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Title: *An Autonomous Bridge Load Rating Framework Using Digital Twin*

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ABSTRACT

Load rating of bridges is used to understand the working status and carrying capacity of bridge structures and components and is necessary to the safety of transportation. The current manual load rating procedure is, however, time-consuming. An intelligent and automatic load rating approach can be beneficial to supplement or eventually perhaps replace the current manual procedures. The innovation of this paper lies in developing an autonomous load rating framework by leveraging Digital Twin (DT) techniques. Full-scale laboratory testing of a bridge slab was conducted to verify the efficiency of the proposed framework. The ultimate moment capacity of the slab was obtained by carrying out four-point bending test. The testing procedure was monitored in real-time with multiple strain gauges. A real-scale finite element model of the slab was developed and calibrated with the testing results. The proposed DT framework of the bridge slabs was developed by integrating the numerical modeling and the strain monitoring. The proposed DT framework is intended for field application, and field results will be discussed.

INTRODUCTION

One of the common approaches to evaluate bridges is using simplified models that represent the structural dimensions and properties obtained from the original design plan during the on-site inspection. Since most of the bridges in the United States were built years ago, it is common to have bridges with no structural plans [1], or structural plans that may vary from as-built conditions. Performance of the bridges decreases during their service life due to different reasons such as corrosion in reinforcement, cracks in concrete, concrete strength reduction, etc. Therefore, as a result, the load-

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carrying capacity of the bridges generally decreases over time [2]. Load rating is a process of determining the safe load-carrying capacity of a bridge and is expressed as a rating factor (RF), which is the ratio of total live load capacity to the weight of the truck used for load rating. However, when plans and details are insufficient to determine the structure's overall capacity, alternative methods must be used to infer what the live load capacity is. Two viable methods allowed by the American Association of State Highway and Transportation Officials (AASHTO) Manual for Bridge Evaluation are the commonly used but subjective engineering judgment and experimentally based proof testing [3]. However, these methods suffer from limitations. Engineering judgment is typically not based on physical phenomena and creates a degree of risk in unconservative estimates or unnecessarily restricting traffic and commerce if estimates are overly conservative. On the contrary, proof testing can cause damage during testing, tends to be expensive, and cannot be extrapolated to future performance. In all cases, load rating is a time-consuming and costly process [4]. The time required for the on-site inspection and load rating ranges between one to four days, which generally involves the closure of lanes and leads to traffic congestion. These lane closures are required for both the safety of the inspectors and due to the size of the equipment used to identify and classify deficient portions of the bridge. The finding of deficiencies leads to increased frequency of inspections and thereby increased costs [5].

The effectiveness of bridge inspections should increase by making the bridge inspection ratings more objective and accurate. The total inspection cost should be minimized by eliminating traffic control costs and reducing labor and equipment costs. Moreover, there is a need to remove the safety risk of personnel in bridge inspections. The prominent objective is to reduce the cost and time of inspections while maintaining and/or increasing inspection quality by making it objective and safe for users [6]. The AASHTO (2011) [7] states that “Many older reinforced concrete and prestressed concrete beam and slab bridges whose construction plans, design plans, or both are not available need proof testing to determine a realistic live load capacity.” Current load rating approaches include diagnostic load testing and proof load testing [8].

In diagnostic load testing, the actual responses of key structural components, in terms of measured strains, deflections, rotations, etc., to known test loads are measured. Typically, an analytical model, based on the best available information, is developed for comparison with the load test results [9-11]. After the analytical model is adjusted and validated against the test results, it can be used to predict structural behaviors for various purposes, including assessing the maximum load effects of dead load and all required rating vehicles. To calculate refined bridge load ratings through diagnostic load testing, member capacities must still be quantified based on section and material properties per construction documents, field measurements, or through in situ material testing. Load factors must also be applied according to the applicable code.

Proof load testing physically demonstrates the bridge's ability to carry its full dead load plus some magnified live load. Test loads are applied to the bridge in multiple steps using loading and unloading processes progressively toward a predetermined target proof load [12-14]. The target proof load is established to be sufficiently higher than the rating vehicles in order to include a live load factor for the required margin of safety and to account for the effects of dynamic impact. During each loading and unloading step, key responses of the structure are measured and monitored for possible signs of distress or non-linear-elastic behavior. Proof testing (e.g., loading of the bridge with very heavy trucks) is costly and requires traffic control, and for prestressed concrete bridges of questionable capacity, proof testing is a challenge due to the potential for exceeding the failure capacity for the target proof load.

