

# **INSTRUMENTED MONITORING AND DIAGNOSTIC LOAD TESTING OF STEEL STRINGER BRIDGES**

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**ABSTRACT** This paper presents the instrumented monitoring and diagnostic load testing efforts on a typical steel-stringer bridge located in Cincinnati (HAM--561-0683). The bridge is subjected to a series of deliberately induced damage, simulating typical deterioration and damage scenarios which may affect steel-stringer bridges. A recommended methodology is under investigation for the condition assessment, structural evaluation and damage detection of the bridge through load testing. A complete set of strain, tilt, displacement and temperature response data is collected and analyzed before and after each damage utilizing static load testing. This information is shown to both corroborate and augment the results of modal testing.

## **1. INTRODUCTION**

One common issue in civil infrastructure systems is the need to monitor, assess, and diagnose structural integrity in the global structure and in various local components. To avoid hazardous collapse and/or disruption of the service, officials must evaluate the expected useful life of the structure and plan repair or renewal accordingly. Understanding and quantifying the fundamentals of bridge behavior by instrumented monitoring of actual bridges is not just an academic interest. In view of the well-publicized \$90 billion backlog in bridge maintenance, engineers should be very concerned with improving long-term bridge performance. To improve design, construction, and maintenance practices for longer performance at a sustained level of investment, there is a need to clearly understand the consequences of less-understood design or maintenance decisions on bridge performance. Instrumented monitoring of the global and local responses of bridges is the only reliable manner of improving the knowledge of such fundamentals.

## **2. VALIDATION OF TOOLS VIA DAMAGE SIMULATION PROJECT**

A research project is underway to rigorously demonstrate and verify that the experimental tools of modal testing and instrumented monitoring are effective for the condition assessment and evaluation of steel-stringer bridges, which may be possibly affected by any level of hidden deterioration or damage. For this paper, results from this project will serve to exemplify the developed methodology for nondestructive evaluation of highway bridges.

The objective of the research will be accomplished by utilizing a "typical" steel-stringer bridge, located in Cincinnati (HAM-561-0683) and scheduled for renewal, as a test specimen. This bridge will be instrumented and subjected to modal tests in the first month of the project to establish its baseline. Over the course of the first year, the bridge will be subjected to a series of deliberately induced damage, simulating typical deterioration and damage scenarios which may affect steel-stringer bridges. Damage scenarios will include long-term deterioration effects such as due to the loosening and/or breaking of connections, fatigue-fracture, dislocated bearing, corrosion and reduction of effective area and inertia of steel members and connections, loss of chemical bond providing composite action, and cracking and delamination of deck concrete. Retrofit in terms of stiffening and strengthening of certain connections and members will be simulated. At the end of the first year, the bridge will be demolished. Streamlined procedures and algorithms will be developed in the second year for the detection of these damage types.

Successful simulation of the deterioration, damage, and retrofit scenarios will be accomplished through the guidance of an expert panel of ODOT, FHWA, and private consulting engineers. This panel will design

each type of induced-damage to correspond to a realistic natural deterioration and damage scenario. Following each damage-induction, researchers will conduct their experiments (modal and truck-load tests) and evaluate the results together with the expert panel.

### 3. INSTRUMENTED MONITORING

While the basic issues for reliable application of experimental approaches have been explored [1, 2], diagnostic load testing appears to offer a significant benefit/cost ratio. This type of test may be carried out successfully by properly extending the know-how available in the experimental structures laboratories to field applications. A recent AASHTO *Manual* [3] envisions the use of diagnostic load tests as an effective means of evaluating the structural performance of a bridge or selected components. If the guidelines are developed for designing diagnostic tests and properly conducted example applications are documented, this approach may become a widely and reliably applied field testing technique. Diagnostic testing, however, does not permit direct measurement of the state parameters as in modal analysis. In many cases, it would not be possible to directly measure more than just a few global responses, such as displacements, due to practical difficulties. This type of test is an excellent complement to a modal test for its verification, as well as for further exploration of any localized phenomena indicated by the modal test results. Moreover, there may be promise in using truck-load tests with a limited scope as follow-up, once a rigorous modal baseline is accomplished.

