Structural Identification Study of International Bridge Based on Multiple Reference Impact Test

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SUMMARY:
The US FHWA Long-term Bridge Performance Program initiated an International Bridge Study to demonstrate best practice guidelines for the integration and application of technology to mitigate performance deficiencies of bridges. Wayne bridge was selected for IBS study which are relatively common for the large population of steel bridges older than 25 years. Teams from the world visited the bridge and performed a series of experiments to conceptualize its performance. Drexel research team conducted a serious of multiple reference impact tests on one span of the IBS Bridge. To achieve this goal, a rebound controlled Drexel drop hammer was successfully developed to conduct a series of rigorous hammer impact tests on the International Bridge. The modal parameters were identified from the test data and used to generate modal flexibility. A statistic strategy considering different combinations of reference points was utilized in truck load surface analysis to mitigate the epistemic uncertainty.

Keywords: International bridge study; structural identification; multiple reference impact test; modal flexibility

1. INTRODUCTION

According to the U.S. Federal Highway Administration (FHWA, 2011), 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 (ASCE, 2011) 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 (ASCE, 2011).

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 (Aktan et al. 1991, 1992, 1998) 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.

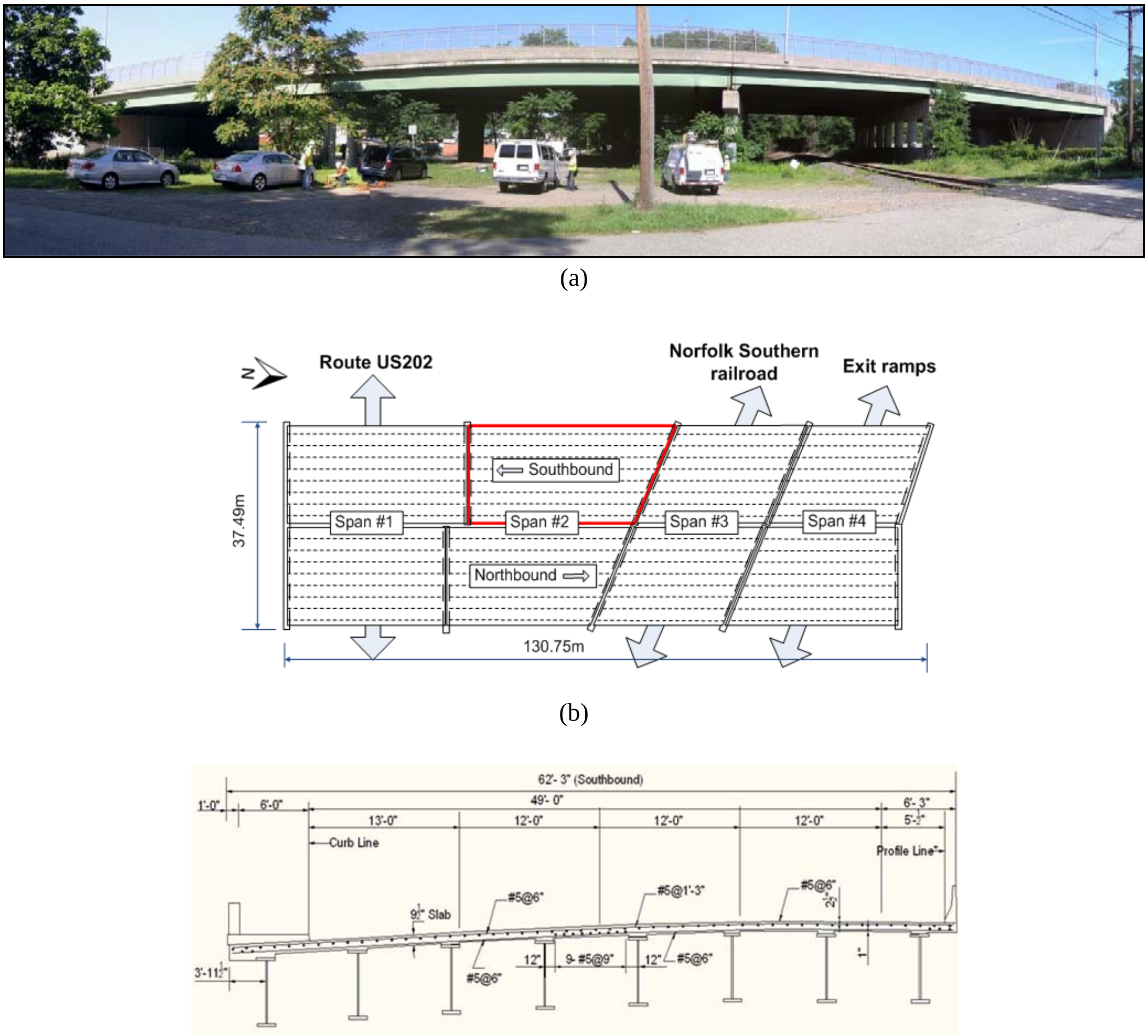
Beginning in the late 1980s, writers have been exploring field testing and St-Id of a wide-range of operating bridges using both static testing under truck-loads and multi-reference impact testing (MRIT) (Aktan et al. 2002, 2004, 2006). A Rebound controlled Drexel Drop Hammer was designed to provide large sufficient robust impact force for the bridge test, The research reported herein describes their most recent efforts towards leveraging modal analysis by transient excitation (impact) for measuring the modal flexibility of an International Bridge superstructure to be used as a quantitative measure of condition and changes in condition.

