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Title:

FIELD VERIFICATION OF A NONDESTRUCTIVE DAMAGE LOCATION ALGORITHM

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Field Verification of a Nondestructive Damage Location Algorithm

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Abstract

Over the past 25 years, the use of modal parameters for detecting damage has received considerable attention from the civil engineering community. The basic idea is that changes in the structure's properties, primarily stiffness, will alter the dynamic properties of the structure such as frequencies and mode shapes, and properties derived from these quantities such as modal-based flexibility. In this paper, a method for nondestructive damage location in bridges, as determined by changes in the modal properties, is described. The damage detection algorithm is applied to pre- and post-damage modal properties measured on a bridge. Results of the analysis indicate that the method accurately locates the damage. Subjects relating to practical implementation of this damage identification algorithm that need further study are discussed.

Introduction

To date, field verification of damage detection algorithms applied to large civil engineering structures are scarce as few full size structures are made available for such destructive testing. Because the Interstate 40 (I-40) bridges over the Rio Grande in Albuquerque, New Mexico were to be razed, the investigators were able to introduce simulated cracks into the structure and then test damage identification methods. Staff from Los Alamos National Laboratory (LANL) performed experimental modal analyses on the bridge in its undamaged and damaged conditions. Researchers from Texas A&M University subsequently applied a damage detection algorithm to these data. The same damage detection algorithm was independently applied by the LANL staff to these data and to numerical data from finite element simulations of the I-40 bridge where other damage scenarios were investigated. The data required by the damage identification algorithm are mode shapes for the damaged and undamaged bridge. However, length limitations of this paper allow only a cursory summary of the experimental modal analyses or the finite element modal analyses.

I-40 Bridge Geometry and Damage Scenarios

The existing I-40 Bridges over the Rio Grande consists of twin spans made up of a concrete deck supported by two welded-steel plate girders and three steel stringers.

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Loads from the stringers are transferred to the plate girders by floor beams. Figure 1 shows an elevation view of the portion of the bridge that was tested. The cross-section geometry of each bridge is shown in Fig. 2.

The damage that was introduced was intended to simulate fatigue cracking. This cracking has been attributed to out-of-plane bending of the plate girder web at locations where cross beams are supported by seats welded to the web. Four levels of damage were introduced to the middle span of the north plate girder close to the seat supporting the floor beam at midspan. The first level of damage, designated E-1, consisted of a two-foot-long (61.0 cm) cut through the web approximately 3/8-in-wide (0.95-cm-wide) centered at mid-height of the web. Next, this cut was continued to the bottom of the web, E-2 . The flange was then cut halfway in from either side directly below cut in the web, E-3. Finally, the flange was cut completely through leaving the top 4 ft (122 cm) of the web and the top flange to carry the load at this location, E-4. Table I summarizes the additional cases that were analyzed with benchmarked finite element models. To reduce the run times, the piers were removed from the numerical models.

Mode Shape Measurement

Mode shapes were obtained using two sets of accelerometers. For the refined set of sensors (denoted SET1) shown in Fig. 3 eleven accelerometers were placed along the span where the damage was introduced. Experimental modal data were obtained from the cross-power spectra where sensor N-3 was used as a reference. A course set of accelerometer data (denoted SET2) shown in Fig. 4 was also used. Modal data were determined from frequency response functions obtained during measured input, random, forced-vibration tests. An input applied directly above the south girder, midway between the abutment and first pier, was used to excite the structure when data were acquired with either SET1 or SET2. A summary of the experimental methods can be found in Farrar, et al., (1994).

