subjective information is recognized, the present inspection procedure does not have the capability to incorporate systematically the subjective information into the rating process.

Consequently, a method that combines both the objective knowledge and the imprecise subjective wisdom of bridge inspectors to make logical and systematic evaluations would be very useful. One such technique that uses this wisdom is the fuzzy logic approach.

OBJECTIVE

The primary aim of this paper is to present a fuzzy logic approach for assessing the combined effects of imperfections on the overall condition of a bridge.

The imperfections discussed in this paper are the corrosion of steel reinforcement, and the scaling, cracking, and spalling of concrete. Membership functions describing the various states of structural condition for these imperfections are presented. A simple example is also included to illustrate the application of the fuzzy logic methodology and to highlight the advantages and limitations of the proposed method for bridge inspection.

BRIDGE DECK DETERIORATION

The deterioration of concrete bridge decks along the nation's highways is a major problem for many states. The common structural deficiencies associated with the deterioration of bridge decks are the corrosion of steel reinforcement and the cracking, scaling, and spalling of concrete.

The effect of these imperfections on a bridge deck is imprecise and subjective knowledge and can best be handled by employing the fuzzy logic via the membership functions. The central feature of the fuzzy logic approach is the membership function, which represents numerically the degree to which an element belongs to a set. Instead of using only 0 and 1 when dealing with objective infor-

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mation, the degree of membership can take on values between 0 and 1 to fully describe subjective concepts. The membership functions describe the various states of structural condition as a result of the structural imperfection. This new system is a closer representation of the subjective information of the human cognitive process (*5*).

The membership functions presented in this paper are developed on the basis of structural analyses and information extracted from the literature. It should be emphasized that the membership functions, albeit reasonable, are subjective in nature and can be further enhanced through expert opinion or availability of additional information if necessary.

Although corrosion, scaling, spalling, and cracking are not the only types of imperfections that occur on a concrete bridge deck, they represent some of the most common and severe problems. Thus, the development of membership functions described herein applies to corrosion, scaling, spalling, and cracking only.

CORROSION OF REINFORCING STEEL

Although several factors contribute to the deterioration of concrete structures, one of the primary causes is corrosion of the reinforcing steel. The repeated applications of deicing chemicals on bridge decks and roadways during the winter months release large quantities of chloride ions that penetrate to the reinforcing steel level. In the presence of moisture, an electrical potential difference occurs and the corrosion process is initiated (*6, 7*). The corrosion process is accelerated by the presence of oxygen. The corrosion products increase the volume of the reinforcing steel, thereby creating tensile stresses in the surrounding concrete. When these stresses exceed the tensile strength of the concrete, the concrete cracks and eventually spalls or delaminates (*8*).

Corrosion can also cause loss of bond between concrete and the reinforcing bars. When this happens, the tensile stress is decreased in the region of bond loss and the bond stresses are increased in the remaining bonded regions. If this process continues, a loss of concrete cover will occur and the available strength of the bridge section will be reduced (*9*).

Development of the membership functions for evaluating the effect of corrosion on the structural condition is based on the ratio of the ultimate moment capacity to the service load moment at critical points of the bridge (*10*). For the positive steel of a continuous slab bridge, the critical locations are assumed to be approximately at the $\frac{4}{10}$ point of the exterior span and the center of the interior span; for a simply supported slab bridge, the critical location is at the center of the span. The critical point of the negative steel in a continuous slab bridge is at the interior support. In short, these critical locations are the points of maximum positive and negative moment along the bridge deck. The ratio of the ultimate moment capacity to the service load moment is taken to be the factor of safety. It should be noted that the reduction in reinforcement cross-sectional area is taken as the critical corrosion parameter in the present study. The effect of bond loss caused by corrosion was not included in the analysis for development of the membership functions. Consequently, a summary is presented in Tables 1 and 2 of the computed factor of safety corresponding to the percent reduction in the area of positive and negative steel, respectively. Different slab thicknesses were examined to illustrate the influence of slab thickness on the corresponding safety factors.

From these tables, it can be observed that an increase in the slab thickness yields a slight increase in the factor of safety. It should be noted that in the analyses a thicker slab permits a reduction in the required area of steel for a given loading condition. However, a thicker slab results in a higher dead load moment, and the reduction in the required area of steel is not directly proportional to the thickness increment.