2. INTERNATIONAL BRIDGE STUDY (IBS)

The Federal Highway Administration's (FHWA) Long-term Bridge Performance (LTBP) Program is a major strategic initiative, developed by the Office of Infrastructure Research and Development within FHWA, and designed to address the growing concern with aged and deteriorated infrastructure throughout the U.S. The primary objectives of the program are three fold and include developing more accurate estimates of bridge health, improve and disseminate knowledge of bridge performance, and to promote the safety, longevity and reliability of the United States highway transportation system. As part of this flagship program, the FHWA launched an International Bridge Study (IBS) with the goal of establishing the worldwide "best practices" for the integration and application of technology to diagnose, perform prognosis, and design treatments to mitigate performance deficiencies for a given bridge. Almost 19 universities and companies from Asia, Europe and USA took part in the IBS test to demonstrate their 'best practice' in bridge condition assessment.

In total, 15 bridges were identified by the NJDOT as bridges for which there was no clear path forward in addressing the identified performance deficiencies, which was the primary criteria for candidate bridge selection. By leveraging the bridge performance, the availability of documentation, inspection challenges and the ease of access, finally Wayne bridge was selected as the test bed and it provided the platform for the researches from different countries. This bridge was built in 1983 and was located at NJ 23 highway over US 202 in Wayne, New Jersey, US. It displays very common problems associated with approach settlement, bearing alignment/walking, substantial vibrations and fatigue cracking. The bridge consists of two nominally separate superstructures for southbound and northbound traffics. From south to north, the bridges span route US202, an open field, train tracks, and an exit ramp. 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. In this study, the static and dynamic measurements were taken out on the southbound span 2, as marked in Figure 1(b) with the cross section as shown in Fig.1(c).

The girders are built-up members with variable flange thicknesses. The change in flange thickness is a smooth, well-detailed transition that would not cause fatigue issues. The flange thickness varies from 1 in. to 2.5 in., depending on the girder length, with the top flange transitioning once and the bottom flange transitioning twice. This results in up to five different cross-sections on a given girder and adds to the overall complexity and irregularity caused by the varying skew conditions. The decks of the two directions are cast using stay-in-place forms which prevent any visual assessment of the condition of the concrete from the underside of the structure. The bridge deck contains diagonal wind braces between the fascia and first interior girders on every span, which are connected via a 'Category E' gusset-to-girder web detail. The diaphragms are a standard truss-type composed of four single angles connected to the girders with bolted connections and gusset plates. Reinforced concrete piers support the spans via bearings. The structures had an overall rating of 5 (Fair) due mainly to the condition of the superstructure according to the recent inspection report. A serious of fatigue cracks, bearing and joint deterioration and a heavy vibration of the bridge under traffic loads were reported, the bridge had an Average Daily Traffic (ADT) of 93,400 with 4% being truck traffic.