With controlled truck-load tests, the critical local responses of bridge members and elements may be used to calibrate the analytical finite-element model such that the actual state and all the critical behavior mechanisms are captured and simulated accurately. The instrumented monitor system makes such tests feasible. The field-calibrated FE model accurately simulates the element stiffnesses and local kinematics at the exterior and interior supports as well as connections. If damage has been diagnosed, this step permits localizing it.

One may consider several different scenarios for monitoring a bridge for measuring global or local responses:

- (a) instrumenting the bridge for intermittently measuring any changes in the global geometry,
- (b) instrumenting the bridge for measuring incremental global and/or local responses under static or dynamic loads over a short term, and
- (c) instrumenting the bridge for measuring incremental global and/or local responses under static or dynamic loads over long term.
- (d) instrumenting a bridge through fabrication and construction for measuring the absolute local and global responses over a long term.

Although the second and third of these scenarios were explored in this research (Fig. 1), the experiences which were gained also have important implications for scenario (a).

#### 3.1 Diagnostic Truck-Load Testing

Static loading is a simple and practical method for applying a known load pattern to the test bridge. Using truck-load tests with extensive instrumentation to measure all the critical aspects of bridge response, we have been able to calibrate comprehensive finite-element analytical models that accurately simulate the global behavior as well as the localized forces and distortions of a test bridge. The main issues in static load testing are:

- (a) Instrumentation and data-acquisition design;
- (b) Test and loading design. Truck types, number, positions, speed are important issues;
- (c) Test execution, response monitoring and on-site data-interpretation design;
- (d) Post-processing and long-term data interpretation for structural identification, evaluation and damage detection purposes;

#### 3.2 Instrumentation and Data Acquisition Design

Researchers developed particular guidelines and design criteria for designing a complete bridge monitoring system in recent researches by UCII[2]. Here a summary of criteria relevant to this research is listed below:

- (a) State-of-force due to live loads at the critical regions of the critical elements should be inferred from the monitor; A field calibrated FE model should be employed for finding the critical sections due to live load. Only then a complete and accurate characterization of the as-is structural condition can be related to the structural capacities and structural reliability.
- (b) Monitor should provide sufficient local response information to assess the Live Load Stress envelopes;
- (c) Monitor should provide sufficient information so that bridge-specific deterioration and damage indices may be extracted from the monitor; In order to do that researchers must be able to predict critical locations for possible deterioration and damage specific to that kind of bridge; Then indices should be developed to capture deterioration and damage from the readings. For example, force distribution changes between critical elements due to live loads should be discerned;
- (d) Monitor should permit to evaluate force amplifications due to live loads applied at different speeds as well as due to any interactions between vehicle and structure dynamics. If there are extensions of the structure which have different dynamic characteristics from the main bridge, interaction between these components and the main structure should also be assessed.

Considering the issues above the monitor shown in Fig. 2 was designed and implemented. A finite element analysis, was utilized in order to get the optimum sensor locations on the bridge. The monitor consisted of:

- (a) 52 Vibrating wire based strain gages for long term (days-months) strain measurements as well as diagnostic truck load tests;
- (b) 20 resistance based strain gages for short term diagnostic truck load tests;
- (c) 22 SWP displacement gages for short term diagnostic truck load tests;
- (d) 9 LVDT displacement gages for short term diagnostic truck load tests;
- (e) 8 Tiltmeters for rotational measurements.

The data acquisition systems selected for implementation at the bridge site is MEGADAC 3108DC from Optim Electronics and CR-10 from Campbell Scientific, Inc. As shown in Fig. 3, Megadac is used for high speed measurement of transducers and CR-10 is used for slow speed measurements. Both systems were employed for diagnostic truck load testing.

### 3.3 Test Conduct and Loading Design

The loading configuration should be able to simulate the critical as well as typical loads, deformations, and stresses, expected in the critical elements of the bridge. The load locations and responses to be measured must be located considering the objectives of the test. A preliminary analysis for determining the load locations and for response prediction is usually a good practice.