TABLE I

Summary of Damage Cases and Results of Damage Identification Process

Case	Location of Damage	Damage Description	Result
E-1	midspan	cut at center of web	Set1 •,Set2 *
E-2	midspan	E-1 extended to bottom flange	Set1 •,Set2 *
E-3	midspan	E-2 plus cut through half of flange	Set1 •,Set2 *
E-4	midspan	E-3 extended through entire flange	Set1 •,Set2 •
A-1	midspan	lower one-third portion of web cut	• •
A-2	midspan	A-1 plus half of bottom flange cut	• •
A-3	midspan	A-1 plus entire bottom flange cut	•
A-4	halfway between midspan and support	A-1 plus entire bottom flange cut	•
A-5	one floor-beam-panel from support	A-1 plus entire bottom flange cut	•
A-6	halfway between midspan and support one floor-beam-panel west of midspan	A-1 plus entire bottom flange cut	one located, the other was not
A-7	halfway between midspan and support	lower one-third portion of web cut	○
A-8	one floor-beam-panel from support	lower one-third portion of web cut	• •
A-9	No Damage, False-Positive Test	No Damage, False-Positive Test	No Indication

• Damage located, • • Damage narrowed down to two locations, ○ Damage not located,
* Damage located using only first 2 modes; damage location unclear using 6 modes

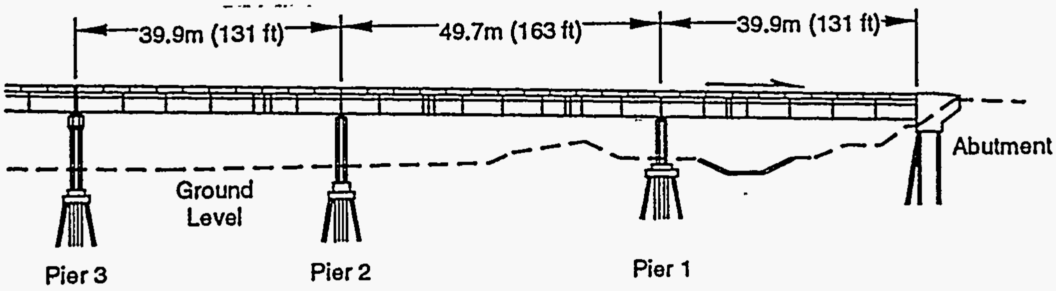

Figure 1. Elevation view of the portion of the eastbound bridge that was tested.

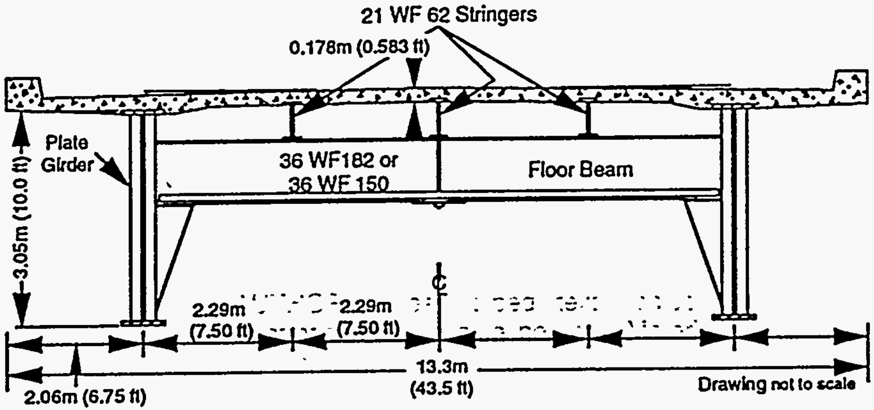

Figure 2. Typical cross-section geometry of the bridge.

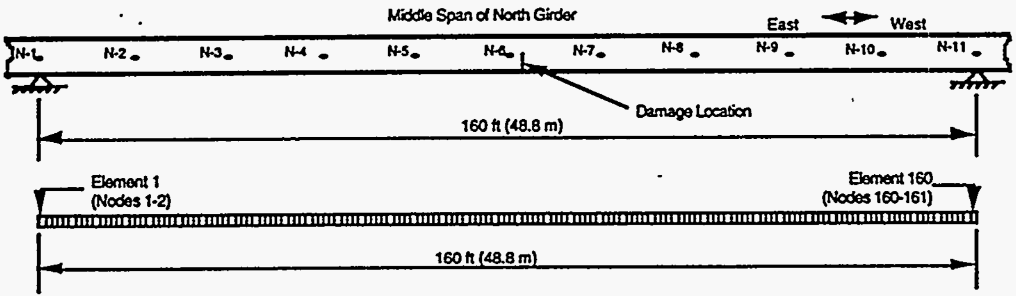

Figure 3. Refined accelerometer locations.