(a)

(b)

(c)

Figure 1. (a) Photo of the Wayne highway bridge (b) Schematic of the Wayne Bridge (c) Cross section of the Southbound span 2 of the Wayne Bridge

3. REBOUND CONTROLLED DREXEL DROP HAMMER

Drop hammer and sledge hammer are two types of devices are often used in MRIT .The Drexel Drop Hammer was designed by the Drexel research team as shown in Fig.2. An adjustable heavy moving mass drops from an adjustable height and a PCB 200C50 load cell (0.10mv/lb, <50000lb) with a medium polyurethane impact tip (Model 084A32) provides an impact on the surface of the deck. Since the impact carriage bounces off the bridge deck, several impacts occur. The rebound control system aims to stop these multiple impacts and consists of a brake system activated by a control system that tracks the position of the impact carriage (Fig. 2).

The brakes are engaged by pneumatically activated springs that have a maximum response time of 0.05s. The brakes are released when the air pressure drops below 5.52e5Pa (80psi) which is achieved through a computer controlled 3-way valve. Upon detection of zero velocity at the apex of the first rebound, the 3-way valve is activated, which in turn initiates two quick exhaust valves that rapidly purge the air pressure and engage the brakes. The sensing/control system includes a National

Instruments (NI) Compact RIO Data Acquisition system (cRIO DAQ) that interfaces with an Acuity AR700 laser distance gauge. The cRIO controller runs a NI LabVIEW Real-Time program that interfaces with the NI 9112 cRIO chassis as well as a host PC that runs an interactive user interface. An NI 9205 analog input module receives distance measurement data from the laser while an NI 9269 analog output module provides control signals to the mechanical control system described above.

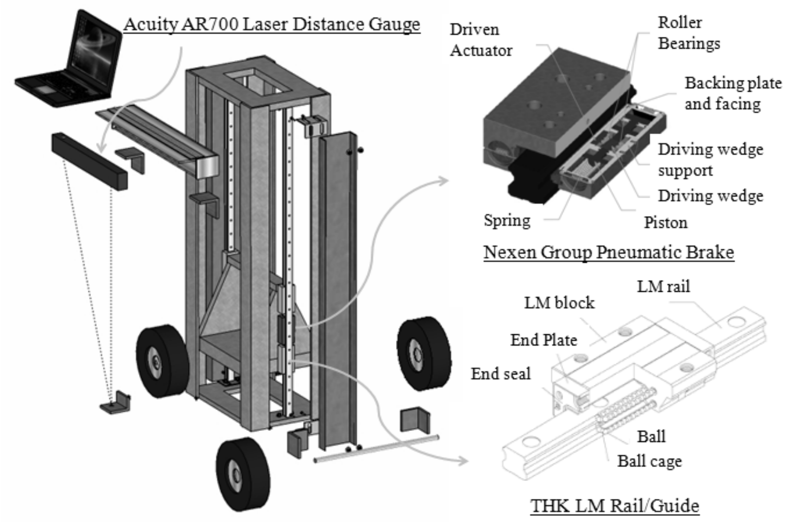


Figure 2. Rebound controlled Drexel drop hammer

4. INSTRUMENTATION LAYOUT

The Southbound Span 2 with unusual skew was selected for dynamic testing with dense instrumentation (Fig. 3). A National Instrumentation 9234 dynamic signal acquisition module with CompactRIO system (32 Channels, +/-5V, 24-bit IEPE) was used to collect the data. The Modal View software by ABSignal was utilized for test control and on-site data verification. The Drop Hammer and PCB model 086D50 sledge hammer were utilized for impacts. 31 PCB 393C seismic accelerometers were used for collecting the data. The accelerometers were installed at the bottom of girders 6 and 8, while the remainder of the sensors were installed on the top of the deck and all of the sensors were oriented to measure vertical accelerations. The wired accelerometers were installed in a wide range including boundary locations. Each accelerometer measured acceleration along the vertical direction. The experiments were conducted at night, so that traffic can be closed for three outside southbound lanes with one inside lane still be open. Fig.4 shows the picture of Drexel Drop hammer being applied.

