Engineering Structures 126 (2016) 264–277

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Finite element model updating of semi-composite bridge decks using operational acceleration measurements

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ARTICLE INFO

Article history:
Received 22 May 2015
Revised 16 April 2016
Accepted 28 July 2016

Keywords:
Model updating
Bridge decks
Composite action
Finite element models

ABSTRACT

Composite bridge decks provide higher flexural moment capacity and stiffness compared to their non-composite counterparts. In order to achieve composite behavior, differential slip between the steel member and the concrete slab must be restrained by means of shear connectors. In older bridge decks composite behavior is uncertain. Uncertainty arises, among other things, due to lack of knowledge regarding the type of shear connector used (if any), cumulative damage due to fatigue, and aging effects. In this paper the authors propose the use of sensitivity-based finite element model updating to determine the degree of composite behavior of operational bridge decks with uncertain shear connectors. The free parameters of the models are: rigidity per unit length of the beam-slab interface and the elastic modulus of the concrete slab. The features used in the model updating procedure are the identified modal frequencies from operational acceleration measurements. A sequential sensitivity-based weighted least-squares solution was implemented. The proposed methodology is verified in various simulated bridge deck structures and validated in an operational and partially instrumented bridge deck with uncertain composite action.

1. Introduction

Based on data from the National Bridge Inventory approximately 24% of all multi-span bridges in the United States are constructed using steel girders and a concrete slab [1]. This percentage is higher in the Northeast where it reaches approximately 63%. One important component in this type of deck construction is shear connectors. Shear connectors enable composite behavior by transferring horizontal shear stresses between the steel beam and the concrete slab. Composite decks possess a significantly larger flexural strength and stiffness with respect to non-composite ones [2]. Shear connectors are typically constructed by welding vertical steel studs to the top face of the top flange in steel girders prior to pouring of the concrete slab. The design of shear connectors is governed by two criteria; static strength and fatigue. Shear connectors are first designed for fatigue loads due to moving vehicles and then checked for static ultimate strength. Girders are checked for static ultimate strength assuming full composite action, i.e. the number of shear connectors is enough to transfer the horizontal shear force at the interface that results when the steel girder has fully yielded and the concrete slab has simultaneously reached its maximum compressive capacity. AASHTO LRFD Specifications require that steel girder/concrete slab decks be designed as fully composite [7]. If a beam does not have enough connectors to guarantee fully-composite behavior, then it is categorized as partially composite and its ultimate load capacity is typically governed by the failure of shear connectors.

Whenever the structural integrity of an existing bridge deck needs to be assessed; the presence and effectiveness of shear connectors becomes a central issue. In older bridges with unknown construction practices, lack of as-built drawings and(or) cumulative damage effects such as fatigue, the effectiveness of shear connectors is uncertain. The most widely used approach in the practice of structural assessment of bridge decks with uncertain composite action consists in assuming no interaction between the concrete deck and the steel beam. This practice typically results in a diagnosis that is not cost effective and inconsistent with the fact that over the years of service some of these decks have withstood traffic loading beyond the strength provided by the non-composite assumption. An overly conservative diagnosis regarding a bridge deck could result in an unnecessary decision to replace, retrofit, or to reduce the load rating of the deck. Development of technologies capable of assessing the effectiveness of shear connectors and the degree of composite action in uncertain

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http://dx.doi.org/10.1016/j.engstruct.2016.07.057
0141-0296/

bridge decks would prove useful for engineers and public transportation decision makers.

A reasonable approach to assess the effectiveness of composite action in a deck is to instrument it with sensors capable of measuring the strains in the vicinity of the steel–concrete interface. If the strain measurements in the steel and concrete near the interface are close, then one can infer that there is negligible relative slip between the two surfaces and composite behavior is verified (at least within the range of loading consistent with the measurements). As an alternative, one can measure the strain at various points along the depth of the steel girder and interpolate (or extrapolate) the location of the neutral axis. Using principles from structural mechanics, the level of composite action can be inferred from the estimated location of the neutral axis. This last approach is only valid if no net axial force is present in the deck. One drawback of strain-based approaches is that they require significant instrumentation and can only assess composite action at a local level, i.e. at the section where the strain is measured.

