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Fuzzy modeling of combined effect of winter road maintenance and cyclic loading on concrete slab bridge

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ABSTRACT

The reinforced-concrete slab road bridges in their simplest form are used as a cost-effective solution for local infrastructure in various parts of the world. Since the reinforced concrete slab is the load-carrying element whose upper surface is directly exposed to both road traffic and weather, the integrity of the upper layer of the concrete slab becomes the decisive factor for estimation of durability of these bridges. This paper presents a fuzzy-logic based approach to estimation of stiffness reduction of concrete in the compressed zone of the cross section which takes into account the combined effect of the cyclic loading, freeze–thawing and chloride contamination. The fuzzy logic is used for derivation of numerical relations from available experimental data on the three relevant effects, which can be readily implemented in or used with existing finite element codes. The proposed approach is demonstrated in an example of a model bridge subjected to moderate road traffic and mountainous climatic conditions.

1. Introduction

Reinforced concrete slab bridges have been used since the broader introduction of reinforced concrete at the beginning of the twentieth century for spanning obstacles, such as rivers and streams, no wider than ten meters. The simple construction, which comprises in situ placement of concrete and ordinary quality local workers, renders their range of application for roads in remote mountainous regions. Even though the reinforced concrete slab bridges are viewed as a cost-effective, or low-cost, solution by local authorities, in some regions such as North India this simple structural system is the only choice due to the limited access of construction equipment via the narrow roads, while its durability is the critical factor for viability of the local economy. Hence, the inherent feature of the reinforced concrete slab of the bridge, which is the combination of the load-carrying function with the direct exposure of its upper surface to both road traffic and weather (Fig. 1), becomes the key issue to be considered in the design.

Bearing in mind the fact that the reinforced concrete slab bridges are quite simple to design and thus the project work presents little cost, it is natural that the analysis of the durability should be in a similar range of expense. One can imagine that this goal can be achieved by asking an expert who would go through the meteorological and traffic data for the particular location and provide some recommendation. The approach proposed in this paper follows the same line of reasoning.

The analysis of durability of the reinforced concrete slab bridge is a complex process that should take into account at least the effect of cyclic loading, freeze–thawing and chloride contamination on concrete performance. Based on the literature review, it is evident that relevant experimental data, in terms of combination of fatigue of concrete and freeze–thawing for typical types of concrete used, for example, in North India, are non-existent. Therefore, it is necessary to draw conclusions based on the data that is most suitable for the given case. The fuzzy logic [1,2] was selected for this task because it allows to include relevant experimental data in the knowledge base and to combine them through optimized decision-making rules, which eventually provides quantitative results that are readily applicable in existing finite element codes related to structural dynamic analysis, heat and moisture transfer, and the like.

In this light, this paper presents an approach to the durability analysis of reinforced concrete slab bridges which is based on fuzzy logic. The durability of the bridge is closely related to damage of concrete caused by cyclic and climatic loading, which are commonly analyzed using the finite element codes. Therefore, the loss of stiffness in terms of the modulus of elasticity can be taken as the measure of the damage as it enters directly the calculations. Even though the theoretical background for behavior of concrete under cyclic loading is less developed than that for metals, useful concepts such as the fatigue damage function have been developed

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Fig. 1. Reinforced concrete slab bridge.

[3]. This concept, which corresponds with assumptions included in construction standards and in a modified version, was defined using the fuzzy logic [4]. The developed approach is implemented in the presented analysis for its simple applicability. The effect of freeze–thawing has been studied and relevant experimental data suitable for the presented analysis were obtained from [5,6]. The effect of chlorides on structural integrity of concrete has been studied mostly in relation to marine environment; however, several studies on the effect of deicing agents on concrete surfaces can be also found. The relevant data for chloride induced damage were taken from [7–9]. The definition of the fuzzy-logic models for the three effects and the combination of theirs are described in the following sections, which also include detailed explanation of the optimization of the fuzzy sets. The flow of the simulation, which includes standard finite element analyses, is described in an illustrative example of a reinforced concrete slab bridge situated on Mughal Road in North India.

