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A nondestructive method for load rating of bridges without structural properties and plans

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ABSTRACT

Load rating describes the processing of quantifying the safe live load carrying capacity of an existing bridge. For most bridges, this load rating is derived as an analytical solution based on the structural design details and operational condition state. However, for structures without plans or insufficient structural details available it is difficult to formulate an analytical solution, especially for concrete structures where internal reinforcement details are needed to determine section capacity. For structures within this category, the potential solutions involve destructive evaluation to characterize the materials and components, proof load testing, or engineering judgement-based characterization. In this paper, a nondestructive method for load rating of reinforced concrete (RC) slab bridges without structural plans is proposed. To determine a bridge's load rating factor, the capacity as well as dead load and live load effects need to be determined. In the proposed approach, a series of finite element analyses were conducted to describe the modal properties of a large population of bridges with different geometric characteristics. Results and geometric inputs were then used to develop an artificial neural network model that predicts the flexural rigidity of a bridge based on the measured modal frequencies derived from vibration testing. Due to the uncertainty in internal geometry of concrete, nondestructive approaches are presented to obtain the cross-section dimensions of bridge as well as the elastic modulus and compressive strength of concrete. Next, the cross-sectional area of the internal reinforcing steel is estimated through a quasi-static load test coupled with an optimization approach. These structural and material properties are then used to determine load effects and ultimately the bridge's capacity. As a validation of the proposed approach, a skewed RC slab bridge with structural plans was tested and analyzed as if plans were not available. The bridge was instrumented with accelerometers and strain gages to record its response under ambient vibration, impact excitation, and quasi-static live load testing. Results show that the proposed nondestructive approach can be used to satisfactorily determine the load rating factor of the test bridge and can ultimately be used for load rating of concrete slab bridges without structural information.

1. Introduction

Given the current state of aging bridges, an understanding of their operational integrity and safe load carrying capacity is critical for life safety as well as the efficient movement of goods, services, and people [1–5]. For highway agencies, load rating defines the process of determining the safe load-carrying capacity of a bridge and, thus, serves as a basis for prioritizing maintenance operations and allocation of resources. Typically, load ratings are developed in accordance with the rules of structural mechanics using design drawings and details that define the geometry and material properties of the bridge [6–11]. Therefore, the information needed to carry out load rating includes critical geometric details such as cross-sectional details, reinforcement configuration that can be extracted from design or as-built plans, often also includes the latest inspection report and even prior load rating files.

However, there are cases where these design plans are missing or incomplete due to lack of documentation at the time of construction, improper storage or the evolution of data management practices. An analysis of the National Bridge Inventory (NBI) database [12] shows that of the 610,000 bridges in-service in the United Sates, 21,374 of these bridges are currently rated solely using engineering judgment. Reinforced concrete (RC) slab bridges represent the largest fraction of bridges within this category at over 4500 structures. For the majority of these structures, detailed structural drawings or as-built plans do not exist or are insufficient for a routine structural analysis; thus requiring

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alternative behavior characterization methods [13]. However, the AASHTO Manual for Bridge Evaluation (MBE) provides limited guidance on the load rating process of bridges without plans [14]. The language in the MBE indicates that an inspection by a qualified inspector and evaluation by a qualified engineer may be sufficient to establish an approximate load rating. This guidance does not explicitly state, but does imply, that engineering judgment may be necessary in which an experienced engineer considers relevant factors such as the original design live loads, past performance and current physical condition of the bridge, current loads, and age to arrive at a judgment-based load rating. However, this engineering judgment-based rating has the potential to yield conservative estimates, which ultimately would lead to unnecessary load postings and restrictions, a potential barrier to the movement of goods and services within the United States. Therefore, accurate load rating strategies for bridges with limited or missing as-built information are needed.

