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# Development of improved natural frequency equations for continuous span steel I-girder bridges

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**Abstract**

Field testing and analytical studies to predict natural frequencies of steel stringer bridges are reviewed in this paper. A three-dimensional (3D) finite element analysis (FEA) procedure using the commercial software ABAQUS, which efficiently captures the vibration characteristics of such bridges, is proposed. Two continuous-span composite steel bridges dynamically (field) tested by others were used to validate the proposed FEA model, which indicates excellent agreement between the analytical and field data. A natural frequency parametric study has been conducted by utilizing the FEA procedure. Based on the regression analysis of the parametric study results, practical equations are proposed to predict the natural frequencies of continuous-span composite steel bridges. The parametric study results are also compared with existing prediction methods, showing that the proposed equations represent a significant improvement over the existing prediction methods.
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## 1. Introduction

High performance steel (HPS), specifically HPS 70W, was first introduced in the United States bridge market in 1997. With its added strength, greater durability, and improved weldability, HPS allows engineers to design longer and shallower spans, which may increase live-load deflections. The AASHTO Standard Specifications [1] limits live-load deflections to $L/800$ for ordinary bridges and $L/1000$ for bridges in urban areas subjected to pedestrian use, where $L$ represents span length. Bridges designed by the AASHTO LRFD Specifications [2] have an optional deflection limit. Previous research by Roeder et al. [3] has shown that the justification for the current AASHTO live-load deflection limits is not clearly defined, and the best available information indicates that these limits were developed to control undesirable bridge vibration and to ensure user comfort. Because these live-load deflection requirements often control the designs of HPS bridges, significant savings in design costs may be achieved if more rational live-load serviceability criteria are adopted.

The bridge design specifications of the Ontario Highway Bridge Design Code (OHBDC) [4] and Australian Code [5] do not explicitly employ live-load deflection limits. Instead, as shown in Fig. 1 from OHBDC, vibration control is achieved through a relationship between the first flexural natural frequency of the bridge and live-load deflection. Australian codes [5] use a similar curve to control superstructure vibration of road bridges with footways. However, no specific equations are provided regarding the calculation of the first flexural natural frequency in the OHBDC. A simple beam equation (discussed below) is suggested to calculate the frequencies of simple-span bridges in the Australian code.

While several previous studies developed empirical expressions [7–11] based on analytical and experimental work to predict better the natural frequency of typical highway bridges, these studies are limited in scope having focused on a narrow range of parameters, and none of the reported results can be coded. Also, various analytical models are available to predict the natural frequencies of highway bridges, but most of the

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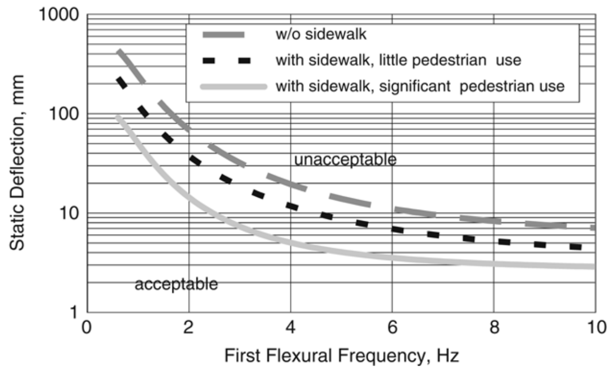


Fig. 1. Deflection limitations.

methods are of little use for design or too complicated to be applied by practicing engineers.

This paper presents an FEA procedure using ABAQUS [6] to analyze the natural frequencies of composite steel bridges. The proposed procedure has been applied to the parametric study of the first flexural natural frequency, which covers a wide range of variables that may affect the natural frequencies of typical composite steel bridges. Results from the FEA parametric study are compared with existing frequency prediction equations, indicating that the existing equations are not sufficiently accurate. Alternatively, a set of more rational and practical equations for predicting the first flexural natural frequency of continuous-span composite steel bridges are developed based on the parametric study results by using the multiple variable nonlinear regression method. The effect of the parapets on the natural frequencies is also investigated.