For HAM--561-0683 14 loading combinations were designed with one or two trucks (Fig. 4). The loadings were selected to intensify responses at abutments, middle of spans and piers as well as damage locations. Several loadings were incorporated for the sole purpose of checking and correlating results obtained from modal flexibility.

In addition, a crawl speed truck test was done each time a static tests was performed.

### 3.4 Response Monitoring and On-Site Data-Interpretation

The need for on-line and on-site evaluations is due to:

- (a) We have to decide on the health of the sensors and data-acquisition system as the test is conducted;
- (b) We have to decide on the load level and positions (or reconsider those decisions made earlier) in the course of a test;
- (c) We have to decide on whether our test caused distress on the bridge, and whether the bridge should remain closed following the test;
- (d) We have to decide on whether the instrumentation is indeed covering all critical responses;
- (e) We have to ensure the safety of the test personnel and the bridge.

Data/Information can be available from a test in the following forms: (a) real-time digital; (b) real-time graphical; (c) peak responses throughout the test; (d) after test on-site post processing. The issue is deciding on which channels should be graphically viewed, which should be digitally monitored and how information should be on-site processed for a quick evaluation.

Since in many cases time allowed for a test, and for the use of trucks, is strictly limited, several digital and graphical monitors were prepared for quick decisions about the success and adequacy of a test. The data is then transferred to UCII for in depth postprocessing, evaluation and damage detection purposes.

## 4. GENERAL RESULTS

Continuous monitoring of the bridge is accomplished between May 96 and October 96. 53 temperature gages and 52 strain gages were used for this purpose. Some preliminary results obtained from these tests are:

- (a) The bridge temperatures are following the ambient temperature with smaller magnitude and with phase lag.
- (b) A temperature gradient between the top and bottom of the steel girders is observed. This causes a stress gradient at the section.
- (c) Axial and rotational restraints, causing axial force and moment at abutment sections, are noticed.
- (d) A low frequency vertical movement of the bridge spans is seen due to temperature effects.

Between the same period (May 96- October 96) 10 Static truck load tests were performed. As mentioned before following each damage-induction, researchers conducted their experiments and evaluated the results. Fig. 5 & 6 show an example of the postprocessing and damage detection process performed. A sample damage scenario (removal of the bearing plate from north abutment 3<sup>rd</sup> girder) is selected for presentation purposes. The damage location can be picked up by excessive deformation at that location and also the change in the stress characteristics under load. The same girder shows considerable deflection at the south span abutment. After visual inspection it was identified that the contact area of that bearing was reduced to 25% of the original.

An important error mitigation measure at this step is correlating the results obtained by truck load testing with the modal flexibility obtained with the modal tests (Fig. 7& 8). After each tests these results were plotted to double check for any erroneous readings and for verification of postprocessing.

## 5. ACKNOWLEDGMENTS

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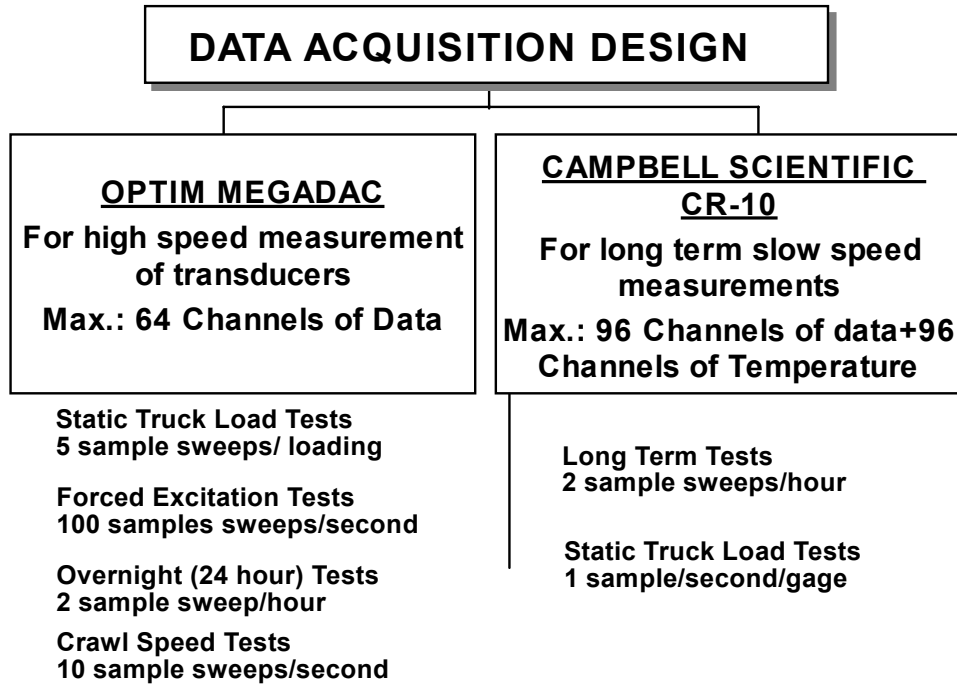


