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Structural Identification Study of a Steel Multi-Girder Bridge Based on Multiple Reference Impact Test

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ABSTRACT

A round robin style investigation to demonstrate best practices for the integration and application of technology to mitigate performance deficiencies of bridges was conducted. The structure selected for study, typical of Northeastern US construction, was part of a relatively large population of steel bridges older than 25 years. Teams from around the world visited the bridge and performed various experiments to conceptualize its performance. The research team conducted a series of multiple reference impact tests (MRIT) on one span of the bridge. The modal parameters were identified from the test data and used to generate modal flexibility. To mitigate epistemic uncertainty in the estimation of modal flexibility, the effect of reference point selection was investigated. A statistic analysis of deflections generated by modal flexibility was compared with displacements measured during a static truck load test and several conclusions and observations were including the identification of the effect of a large pier cap crack within the modal data.

KEYWORDS: structural identification; multiple reference impact test; modal flexibility, epistemic uncertainty

INTRODUCTION

According to the U.S. Federal Highway Administration [1], over 33% of the 604,485 bridges in the U.S. are more than 50 years old, among which 43% are either structurally deficient or functionally obsolete. Given the scale of this problem, the current political climate, and the enormous budget shortfalls many states are experiencing, wholesale replacement is not realistic. This places significant emphasis on proper diagnosis/prognosis and effective intervention. Visual inspection remains as the standard practice for condition evaluation of highway bridges, but there is ample evidence that they are highly unreliable in many cases. To augment visual inspection and improve reliability, structural identification (St-Id) has been explored as a means of characterizing constructed systems from a mechanistic and quantitative standpoint. St-Id was summarized as a six-step analysis-experiment-decision integration cycle by the ASCE St-Id of Constructed Systems Committee [2] as follows: (1) Objectives, observation and conceptualization; (2) A priori modeling; (3) Uncontrolled and controlled experiments; (4) Processing, validation and interpretation of data; (5) Model calibration and parameter identification; and (6) Utilization of the calibrated model for simulations and decision-making. Over the last few decades, the state of the art in St-Id of constructed systems has advanced significantly and dozens of successful applications to large structural systems have been documented [2].

In case visual inspections are inconclusive or a closer evaluation is needed, the AASHTO Manual for Bridge Evaluation discusses load testing. Dynamic testing (or modal analysis) offers advantages over truck load testing if the expertise, hardware and software required for this type of test are available. One form of modal analysis is multi-reference impact testing (MRIT) that has been shown to yield reliable estimates of bridge flexibility. In this test technique, the structure is subjected to an impact, measuring both the impact and the corresponding decaying vibration responses at carefully selected coordinates. These characteristics can be processed to obtain "modal" flexibility which is a close estimate of static flexibility if a sufficient number of frequencies, modes and their damping ratios have been correctly identified. Past research [3-5] has revealed that flexibility and changes in flexibility offer excellent potential to serve as a more robust measure of bridge condition and performance than just frequencies and mode shapes, which have no physical meaning in reality. Beginning in the late 1980s, writers have been exploring field testing and St-Id of a wide-range of operating bridges using both static testing under truck-loads and multi-reference impact testing (MRIT) [6-8].

Epistemic uncertainty and aleatory uncertainty are two kinds of uncertainties exist in the experiment and analysis [9]. Aleatory uncertainty is an inherent variation associated with the physical system or the environment, while epistemic uncertainty means an uncertainty that is due to a lack of knowledge of quantities or processes of the system or the environment, also referred to as subjective uncertainty. The authors investigated the most appropriate approaches to reducing epistemic uncertainty in St-Id [10]. There is a pressing need for a comprehensive investigation to establish the true influence of various sources of epistemic uncertainty on modal flexibility calculation. The research reported herein describes their most recent efforts towards leveraging modal analysis by transient excitation (impact) for measuring the modal flexibility of one span of a multi-girder bridge to be used as a quantitative measure of condition and changes in condition, in which the influence of the selection of reference points on the final modal flexibility results were investigated to mitigate epistemic uncertainty.