Automated evaluation methods, including structural monitoring, may provide benefit through addressing the safe load carrying capacity of reinforced concrete bridges in general and reinforced concrete bridges without plans in particular.

Digitalization (instrumentation and interpretation of the response of bridges) can bring substantial improvements in operational efficiency, decision making, and cost-efficiency of infrastructure. A tremendous amount of data is generated by 'smart' (meaning instrumented without without real time decision-making ability) systems each day [7]. However, the data generated is rarely analyzed or optimized. It is necessary to develop new models based on data-driven and theory-driven methodologies in the real operation of smart systems such as bridges and to understand the validity of existing models by synthesizing prior knowledge and multimodal data in machine learning approaches. The Digital Twin (DT) is an emerging concept that [8] can utilize complex data and combine it with recent findings in physical modeling along with advanced statistical algorithms to provide a near-real-time representation of a bridge system in operation. A digital twin is usually defined as "a digital model capable of rendering state and behavior of a unique real asset in (close to) real-time." It is a digital replica of the real-world physical asset which is constructed using sensor data and historical information of physical systems. With such a continuously updated digital model, remote monitoring can be conducted to save the efforts of physically inspecting the real asset. This approach can also serve to inform an intelligent decision support system. Moreover, what-if scenarios can be simulated for appropriate planning of operation and maintenance activities and to estimate the effect of any future changes on the overall smart system.

Shim et al. [10] proposed incorporating a digital twin concept for decision making by combining a digital inspection system based on image processing and a 3D information model. A geometric model of the bridge was developed through parametric modeling based on the as-built documents of the bridge. Image processing and unmanned aerial vehicle (UAV) scanning were used to develop a surface model in real-time analysis to detect cracks on the structure. The model will receive data and an analysis model was developed that showed the response of the bridge to damage and temperature changes. Ye et al. [11] discuss a two-year study for monitoring railway bridges and a framework for generating a digital twin. They combined both physics-based approaches and data-driven approaches to augment the creation of a digital twin by a data-centric engineering approach. Fiber optic sensors were installed on the bridge at the time of construction, and a Building Information Model (BIM) model was created to show strain and stress along the girders in the bridge during a train passage event. A 3D finite element (FE) model was created with data collected and was verified with the strain measurements from the BIM. They emphasized that integrating multiple data simulation models (BIM, FE, and statistical) is key to arrive at more confident predictions. Dang et al. [12] created 3D geometric models for bridges using 3D scanning, and alignment-based parametric modeling and damage records were linked to components of the bridge. The digital model was updated with inspection results, and the digital twin model facilitated the possibility of big data analysis for a more reliable prediction of future performance. Additional recent applications of digital twin related to the maintenance of bridges may be found in the open literature [13-14].

In this paper, a new implementation of the Digital Twin for assessing the safe load-carrying capacity of precast reinforced flat slab bridge is presented. Laboratory testing has been conducted and a calibrated numerical model is generated to develop the Digital Twin model. The proposed approach is thought to provide a reasonable load-carrying assessment for precast reinforced flat slab bridges and may better account for uncertainties inherent in traditional load rating procedures.

EXPERIMENTAL TEST SETUP

A four-point flexural test (ASTM, C1399) set up was utilized as shown in Figures 1 and 2. Figure 2 displays the experimental test set up of the original slab at the University of South Carolina laboratory. A special loading frame was used to test the specimens. The slab type is commonly used in rural South Carolina bridges. The slabs were simply supported. A rectangular seat was placed between the hydraulic jack and the steel plate to avoid uneven application of load. The specimens were loaded centrally up to the failure of the concrete in compression. A string potentiometer was used at the midspan of the slab to measure vertical displacement. The experimental test set up information can be found in Table 1. Two LVDT sensors were placed at both ends of the slab to measure vertical and horizontal displacement. A 100-kip capacity load cell was used and located between the hydraulic ram and the spreader beam as shown in Figure 4. Two loading scenarios were utilized for a slab in the test procedure. In scenario 1, three Bridge Diagnostics, Inc. (BDI) gauges were attached on the midspan of the slab top surface to obtain the strains. The specimen was loaded from zero until the midspan strain reached the maximum range of the BDI strain gauges. In scenario 2, the same specimen was continuously loaded from zero until it reached a peak load of 84.3 kips, then unloaded.