It should also be pointed out that the area of steel provided is slightly more than the area of steel required, depending on the bar size and spacing selected. For example, if the required area of steel per foot of slab width

TABLE 1 FACTOR OF SAFETY CORRESPONDING TO CORROSION OF POSITIVE STEEL

Bridge[a] Type	Slab Thickness (in.)	Percent Reduction in Area of Steel					
		0	10	20	30	40	50
A	12½	1.81	1.64	1.48	1.31	1.14	0.96
	14½	1.87	1.70	1.52	1.35	1.16	0.97
	16½	1.90	1.72	1.55	1.36	1.17	0.98
B	12	1.87	1.70	1.52	1.34	1.16	0.98
	14	1.90	1.73	1.54	1.36	1.17	0.99
	16	1.93	1.75	1.56	1.38	1.18	1.00
C	12	1.77	1.62	1.46	1.29	1.13	0.95
	14	1.84	1.67	1.50	1.33	1.15	0.97
	16	1.90	1.72	1.54	1.37	1.17	0.99
	18	1.92	1.73	1.55	1.37	1.18	0.99

[a] A = Simple-span reinforced concrete slab bridge (span length, 20 ft); B = Simple-span reinforced concrete slab bridge (span length, 15 ft); C = Continuous reinforced concrete slab bridge (3 spans 27-34-27 ft).

TABLE 2 FACTOR OF SAFETY CORRESPONDING TO CORROSION OF NEGATIVE STEEL

Bridge Type[a]	Thickness (in.)	Percent Reduction in Area of Steel[b]					
		0	10	20	30	40	50
	12	1.58	1.42	1.27	1.10	0.95	0.79
A	14	1.71	1.54	1.37	1.20	1.02	0.85
	16	1.79	1.61	1.42	1.25	1.07	0.90

[a] A = Continuous reinforced concrete slab bridge (3 spans 27-34-27 ft).
[b] Reduction in area of steel at the first interior support.

computed is 1.56 in^2, the selected steel will most probably be No.8 bars at a 6-in. spacing, providing an area of steel of 1.58 in^2. The area of steel provided per foot of slab width in this case is 0.02 in^2 more than that required. Such minor variations in reinforcement provided cause the computed factor of safety to fluctuate slightly in these tables.

The variation of the factor of safety with respect to the percent reduction in the area of steel for different slab thicknesses can be represented by a relatively narrow band or envelope, as shown in Figure 1. Membership functions describing the various states of structural condition with respect to the reduction in area of steel for slab bridges are presented in Figure 2. The safety factors shown in Tables 1 and 2 and the corrosion envelope depicted in Figure 1 were used as guidelines in the development of the various membership functions. It should be emphasized that the position and magnitude of the membership functions, albeit reasonable, are subjective in nature. This can be further fine-tuned through the availability of additional information or expert opinion.

CONCRETE DETERIORATION FACTORS

Characteristics of Cracking

Cracking is defined as an incomplete separation of concrete into one or more parts, with or without a space between them (*11*). A comprehensive review of the common causes and characteristics of cracks in concrete can be found in the report by Manning and Bye (*12*).

Cracking was once viewed as a fault of design or workmanship (*13*). However, it can be readily shown that under normal and reasonable stress conditions, reinforced concrete members are already cracked and will generally perform satisfactorily with respect to their load-carrying capacity. Cracks appearing at the time of construction because of shrinkage or settlement of the falsework are usually fine and do not adversely affect the performance of the bridge deck (*13*). Conversely, pattern cracking resulting from the use of reactive aggregates may occur several years after construction, increase in magnitude,