INTRODUCTION OF THE TESTED BRIDGE

The multi-girder bridge tested in this study was built in 1983 and is shown in Fig.1 (a). The bridge consists of two separate superstructures for carrying northbound and southbound traffic. Each direction has four lanes and a sidewalk, and each direction comprises four simply supported spans using a standard steel stringer design that consists of eight girders. During this study, static and dynamic measurements were taken on one of the 8 spans which is shown in Fig. 1 (b). The concrete deck is supported on eight girders with variable flange thicknesses. The cross section of the span is shown in Fig.1(c). The decks of the two directions are cast using stay-in-place forms. Reinforced concrete piers support the spans via rocker bearings. The structures had an overall rating of 5 (Fair) due mainly to the condition of the superstructure according to the recent inspection report. The bridge condition is characterized by a series of fatigue cracks, bearing and joint deterioration and perceptible vibration under the passage of heavy trucks.

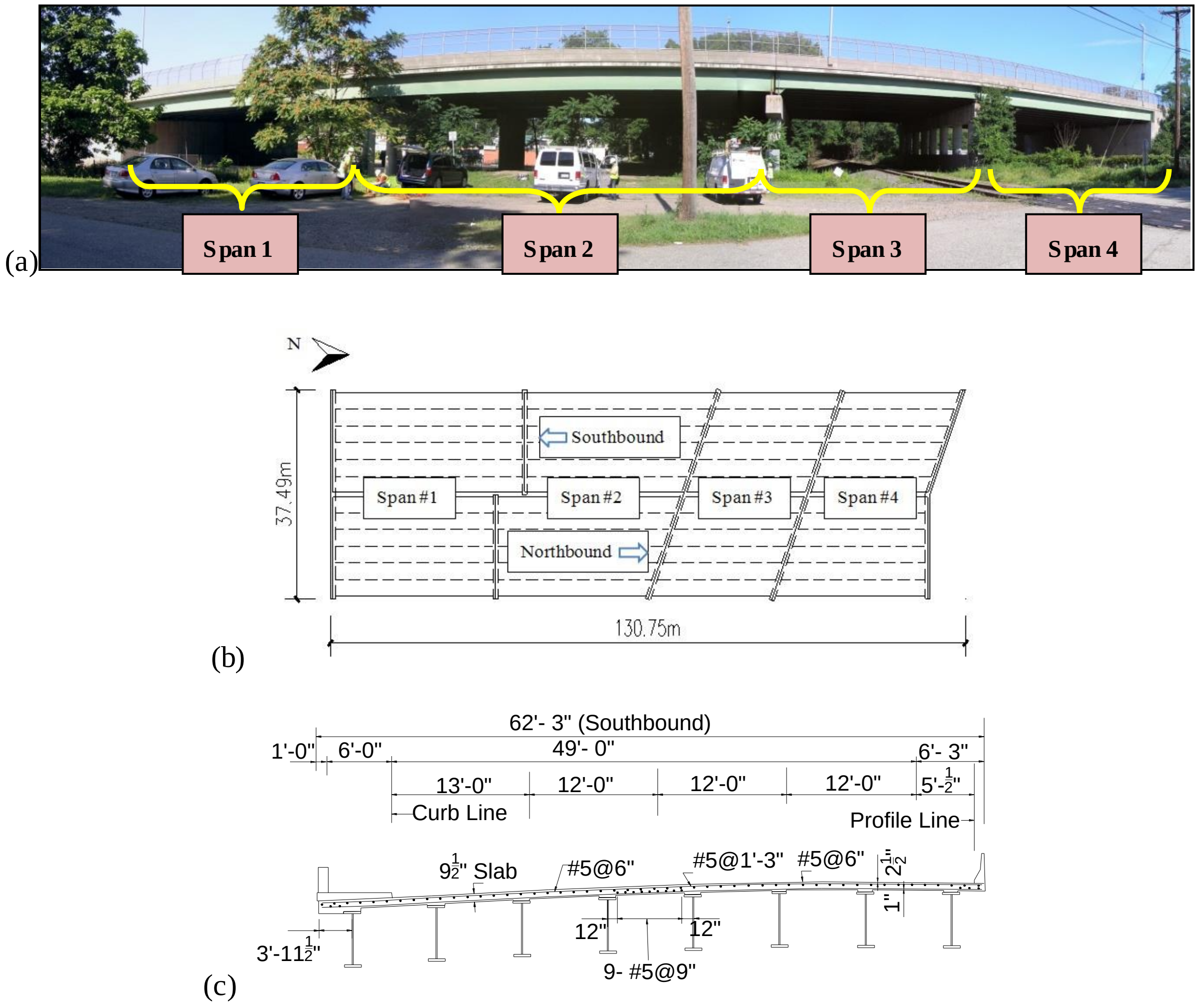


Fig. 1. (a) Photo of the bridge; (b) Schematic of the bridge; (c) Cross section of the tested span