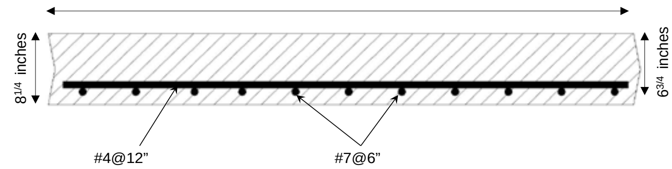

Figure 1. Dimensional information and reinforcing details

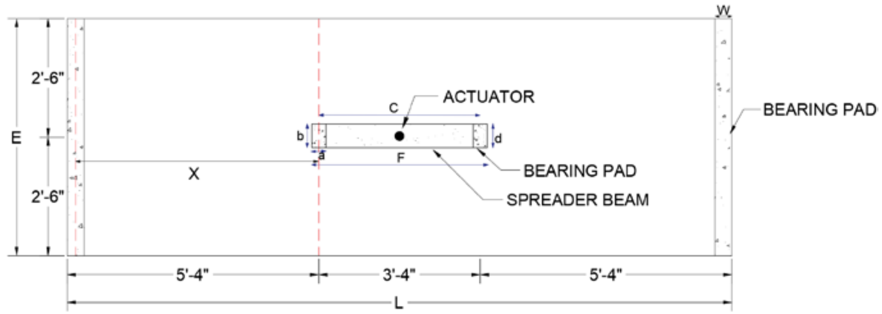

Figure 2. Plan view of 14' slab test set up

TABLE I. THE EXPERIMENTAL TEST SET UP INFORMATION

L (ft)	E (ft)	D (in)	Support condition	W (in)	a (in)	b (in)	A (a*b) in^2	c (in)	D (in)	F (in)	X (ft)
14	5	8.25	Bearing	9.5	8.5	8.5	72.25	40	8.5	51.7	4.93

NUMERICAL INVESTIGATION

A 3D finite element (FE) model of the flat slab test was generated in ABAQUS. The geometry of the slabs and the bearing supports reflected the experiments. The slab was modeled with 8-node linear brick elements with reduced integration (C3D8R), and the rebar was modeled with 2-node linear elements (B31). The typical mesh size of the concrete was one inch x one inch x one inch. Details of the model are provided in Figure 3. In the FE model, the Young's modulus of the rebar was set as 29,000,000 psi, the yielding stress of the rebar was set as 60,000 psi. The Young's modulus of concrete in the model was assumed to be 3,605,000 psi. To be consistent with the loading condition in the two loading scenarios of the experiment, the loading versus time curves (Figure 4) which were identical to the experiment were applied on the model.

