Estimating Bridge Stiffness Using a Forced-Vibration Technique for Timber Bridge Health Monitoring

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Abstract

This paper describes an effort to refine a global dynamic testing technique for evaluating the overall stiffness of timber bridge superstructures. A forced vibration method was used to measure the frequency response of several simple-span, sawn timber beam (with plank deck) bridges located in St. Louis County, Minnesota. Static load deflections were also measured to establish the benchmark stiffness level for each bridge superstructure. Analytical models based upon simple beam and plate theory were utilized to characterize the relationship between the 1st bending mode frequency and the stiffness of the bridge superstructure. The results indicate that forced-vibration methods have potential for quickly assessing timber bridge superstructure stiffness. However, improvements must be made to the measurement system to correctly identify the 1st bending mode frequency of the field bridges. The beam theory model matched the physics of the single-span, timber beam superstructures better than plate theory. This global vibration technique has potential benefits for routine inspections and long-term health monitoring of timber bridge superstructures.

INTRODUCTION

Recently the Federal Highway Administration (FHWA 2002) expanded the usage of federal "preventative maintenance" funds to include state and local bridges. This has resulted in several states developing bridge asset management systems that are preserving highway bridges by implementing new and cost-effective preventative maintenance practices. These developments have focused current research efforts on developing new technologies to monitor performance of highway bridges. By monitoring key parameters of deterioration, early signs of distress can be detected and appropriate preventative maintenance activities can be performed thereby extending the useful service life of highway bridges.

Frequency response is one bridge inspection tool that has been widely used to detect deterioration of bridge components. However, its use has been limited mostly to longer span steel and concrete bridges. Investigations into the frequency characteristics of timber bridges has been studied recently (Morison et al 2002, Peterson et al. 2003) and found to have several areas that needed further study. These inspection methods involve measuring the frequency characteristics of the bridge superstructure under induced vibration. The frequency data is analyzed and converted to an equivalent measure of the bridge superstructure system stiffness which can be valuable as an inspection tool

This study is part of a comprehensive research effort between the USDA Forest Products Laboratory and the University of Minnesota-Duluth to characterize and further validate the relationship between forced-vibration frequency and overall bridge stiffness. The initial report (Morison 2003) covered the laboratory and initial field work on sawn timber girder and plank bridges. The secondary report (Wang et al 2005) reported results of an additional set of five sawn timber girder and plank deck bridges tested on Ottawa National Forest in Michigan. This study aims to further investigate the potential for forced-vibration techniques to measure the superstructure stiffness by testing several short span timber highway bridges located in northern Minnesota.

OBJECTIVE AND SCOPE

The main objective of this study was to refine a global dynamic testing technique for evaluating the overall stiffness of timber bridge superstructures. A forced vibration method was used to measure the frequency response of several simple-span, sawn timber stringer and plank deck bridges located in St. Louis County, Minnesota. Static load deflections were also measured to establish the benchmark stiffness level for each bridge superstructure. Analytical models based upon simple-beam and plate theory were utilized to predict bridge stiffness levels based upon the 1st bending mode frequency and various physical parameters of the bridge superstructure. A comparison between predicted and benchmark bridge superstructure stiffness indicated the potential for this global NDE technique for health monitoring purposes.

BRIDGE DESCRIPTIONS

All bridges were tested during summer 2005 in St. Louis County, Minnesota. The superstructures consisted of sawn timber beams with transverse deck planking. The typical wearing surface was timber running planks. A summary of the physical dimensions of the test bridges is provided in Table 1.

Table 1 Physical Dimensions of Timber Stringer Bridge Superstructures

Bridge No.	Span (ft)	Width (ft)	Stringer Size (in. by in.)
619	16.0	18.1	4 x 16
CR1	18.3	15.0	6x15
CR2	17.7	15.0	6x15
85-span1	18.8	24.0	9x18
85-span2	19.1	23.9	9x18
242-span1	17.8	24.0	6x18
242-span2	18.1	24.0	6x18
153	18.0	23.4	4x12
305-span1	21.8	27.0	6x19
305-span2	22.3	27.1	6x19
357-span1	11.9	23.7	4x18
357-span2	11.1	23.8	4x18

All of these bridges were constructed more than 50 years ago with varied levels of deterioration. The timber pile bent substructures were mostly in acceptable condition. However, the intermediate pier support at one test bridge were in very poor condition making it impossible to obtain reliable static-load deflection data. Therefore, the data from this bridge was not included in the results included and urgent repairs were recommended to the bridge owner.

METHODS

A brief overview of the methods, including both field and analytical work is provided. A more detailed description of the methods used in this study is available (Wang et al 2005).

Field Work

At each bridge site, both static live-load and forced-vibration testing was conducted at each site. Static live-load tests involved placing loaded and weighed gravel trucks on the bridge and measuring the resulting deflections using suspended rulers with an optical surveying instrument (Fig. 1). Forced vibration testing involved the attachment a motor to the bridge deck planking near midspan in order to induce vibration into the superstructure (Fig. 2). As the motor speed is ramped upward, the frequency response is measured with two accelerometers (at the deck edges near midspan) until the 1st bending mode is recorded (Fig. 3).

Fig. 1 Static live-load testing.

Fig. 2 Forced vibration testing.

Fig. 3 Data acquisition system.

Refinements to Field Testing Procedures

Several adjustments to field testing techniques were examined in this study. A larger motor with finer speed controls were utilized to induce vibration. Instead of relying upon a single transducer, two transducers with each placed at midspan near deck edges were used to measure frequency data. Also, the addition of sand bag live-loads were added to the bridges during forced-vibration tests in order to obtain a clearer and stronger frequency signal.