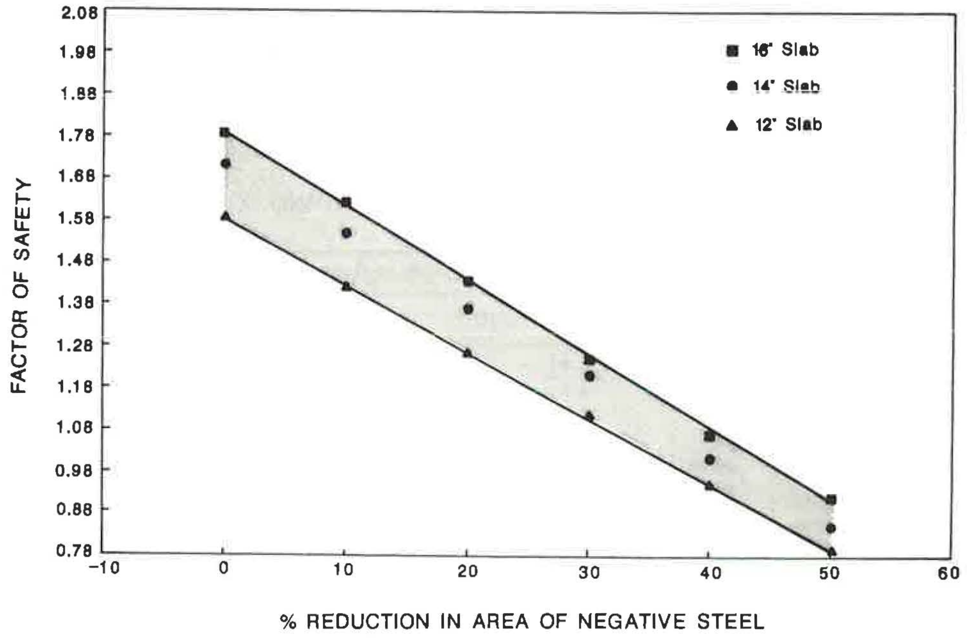

FIGURE 1 Factor of safety envelope for reinforcing steel corrosion.

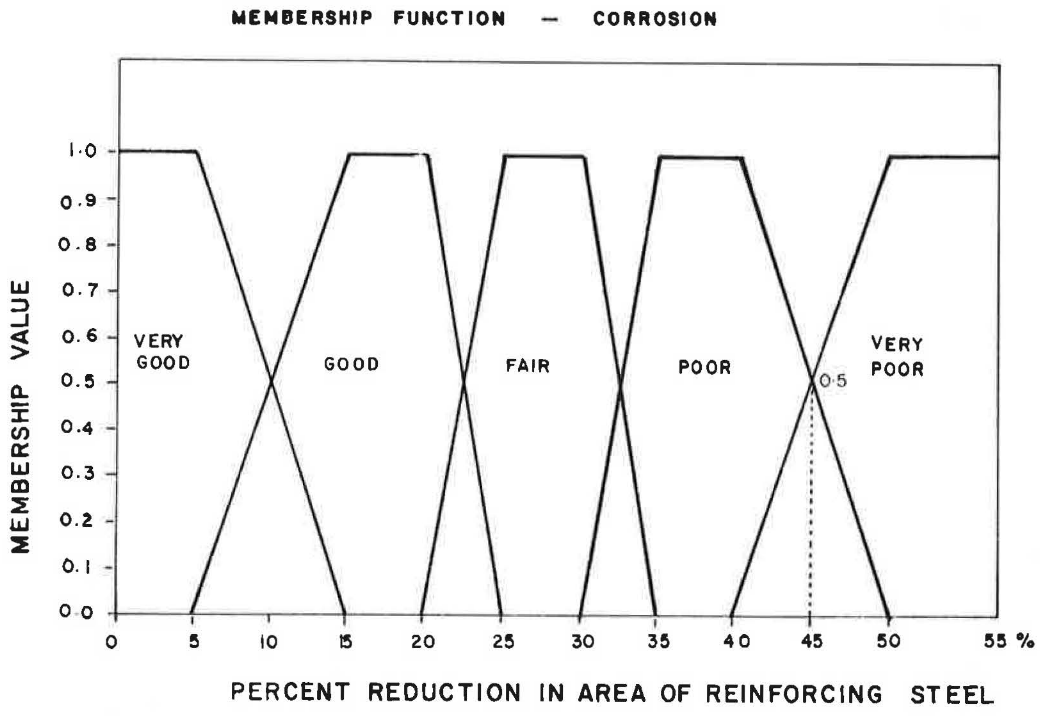

FIGURE 2 Structural condition membership functions for reinforcing steel corrosion.

and eventually result in complete disintegration of the concrete.

It is desirable to limit crack widths for corrosion protection, leakage prevention, and aesthetic reasons. The concrete crack width classification proposed by Ryell and Richardson (*14*) is given as follows:

Description	*Crack Width*
Hairline	Less than 0.004 in.
Narrow	0.004 to 0.01 in.
Medium	0.010 to 0.030 in.
Wide	More than 0.030 in.