Analytical Modal Analysis

Using benchmarked finite element models as described in Farrar, et al. (1996), forced vibration tests similar to the ones conducted on the I-40 Bridge were simulated numerically. The finite element model of the bridge is shown in Fig. 5. A random force was applied to the finite element model to simulate the input force applied by the shaker during the experiments. Using the random force input, a dynamic time history analysis was conducted and the responses (i.e., vertical acceleration-time histories) at the nine monitored nodal points were recorded. A forced vibration dynamic analysis was initially done with the bridge in its undamaged state and then repeated for each damaged case A-1 through A-8 and the second undamaged case, Case A-9. Results from these analyses (node point accelerations) were then analyzed using similar signal processing techniques as those applied to the refined set of accelerometer data discussed in Farrar and Jauregui (1996).

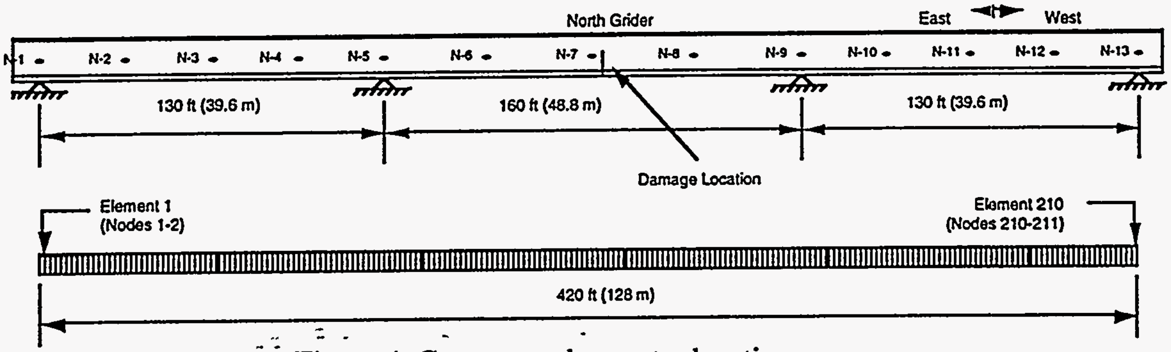

Figure 4. Coarse accelerometer locations.