## 2. Background

### 2.1. Field testing

Empirical expressions have been proposed by several researchers based on limited field testing and natural frequency data. The scope of these works and the limits of these expressions are discussed below.

Wood and Shepherd [7] measured vertical fundamental frequencies on eight composite steel bridges. They developed the expression, $f = -0.21L + 10.3$, for the frequency as a function of span length. But this expression provides an inadequate representation of frequency when compared to the testing data.

Billing and Green [8] obtained natural frequencies from the dynamic testing of 27 structures (12 steel spans). The frequency equation, $f = 110/L_{\max}$, was proposed. But with limited data on the diversity of construction, it is unreasonable to expect that a simple relationship between frequency and span could be codified.

Cantieni [9] conducted dynamical testing on 226 bridges, with 205 (90.7%) of these bridges being prestressed concrete bridges. Cantieni developed the expression, $f_0 = 95.4 * L_{\max}^{-0.933}$. Extreme bridge structures were eliminated from consideration in order to reduce the standard deviation, and the results of only 100 bridges were used to propose the following equation, $f_0 = 90.6 * L_{\max}^{-0.933}$. The variability of the measurement values around the regression curves was considerable for both equations. Tilly [10] added more field-testing natural frequency results into Cantieni's data such that the total number of highway bridges considered was 871. Most of these 871 bridges were concrete highway bridges. Based on these bridges, the expression, $f_0 = 82 * L_{\max}^{-0.9}$ was developed.

Dusseau [11] conducted ambient field testing for 12 highway bridges and proposed the empirical formula, $f_v = 588.118 D^{-0.4} L_s^{-1.45}$, where $D$ is the steel girder depth and $L_s$ is the span length. The empirical formulas only moderately fit the field-measured frequencies.

### 2.2. Analytical studies

Previous researchers have used the Rayleigh–Ritz method, and other rigorous approximate methods, as well as finite element analysis to predict natural frequencies. However, most of these analytical studies involved considerable computation.

Yamada and Veletsos [12] proposed the use of both the Rayleigh–Ritz energy procedure and orthotropic plate theory to obtain numerical solutions for the natural frequencies of a number of simple-span right bridges. Veletsos and Newmark [13] proposed a rigorous numerical method for determining the natural frequencies of straight continuous beams having rigid supports.

Biggs [14] developed the equation, $f = \lambda^2 f_{sb}$, for the first natural frequencies of a simple beam with common classical boundary conditions:

$$f_{sb} = \frac{\pi}{2\,L^2}\sqrt{\frac{E_b\,I_b\,g}{w}} \tag{1}$$

where
- $\lambda = 1$ for simple beam
- $\lambda = 1.25$ for pinned-clamped beam
- $\lambda = 1.5$ for clamped-clamped beam
- $L$ = span length
- $E_b I_b$ = flexural rigidity of the composite steel girder
- $g$ = acceleration due to gravity
- $w$ = weight per unit length of the composite steel girder.

A three-moment equation was also developed to obtain the natural frequencies of normal modes for continuous uniform beams.

Heins and Sahin [15] revised the simple beam equation to calculate the first natural frequencies for curved box-girder bridges utilizing a finite difference analysis.

Billing [16] conducted a parametric study using the lumped mass method to develop normalized tables of natural frequency factors for symmetric multi-span continuous uniform beams. A procedure for the estimation of natural frequencies of continuous bridges was presented which multiplied the base first-frequency, $f_{sb}$, for a simple beam, determined from Eq. (1), with a frequency factor from the presented tables.

Gorman [17] proposed a procedure by solving the differential beam equation to calculate the natural frequencies of beams subjected to prescribed classical and nonclassical boundary conditions, such as a rotational spring support.

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