Condition Assessment/Damage Identification Of An Aged, Deteriorated Steel-Stringer Bridge

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ABSTRACT

The primary objective of this paper and its affiliated research is to rigorously demonstrate that modal analysis and the measure of flexibility extracted from modal test data are effective tools for the condition assessment of civil-engineered structures. The use of flexibility as a condition assessment/damage identification index is the fundamental concept, therefore two basic questions need to be resolved scientifically through the analysis and synthesis of modal test data. These are:

1) Is a linear parameter such as modal flexibility reliable as an index for infrastructure condition and damage identification?; and,
2) What are the attributes of modal flexibility when obtained through modal test methods?

The investigation of these fundamental questions is intended to reveal and characterize behavioral tendencies of modal flexibility (such as stationarity and accuracy). This involves determining how severely flexibility is influenced, or affected, by not only damage, but also by variations in ambient conditions and experimental errors. Consequently, a typical reinforced-concrete deck on steel girder bridge (steel-stringer bridge) will be subjected to a series of deliberately induced damages that simulate typical steel-stringer bridge deterioration and damage scenarios. Throughout this paper, the authors will summarize not only their field test efforts on this bridge, but also the results of the field tests and, in particular, the reliability, practicality, and usefulness of modal testing and flexibility as condition assessment/damage identification tools for typical steel-stringer bridges.

INTRODUCTION

Premature deterioration and structural deficiencies plague highway bridges throughout the United States. Over 40% of the nation's bridges are currently classified as structural and traffic liabilities. These bridges are either a) in poor physical condition; b) not capable of supporting legal truck loads; c) not capable of meeting minimum geometric standards (i.e., height, deck width, etc.) and are thus labeled as structurally deficient or functionally obsolete [Rept. of the Secretary of Transportation 1993, Parsons Brinckerhoff 1993]. Although major efforts are underway to rebuild the nation's infrastructure, there still exist many issues that need to be addressed. For example, to simply maintain current conditions, an average annual cost of $5.2 billion is needed through the year 2011 [Rept. of the Secretary of Transportation 1993]. It is therefore imperative, from both a safety and economic standpoint, to a) develop structural systems and materials that extend service life and improve bridge performance [NSF 1993]; and, b) develop/implement methods that properly identify which bridges need rehabilitation or replacement. To properly identify a deficient bridge and any subsequent rehabilitation or repair, a sufficient understanding of existing bridge condition is needed. Although the American Association of State Highway and Transportation Officials (AASHTO) developed highway bridge inspection criteria after the December 1967 collapse of the Silver Bridge over the Ohio River, the National Transportation Safety Board (NTSB) has criticized the manner in which bridge condition is assessed when using such techniques [White et. al. 1992]. Assessment is typically accomplished through visual methods and NTSB criticism, along with the evidence of actual bridge catastrophes [White et. al. 1992], indicates that visual inspection data does not provide proper characterization of the mechanisms that influence bridge stiffness, toughness, durability, and load capacity. Essentially, subjective evaluation of visual data does not appear to enhance the structural engineer's understanding of bridge behavior.

In order to develop effective and reliable inspection/condition assessment techniques, the in-situ behavioral mechanisms of a bridge should be incorporated into the condition assessment process. The "best" possible method of incorporating in-situ behavior is through the use of objective data acquired through on-site, nondestructive field tests. Such data can provide quantitative, comprehensive, and damage-sensitive information about a bridge [Aktan et. al. 1996]. As a result, the Federal Highway Administration (FHWA) and various state DOTs have provided funding for the development and implementation of field-based, nondestructive bridge assessment techniques.