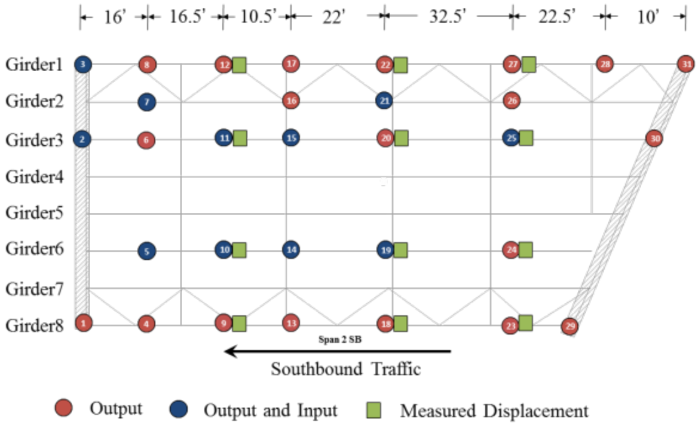


Figure 3. Instrumentation layout on Southbound span #2

Figure 4. Excitation by (a) Sledge hammer (b) Drexel drop hammer

5. STATIC TRUCK LOAD TEST

Truck load test was conducted on the Southbound Span 2 to measure the deflection basin of this bridge. All sensors were installed on Girder 1, 3, 6, and 8 due to the limitation of the number of sensors. The displacement sensor layout can be seen in Fig.3. 16 displacement sensors were located on Southbound Span 2 in a rectangular grid. These locations coincide with other modalities of instrumentation including strains and accelerations. Distributed data acquisition was used for field test, the system consists of several small DAQs mounted on the structure, as opposed to a single DAQ on the ground. National Instruments CompactRIO (cRIO) model line was selected for the basis of the distributed data acquisition system. A program written in Lab View has been deployed to run on any NI hardware as well as on a PC to provide intuitive, real-time visualization of the data during the test, including spatial variation. The static testing was conducted throughout the night on October 1st 2010, the final six truck test was conducted in the morning (Fig.5) after hammer impact dynamic testing was done. Under the final load case of 6 full trucks, the measured peak value of displacement was -0.845 inches at midspan of Girder #3. The recommended deflection criterion of L/800 corresponds to a displacement of 1.83 inches which is much greater than the actual measured response. During the test, the results basically remained in the linear range of load-response behavior.

Figure 5. Picture for six truck load test on Southbound Span 2

6. SIGNAL QUALITY CHECK AND MODAL ANALYSIS

The sampling frequency was set at 3200 Hz and 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 traffic intervals to avoid uncontrolled vibrations by vehicles. Reciprocity of the FRF’s between point 11 and point 21 when traffic noise was avoided is shown in Fig.6, revealing that the drop hammer provided robust coherence and reciprocity while the sledge hammer reciprocity and coherence were poor.