Fig. 3 Data Acquisition Design

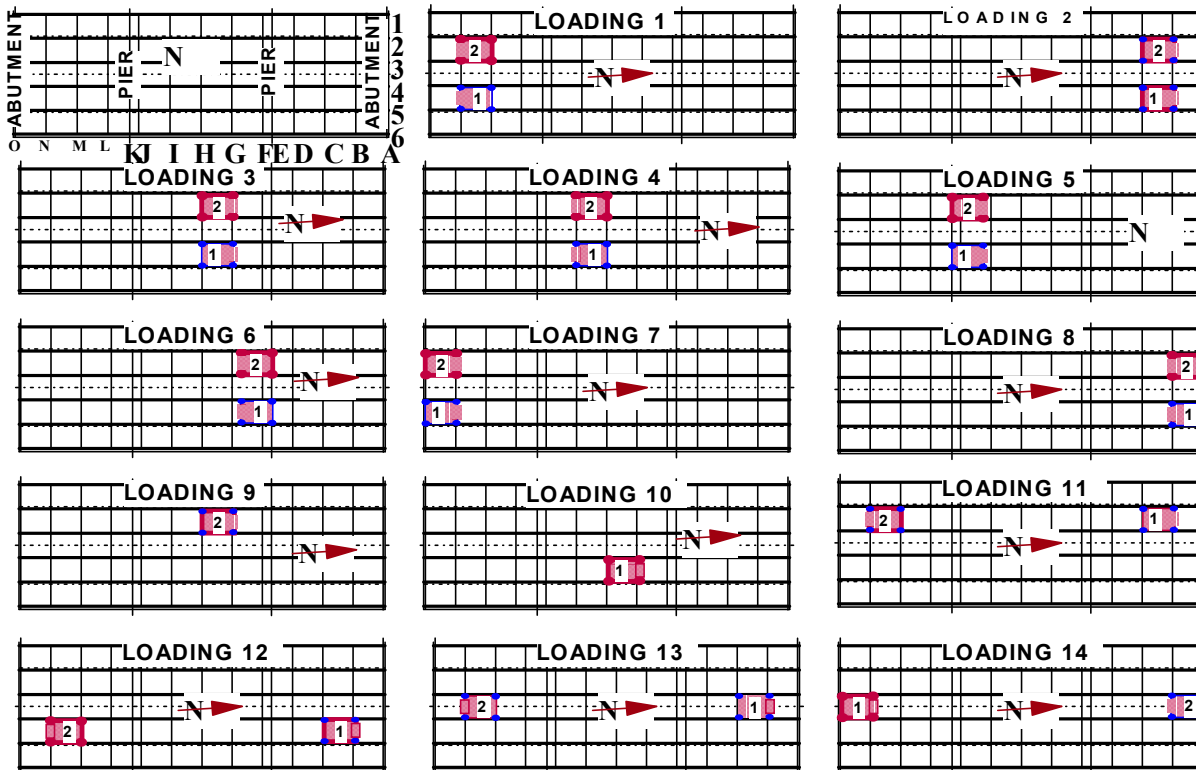


Fig. 4 Loading Design

## TRUCK LOAD TEST @ 9/4/96 (*before* removal of bearing plate)

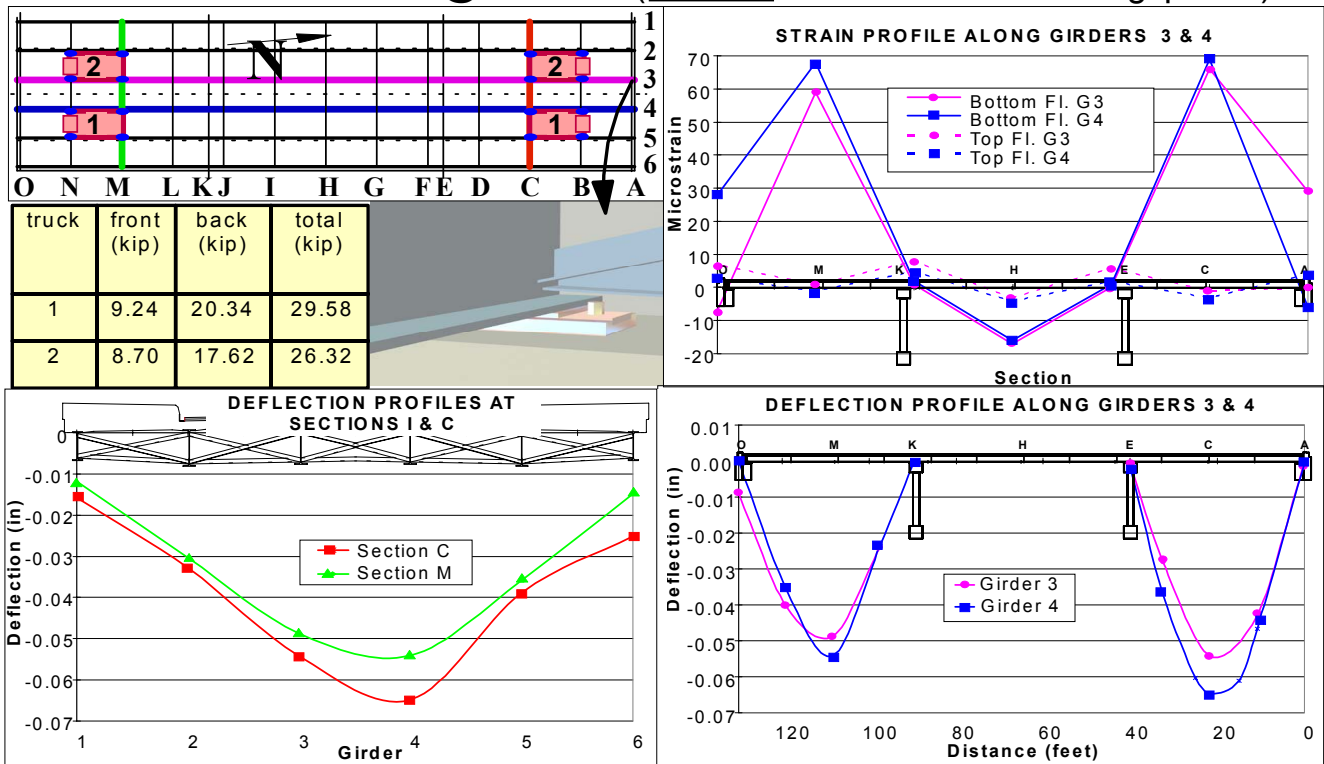


