Engineering Structures 66 (2014) 159–172

Contents lists available at ScienceDirect

Engineering Structures

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

Evaluation of dynamic deformations of slab-on-girder bridge under moving trucks with corrosion-damaged columns

Amina M. Mohammed [a], Husham H. Almansour [b,*], Beatriz Martín-Pérez [a]

[a] University of Ottawa, Department of Civil Engineering, CBY A106, 161 Louis Pasteur, Ottawa, ON, K1N 6N5, Canada
[b] National Research Council Canada, Civil Engineering Infrastructure, 1200 Montreal Rd, Building M20, Ottawa, Ontario K1A 0R6, Canada

ARTICLE INFO

Article history:
Received 31 October 2013
Revised 27 December 2013
Accepted 10 February 2014

Keywords:
Semi-quantitative assessment approach
Corrosion damage
Slab-on-girder bridge
Nonlinear dynamic analysis
Finite element method

ABSTRACT

A simplified hybrid linear/nonlinear dynamic finite element analysis (SHDFEA) based on visual inspection is introduced as part of a proposed semi-quantitative assessment approach of aged bridge columns. The focus is on the evaluation of the dynamic characteristics and behaviour of slab-on-girder bridges under moving trucks when their columns are subjected to severe corrosion damage. The proposed SHDFEA uses nonlinear finite element analysis to evaluate the damaged columns stiffness, mass and damping throughout the step-by-step time history analysis. The efficiency, accuracy and stability of the proposed SHDFEA are verified through different case studies, where very high numerical stability and fast convergence are achieved. The results show that the nonlinear dynamic analysis presents the most general approach to evaluate the effects of any level of corrosion damage in the column for any case of loading, boundary conditions and any progressive change in the column properties. However, linear dynamic analysis is found to be the most economical alternative when the columns are overdesigned. It is found that with severe local corrosion damage in traditionally designed slab-on-girder bridges columns, their static behaviour mostly remains in the elastic range, and the traffic load magnitude remains below their ultimate static capacity. It is also found that the changes in the bridge dynamic performance parameters are marginal when over-designed columns have severe corrosion damage and their safety and stability are critical.

1. Introduction

Evaluating the dynamic performance of a bridge structure under service loads is a major component of the bridge design requirements as well as the assessment of aging bridges. At present, qualitative assessment approaches are used in most of North American states and provinces. With the lack of accuracy of existing assessment approaches, it is required to develop a more efficient assessment approach that can quantitatively evaluate the bridges structural performance when safety critical elements (the bridge columns, for instance) are partially damaged. The authors have proposed a semi-quantitative assessment framework (see Mohammed et al. [1]) introducing a limit states evaluation (LSE) approach in parallel to the limit states design (LSD) approach currently in practice in North American bridge design codes [2,3]. The major evaluation limit states are: evaluation ultimate limit state (ULS), evaluation serviceability limit state (SLS) and evaluation earthquake limit state (ELS). The focus of this paper is on the evaluation serviceability limit state, which is mainly based on evaluating the maximum static and dynamic deformations when the aging structure is under service loads.

The requirements for a quantitative assessment of the serviceability of aging bridges address the importance of estimating, measuring and monitoring the changes in bridges dynamic characteristics for different critical levels of corrosion damage. The damages that result from reinforcement corrosion of the bridge column, such as spalling of concrete cover, reduction in reinforcement section, fracture of one or more stirrups, etc., can be defined as critical damage levels. As a transition stage preceding the development of a time-dependent quantitative assessment approach, enhanced visual inspection (or simply enhanced inspection) can be employed as the major source of input to the proposed quantitative assessment framework.

It is thought that the changes of basic dynamic characteristics such as the natural frequencies of the bridge systems (or bridge elements) can be used as an accurate measure to identify and quantify their state of damage. This is based on the observed reductions of the stiffness and the mass of the affected bridge

* Corresponding author. Address: National Research Council Canada, Civil Engineering Infrastructure, 1200 Montreal Rd, Building M20, Ottawa, Ontario K1A 0R6, Canada. Tel.: +1 (613) 993 0129; fax: +1 (613) 952 8102.

E-mail addresses: Husham.Almansour@nrc-cnrc.gc.ca, husham.almansour@uottawa.ca (H.H. Almansour).

http://dx.doi.org/10.1016/j.engstruct.2014.02.005
0141-0296/

members. However, the natural frequencies are proportional to the square root of the structural element stiffness-to-mass ratio, and hence they are not apparently affected by the discretization approach or to the variation of the finite element characteristics. Most bridge columns are conservatively designed (over-designed) and their service-load-over-capacity ratios (SLOCR) are usually low or sometimes very low (usually 25–50%). For aging bridges, the increase in the truck load, traffic density, frequency and speed in addition to the reduction in the load capacity of corrosion-affected columns could apparently increase their SLOCR. Higher design SLOCRs are targeted for newly constructed bridges to reduce their initial cost or to satisfy aesthetical needs, for the increasing use of high performance (HP) materials, and for performance-based design and structural optimization approaches. On the other hand, the design truck load, traveling velocity, number of truck axles, and the average number of trucks passing over bridges have been extensively increased in the past four decades. This has raised the concern about the possible increase of the vibration and dynamic deformation of the bridges, which could exceed the acceptable limits in the bridge design codes.