INSTRUMENTATION LAYOUT

Multi-reference impact test (MRIT) and operational modal analysis (OMA) are two modal test methods often utilized to test large infrastructures such as buildings and bridges. However, if the estimation of modal mass is desired, the development of an input/output relationship is required and OMA cannot be used since the analysis is performed using solely system outputs. To obtain the dynamic characteristics of the tested span, MRIT was performed on the selected span using a spatially broad instrumentation covering the full length and width of the structure (Fig.2). Eight National Instruments 9234 dynamic signal acquisition modules paired with a National Instruments CompactRIO system (32 Channels, +/-5V, 24-bit IEPE) was used to collect the input and output signals. ModalView software developed by ABSignal Inc. was utilized for test control and on-site data verification. A rebound controlled drop Hammer and PCB model 086D50 sledge hammer provided controlled input forces in Fig.3. More details regarding the modal test can be found in [11]. 31 PCB 393A03 seismic accelerometers were used to capture the response of the bridge to the input forces. The accelerometers were installed on the bottom flange of girders six and eight, while the remainder of the sensors were installed on the top of the deck. Each accelerometer was oriented to capture accelerations normal to the bottom flange of the girder and the top of the deck. The overall instrumentation plan utilized in the MRIT is shown in Fig.2. A truck load test was conducted on the span to measure the deflection basin of this bridge for comparison with the deflection via modal flexibility. All sensors were installed along Girder 1, 3, 6, and 8 due to the limitation of the number of sensors. The displacement sensor layout can be seen in Fig.2. The details regarding static test can be found in [12].

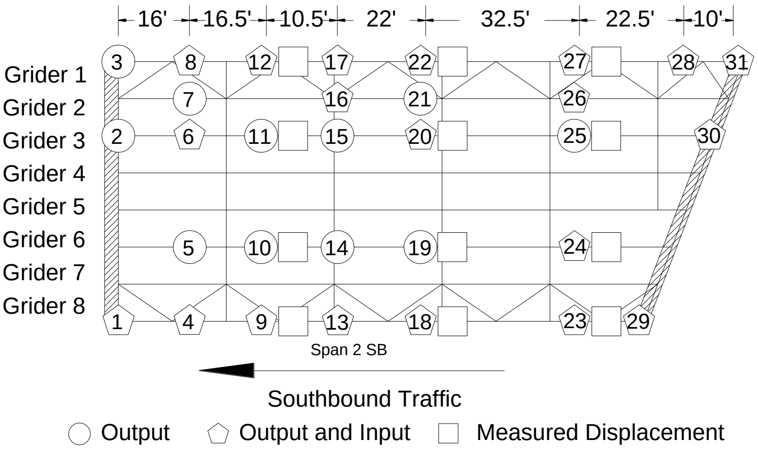


Fig.2. Instrumentation layout of the tested span

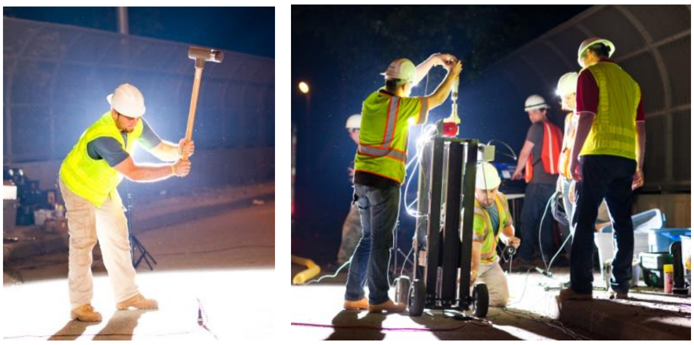


Fig.3. Excitation by (a) Sledge hammer; (b) Drop hammer (Drew Noel Copyright, 2011)