Fig. 5 Truck Load Testing Results Before Removal of Bearing Plate

## TRUCK LOAD TEST @ 9/13/96 (*after* removal of bearing plate)

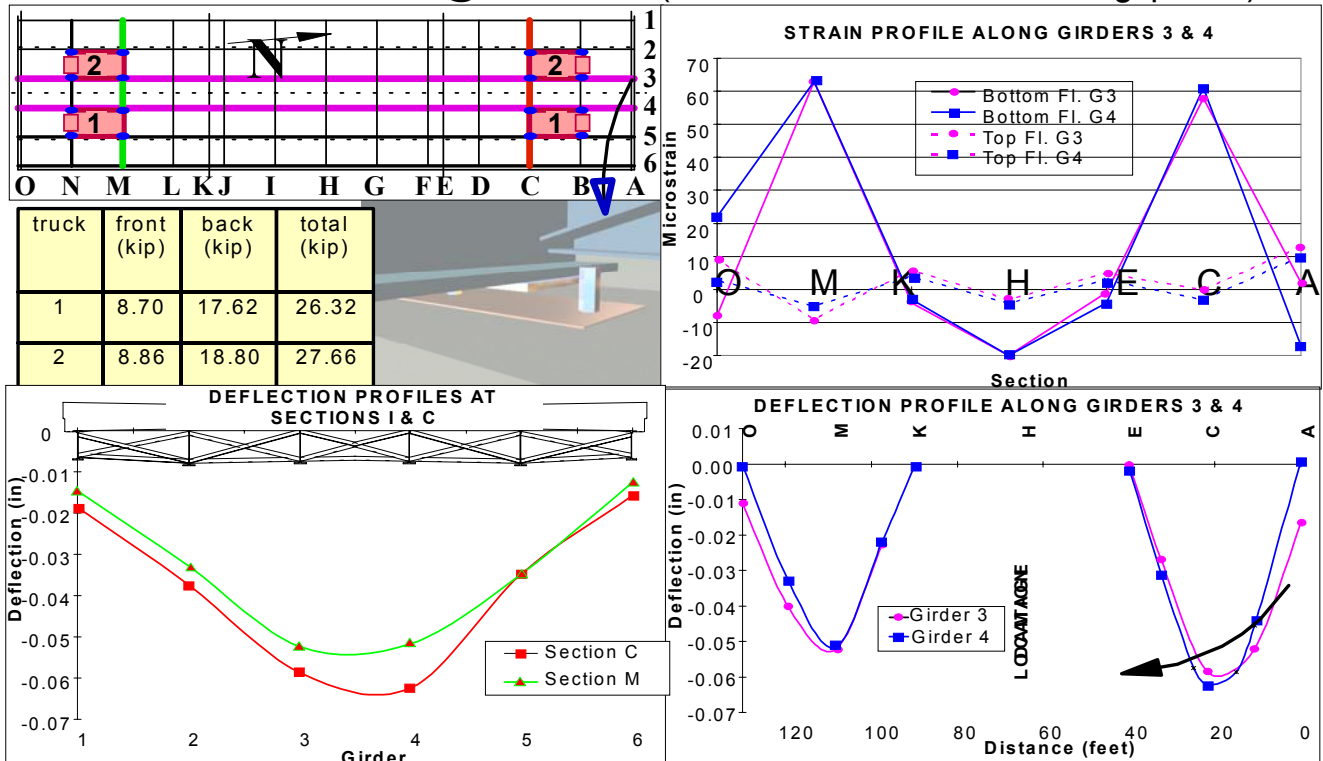