Although the depth of a crack can be an important classification parameter, it is generally neglected in most studies. This is because the depth of a crack can be determined only by coring, except in those cases in which the crack is visible on the opposite surface of the member. Because coring samples are usually not taken during routine inspection, the depth of cracks in bridge decks or structural members is not readily available. Thus, cracks are generally categorized using crack width as the only parameter (*15, 16*).

Membership Functions for Concrete Cracks

Based on the classification of crack width previously described, it can be safely assumed that a concrete member having an average crack width falling within the 0.013- to 0.020-in. range is in fair condition, provided that there are no other flaws. From the values given in the concrete crack width classification, it can be inferred that concrete members having average crack widths greater than 0.030 in. are in very poor condition. Similarly, a concrete member can be said to be in very good condition if it contains average crack widths of less than 0.004 in. The intermediate ranges between very good and fair, and from fair to very poor are described using the linguistic variables "good" and "poor," respectively.

Hence, the structural condition membership functions for concrete cracks were formulated using the crack width classifications. These are shown graphically in Figure 3.

Characteristics of Scaling

Scaling is the flaking of surface mortar often accompanied by the loosening of surface aggregates. Scaling is believed to be caused by freezing and thawing, poor workmanship, or inadequate curing of the concrete (*17, 18*). When concrete cools below the freezing point of water, there is an initial period of super-cooling during which ice crystals form in the large capillaries. Because water in the cement paste is in the form of a weak alkali solution, the alkali content in the unfrozen portion of the solution in these capillaries increases. An osmotic pressure is created, and water migrates from the unfrozen pores to the frozen cavities. The combination of pressures caused by ice accretion and osmosis causes the paste to crack.

Since the introduction of air-entrained concrete, the incidence of scaling has been reduced to minimal proportions (*18*). Heavy and severe scaling, where it occurs, may be corrected by using a thin epoxy mortar patch to waterproof the area and prevent penetration of water to the reinforcing steel.

Membership Functions for Scaling

Scaling is described qualitatively in terms of its depth, as reported in a number of studies (*2, 15, 16, 18*). A classification of scaling as a function of its depth, which was reported in a cooperative study by the Bureau of Public Roads and the Portland Cement Association (*18*), is given as follows:

Description	*Depth*
Light	0.0 to 0.25 in.
Medium	0.25 to 0.50 in.
Heavy	0.50 to 1.0 in.
Severe	More than 1.0 in.

Membership functions describing the various structural condition states caused by scaling were developed using the values in this scaling classification table as general guidelines. Because the average depth of medium-to-heavy scaling is approximately 0.5 to 0.6 in., the structural condition that corresponds to scaling having a depth of between 0.5 to 0.6 in. can be described using the linguistic variable "fair." On the other hand, the structural condition for scaling with a depth in excess of 1 in. can be described as very poor. The poor classification is, of course, between the fair and very poor range. Similarly, the structural condition for scaling less than 0.25 in. in depth is classified as very good. The classification "good" falls between the classifications "very good" and "fair." The shape, position, and magnitude of the membership functions for structural inadequacy when scaling is present are shown graphically in Figure 4.

Characteristics of Spalling

Spalling is the breaking loose of pieces of concrete, and often occurs initially near the top reinforcing steel (*9, 16, 18*). Spalling results from large tensile stresses within the concrete that are usually caused by corrosion of reinforcing bars and freezing of the concrete member. The products of corrosion exert stresses within the concrete that cannot be supported by the limited plastic deformation of the concrete, thereby causing the concrete to disintegrate. Also, when a structural member is frozen, separation of cement and the reinforcing bars can occur and lead to the formation of cracks and spalls.

Membership Functions for Spalling

The classification of spalling, as reported in the U.S. Army Corps of Engineers bridge inspection brochure (*16*) is given as follows:

Size	*Description*
Small	A roughly circular or oval depression no more than 1 in. deep and 6 in. in diam.
Large	A roughly circular or oval depression more than 1 in. deep and 6 in. in diam.

The membership functions describing the various structural condition states for spalling are expressed as a function of the spalling width, as shown in Figure 5.