MRIT MODAL ANAYSIS

The sampling frequency was set at 3200 Hz and Fast Fourier transform (FFT) points were set as 32768. During the test the 4th lane between girder 6 and girder 8 remained open to the traffic, so impacts were applied during periods with no traffic on the structure to avoid extraneous vibrations induced by vehicles crossing the span. Reciprocity of the frequency response function (FRF's) between point 11 and point 21 when traffic noise was avoided is shown in Fig.4, revealing that the drop hammer provided robust coherence and reciprocity while the sledge hammer reciprocity and coherence were poor. The data collected from the drop hammer test was used in a MRIT analysis by selecting several reference points (RPs) including 5, 7, 11 14, 19 and 21. The MRIT analysis identified 9 modes between 0-20 Hz which are shown in Fig. 5. The identified mode shapes presented in Fig. 5 have been interpolated into smooth surfaces using grid data interpolation. The Complex Mode Indicator Function Algorithm (CMIF) method was utilized for modal parameter identification and the singular value plot generated in the CMIF analysis is shown in Fig.6. In this paper, the main purpose was to investigate the mitigation of epistemic uncertainty through reference point selection, and not the effect of the selected modal parameter estimation technique. Therefore, the CMIF method was the sole modal parameter estimation technique used in this study.

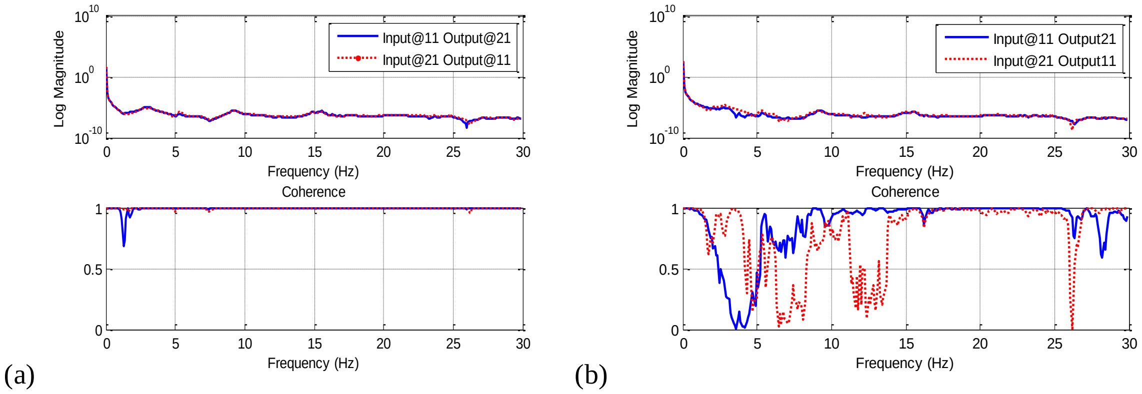
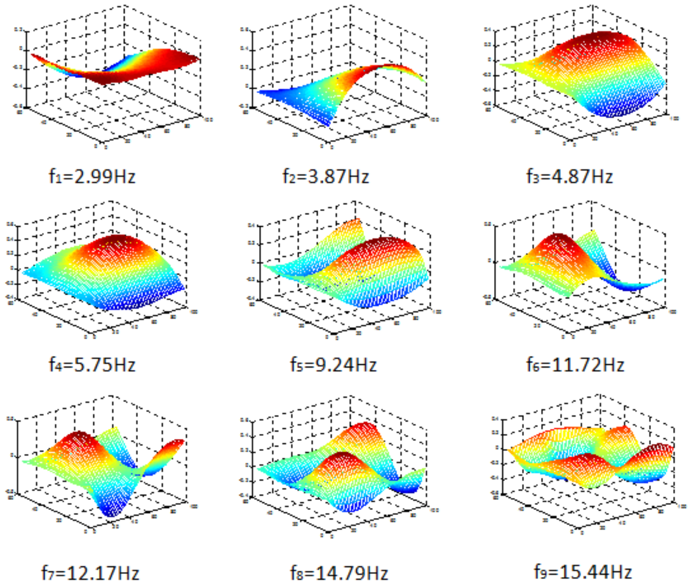