Potential Of Flexibility As Condition Assessment Tool

Discretizing a structure into numerous spatial nodes, or measurement locations, permits direct measurement of in-situ behavior at pertinent structural locations. Measurements at such locations can provide the basis for development of a discretized flexibility matrix of the structure, which can be used to evaluate structural displacements due to applied loads. The coefficients that comprise the flexibility matrix are a function of the modulus of elasticity, E, inertial properties, I, and span lengths, L, of the structural components. Variations in these parameters, particularly E and I, are indicative of structural deterioration and/or damage. Such variations will directly effect flexibility coefficient magnitudes and subsequently influence flexibility-derived structural displacements (deflection profiles). Consequently, variations in flexibility may be indicative of global and local structural deterioration and therefore have potential as objective indices for periodic evaluations of structural condition. Note that measurements of in-situ flexibility for a bridge superstructure can be acquired through truckload testing. By normalizing measured displacements with the applied truckload, a flexibility coefficient can be derived at each discretized, or spatial, measurement location. However, using truckload testing to obtain direct static measurements of flexibility is neither simple nor straightforward. Numerous displacement sensors positioned below the superstructure are needed to define a comprehensive flexibility matrix. This not only poses a variety of sensor mounting issues, especially if there is steep slope protection beneath the end spans or rivers/creeks and roadways beneath the interior spans, but also time and manpower issues. As a result, modal test methods and the measure of flexibility obtained from such methods are investigated to evaluate their practicality, usefulness, and effectiveness as condition assessment tools for civil structures.

TEST SPECIMEN

Modal test methods and modal flexibility were utilized on a decommissioned overpass that spans Ohio State Route 561 in Cincinnati, Ohio (Figure 1). The three continuous spans of this bridge measured 12.2 m, 15.2 m, and 12.2 m (40 ft, 50 ft, and 40 ft) and consisted of a reinforced concrete deck supported by six rolled steel W shapes spaced at 2.3 m (7.58 ft) center-to-center. The deck was a 12.2 m (40 ft) wide reinforced concrete slab that carried two lanes of traffic. It was 16.51 cm (6.5 in.) thick under the traffic lanes and was covered by a 6.35 cm (2.50 in.) thick asphalt overlay. Thirteen crossframes spaced at 3.3 m (10.8 ft) completed the superstructure. The substructure consisted of two stub abutments and two cap-column piers. Sliding-angle expansion joints and sliding bearings were positioned at the abutments to account for expansion and contraction of the superstructure. In addition, a “bumper angle” had been fillet welded to the bottom flange of each girder near the abutment seats. The intent of these bumper angles was to restrain longitudinal superstructure expansion and prevent complete closure of the expansion joints.

Construction on this bridge was completed in 1953 and throughout it’s 40+ years of service, significant levels of deterioration developed along the top and bottom of the reinforced concrete deck and at the bridge abutments (Figure 2). This included the expansion joints at both abutments, which were jammed shut, and severe rusting of the sliding bearings at the abutment seats below the deck. Ohio Department of Transportation (ODOT) inspectors deemed all observed deterioration to be severe. When DOT officials took note of this deterioration as well as the extremely low volumes of traffic carried by the bridge, it was considered more practical to decommission and demolish this bridge rather than refurbish it. However, due to it’s deterioration and decommissioned status, this bridge was considered the perfect specimen upon which to evaluate, prior to demolition, the usefulness of objective information associated with modal testing, including the resulting measure of in-situ flexibility, or modal flexibility. If such objective tools and information could provide a reliable measure of this bridge’s existing as well as intentionally altered conditions, it was believed that the respective technology/methods could be utilized for condition assessment of any typical short-to-medium span steel-stringer bridge.

RESEARCH PROCEDURE

The bridge described above was subjected to various controlled damage and retrofit scenarios. For the inherited, or as-is, condition as well as before and after each induced change, field data regarding the respective bridge state was acquired through nondestructive modal test methods, in particular multiple reference impact testing. Additional data pertaining to in-situ structural state was acquired through diagnostic truckload testing. The results of the various tests were compared and correlated to evaluate a) the consistency of modal test data, in particular modal flexibility; b) the effectiveness of modal flexibility for assessing existing bridge condition; and, c) the sensitivity of modal flexibility to changes in structural state/condition.

Induced Damage Scenarios

Controlled, or induced, damage scenarios were established through collaboration with the Ohio DOT and FHWA. Scenarios focused on boundary condition alterations and superstructure damages. Boundary condition alterations involved:

- Removal of jammed expansion joints and bumper angles at abutments;
- Removal of a sliding bearing at north abutment; and
- Restoration of this sliding bearing.

Superstructure damages involved:

- Incremental cuts along a girder bottom flange in the south end-span;
- A web cut up to 67 percent of girder depth made on the same girder and in the same location as the flange cuts;
- Crossframe cuts in the vicinity of the web and flange cuts; and
- Deck delamination in the north end-span.