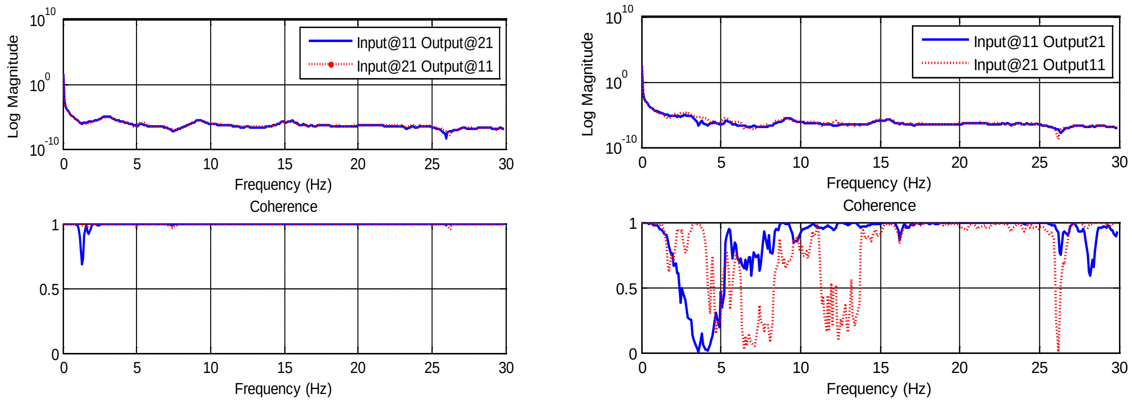


Figure 6. Reciprocity provided by (a) Drop hammer and (b) Sledge hammer

The data collected from the Drop Hammer was used for MIMO analysis by choosing the reference points (RPs) 5, 7, 11 14, 19 and 21. The first 9 modes within 0-20 Hz are shown in Fig.7. The CMIF method was utilized for modal parameter identification and the singular value plot that was used for CMIF analysis is shown in Fig.8 (a). A preliminary correlation between deflected shapes along Girder 3 measured during the truck-load test and simulated by modal flexibility is shown in Fig. 8 (b), revealing the promise of rapid impact testing under high level repeatable impacts for objective condition evaluation of typical bridge structures.

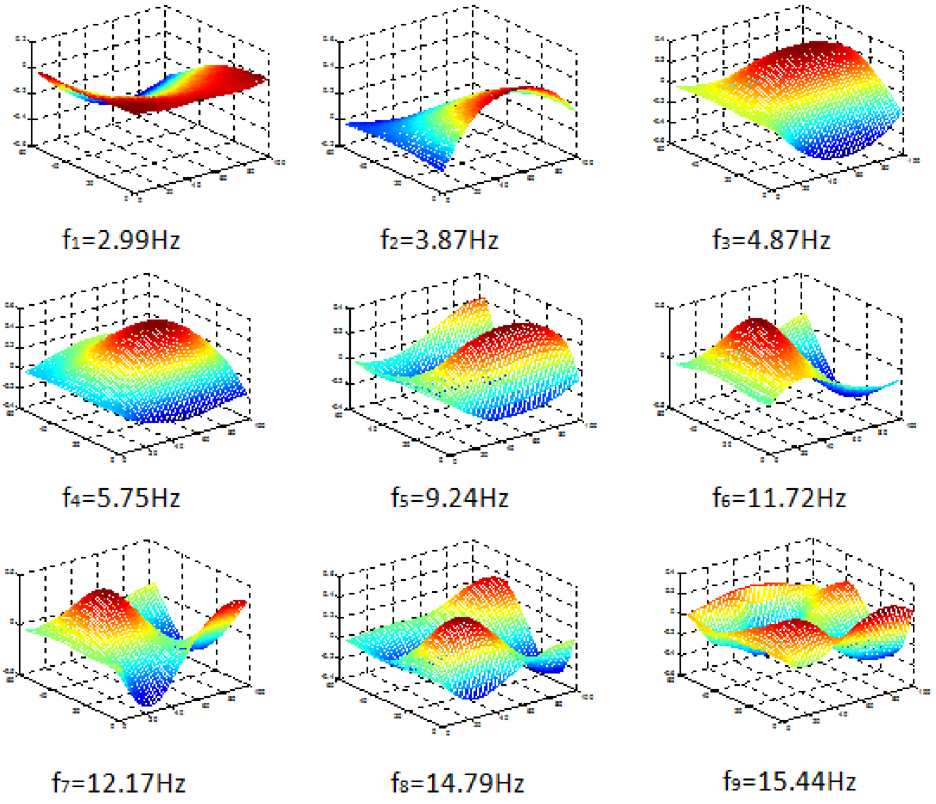

f_1=2.99Hz
f_2=3.87Hz
f_3=4.87Hz
f_4=5.75Hz
f_5=9.24Hz
f_6=11.72Hz
f_7=12.17Hz
f_8=14.79Hz
f_9=15.44Hz