2. Fuzzy logic

The fuzzy set theory, first introduced by Zadeh [10], corresponds to a natural way of thinking where verbally expressed rules are applied to deal with vagueness and imprecision. This represents an interesting solution because it allows for dealing with verbally expressed phenomena to obtain a numerical solution [2]. The use of fuzzy logic is a relatively new approach for solving problems where it is necessary to input expert opinions into a controlling or simulation system.

Within the applications of fuzzy logic, an emphasis is put on Mamdani's publication [1], which was the first to demonstrate that fuzzy logic could be used in a profitable manner in controlling systems. After that, several applications followed, e.g., in commercial systems [11] and improvement of car performance [12]. The application of fuzzy logic has also presented successful results in concrete technology, e.g., for the prediction of bond strength of concrete [13], diagnosis of concrete bridge deterioration [14], simulation of cement hydration [15] and control of Ready-mixed concrete production process [16], to mention a few.

2.1. Basic concept of fuzzy logic

Fuzzy logic is represented by fuzzy expressions that consist of mapping functions from $[0,1]^n \rightarrow [0,1]$, where n relates to the number of relations from the fuzzy sets. The fuzzy expressions can be translated as *if–then rules*, e.g., "*if x is a, then y is b*". The rules are composed of an antecedent, i.e., the *if* part "*x is a*", and a consequent, i.e., the *then* part "*y is b*". In fuzzy logic, the antecedent and the consequent are usually linguistic variables. The *if-then rules* can be declared by the relation R_n, which is expressed as

$$R_n : \widetilde{A}(x) \rightarrow \widetilde{B}(y). \tag{1}$$

where $\widetilde{A}$ represents the input fuzzy set defined on X, whereas $\widetilde{B}$ is the output fuzzy set defined on Y, and the index n is the number of rules of the system.

The interpretation of rules in fuzzy systems involves three basic steps: fuzzification, inference engine and defuzzification. The fuzzification is the process of mapping the input data to compute the degree of membership $\mu_{\widetilde{A}}(x)$ of an input x in each of the nth rules of the system. The inference engine is responsible for deducing an output for a corresponding input by operating the n rules of the system. The output from the inference engine depends on the type of operator that is used to deal with the input variables. Among the several methods, emphases are put on Mamdani, Larsen, Tsukamoto and Sugeno methods since they are usually applied in fuzzy systems [2,17]. The defuzzification, which is the last procedure of the system, consists in converting a fuzzy value into a crisp value that will correspond to the output of the system. In general, the defuzzification methods can be classified in two types: composite moments and composite maximum. The former is connected to the first moment of inertia of the sets, while the latter relates to the maximum value from the output fuzzy sets [18]. It should be noted that selecting the most suitable inference engine and defuzzification techniques is a context-dependent problem. Although strategies for selection are not properly defined, some criteria can be considered for guidance, e.g., continuity and computational simplicity. Additional criteria are discussed by [19]; however, it is important to observe that the decision is always connected to how well the output relates to the analyzed problem.

The combination of the above described steps provides a decision-making framework of representing human expert rules to infer human decision. The key factors to achieve an acceptable performance in a fuzzy system are connected to the number of fuzzy sets and consequently the size of the system's rule base. Commonly, there are m^k fuzzy rules, where m and k are the number of fuzzy sets and input variables, respectively.

In the classical fuzzy-logic approach, the number of fuzzy rules can be reduced by the user's experience, and the shape of the fuzzy sets is usually linear in order to simplify calculations. Examples of the classical approach in the designing of different material models can be found in [15,20,21]. Nonetheless, when this approach is implemented to model the behavior of non-linear materials, the final result is a rather roughly shaped piecewise curve. Notice that the use of the classical approach is also feasible for material modeling; however, a larger number of linear fuzzy sets is required to obtain smooth curves [15,22]. As a result, this leads to a longer data collection time and high computational cost. Then, in this paper, to improve the modeling process for fatigue of concrete and thus reduce the user's workload, the shape of the membership functions from the prediction model will be adjusted when necessary. The adjustments are performed based on an approach that is similar to the one presented in [22].

2.2. Methodology for optimization of fuzzy decision-making

The proposed approach combines fuzzy logic and genetic algorithms to optimize fuzzy decision-making, which is achieved by optimizing the shape of the membership functions. The adjustments are performed through the definition of the exponent value e that is related to each of the membership functions of the system.