Figure 3 displays when and where each induced scenario was applied.

Impact Test Procedures

The modal test procedure emphasized throughout this research was multiple reference impact testing. The following features make multiple reference impact testing an attractive modal test method for civil structures such as bridges:

- Multiple reference impact testing requires minimum set-up time;
- Multiple reference impact testing can be used to test a structure in its in-situ state with existing boundary conditions; and,
- Multiple reference impact testing requires minimum equipment for both the measurement and data analysis processes [Fladung 1994].

In addition, impact test methods use a simple excitation technique - a portable, roving, instrumented impact hammer (Figure 4) is used by an operator to apply impulse force to the test structure. In theory, impulse force provides energy over an extensive, or broad, frequency range. Consequently, it provides the energy to excite multiple modes of the test structure as long as their natural frequencies are within this broad frequency spectrum. Characteristics of the excited modes may be measured with response sensors such as accelerometers. Significant spatial information regarding the modal behavior of the test structure may be generated/acquired by providing impact at multiple points (multiple references). Such information is needed to uncouple closely-spaced modes – modes whose frequencies are close in magnitude - and establish good global estimates of modal parameters. Without good estimates of the modal parameters/characteristics, a reliable modal flexibility, or measure of true structural flexibility, cannot be established.

The sensor layout used for impact testing of the test bridge is displayed in Figure 5. This layout used numerous accelerometers on the upper side of the bridge deck. All accelerometers were positioned directly above girder-crossframe intersections and girder-bearing positions associated with the two innermost girders. Setup time for this layout typically required two hours. With the portable impact hammer, impulse force was applied near six different sensor positions to ensure excitation and acquisition of pertinent modal characteristics (natural frequencies, mode shapes, etc.). Impact force and acceleration response signals were acquired and processed into frequency response functions with a dynamic signal analyzer. Modal characteristics were subsequently identified through post-processing of the frequency response functions.

When using the layout shown in Figure 5, impact test duration was approximately one hour. Within this time period, ambient conditions such as temperature and humidity – factors whose variations could significantly influence bridge behavior during the course of the test – did not undergo large variations. To assess the quality and reliability of multiple reference impact test data, modal flexibility, which was interpreted as the in-situ structural flexibility for the tested region of the superstructure, was computed from identified modal characteristics and flexibility-based (i.e., simulated) displacements were compared with displacements measured during independent truckload tests.

Computation Of Modal Flexibility/Corroboration Of Experimental Results

A sufficient number of modal parameter estimates - λ_r (= $\sigma_r + j\omega_r$), $\{\psi\}_r$, and M_{Ar}, which are the eigenvalue (with damping and natural frequency information), eigenvector (modal vector), and modal vector scaling associated with each of the *r* modes identified from a group of experimental frequency response function measurements – are needed to establish modal flexibility, which is defined according to the following equations:

$$[H(\omega = 0)] = \frac{1}{[K]} = [f] = \mathit{flexibility}$$

$$[f] = \sum_{r=1}^{N} \left[\frac{\{\psi\}_r \{\psi\}_r^T}{M_{A_r}(-\lambda_r)} + \frac{\{\psi\}_r^* \{\psi\}_r^{*T}}{M_{A_r}^{\ *}(-\lambda_r^*)} \right]$$

Essentially, the flexibility matrix, [f], may be interpreted as the frequency response function matrix, [H(ω)], at zero frequency [Catbas et. al. 1997].

As previously indicated, the reliability of an applied impact test and its derived modal flexibility can be evaluated by comparing modal flexibility-based, or simulated, displacements with displacements measured during independent truckload tests. Such comparisons were performed for the bridge in its original, or as-is, state as well as for each of the induced bridge states (i.e., damage scenarios). Because impact test measurements were made along the innermost girders of the bridge, the resulting modal flexibility matrix permitted the virtual loading of these girders and the simulation of their response (displacements).