Figure 7. Analysis results for the first 9 modes for the Southbound span2

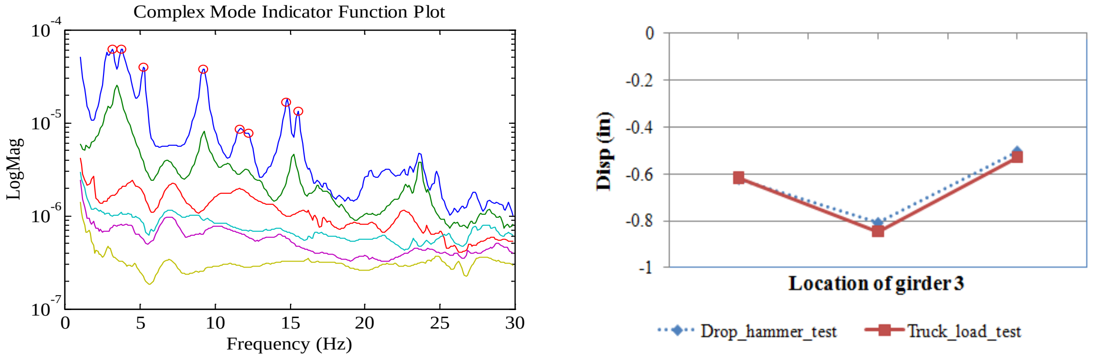


Figure 8. (a) CMIF singular value plot; (b) Correlation of displacements measured under truck-loads and simulated by modal flexibility along Girder 3

7. EPISTEMIC UNCERTAINTY ANALYSIS

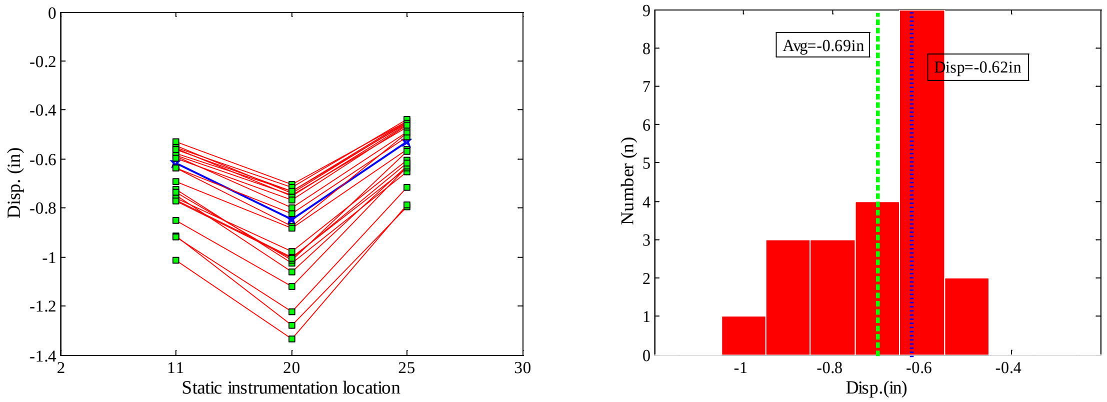
There are two types of uncertainties named aleatory uncertainty and epistemic uncertainty. Aleatory uncertainty is an inherent variation associated with the physical system or the environment, while epistemic uncertainty means an uncertainty that is due to a lack of knowledge of quantities or processes of the system or the environment, also referred to as subjective uncertainty. In the process of generating truck load surface (TLS) from original hammer impact, the biggest source of epistemic uncertainty comes from the selection of the RPs in MRIT modal analysis. In this analysis process, modal flexibility coefficient could be generated either from single input and multiple output (SISO) strategy or from multiple input and multiple output (MIMO) strategy. Due to the influence of traffic noise and the coincidence of the reference point with mode node point, not all the combination of RPs would bring out the same results, generally the researcher would choose the RPs as more as possible because they believe it would mitigate the possible aleatory uncertainties, but epistemic uncertainties still exists and should be evaluated in another way.