Bridge design codes in North America [2,3] limit the vibration amplitude to an acceptable level as part of the serviceability limit state checks. Depending on the slenderness, damping, and continuity of the bridge superstructure and its integration with the bridge substructure, the vibration of the bridge could be sensitive to the dynamic excitation of the traffic load. For short and medium-span bridges, the significant changes of the superstructure or substructure stiffness and mass due to reinforcement corrosion of the bridge columns can result in distinguished changes of the vibration amplitude and/or mode shape. Corrosion-related damages to bridge substructures could result in significant reduction in their structural capacities and safety. However, it is not reported whether the changes in bridges substructures (columns) capacity to a critical level result in a similar critical change in the dynamic characteristics of the bridge superstructure under traffic load. Such changes in the bridge dynamic characteristics are of major interest to the bridge owners and maintenance industry as a basis for the development of health monitoring and/or non-destructive evaluation techniques. On the other hand, many observations of the change of vibration amplitude of the bridge superstructure related to reinforcement corrosion of the deck slab or girders or both are reported [4].

With the progress of reinforcement corrosion in the affected zones, the bridge column capacity is reduced, and hence the load-over-capacity ratio of the substructure (bridge columns) is increased. Although the service load is lower than ultimate capacity and the structural behaviour is mostly in the elastic range when subjected to traffic loads, the resulting damage of reinforcement corrosion and its effects on the concrete strength and confinement could shift the elastic behaviour of the column to the plastic range. Many researchers have observed that the ductility of the reinforcement is also reduced with the progression of corrosion [5]. Typically, linear dynamic finite element analysis is used to evaluate the bridge vibration. However, with the shift of the structural behaviour of the bridge columns to the plastic region, the material nonlinearity should be taken into account when estimating the instantaneous element stiffness in the corrosion affected zones. Hence, nonlinear modelling of the substructure should be essential.

The objective of this paper is to develop a simplified hybrid linear/nonlinear dynamic finite element analysis (SHDFEA) that enables an accurate evaluation of the vibrations of aging bridges when the bridge columns are subjected to severe reinforcement corrosion, as part of a proposed semi-quantitative assessment framework. The emphases are on: (i) the numerical efficiency and stability of the analysis approach; (ii) the approach capability to capture the characteristics changes in dynamic deformation distributions over the superstructure and the substructure; (iii) the approach ability to determine the changes in the dynamic load allowance (or the impact factor); (iv) the validation of cases where the simplified linear dynamic finite element analysis (SLDA) is adequate.

2. Simplified hybrid linear/nonlinear dynamic finite element analysis (SHDFEA) as a part of semi-quantitative assessment framework (SQAF)

Fig. 1 shows the proposed SQAF, which has six major parts: (I) data input; (II) quantifying the reinforcement corrosion and their effects; (III) evaluating columns performance under combined corrosion and ultimate loads (evaluation-ULS); (IV) evaluating columns performance under combined corrosion and service (or traffic) loads (evaluation-SLS); (V) evaluating columns performance under corrosion and seismic loads (evaluation-ELS) (only in high risk seismic zones); and (VI) semi-quantitative assessment and reporting. In North American bridge codes [2,3]; the serviceability limit state is a major limit state to be verified for bridge design. The nonlinear dynamic finite element analysis is the basis for the evaluation serviceability limit state of the proposed semi-quantitative assessment framework (SQAF). The evaluation of the column structural performance under combined reinforcement corrosion and ultimate loads, and the evaluation of the column structural performance under combined reinforcement corrosion and seismic loads are presented in two separate papers [1,6].

The first part of the proposed SQAF includes three data-input tasks: (i) the structural material and geometrical data including boundary conditions; (ii) the loading data; and (iii) the enhanced inspection and reinforcement corrosion data. In the first task, the data are collected from the original design information/report

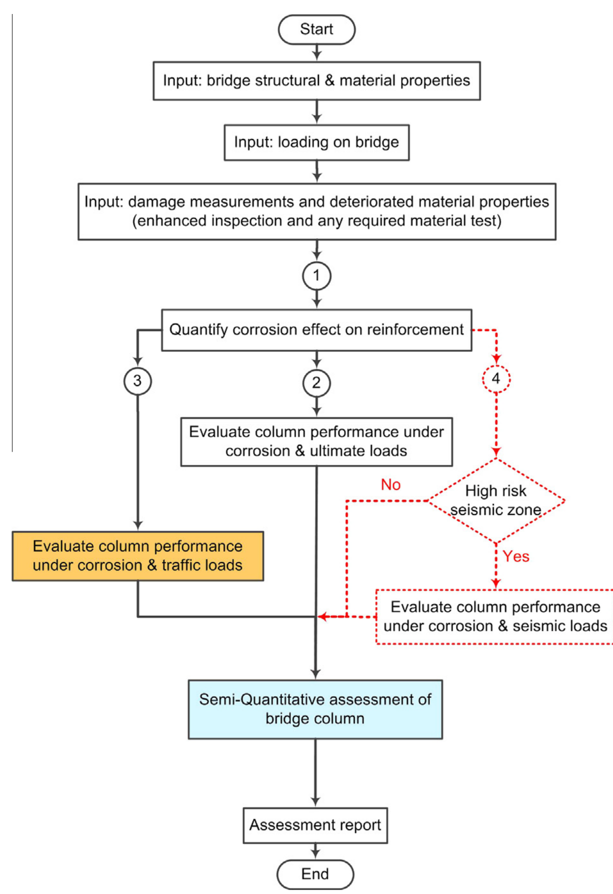

Fig. 1. Framework assessment of aging RC bridge columns.