Comparisons between simulated and measured displacements are shown in Figure 6 for several of the induced bridge states. Note that simulated truckload displacements were computed by multiplying the flexibility matrix [f] with a truckload vector {P} based on the magnitude, direction, and position of applied truckloads. As shown in Figure 6, the simulated and measured displacement profiles display similar magnitudes and directions and thus correlate well. Because such good correlation was observed for each investigated bridge state, it was concluded that modal flexibility provides a reliable measure of in-situ structural flexibility and is thus a reliable measure of existing bridge behavior. Such correlation not only validated the computed modal flexibility, it also revealed that the frequency response function data acquired through the multiple reference impact test routine of Figure 5 was of high quality and that the modal parameters/characteristics identified from this data were proper estimates of true modal parameters. Essentially, the multiple reference impact test routine displayed in Figure 5 was established as a reliable and legitimate bridge test procedure.

CONDITION ASSESSMENT USING MODAL FLEXIBILITY

Condition assessment of a bridge involves acquiring information about its mechanical characteristics and using these characteristics to evaluate behavior and performance. Condition assessment also involves identifying changes in structural condition. Typically, significant changes in bridge condition are caused by an accumulation of deterioration and/or the occurrence of damage. Deterioration and damage are phenomena that induce a permanent, irreversible change in the appearance, geometry, mechanical characteristics, and/or intrinsic force state of a structure, thus affecting its serviceability and safety. Any parameter or index that is used to identify changes in condition should be sensitive to the effects of deterioration and damage but insensitive to the changes in structural behavior induced by ambient inputs and other influences unrelated to deterioration and damage. Recall that the flexibility obtained through multiple reference impact testing (e.g., modal flexibility) provides a reliable measure of in-situ flexibility and thus of existing behavior/condition. Because modal flexibility can provide engineers with meaningful structural characteristics, such as the deflected shape under any loading pattern, it has potential as a successful and reliable index for identification of deterioration/damage-induced changes in structural condition. It is possible that changes in the shape and magnitudes of deflection profiles obtained from flexibilities acquired at different life-stages of a bridge can be used to identify changes in condition caused by deterioration and/or damage.

Stationarity Aspects Of Modal Flexibility

Although the aforementioned multiple reference impact test method displayed in Figure 5 takes appropriate measures to minimize time-variant, or nonstationary, behavior during an actual test, tests conducted at different times of the day may yield dissimilar results - non-damage related inputs, such as changes in temperature, etc., that occur between the respective test times may alter boundary conditions as well as other factors that influence the dynamic properties of the bridge. For this reason, multiple tests were performed during each scenario (including the "as-is" condition of the bridge) to permit direct observation of how ambient variations and other non-damage related inputs influenced the stationarity of modal flexibility and its derived displacement profiles. Typically, the impact tests for a particular scenario were performed on different days at different times of the day. When possible, several tests were conducted within a one-day period. In general, the flexibility results acquired from numerous impact tests performed during a particular damage state or structural condition yielded similar displacement profiles regardless of the ambient conditions at the times of the respective tests – displacement profile variation from test-to-test was typically less than 10% (Figure 7). Essentially, all multiple reference impact tests conducted for a particular structural state yielded the same flexibility information, or measure of in-situ flexibility. Because it was demonstrated that modal flexibility provides a relevant, accurate measure of structural state and was revealed, along with its simulated displacement profiles, to be a highly consistent index generally insensitive to ambient conditions, modal flexibility and its respective simulated displacement profiles were deemed ideal indices for detection of damage-induced changes in structural state. Whether flexibility and simulated displacements were found to be sufficiently sensitive to the influence, or effects, of damage is the topic of the following section.

Identification/Detection Of Induced Damage Scenarios

To evaluate whether modal flexibility could be used to identify deterioration/damage-induced changes in condition, displacement profiles based on the modal flexibilities acquired during the different bridge states were subsequently compared. The displacement profiles used for comparison purposes were obtained by virtually loading one girderline with a uniformly distributed line-load. In other words, a virtual load of unit magnitude was positioned at each measurement location along the length of the respective girder and this resulting load vector was multiplied with the flexibility matrix for a particular bridge state to obtain a simulated displacement profile for the loaded girder. Comparing the loaded girder displacement profiles from various bridge states revealed that modal flexibility was an excellent objective, kernel index for both global and local condition assessment. Observable anomalous changes in deflected shapes derived through modal flexibility, accompanied by a 10% or greater change in deflection magnitude at a particular location, permitted detection of global and/or local variations in bridge (superstructure) condition. Examples of anomalous changes in deflection profile that permitted detection of global and local changes in condition are presented in Figure 8.

