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FUZZY-BASED METHOD TO ACCOUNT FOR SUBJECTIVITY AND UNCERTAINTY IN BRIDGE CONDITION ASSESSMENTS

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Abstract: Bridges are important element of civil infrastructure systems as they support the society and the economy on daily basis. In many countries, existing bridge infrastructure is aging and deteriorating. Bridge Management Systems (BMSs) have been utilized to select appropriate Maintenance, Repair and Replacement (MR&R) actions to maintain existing bridges within acceptable safety and serviceability limits. Bridge inspection and bridge condition assessment are important steps needed to make bridge management decisions. The main limitation of bridge condition assessment through inspection is the uncertainty inherent in bridge inspectors' subjective ratings while using linguistic expression to quantify defects associated with the various bridge elements. This can significantly affect reliability of the condition assessment process. This research reviews the fuzzy logic and the stochastic analysis utilized in bridge condition assessment to account for uncertainty and subjectivity and proposes a combined method to address both limitations in bridge condition assessment. Then, a systematic method for bridge deck condition assessment is proposed and demonstrated with a case study. The method benefits from both the fuzzy membership functions and the stochastic approach to account for uncertainty in bridge condition assessment. The method is simple and practical but it needs be validated further with more case studies to be accepted in practice.

1   INTRODUCTION

Several Countries all over the world have developed and used Bridge Management Systems (BMSs) to manage their bridge infrastructure and to assist managers in making Maintenance, Repair and Replacement (MR&R) decisions under limited budget availability. In the United States, Pontis is one of the most commonly used systems. A report by the Federal Highway Administration (FHWA, 2005) indicated that 39 states, 5 municipalities, and 5 international agencies used Pontis. In Canada, Ontario and Quebec developed and used BMSs (Ellis et al., 2008; Thompson et al., 1999). BMSs are also utilized in several countries including Canada, the United States, Australia, Germany, England, Norway, Finland, Poland, and Japan. Bridge condition assessment and rating are the basis for bridge management. While developing BMSs, the various departments and ministries of transportation, and local municipalities have developed their own practices in bridge condition assessment and condition rating. The details and frequency of concrete bridge inspection procedures can differ from one place to another. However, visual inspection main procedure has the same purpose.

The visual inspection procedure starts with a controlled visit by bridge inspection team to the bridge site to detect defects and deterioration, to quantify the extent of deterioration, and to rate elements' condition. The inspection team produces reports to document the findings of the inspection process. Locations of defects are detected visually by examining the various bridge elements, while the extent of defects are assessed with the use of some basic tools such as measuring tapes, hammers, and chains. Among the common

defects of concrete bridge decks are corrosion of reinforcing steel, which leads to delamination. Delamination is an internal fracture inside concrete slabs at the level of steel due to internal stresses imposed by increase of volume of the corroded reinforcing bars. Typically, inspectors identify delaminated areas by noting sound changes while striking the concrete slab of the deck with a hammer or while dragging a chain over it. Subjectivity and uncertainty are inherent in inspectors' judgments while implementing such procedures.

Inspection procedures use some tools and techniques to assess subsurface defects. These techniques are indirectly identifying and quantifying the subsurface defects locations and extent. For instance, changes in echo sound while tapping on the concrete with a hammer is typically used to detect delamination. In certain cases, internal distresses cannot be directly detected using visual inspection until it reaches the surface once deterioration has reached the surface. The limited visualization of exact location and extent of subsurface defects and distresses introduces uncertainty to the visual inspection process. Inspection reports normally use comments to document previously repaired areas. It is normally not clear if a delaminated area has delaminated again or extent of crack propagation compared to crack condition detected during previous inspections.

Visual inspection reports provide assessment of the situation but do not provide adequate recommendations on the appropriate actions to be taken. This decision is typically made based on bridge engineers' judgment after reviewing and interpreting data included in the inspection report. Current research investigates the technical aspects of the visual inspection process and focuses on limitations related to uncertainties associated with the inspection procedure in term of data collection and data processing. Below is a summary of the main technical limitations of the visual inspection process identified in bridge inspection current practices. This paper discusses subjectivity and uncertainty issues associated with bridge inspection and introduces a method to account for these limitations.