Analytical Work

Continuous system theory was chosen as the means for developing an analytical model that is based on general physical properties of bridges, such as length, mass, and cross-sectional properties. Specifically, beam theory was investigated as the basis for the model, providing an initial relationships between bending mode frequency and *EI* product:

Beam theory

The following expression was used to predict bridge stiffness based upon beam theory and the measured 1st bending mode frequency.

$$EI = \left(\frac{1}{Kg}\right) f_1^2 W L^3$$

where

f_1 is fundamental natural frequency (first bending mode),
K is system parameter dependent on beam boundary conditions
(pin–pin support, K = 2.46; fix–fix support, K = 12.65),
W is mass per unit length, and
g is acceleration due to gravity.

RESULTS

The results are summarized in Table 2. Static midspan deflections ranged from approximately 0.10 in. to 0.25 in. and were all less than the recommended L/360 span –to-deflection criteria. First mode frequencies ranged from 17 to 35 Hz and generally decreased with increasing span length. Fig. 4 shows a good relationship between frequency and static load stiffness.

Table 2 Summary of Static and Dynamic Bridge Stiffness Values

	Static loading		Dynamic vibration	
Bridge No.	Midspan deflection (in.)	Measured stiffness, EI (x 10^6 lb-in.^{4})	1st mode frequency (Hz)	Predicted stiffness, EI* (x 10^6 lb-in.^{4})
619	0.25	17,906	22.2	14,049
CR1	0.24	24,899	21.2	27,644
CR2	0.24	22,397	18.9	20,265
85-span1	0.18	56,051	25.4	77,348
85-span2	0.12	89,107	27.7	97,236
242-span1	0.12	48,851	22.0	34,222
242-span2	0.11	56,488	21.7	35,186
153	0.12	50,768	27.5	62,454
305-span1	0.12	107,745	31.9	164,941
305-span2	0.09	154,189	34.6	207,704
357-span1	0.12	15,141	18.5	7,047
357-span2	0.12	11,899	17.6	5,176

* based upon beam theory

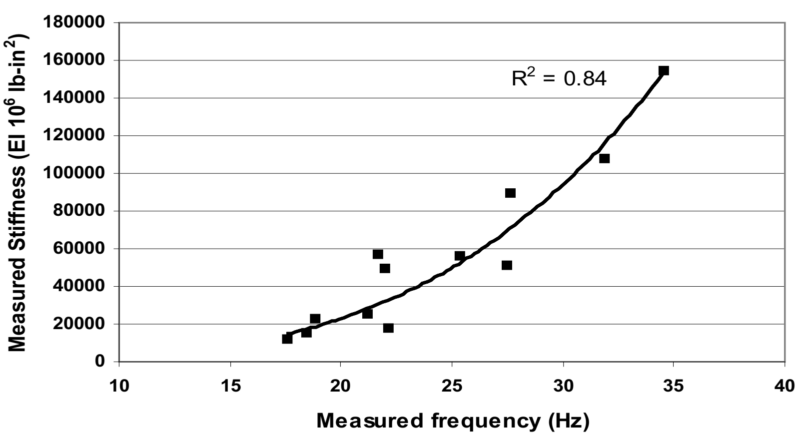

Fig. 4 Relationship ($y = 0.7007x^{3.4714}$) between static-load measured stiffness and measured frequency.

The results of adding live load during vibration testing are shown in Fig. 5. Nearly all bridges exhibited had increased frequencies as live load increments of 1,000 and 2,000 lbs were added to the bridge deck (see Fig. 2). Future testing will include much heavier live loads added during vibration tests.

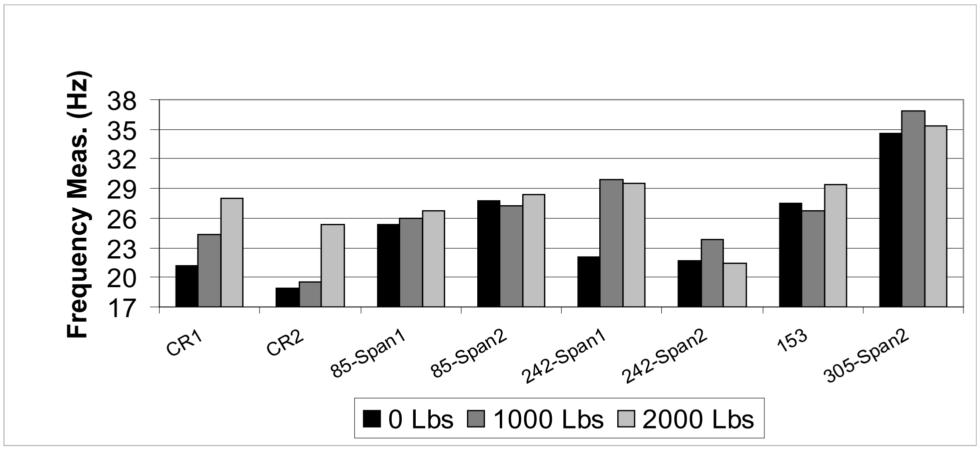

Fig. 5 Effect of adding live load during forced-vibration testing.

CONCLUSIONS

The results indicate that forced-vibration methods have potential for quickly assessing timber bridge superstructure stiffness. However, further improvements need to be made in identifying 1st bending mode and estimation of bridge weight. The beam theory model matched the physics of the single-span, timber beam superstructures better than plate theory. This global vibration technique has potential benefits for routine inspections and long-term health monitoring of timber bridge superstructures.

FUTURE WORK

Additional studies should utilize field instrumentation that can clearly identify 1st bending mode frequencies with real time data processing tools. The effect of adding much heavier live loads during vibration testing should also be studied.

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