The load rating factor (*RF*) is defined as the ratio of the remaining capacity of bridge for carrying live loads to the effect of live loads [14]. Based on this definition, *RF* is a function of the bridge's capacity as well as the dead and live load effects. In most of the previous studies on bridge load rating, it was assumed that the bridge's as-built information is available to determine its capacity; and the results of a live load and/or vibration test were used to calibrate a finite element model of bridge to provide a more reliable estimate for the load effects [15–18]. Limited studies have been conducted on load rating of bridges with limited or missing as-built information [15]; especially in RC bridges where the complexity and number of unknown structural parameters increase. Huang [19] and Huang and Shenton [20] investigated a method for load rating of RC bridges without as-built information. The method, which was developed was based on the findings of a similar previous study [21] and uses strain or displacement data to estimate the unknown area of reinforcing steel in a bridge. This estimated reinforcing steel area is then used to determine the bridge's capacity based on a sectional analysis. To utilize the proposed approach, strain sensors need to be mounted on the top and bottom surface of a deck to quantify the internal stain distribution of the bridge's cross-section. This approach also requires knowledge of the relevant mechanical properties for the selected materials. Subedi [22] used non-destructive technologies including a concrete rebound (Schmidt) hammer and cover meter (Profoscope) to estimate concrete strength and rebar details, respectively, and compared their results with existing plans for a flat slab bridge. A finite element model of the structure was then built and the bridge model was loaded with the state legal truck. The load was increased such that the model reached AASHTO's maximum serviceability deflection. The ratio of the corresponding allowable load to the original design load was then calculated designed as a rating factor. It should be noted that the method did not include the effects of field factors or bridge condition in load rating, and the use of deflection as the limit state does not correspond with the actual allowable capacity for load rating calculation. In another study, Aguilar et al. [23] presented a four-step load rating procedure for prestressed concrete bridges without plans using proof load test results. Their proposed procedure included estimating the number and eccentricity of strands using Magnel diagrams and typical details at the time of construction. Material properties were estimated based on age using the MBE. A rebar detection system (Hilti Ferroscan) was used to detect location and size of the reinforcement and concrete cover as a verification of the estimates. A diagnostic load test was then conducted to determine the critical transverse truck path and to estimate load effects under the trucks. Finally, a proof load test was performed with a target proof load based on the MBE and the results were used to determine final load ratings. According to the MBE, proof load testing is recognized as a viable solution to determine the safe load carrying capacity of a bridge, but this approach is also potentially a destructive method as the structure is incrementally loaded until signs of distress appear. Proof load testing is considerably complicated and costly in terms of logistics and safety because of the potential for damage to the structure. As such, substantial preparation and experienced personnel are required as well as a careful and cautious procedure to avoid damage or hazards. This is a downside for the widespread application of this method for load rating purposes. These works further highlight that this challenge of bridges with missing or insufficient structural details is one of national interest, but solutions are still needed.

This paper proposes a nondestructive methodology to determine the load rating of RC slab bridges without as-built information by integrating the results of a vibration and quasi-static load test with a numerical modelling strategy. First, an artificial neural network (ANN) was developed and used to create a relationship between the flexural rigidity of a RC slab bridge and its natural frequencies. The training data for the ANN model was derived from a parametric study using finite element analysis and included relevant geometric properties and dynamic characteristics. With a trained model, the natural frequencies identified from a vibration test of a given bridge structure along with its corresponding geometric properties (i.e. span length, width, and skew angle) can be fed to the ANN as inputs of the ANN and the flexural rigidity of the bridge is estimated. With the flexural rigidity is known, a finite element model of the test bridge can be used to determine appropriate dead and live load force effects. Finally, to compute bending capacity unknown parameters such the compressive strength of concrete and cross-sectional area of reinforcing steel need to be determined. In this paper, a numerical approach is used to determine the compressive strength of concrete via the identified flexural rigidity. To estimate the area of reinforcing steel within the cross-section, an optimization-based method is proposed which uses the identified flexural rigidity and strain data collected during a live load test. With geometric and mechanical properties derived, the load rating factor can then be determined using the predicted load effects and capacity. For validation, the proposed load rating method was applied to an in-service skewed RC slab bridge that has structural plans with success. Although this study focuses on load rating of RC slab bridges, the presented methodology is generic and can be applied to determine load rating of other types of bridges.

2. Proposed load rating method

In determining the load rating of a given bridge, the *RF* is used as a scaling factor to estimate the safe carry in capacity of a bridge. The *RF* provides an estimate of the relationship between the remaining live load carrying capacity of a bridge and the live load demand, with a value greater than 1.0 signifying remaining capacity is available and a value less than 1.0 indicating the specified loading exceeds available capacity. The *RF* used within the current AASHTO Manual for Bridge Evaluation is based on a load and resistance factor rating method and is given as follows [14]:

$$RF = \frac{C - \gamma_{DC} DC - \gamma_{DW} DW \pm \gamma_P P}{\gamma_{LL}(LL + IM)} \tag{1}$$

where C is the capacity of member, DC and DW are dead load effects due to structural components and wearing surface, respectively, P is applied permanent loads other than dead loads, LL and IM represent live load effect and its dynamic effect, respectively, and γ is a load factor that depends on the type of load and limit state. For bridges with plans, the parameter C is computed based on material properties, cross-sectional details, reinforcement configuration, and other structural information provided in as-built documents.

For a bridge with missing structural information, there are two types of unknown parameters in Eq. (1) that need to be determined to properly compute the rating factor. The first group of parameters includes the dead and live load effects, which are a function of the bridge geometry, structural stiffness, and support conditions of bridge. The second group of parameters are related to the capacity of the bridge and