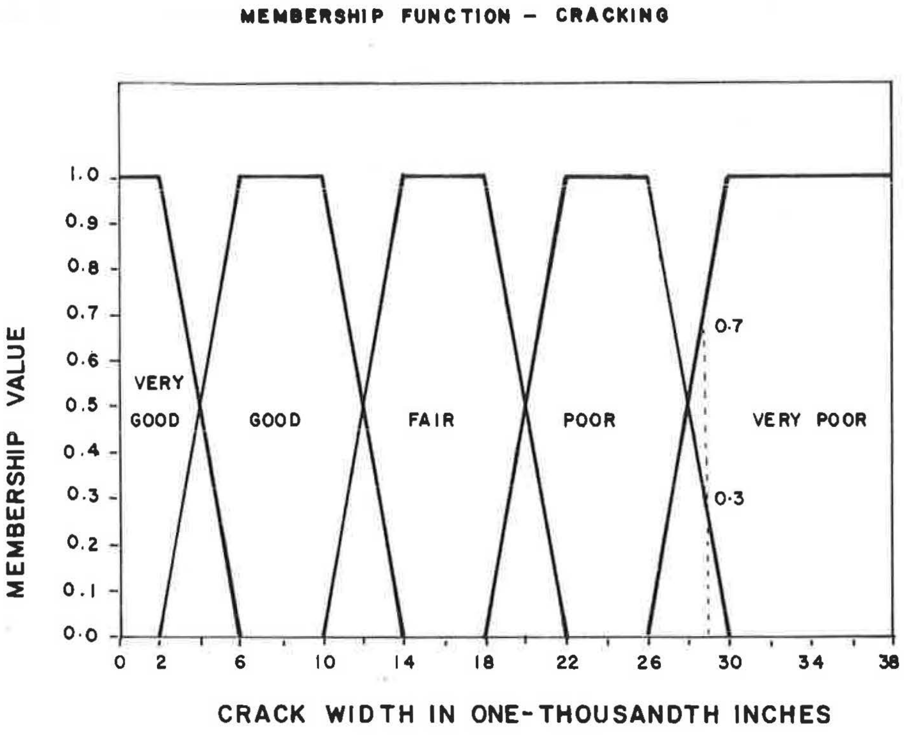

FIGURE 3 Structural condition membership functions for concrete cracks.

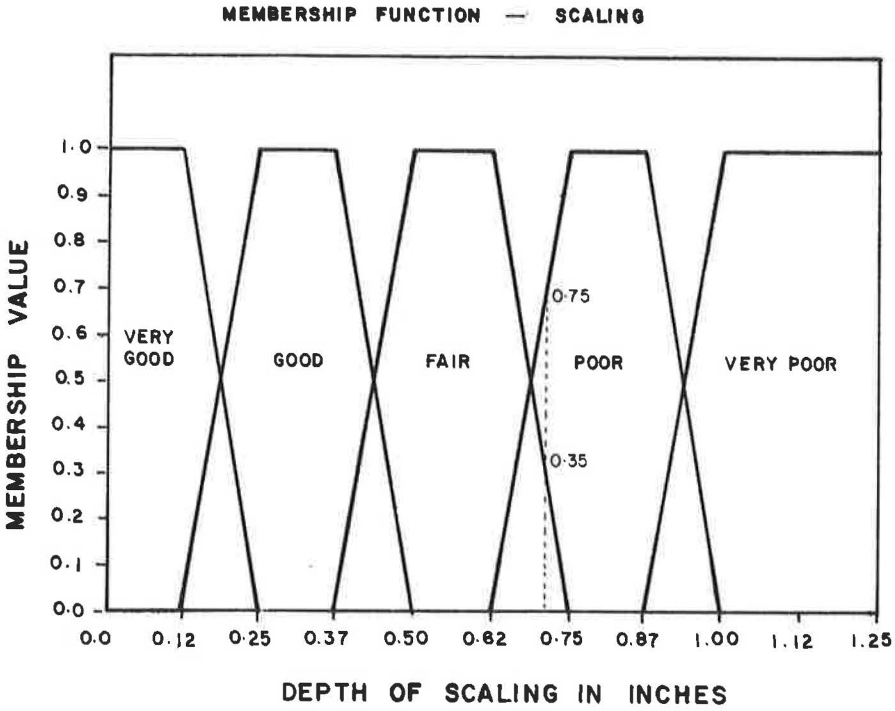

FIGURE 4 Structural condition membership functions for concrete scaling.