2   UNCERTAINTIES IN BRIDGE CONDITION ASSESSMENT

As indicated from above, the main challenge in bridge condition assessment is accounting for uncertainties inherent in bridge inspectors' subjective ratings. Mainly two approaches have been used in the literature to address uncertainty in bridge condition assessment: 1) Fuzzy Logic and 2) Stochastic Analysis. The main question to be addressed in support of using any of these two approaches is the source of uncertainty. If uncertainty is decided to be associated with fuzziness in the subjective evaluation completed by the inspector while assessing bridge condition, then fuzzy logic needs to be used. On the other hand, if uncertainty arises from randomness in measurements, then stochastic analysis can better represent these uncertainties and can produce sound condition's assessments. The following two sections review the two approaches and provide literature review on both approaches.

2.1   Fuzzy logic in bridge condition rating

Back in 1965, Zadeh extended the conventional set theory and introduced the Fuzzy logic to model ambiguity in linguistic expressions and terms. In his famous paper, Zadeh (1965) defined a relationship between fuzzy logic and fuzzy subset theory, which extended and to a certain extent replicated the connection between True/False logic and the subset theory. Instead of saying an element is either belong or does not belong to a set, the concept of membership function was proposed to make an element partially belonging to a set. If the membership function values range from 0 to 1, then the set under consideration is a fuzzy one (Zadeh, 1965). Since its inception, the logic has had significant success in several areas of research and development.

Tee et al. (1988) used the fuzzy logic to quantify subjectivity of language terms such as good, fair and poor typically used for bridge condition assessment and condition rating. They extended the weighted average equation and proposed a fuzzy weighted average (FWA) approach. The traditional weighted average technique combines factors with unequal weights. The FWA approach applies the fuzzy mathematics while estimating weighted average. The FWA is given by Equation 1:

$$[1] \quad FWA = \frac{\sum\limits_{i}^{n} W_i R_i}{\sum\limits_{i}^{n} W_i}$$

where Wi and Ri are is the fuzzy weight and fuzzy condition rating of element I, respectively. The fuzzy mathematics (addition, multiplication, and division algorithms) developed by Zadeh (1965) are applied to find the fuzzy weighted average.

Extensive studies on using fuzzy logic and fuzzy weighted average followed the work of Tee et al. (1988). Liang et al. (2001) evaluated the damage grade of existing bridges using fuzzy logic. Other researchers proposed a fuzzy inference system for bridge damage diagnosis and evaluation (Zhao and Chen, 2002). Kawamura and Miyamoto (2003) proposed a neuro-fuzzy system for bridge condition assessment that is based on integrating fuzzy inference rules with artificial neural networks. The neural network was used to refine the fuzzy expert system. Sasmal et al. (2006) formulated the condition rating of existing bridges using a combination of fuzzy mathematics and an eigenvector priority setting approach. Sasmal and Ramanjaneyulu (2008) developed condition rating method for concrete bridges that is based on the analytic hierarchy process (AHP) and the fuzzy logic.

2.2   Stochastic analysis in bridge condition assessment

Stochastic models include Probability Distribution, Simulation Techniques, and Markovian Models. Probabilistic methods are typically selected to address and quantify uncertainties in events. Uncertain discrete events are events that may or may not happen. Experts are requested to assess the probability of occurrences of the discrete uncertain event in the form of a single point value in the interval [0,1]. In continuous probability, on the other hand, experts are requested to indicate the numerical value of some parameter w by assigning quantiles of a probability distribution function on an interval x containing w. In this approach, experts are asked to assign 5%, 50% and 95% quantiles. The expert thereby supplies lower and upper boundaries x1 and x2 such that $P(w \leq x1) = 0.05$ and $P(w \leq x2) = 0.95$. Supplementary information such as the mean and median are needed.