CONCLUSIONS

The research performed on the decommissioned bridge over Ohio State Route 561 revealed:

- Multiple reference impact testing was a feasible objective condition assessment test method for short-to-medium span steel-stringer bridges; and,
- Modal flexibility provided an accurate measure of in-situ structural flexibility and was reliable as an index for bridge condition assessment and damage identification.

It is believed that the nondestructive modal concepts and methods utilized on this test bridge can be applied to commissioned bridges for purposes of health monitoring/condition assessment. Consequently, through Ohio DOT and FHWA funded research, University of Cincinnati researchers are currently applying such methods to commissioned steel-stringer bridges that support daily vehicular traffic.

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Figure 1. Decommissioned test bridge

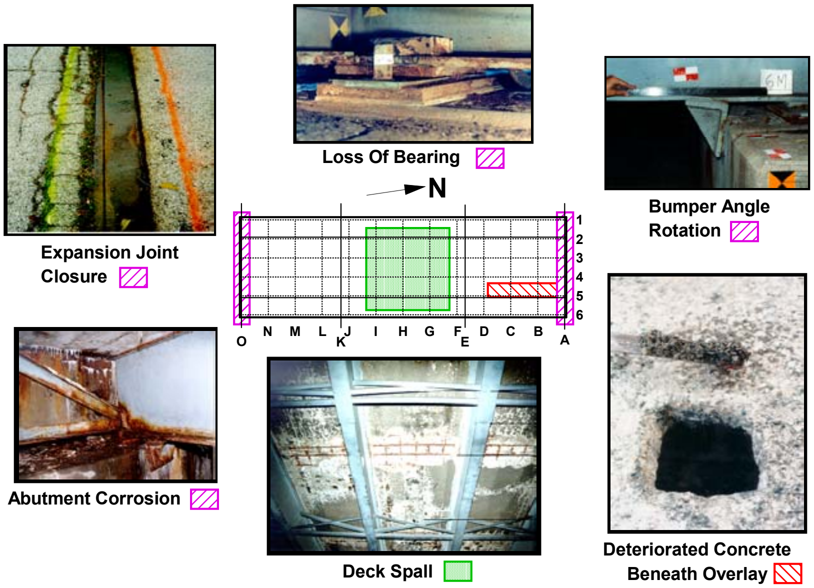


Figure 2. Existing deck/abutment deterioration

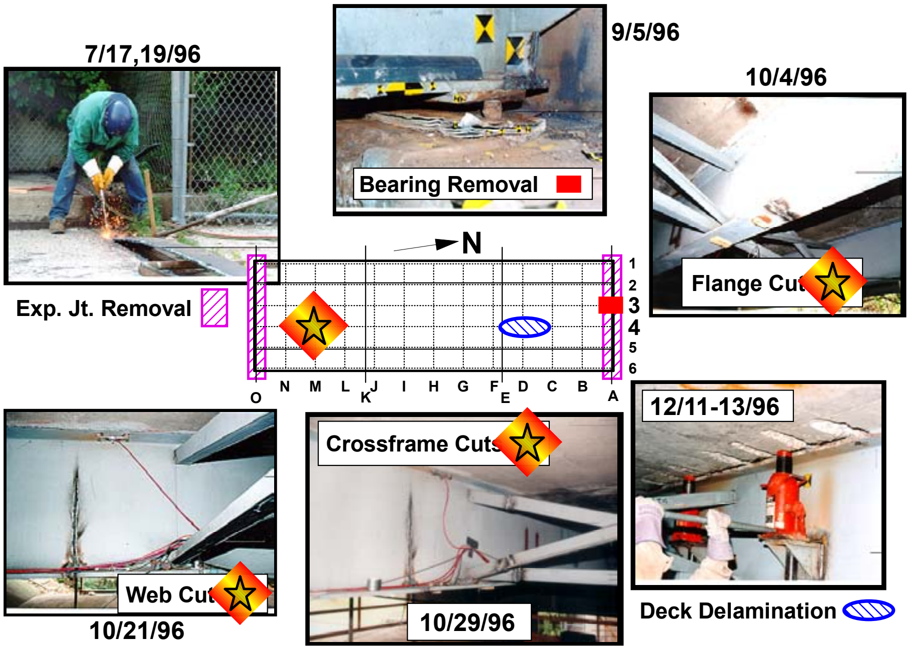


Figure 3. Induced damage scenarios

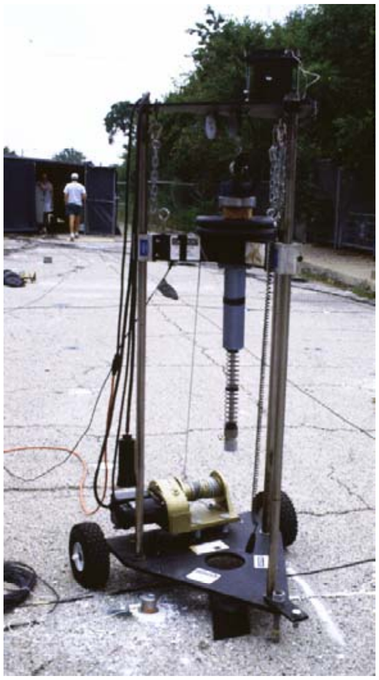


Figure 4. Portable, roving, instrumented impact hammer (drop hammer)