Fig. 4. Reciprocity provided by (a) Drop hammer and (b) Sledge hammer


f_1=2.99Hz f_2=3.87Hz f_3=4.87Hz

f_4=5.75Hz f_5=9.24Hz f_6=11.72Hz

f_7=12.17Hz f_8=14.79Hz f_9=15.44Hz

Fig.5. Analysis results for the first 9 modes for the span

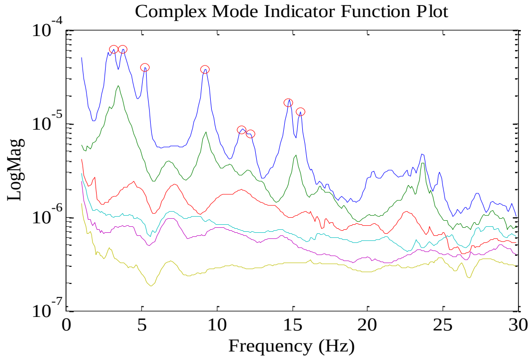


Fig.6. CMIF singular value plot

EPISTEMIC UNCERTAINTY ANALYSIS OF DEFLECTON

Aleatory uncertainty and epistemic uncertainty exist within St-Id. In the process of generating displacement estimates from impact test data, one of the largest sources of epistemic uncertainty arises from the selection of the RPs. In this analysis process, modal flexibility coefficients could either be generated from a single input, multiple output (SIMO) strategy or from a multiple input, multiple output (MIMO) strategy. Due to the influence of induced vibrations from traffic and the coincidence of the RP with the nodal points of some modes, not all combinations of RPs will result in the same estimation of modal flexibility coefficients. Generally more RPs are desired to average the effects of nodal point coincidence and extraneous excitation.

The primary objective of this study was to demonstrate the feasibility of using modal flexibility to validate the displacement measures obtained from a static truck load test for bridge condition evaluation. The displacement basin calculated from modal flexibility and the measured displacement basin from the static load test is compared to show the ability of modal flexibility to predict displacements obtained under a known loading configuration. To further understand the influence of RP selection, a statistic analysis of different RP combinations were utilized in the modal flexibility calculation. Discounting two reference points at the boundaries, six RPs remain for selection. For a combination of three RPs, a maximum of 20 unique RP combinations exist. For a combination of five RPs, a maximum of 5 unique RP combinations exist. In total 25 cases have been analyzed in a standard dynamic signal analysis procedure to generate modal flexibility. The results of the uncertainty analysis for four points located on girders one and three are shown in Fig.7 and Fig.8. The blue dotted line shows the measured deflection from the static truckload test, while the green dashed line shows the average of all modal flexibility estimates. The relative error between the static displacement and the average displacement obtained from modal flexibility is listed in Table 1. It should be noted that the relative error of the measured points along girder 8 were not calculated because the absolute deflection value is small and would artificially present as a large percent error. More combinations of RPs would be in further investigated in the future.

Generally the relative error of each point along girder 3 is less than 10%, but an unexpected large relative error occurs at point 12, which indicates a potential structural deficiency located on this point or a possible problem with the data. After a careful examination and vetting of the measured data, a careful in-situ visual inspection was performed, and a crack on the southern pier cap was noted and was shown in Fig.9. The pier cap on the span had a particularly large flexure-shear crack which was showing evidence of rebar corrosion. Examination of the pier caps showed that most joints allowed water to drain directly through on top of the pier. It was determined that the pier cap crack had a significant influence on the estimation of displacement at point 12 from dynamic data.

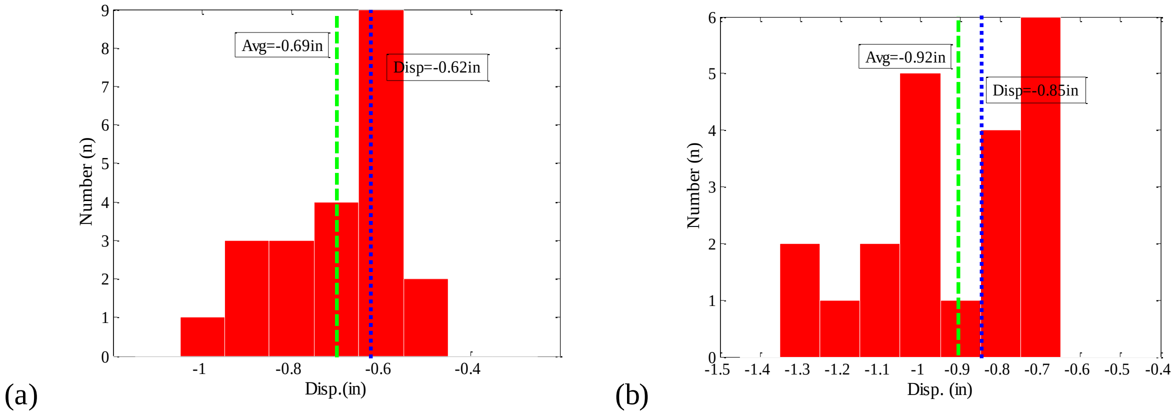


Fig.7. (a) Histogram of point 11 displacement; (b) Histogram of point 20 displacement (Note: blue dotted line shows the measured deflection from the static truckload test, while the green dashed line shows the average of all modal flexibility estimates)