Recent examples of the strain measurement approach can be found in the literature. In [3] Breña et al. present results from monitoring an I-girder type highway overpass under a controlled live load test. A total of 60 strain measurements were used to estimate load distribution factors and these results were compared with the results from a finite element model (FEM). The researchers found that although the deck was designed as non-composite, the strain measurements across the cross section (assuming Bernoulli's hypothesis of linear strain distribution) were consistent with the condition of I-girders acting as composite with the reinforced concrete slab. In [4] Chakraborty and DeWolf developed and implemented a continuous strain monitoring system on a three-span composite I-girder overpass. The instrumentation consisted of 20 uniaxial strain gages. The study reported on data over a period of 5 months. Among other things, the study included the determination of the location of the height of the neutral axes of various structural members when large trucks travel across the bridge. One of the conclusions of this study was that the measured strain levels are typically significantly below those recommended by AASHTO. The authors stated that this is a byproduct of conservative simplifications typically used in conventional designs, such as not including redundancies, connection restraints, and the way in which loads are distributed to different parts of the structure. This conclusion is in agreement with a previous study [5].

Jauregui et al. [6] conducted a series of controlled field loading tests on a standard I-girder bridge built in the late 1950s and assigned for decommission. Measurements consisted of strains and vertical deformations at various points. Results of the investigation show that the deck behaved as if partially composite right up to the onset of yielding. Partial composite action occurred in spite of the lack of shear connectors between the girders' top flange and the concrete slab. This suggests that partially composite action of the girders can be attributed to friction due to the slab bearing down on the girder top flange and mechanical interlock at the girder-deck interface. Jauregui et al. argued that these two forms of shear restraint are dependable if not overcome and thus may be used to arrive at a better measure of the bending stiffness and resistance of the deck.

The main hypothesis of this paper is that global acceleration measurements induced by traffic can be used to estimate the stiffness provided by the presence of partial composite action in bridge decks. Specifically, free vibration response shortly after the vehicle leaves the deck. Laboratory experiments conducted by various researchers on isolated composite beams provide encouraging results which indicate that this approach might be scalable to operational bridge decks [8,9].

Morassi and Rocchetto [8], performed a theoretical and experimental laboratory investigation into the behavior of isolated, free-free steel beams-concrete slab composite beams. They found that if shear connectors are damaged, then their effect can be seen in the changes in vibration frequencies. It is expected that their general conclusions extrapolate to cases with different boundary conditions. Finally, Kwon et al. [9] performed a series of controlled laboratory experiments aimed at testing the effectiveness of post-installed shear connectors. After examination of their experimental results, it is possible to conclude that steel girders with concrete slabs that do not possess explicit shear transfer mechanisms in the form of shear connectors; exhibit a flexural stiffness that lies between the fully-composite and non-composite assumptions. It can also be concluded that the difference between the overall stiffness of a composite beam with shear connectors versus an identical one without shear connectors can be observed even within the range of linear stresses.

The use of acceleration measurements presents several advantages with respect to localized strain monitoring: (i) the overall integrated behavior of the deck can be assessed as opposed to a more local examination provided by the strains measurements (ii) a smaller number of sensors could be used to perform the assessment, making instrumental monitoring of these type of structures more affordable. We propose the use of a sensitivity-based weighted finite element model updating to determine the degree of composite behavior in operational bridge decks with unknown/uncertain installation of shear connectors. The free parameters of the model are the rigidity per unit length of the beam-slab interface and the elastic modulus of the concrete slab. The features used in the model updating procedure are the identified modal frequencies and their corresponding mode shapes extracted from global acceleration measurements. A sequential weighted least-squares solution was implemented with a diagonal weighting matrix on which each element is inversely proportional to the variance of the identified modal features.

From the perspective of model updating, the fundamental challenges addressed in this paper are to determine if: (a) the concrete modulus of elasticity and the interface stiffness are independently identifiable from a subset of modal frequencies and (b) the sensitivity of frequencies to changes in the free parameters is large enough to overcome the "noise" in the identified modal parameters. The identification noise is important because bridges are subjected to variations in environmental conditions that affect boundary conditions and stiffness properties of the material, which in turn get reflected as changes in modal properties.

The proposed approach is verified in the context of numerical simulations and validated in an operational and partially instrumented bridge deck located in the state of Vermont, USA. The bridge was built in 1963 and it supports two lanes of traffic. The deck consists of a concrete slab supported on three inner longitudinal stringers and two exterior girders. The interior stringers are supported on transverse floor beams simply connected to the two main longitudinal girders. The bridge spans a total of 170.08 m (558 ft). A portion of the bridge deck was instrumented with a total of 10 vertical accelerometers distributed along the length of stringers.

The paper begins with a section describing the sensitivity-based model updating procedure to be employed. The procedure uses eigenvalue sensitivity in order to set up the linear set of equations. It also includes a weighting matrix to account for the relative variance in the identification of the modal features. The paper continues with a section describing the various models and assumptions to be used through the rest of the paper. This is followed by sections describing two-dimensional and three-dimensional numerical simulations aimed at verifying the proposed methodology. A section describing the application in the context of an operational bridge deck concludes the computational portion of the paper. The