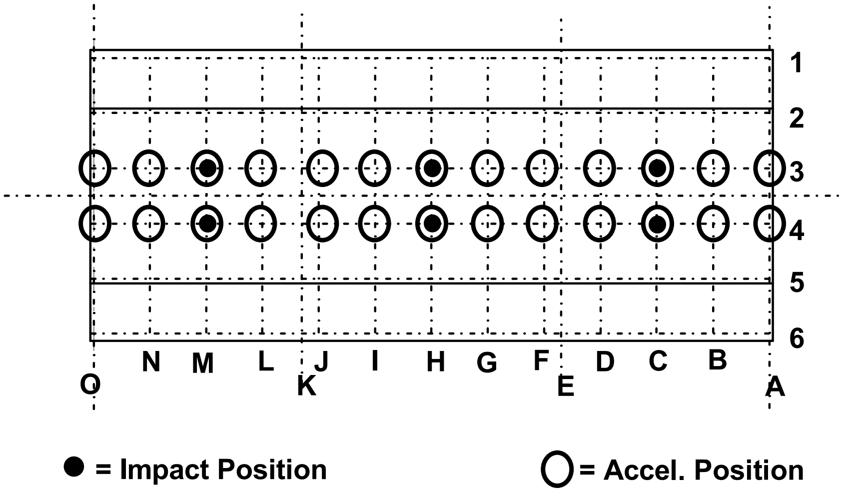
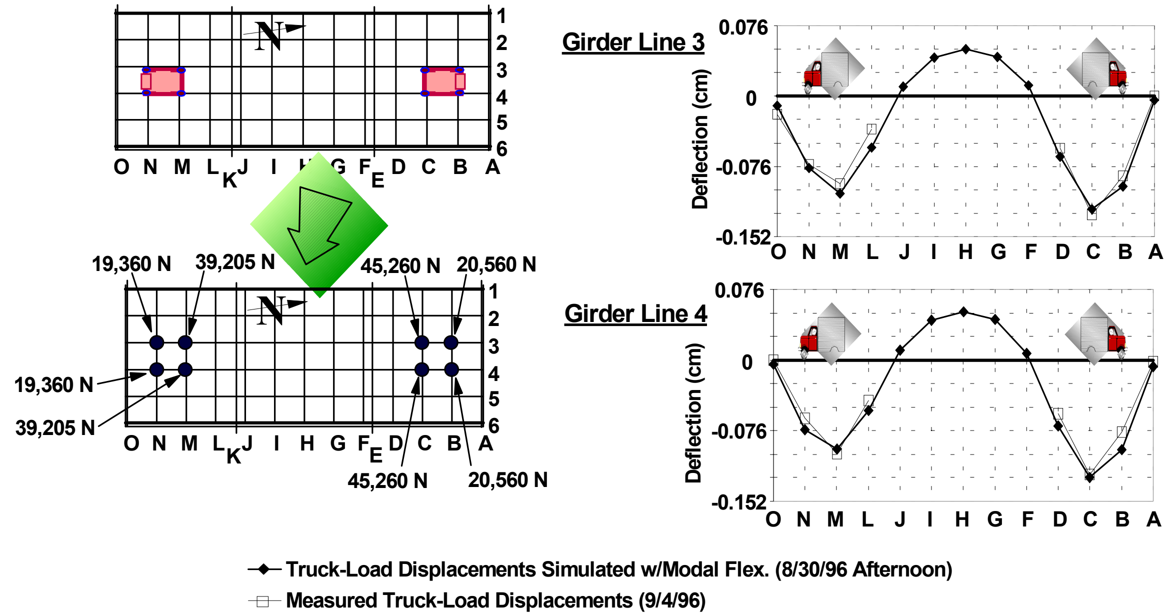