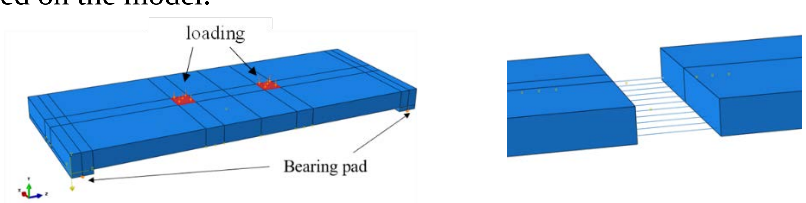

Figure 3. FE model and reinforcing details

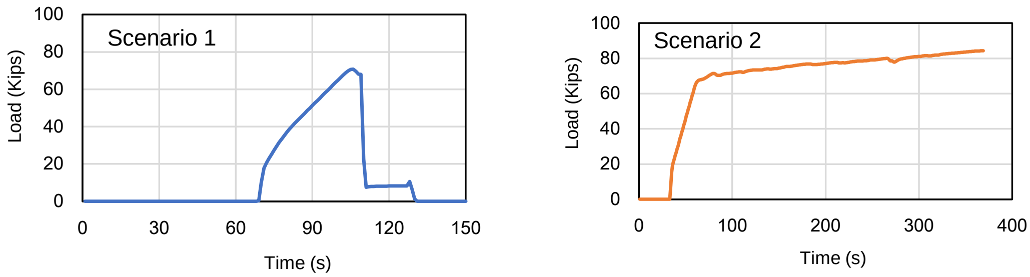

Figure 4. Loading in scenarios 1 and 2

EXPERIMENTAL RESULTS AND FE MODEL VERIFICATION

The midspan strain and moment displacement curves were extracted from the FE model and compared with the experimental results. The FE results in terms of von Mises stress and tensile failure for scenarios 1 and 2 are presented in Figure 5. The red stripes on the concrete slab represents the tensile cracks. Higher stress and more tensile cracks are observed in loading scenario 2, given the fact that the load applied in scenario 2 was higher than scenario 1. In loading scenario 1, the midspan strain extracted from the FE model is compared with the experimental strain captured by the BDI sensors, as shown in Figure 6. The BDI strain presented in this figure is the average value of the strains recorded by the three BDI gauges. The maximum strain obtained by the FE model is -968 με; meanwhile, a similar maximum strain is recorded by the BDI gauges (-1030 με). In loading scenario 2, the moment versus midspan displacement curve derived by the FE model is compared with the experimental result (Figure 6). Relatively reasonable alignment of the trends of the curves can be observed in the FE and experimental results. The yielding moment of the slab acquired by the FE model and the experiment are respectively 185 ft-kips and 172 ft-kips. The ultimate moment of the slab obtained by the FE model and the experiment is 201 ft-kips and 209 ft-kips

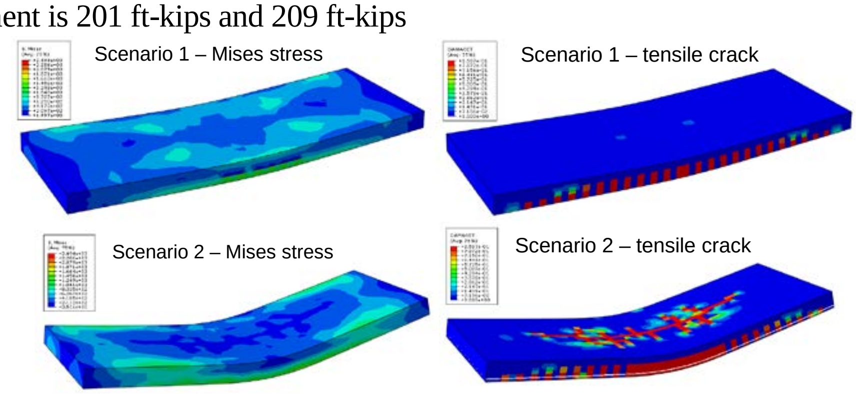

Figure 5. Modeling results

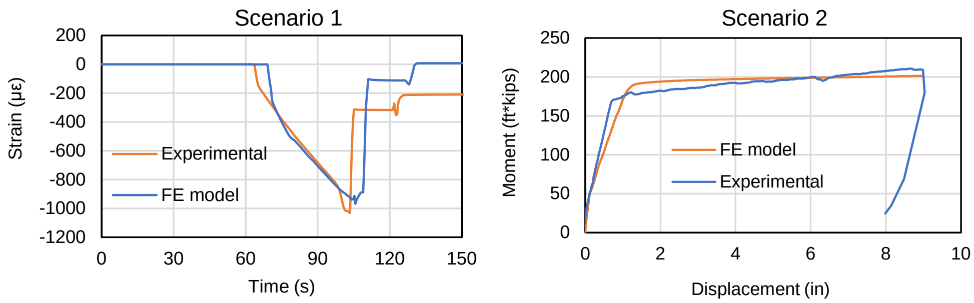

Figure 6. Comparison of FE model and experimental results: Strain versus time curves and moment versus displacement curves

PROPOSED MODIFICATION OF LOAD RATING PROCEDURE

A modified load rating procedure is proposed in this paper through leveraging DT. The overall workflow is presented in Figure 7. The flat slab is awaited for the load rating to be monitored by the strain gauges. An FE model which has the same dimension and materials property as the realistic slab is developed. The model is calibrated and updated by the latest readings of the strain gauges deployed on the realistic slab.

An AASHTO load rating equation [1] is implemented based on the FE model. The equation uses the moments of the slab acquired from the FE model to estimate the load rating factor. The load rating factor can be calculated by:

$$RF = \frac{C - A_1 D}{A_2 L(1+I)} \quad (1)$$

Where, RF refers to the load rating factor, C refers to the capacity of the flat slab, the ultimate moment was employed to represent the capacity in this paper, D is the dead load effect on the slab which is considered as the moment caused by the dead load, L is the live load effect which is considered as the moment induced by the truck loading, I refers to the impact factor utilized in the load rating, A_1 is the factor for dead load, A_2 is the factor for live load. In this paper, The factor A_1 and A_2 for the load factor rating method (LFR) was employed, which are respectively 1.3 and 2.17 for inventory level. The ultimate moment was employed to represent the capacity.