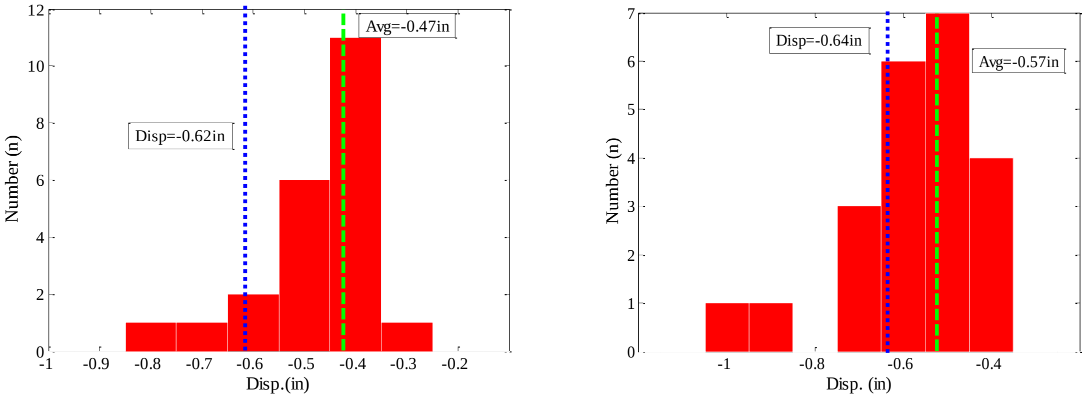


Fig.8. (a) Histogram of point 12 displacement (b) Histogram of point 22 displacement(Note: blue dotted line shows the measured deflection from the static truckload test, while the green dashed line shows the average of all modal flexibility estimates)

Table 1. Comparison of the measured displacement with the average displacement

Girder number	Point number	Average disp.(in)	Measured disp. (in)	Relative error (%)
Girder 1	12	-0.47	-0.62	**-31.92%**
Girder 1	22	-0.57	-0.64	-12.28%
Girder 1	27	-0.41	-0.46	-12.20%
Girder 3	11	-0.69	-0.62	10%
Girder 3	20	-0.92	-0.85	7.61%
Girder 3	25	-0.56	-0.53	5.36%
Girder 6	10	-0.35	-0.36	-2.86%
Girder 6	19	-0.46	-0.45	2.18%
Girder 6	24	-0.21	-0.25	-19%
Girder 8	9	-0.03	-0.07	/
Girder 8	18	-0.03	-0.08	/
Girder 8	23	0.04	-0.02	/

Note: Relative error(%)= (Average disp.-Measured disp.)/Average disp. × 100%

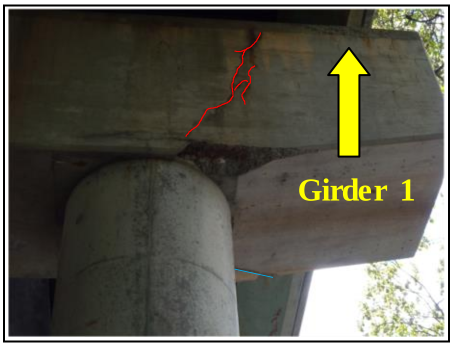


Fig.9. Pier cap crack under girder 1

8. CONCLUSIONS

MRIT impact tests were conducted on a steel multi-girder bridge span using a rebound controlled drop hammer device. The displacements obtained through the estimation of modal flexibility were compared with the displacements obtained from a static truck load test and to quantify the epistemic uncertainty present in the modal flexibility procedure, a statistical analysis of RP selection was conducted. In order to perform the statistical analysis, 25 combinations of RPs were used to generate modal flexibility. Through this analysis it was found that a large crack in the pier cap was significantly influencing one of the measurement locations. Different RP combinations would result in different modal flexibility results, thus the potential damage location can hardly be identified through just once calculation. The proposed method can be used to mitigate the possible epidemic uncertainty in RP selection and can be in further investigated by increasing the possible RPs combinations.

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