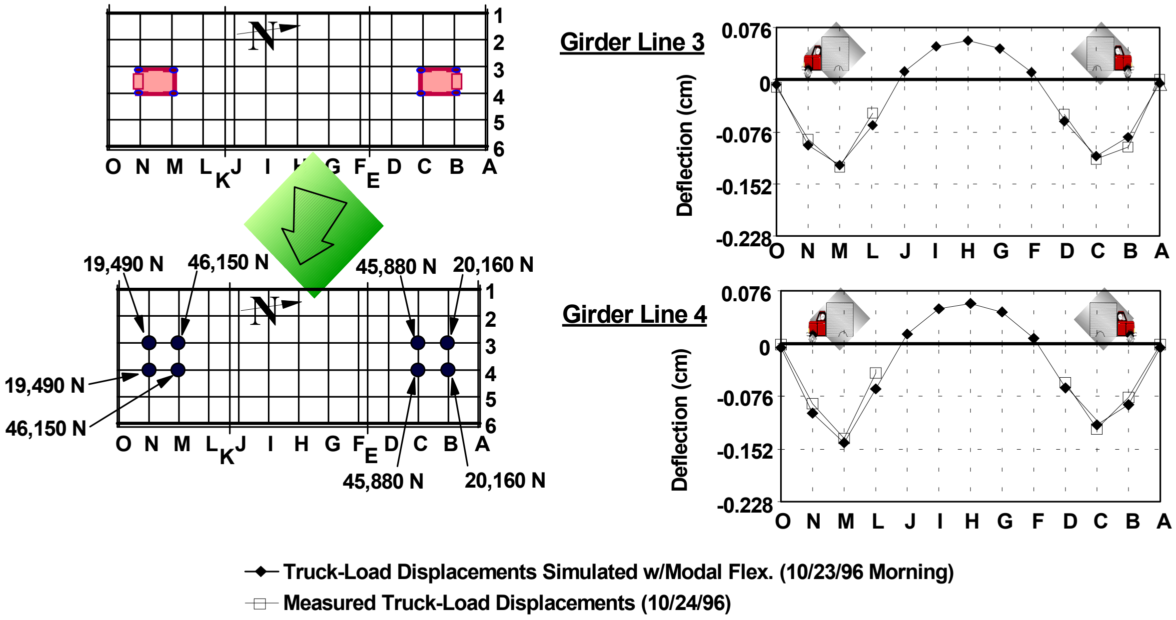