Stochastic approach has been dominant in the area of deterioration modeling. The Markov Chain approach is used extensively and had been adopted by state-of-the-art bridge management systems. However, the literature on stochastic bridge condition assessment is not as rich as deterioration modeling. Wang and Elhag (2008) used an evidential reasoning (ER) approach for bridge condition assessment. They argued that the ER approach has advantages over other approaches such as bridge element can be assessed to two assessment grades to enable more precise assessment than using only one assessment. The main limitation of the evidential reasoning approach is that it builds on some basic probability assignment submitted by the expert. Alternatively, the proposed method here includes a systematic approach of assigning the initial probability assignment with the aid of the membership functions.

3   PROPOSED CONDITION ASSESSMENT METHOD

Understanding difficulties associated with condition rating using linguistic expressions, the proposed method is designed to benefit from both stochastic assessment and fuzzy membership functions. It is evident that direct rating of bridge elements using linguistic expression such as Good or Fair is subjective and may not represent the accurate condition. Instead, probabilistic rating can enhance the assessment so the inspector may rate the element to be in Good condition with 70% confidence and Fair with 30% confidence. The proposed method here facilitate the condition rating process by requesting the inspector to assess the quantity of the defects and their severity, then the method aggregates the assessment and translates them to condition ratings using appropriate membership function. For practical reasons, the proposed method is developed for the bridge deck. However, the same methodology can be used for condition assessment of bridge substructure and bridge superstructure. The proposed method is implemented by applying the following steps:

1. Identify the main elements of the bridge component (deck in this case) and identify the main defects associated with the elements. The elements and defects are shown in Table 1.

2. Assign weights of the elements and the corresponding defects. These weights enable the aggregation of the ratings to produce an overall rating for the bridge component. The bridge deck is divided into Wearing Surface, Deck Top, Deck Bottom and Drainage System. The corresponding defects and their weights are identified based on reviewing bridge inspection manuals and using the author judgments. The weights are assigned with the help of bridge engineer. The breakdown and the weights are provided in Table 1.

Table 1. Relative Weights of Sub-elements of the Bridge Deck

Sub-element	Assigned Weight	Defect
Wearing Surface	0.20	Potholes
		Crack
		Rutting
		Rippling
		-Loss of Bonding
Top of Deck	0.40	-Delamination/Spalling
		Cracking
		Corrosion of R/C
		Pops out
		Scaling
Bottom of Deck	0.30	Delamination/Spalling
		Cracking
		Corrosion of R/C
		Pops out
		Scaling
Drainage System	0.10	Pipe Condition
		Deterioration of connections or fasteners

3. Use the fuzzy membership concept to quantify the linguistic expressions used to assess the material conditions of bridge elements. This research adopted membership functions developed by Moufti et al. (2014). The developed membership functions, shown in Figure 1, are developed to map a given defect-affected area onto the interval [0, 1] for primary deck elements. The membership functions are used to assess the degree of belief assigned to the four condition states via defect measurement values. The membership functions indicate that larger percentage of defected area is associated with lower condition state.

4. Complete bridge inspection procedures to assess quantity and extent of each defect included in Table 1.

5. Use the fuzzy membership functions to rate the bridge deck elements and the basic probability assignment based on the quantity of each defect and its extent. The functions measures the the relationship between the extension of the defect and the assessment grades. The four grades are Excellent, Good, Fair and Poor.