Fig. 6 Truck Load Testing Results After Removal of Bearing Plate

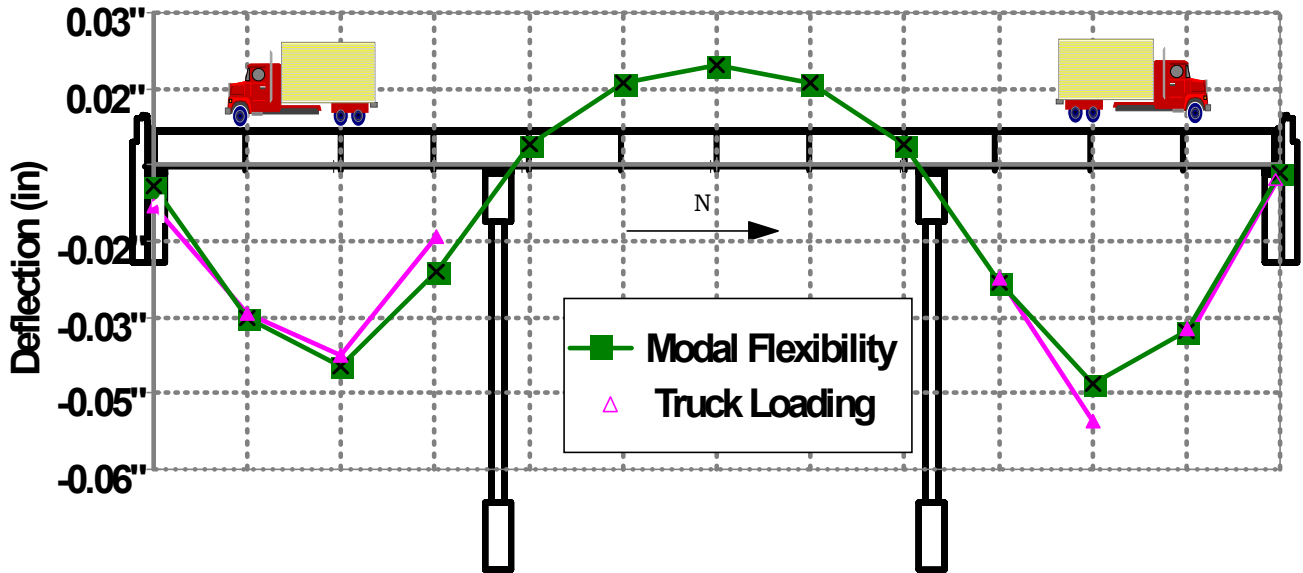


Fig. 7 Correlating Modal Test and Truck Load Measurement for Girder Line 3 Under Loading 