Figure 5. Multiple Reference Impact Test Grid

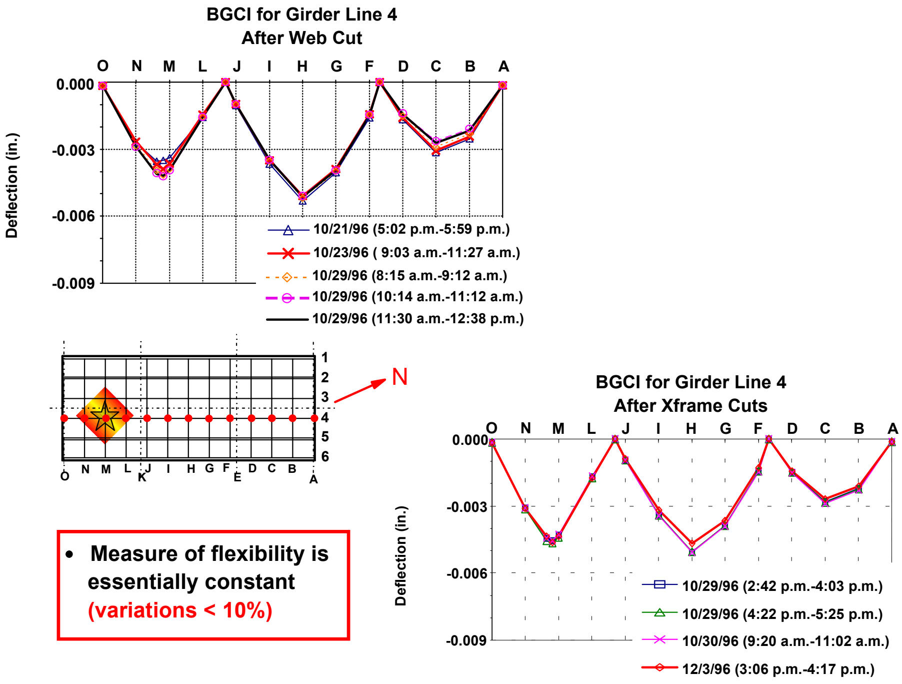


After Removal of Expansion Joints and Bumper Angles at North and South Abutments



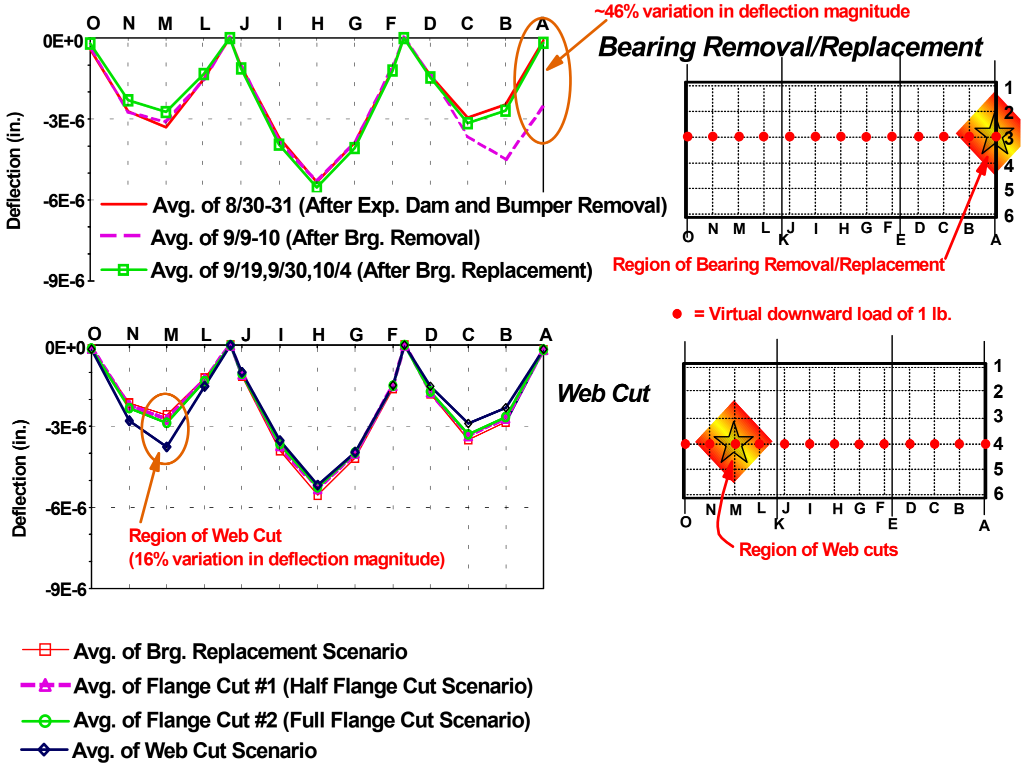
After Web Cut

Figure 6. Simulated vs. measured truckload displacements



- Measure of flexibility is essentially constant (variations < 10%)

Figure 7. Stationarity/consistency of modal flexibility



~46% variation in deflection magnitude

Bearing Removal/Replacement

Region of Bearing Removal/Replacement

● = Virtual downward load of 1 lb.

Web Cut

Region of Web Cut
(16% variation in deflection magnitude)

Region of Web cuts

Figure 8. Condition assessment using anomalous changes in simulated deflection profiles