6. Aggregate the defects using their weights to rate each element of the deck and then aggregate the elements' ratings to find the bridge deck rating.
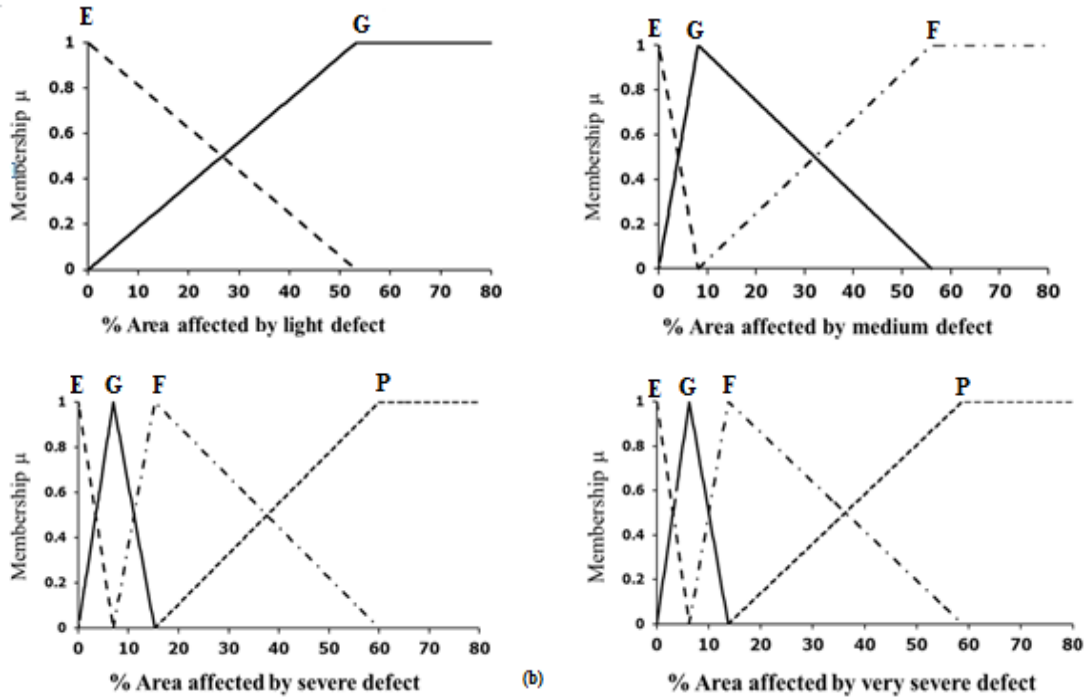
Figure 1. Fuzzy membership functions of defects of different severity levels (E:Excellent, G:Good, F:Fair, P:Poor)

4 CASE STUDY

This case study is based on information gathered from inspection reports conducted on a reinforced concrete bridge. The data provided in Table 2 depicts measurements of defects inspected and identified on the elements of a bridge deck. Defects were detected by means of visual inspection or non-destructive evaluation. The basic probability assignments are estimated and aggregated using the method described above. For instance, the wearing surface element was evaluated by aggregating the assessments of potholes, cracking, rutting, rippling, and loss of bond. Only potholes and cracking are present in the above case. The inspector assessed that total of 20% of the wearing surface is severely deteriorated while in 15% of the area has medium deterioration. Based on 20% of the sever defects, the rating is 11% Poor and 89% Fair or based on 15% medium defects, the rating is 20% Fair and 80% Good. The condition rating of the wearing surface is deemed based on the worse condition state of 11% Poor and 89% Fair.

The obtained evaluations of different deck elements are aggregated to obtain a comprehensive assessment of the bridge deck in this case study. The resulting condition vectors for the deck elements are as follows:

Wearing Surface: {(Excellent, 0%), (Good, 0%), (Fair, 89%), (Poor, 11%)}

Deck top: {(Excellent, 0%), (Good, 0%), (Fair, 90%), (Poor, 10%)}

Deck bottom: {(Excellent, 0%), (Good, 48%), (Fair, 52%), (Poor, 0%)}

Drainage System: {(Excellent, 100%), (Good, 0%), (Fair, 0%), (Poor, 0%)}

Table 2. Defects collected from detailed inspection reports

Elements	Defect	Severity & Extent
Wearing Surface	Potholes	Severe (10%)
	Cracking	Medium (15%), Severe (10%)
	Rutting	None
	Rippling	None
	Loss of Bond	None
Top of Deck	Delamination / Spallig	V. Severe (7%)
	Cracking	Medium (8%), Light (32%),
	Corrosion of Steel	V. Severe (12%)
	Pops out	None
	Scaling	Light (5%)
Bottom of Deck	Delamination / Spallig	V. Severe (2%)
	Cracking	Medium (20%)
	Corrosion of Steel	Medium (18%)
	Pops out	None
	Scaling	None
Drainage System	Pipe condition and Deterioration of connections or fasteners	None

The overall rating can be aggregated based on the weight of each element. The final aggregated assessment calculations are as follow and the assessment results for the bridge deck are shown in Figure 2.