It can be noted in the spalling classification table that 6 in. is the dividing width between small and large spalls. In other words, the structural condition of concrete members with spall widths of 6 in. can be described as fair. The other two extremes, the very good and very poor structural condition classifications, were assumed to correspond to spall widths of less than 2 in. and greater than 10 in., respectively. Similarly, the intermediate stages, the good and the poor classifications, fall between the very good and fair, and fair to very poor classifications, respectively. Obviously, considerable extrapolation of the results in the spalling classification table was used; additional information and expert opinion on spalling can be used to improve these membership functions.

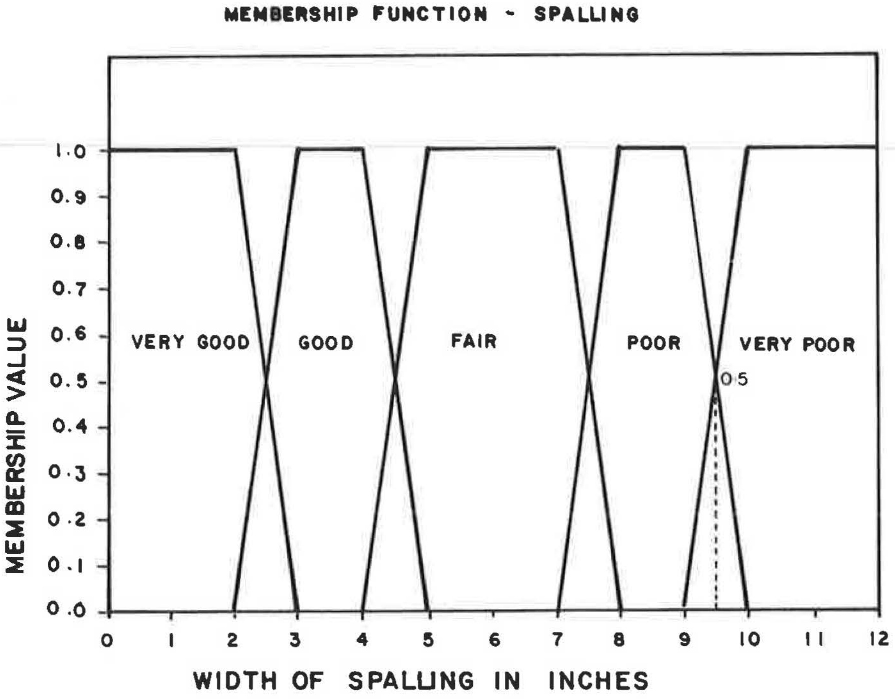

FIGURE 5 Structural condition membership functions for concrete spalling.

ILLUSTRATIVE EXAMPLE

In general, the condition of a reinforced concrete deck can be reasonably estimated by evaluating the severity of various imperfections such as corrosion of the reinforcing bars, and cracking, spalling, or scaling of the concrete and assessing their combined seriousness. The combined effect of these deteriorations on the deck is generally difficult to assess objectively and consistently. However, with the development of fuzzy logic, there is now a method to handle this problem.

As an illustrative example to demonstrate the use of fuzzy logic as a potential tool in modeling the interaction between concrete quality and corrosion, the following imperfections are assumed present on a concrete bridge deck:

Concrete quality: Average crack width = 0.029 in.,
Average scaling depth = 0.70 in., and
Average spalling width = 9.50 in.
Steel quality: Average degree of corrosion = 45 percent.

The overall reinforced concrete quality in this hypothetical example can be modeled based on a combination of the characteristics for the flaws. The method for combining the flaw evaluations is to examine a range in the characteristics that corresponds to either no interaction or complete interaction of the flaws. This fuzzy logic method has been suggested for evaluating metals fatigue by Bowman et al.*(20)*.

Let *A*, *B*, *C*, and *D* stand for the fuzzy sets representing cracks, scaling, spalling, and corrosion, respectively. The effect of each imperfection acting separately is obtained by the union of fuzzy sets *A*, *B*, *C* and *D*, and the effect of all flaws acting jointly is given by the algebraic sum of *A*, *B*, *C*, and *D*. Thus, the grade of membership in a particular structural quality level, represented by fuzzy set *E*, can be evaluated as follows:

$$\mu_{AUBUCUD} \leq \mu_E \leq \mu_{A+B+C+D}$$

where μ_A, μ_B, μ_C, μ_D, and μ_E are the grades of membership in fuzzy sets *A*, *B*, *C*, *D*, and *E*, respectively.