The primary objective of the experimental program was to demonstrate the feasibility of using modal flexibility to validate the displacement measures obtained from a static load test. The displacement basin obtained from modal flexibility and the 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. In this analysis process, the selection of the RPs dominates the correlation of the results due to the different kind of epistemic uncertainties. To further understand the influence of the selection of the RPs, the statistic analysis of different kinds of combination of RPs were utilized in modal flexibility calculation. Except for two RPs at the boundary locations, there still are 6 RPs can be chosen. Here 3 RPs are firstly selected from point 5, 7, 11, 14, 19 and 21, there totally has $C_6^3 = 20$ kinds of combinations. Meanwhile, 5 reference points are also selected from the former 6 points, there totally has $C_6^5 = 5$ kinds of combinations. The total 25 cases have been analyzed in a standard processing procedure to generate modal flexibility. The TLS and the calculated 25ULS results were compared and shown in Figure 10(a) and Figure 11(a). Meanwhile, the histogram of each measured location were also shown in Figure 10 (b)~(d) and Figure 11(b)~(d), and the relative error of each instrumentation point of girder 1 and girder 3 are also listed in Table 1.

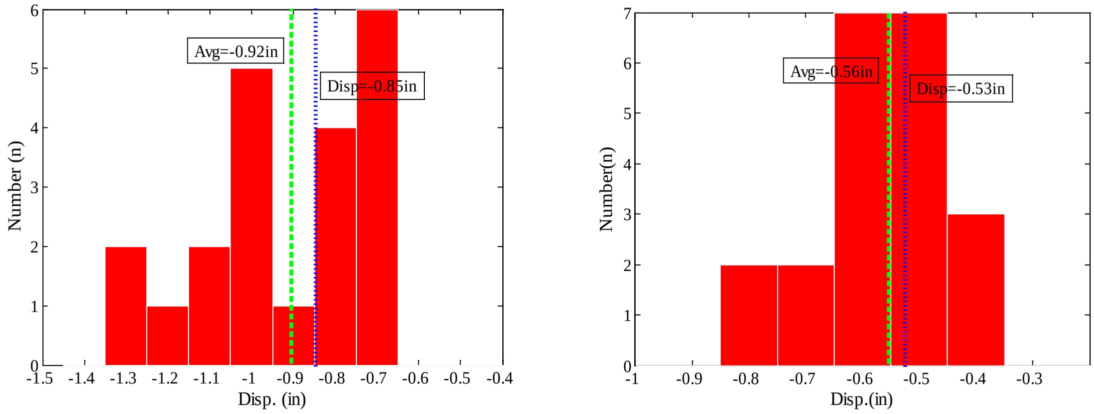
By comparison, the relative error of each point along girder 3 is less than 10%, an unexpected large relative error occur at point 12, which indicate an unusual damage would happen on girder 1. After careful in-situ visual inspection, it was found that a crack on pier cap which is highlighted in red as shown in Fig.12. The pier cap on Southbound span2 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.

8. CONCLUSIONS

A rebound controlled Drexel drop hammer was successful in providing a repeatable single high-level impact force exceeding 75 kN with a bandwidth up to 100 Hz. By using this impact device, MIMO impact tests were conducted on international bridges. Even when the response signals were polluted by traffic noise, this drop hammer provided robust reciprocity and coherence due to large signal- noise ratio. Much work remains for an automated application of the drop hammer for reliable modal flexibility estimation considering different combination of RP selection in MIMO test. A statistic strategy has been used to mitigate the epistemic uncertainty. Eventually such drop hammer system may become an essential prelude to visual inspections, directing the inspector to possible areas of concern implied by any anomalies or changes in flexibility.