One advantage of the modified loading rating procedure is that field load rating with specialized trucks may not be required. This method may potentially be used as an early warning screening for bridges. It provides an approximate load rating factor and determines if a detailed field loading rating test may be necessary.

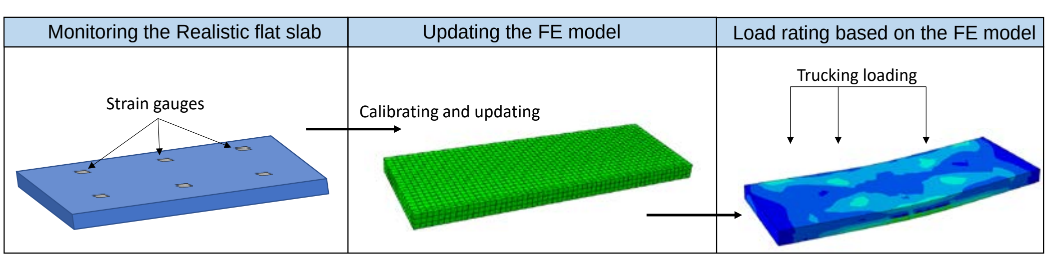

Figure 7. Workflow of the proposed modification of load rating approach

RESULTS OF THE PROPOSED MODIFIED LOAD RATING PROCEDURE

The bridge slab introduced in Section 2 was employed to carry out the modified load rating procedure. A FE model was developed and calibrated by the strains recorded by the BDI strain gauges attached to the bridge slab. Three types of truckloads: H10, H15, and H20 were used in this paper to calculate the load rating factor. These three trucks have the same distance between front and back wheels. The load applied by the front wheels is the same, while the weight applied by the back wheels is 16,000 lbs for the H10 truck, 24,000 lbs for the H15 truck, and 32,000 lbs for the H20 truck [7]. Figure 8 presents the loading and dimensions of the three types of trucks. The scenario with the back wheel positioned at the midspan of the flat slab was considered. In other words, the back wheel truck load was applied to the FE model, as shown in Figure 13. The results of the FE model are employed to compute the load rating factor. The rating factor for H10 and H15 are 1.89 and 1.35, which are significantly greater than 1.00, indicating the slab could operate safely under these truckloads. The load rating factor for H20 (1.05) trucks are slightly greater than 1.00, indicating the slab would be at risk under the truckloads.

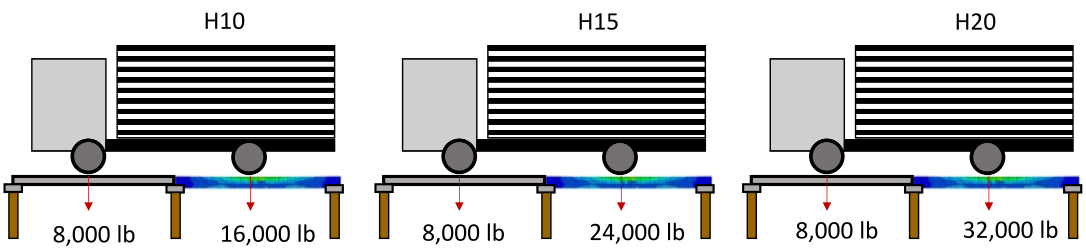

Figure 8. Truck configurations

CONCLUSIONS

In this paper, a Digital Twin (DT) approach is proposed to achieve a load rating factor for precast reinforced flat slab bridges. A DT model was developed based on experimental study and numerical simulations which were verified with the experimental studies for a precast reinforced concrete flat slab specimen. The load rating factor of the flat slab specimen was calculated through the AASHTO load rating procedure. The FE model of the flat slab is aligned with the experimental slab in terms of strain and moment capacity, indicating that the model can simulate the bending of the flat slab and provide the strain in the midspan. The proposed approach is based on the AASHTO load rating procedure. This numerical technique provides information for engineers to load rate bridges through sensor-based information and to continuously update this information. Future work will include expanding the approach to field applications.

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