13 (Before Removal of Bearing)

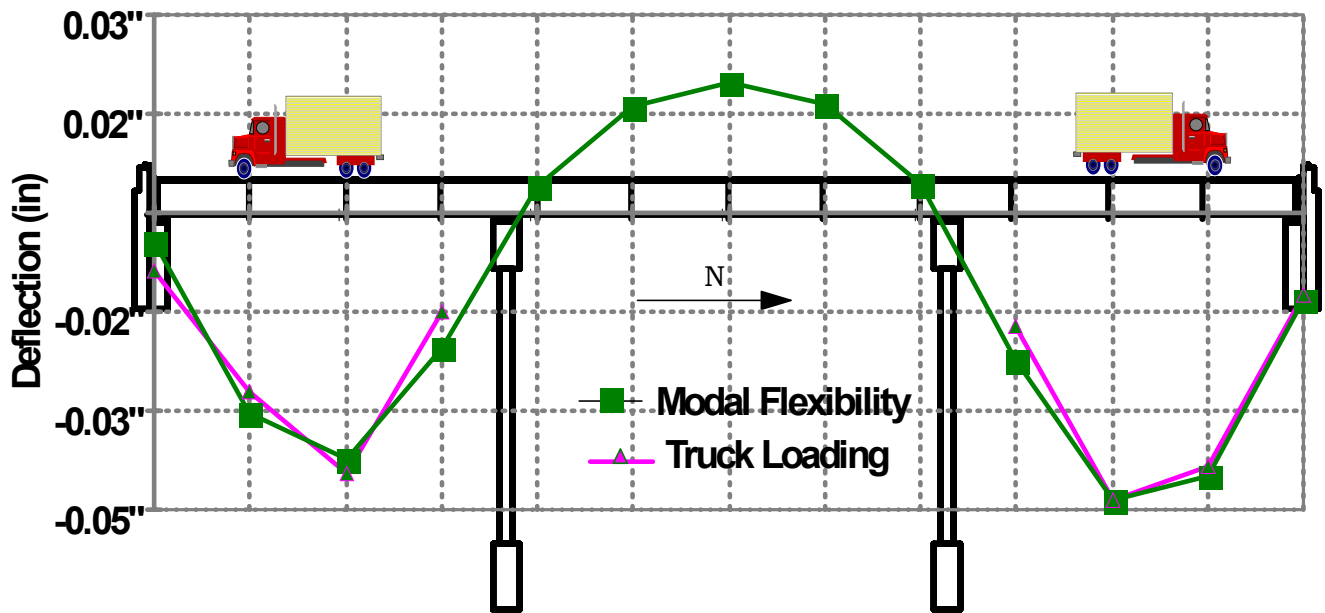


Fig. 8 Correlating Modal Test and Truck Load Measurement for Girder Line 3 Under Loading 13 (After Removal of Bearing)