By using the corrosion and concrete quality parameters in conjunction with the membership functions, the overall deck condition resulting from the combined effect of all parameters can be obtained. To illustrate this procedure, consider the "very poor" structural condition. From Figure 3 it can be observed that a 0.70 membership grade for "very poor" structural condition is indicated for a 0.029-in. crack width. (Note that the same 0.029-in. crack width gives a 0.30 membership grade for "poor" structural condition and a 0.0 membership grade for "fair," "good," and "very good" structural conditions.) Proceeding in this manner, the "very poor" condition can be evaluated for all of the imperfection severities as follows:

$$\mu_{vp}(A) = 0.70$$

$$\mu_{vp}(B) = 0.00$$

$$\mu_{vp}(C) = 0.50$$

$$\mu_{vp}(D) = 0.50$$

Using these values, the very poor structural condition evaluation can be bounded as follows:

$$\begin{aligned}\mu_{AUBUCUD} &= \max[\mu_{vp}(A), \mu_{vp}(B), \mu_{vp}(C), \mu_{vp}(D)]\\ &= \max[0.7, 0, 0.5, 0.5] = 0.7\\ \mu_{A+B+C+D} &= 1 - [1 - \mu_{vp}(A)][1 - \mu_{vp}(B)]\\ &\quad \times [1 - \mu_{vp}(C)][1 - \mu_{vp}(D)]\\ &= 1 - (1 - 0.7)(1 - 0)(1 - 0.5)(1 - 0.5)\\ &= 0.925\end{aligned}$$

Consequently, the membership value for very poor structural condition classification falls in the range:

$$0.7 < \mu_{vp}(E) < 0.925$$

The lower and upper bound in this range can be viewed as the degree of "belief" that the overall structural condition is very poor when the effects of flaws are acting separately and when they are acting jointly, respectively.

The same procedure is repeated to define the upper and lower limits of the remaining structural condition classifications. The grades of membership for fuzzy set *A*, *B*, *C*, and *D*, and the upper and lower limits of fuzzy set *E* are shown in Table 3. Based on the tabulated results, it can be concluded that the strongest membership for the condition of the reinforced concrete deck caused by the combined effect of the various flaws is most closely associated with the "poor" classification.

It should be noted that in this fictitious example it is assumed that each flaw has equal impact or importance

TABLE 3 STRUCTURAL CONDITION GRADES OF MEMBERSHIP

Membership	Cracks 0.029 in.	Scaling 0.70 in.	Spalling 9.5 in.	Corrosion 45%	Union	Algebraic Sum
Very good	0	0	0	0	0	0
Good	0	0	0	0	0	0
Fair	0	0.35	0	0	0.35	0.35
Poor	0.3	0.75	0.5	0.5	0.75	0.956
Very poor	0.7	0	0.5	0.5	0.7	0.925

when computing the overall deck condition. However, in reality, this may not be true because certain flaws may be more important than others. If a flaw were to influence the overall deck condition differently, then an importance coefficient denoted as alpha (α), a number between 0.0 and 1.0, must be assigned to the flaw to reflect its influence on the overall structural integrity. For example, a small alpha value would be assigned to the flaw that is relatively unimportant. Conversely, for "important" flaws, their alpha values would be nearly equal to 1. If all flaws are to have equal importance (as in the example given), then the alpha values would be equal to 1.

The alpha value merely modifies the grades of the membership of a flaw. The alpha value of each flaw may be obtained through expert opinion survey or from structural analyses. The remaining computational steps will still be the same as in the algorithm previously mentioned. The limitation here is that the alpha value cannot be a fuzzy number (a number described by a fuzzy set).

The proposed approach selects the condition classification that has the highest membership range as the overall condition rating. The remaining condition classifications, which have lower membership ranges, were ignored. In some instances, this approach may not yield satisfactory results. For example, if the severity of corrosion shown in Table 3 were to be 5 percent instead of 45 percent, then the strongest membership for the overall condition of the bridge deck would be associated with the "very good" classification, even though the characteristics of all other flaws remain the same. (Note that 5 percent corrosion level gives a membership value of 1 for the "very good" condition classification and a 0.0 membership grade for the rest of the condition classifications.)