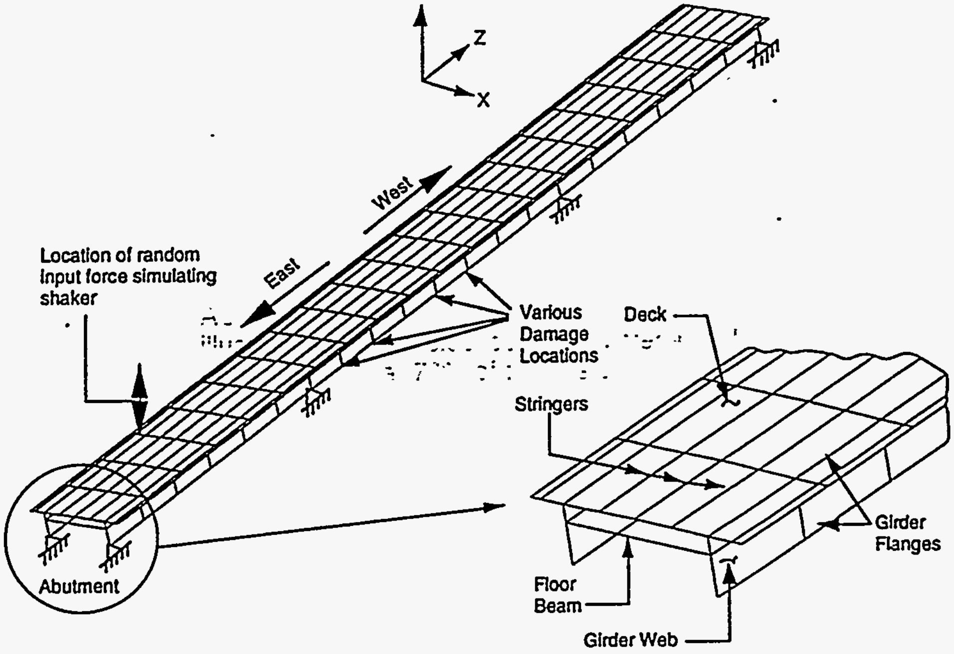

Fig. 5 Finite Element Model of the I-40 Bridge (Piers Neglected).

<u>Damage Index Method</u>

The Damage Index Method (Stubbs and Kim (1993)) locates structural damage given changes in the mode shapes. For a structure that can be represented as a beam, a damage index, β, based on changes in curvature of the ith mode at location j is

$$\beta_{ji} = \frac{\left(\int_a^b [\phi_i^{*}''(x)]^2 dx + \int_0^L [\phi_i^{*}''(x)]^2 dx\right)}{\left(\int_a^b [\phi_i''(x)]^2 dx + \int_0^L [\phi_i''(x)]^2 dx\right)} \cdot \frac{\int_0^L [\phi_i''(x)]^2 dx}{\int_0^L [\phi_i^{*}''(x)]^2 dx}, \quad (1)$$

where $\phi_i''(x)$ and $\phi_i^{*}''(x)$ are the second derivatives of the ith mode shape corresponding to the undamaged and damaged structures, respectively. L is the length of the beam. a and b are the limits of a segment of the beam where damage is being evaluated. Statistical methods (essentially fitting a normal distribution to the β values and picking the 2σ extremes) are then used to examine changes in this index and associate these changes with possible damage locations.

Application of the Damage Index Method to Numerical and Experimental Data

The three sets of mode shape data used in this study are: (1) SET1 - experimental modal data, refined sensor; (2) SET2 - experimental modal, coarse sensor; and (3) SET3 - numerical modal data, refined sensors

When applying the Damage Index Method to experimental or analytical data, values of the mode shape amplitudes at location between sensors were determined by fitting either a cubic spline or a cubic polynomial to the data from the measurement locations. In all cases, the span where damage was introduced was divided into 160 equal length elements. Table I summarizes the results of applying the Damage Index Method to the various sets of data and damage scenarios listed above.

Summary and Conclusions

This paper summarizes the application of a damage location method to experimental and numerical modal data gathered from the I-40 Bridge. Results obtained from the experimental data show that the damage was accurately located in all cases for the refined set of accelerometers. For the coarse set of accelerometers, damage was accurately located when only the first two modes were analyzed. This result suggests the need for a screening procedure that identifies modes that are influenced by damage. Key to locating the damage is the statistical method that is used to distinguish when changes in the damage index are severe enough to be considered indicative of damage. This procedure prevented false-positive readings when the method was applied to two different undamaged data sets (case A-9). However, this method has problems when there are multiple damage locations. Further enhancements to the decision making process must be developed to handle the multiple damage scenario. Finally, it is of interest to note that the damage identification method worked on all experimental cases, but failed on some of the numerical cases (A-1, A-2, A-8) that were more severe than the initial experimental damage case. These results suggest that, when implemented in practice, the modal analysis procedure must propagate a statistical analysis through the mode shape identification procedure. Then the analyst can be confident that the changes being measured are greater than the uncertainties in the modal parameter.

Acknowledgments

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