Excellent: 0.2×0% + 0.4×0% + 0.3×0% + 0.1×100% = 10%

Good: 0.2×0% + 0.4×0% + 0.3×48% + 0.1×0% = 14.4%

Fair: 0.2×89% + 0.4×90% + 0.3×52% + 0.1×0% = 69.4%

Poor: 0.2×11% + 0.4×10% + 0.3×0% + 0.1×0% = 6.2%

As can be seen from the condition assessment outputs, the Fair condition state attained the highest belief percentage with around 70% confidence as suggested based on the collected data. The main limitation of the proposed approach arises when bridge inspectors use different rating grades or linguistic expressions. In this case, a new set of membership functions need to be developed to assess uncertainties. However, if the same method is consistently applied to the same network using the proposed steps, the margin of error, if any, will be the same for all bridges and the ranking of these bridges using the condition ratings will not be affected.
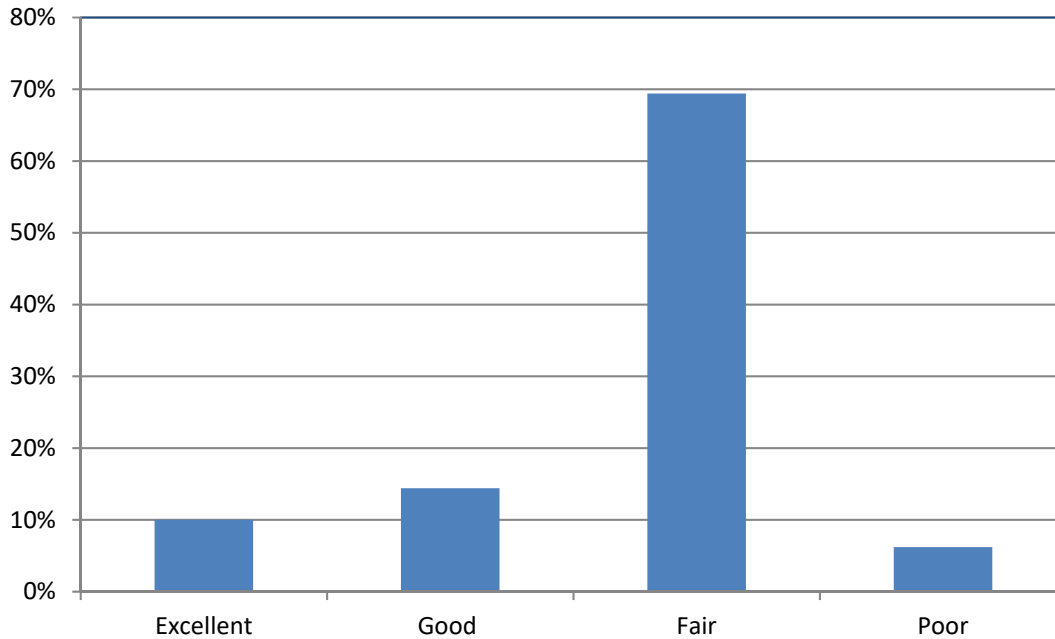
Figure 2. Results of bridge deck condition assessment

5   CONCLUSION

Current practices in bridge inspection rely mainly on visual inspection. Visual inspection results are subjective and the collected data through the process is associated with uncertainty. Two methods are used to account for subjectivity and uncertainty in bridge condition assessment; namely, the fuzzy logic and the stochastic analysis. Integrating the fuzzy logic with the stochastic analysis can enhance the condition assessment results by accounting for both sources of uncertainties. A combined method to address both sources of uncertainties in bridge condition assessment is proposed. The method utilizes the fuzzy membership function to map the linguistic expressions used by the bridge inspectors to condition ratings of the elements. Then, the membership functions are used to assess the basic probability assignment associated with the rating and to generate a probabilistic assessment of the element condition. A step-by-step procedure for bridge deck condition assessment is presented and demonstrated with a case study. The method is simple and practical and could be developed and validated further to be accepted in practice.

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