A more desirable approach would be to consider the membership limits of all condition classifications in determining the final condition rating. The lower and upper membership limits in Table 3 can be graphically represented as intervals, as shown in Figure 6. These intervals can be further depicted in the form of a modified histogram with unit cells, as shown in the same figure. The resultant condition classification can thus be obtained by computing the first central moment of area of this histogram. Using this approach, the final condition assessment resulting from the combined effect of the various flaws is found to be closely associated with the "poor" classification.

The major limitation of this approach is that it is not suitable for computation by hand. However, with the advent of the computer age, this limitation should not prevent the application of this approach to real-world inspection problems.

CONCLUSIONS

The procedure for rating an existing bridge structure requires a careful evaluation of many complex and often conflicting factors. Such evaluation is frequently based on the personal judgment, intuition, and perhaps experience of each inspector. As a result, different inspectors may assess a given bridge differently. Hence, a logical assessment procedure capable of incorporating both objective knowledge and engineering judgment systematically would be desirable. The theory of fuzzy mathematics offers a technique that can be employed to formulate such an assessment procedure.

A number of factors are known to affect the overall quality of a reinforced concrete member. The factors reported herein are cracking, scaling, and spalling of concrete and corrosion of reinforcing steel. Because of imprecise knowledge concerning the severity of these imperfections, linguistic instead of numerical rating variables are used to describe their condition. Successful use of this

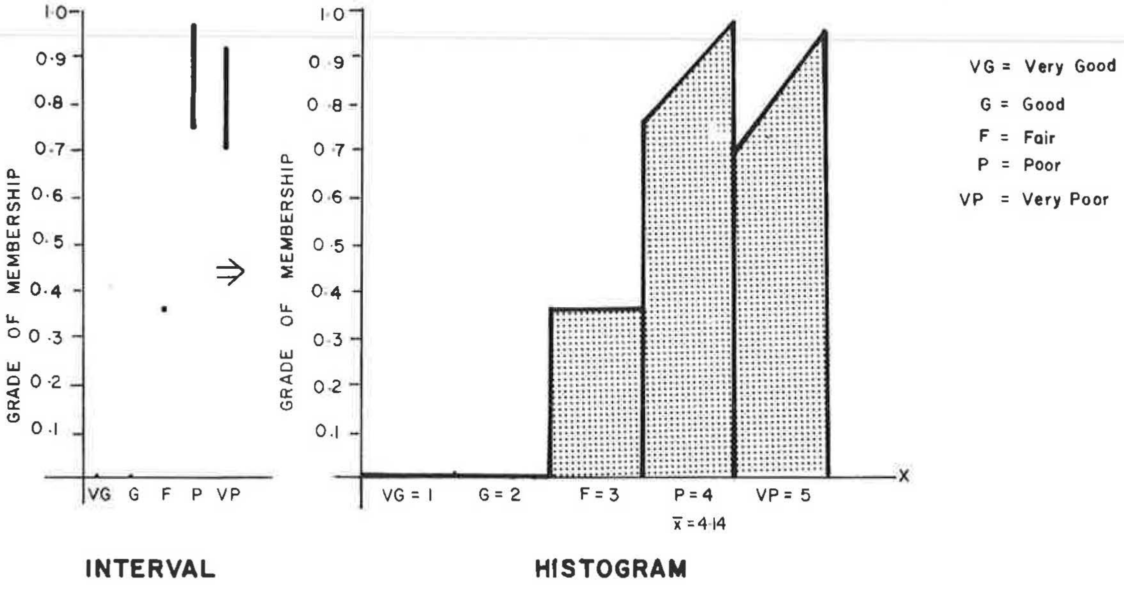

FIGURE 6 Condition classification histogram.

procedure depends on the development of adequate membership functions. The membership functions presented herein are developed on the basis of information extracted from the literature and structural analysis. They can also be formulated or improved through expert opinion.

ACKNOWLEDGMENT

The authors sincerely appreciate the financial support given by the Joint Highway Research Project of Purdue University, the Indiana Department of Highways, and the Federal Highway Administration.

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The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or policies of the sponsoring agencies.

Publication of this paper sponsored by Committee on Structures Maintenance.