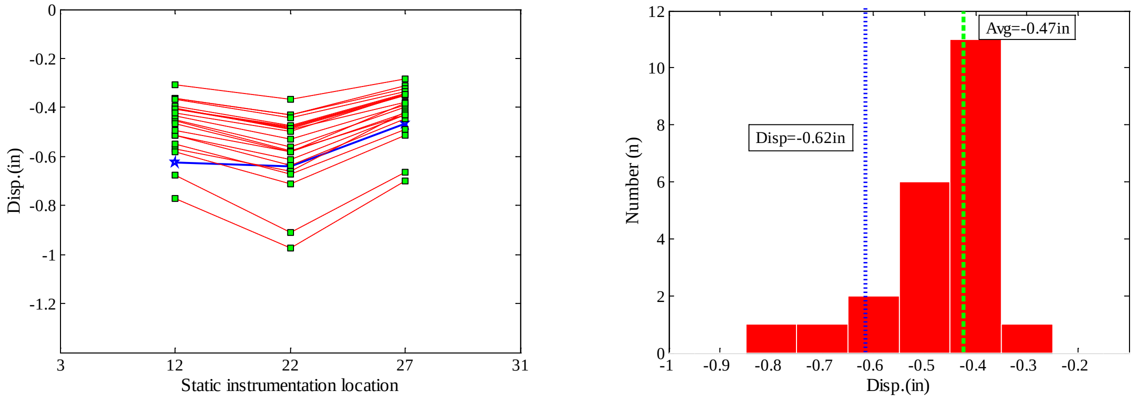


(a)Comparison of static displacement (b) Histogram of point 11 displacement

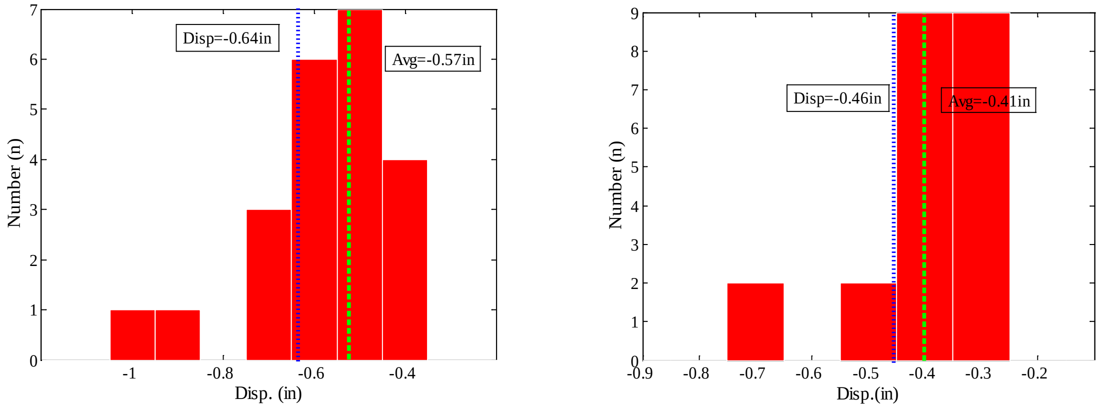


(c) Histogram of point 20 displacement (d) Histogram of point 25 displacement

Figure 10. (a) Comparison of static deflection with 25 MIMO cases deflections along girder 3. (b) Histogram of point 11 displacement (c) Histogram of point 20 displacement. (d) Histogram of point 25 displacement



(a)Comparison of static displacement (b) Histogram of point 12 displacement



(c) Histogram of point 22 displacement (d) Histogram of point 27 displacement

Figure 11. (a) Comparison of static deflection with 25 MIMO cases deflections along girder 1. (b) Histogram of point 12 displacement (c) Histogram of point 22 displacement. (d) Histogram of point 27 displacement

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

Girder number	Girder 3			Girder 1		
Point number	11	20	25	12	22	27
Average disp.(in)	-0.69	-0.92	-0.56	-0.47	-0.57	-0.41
Measured disp. (in)	-0.62	-0.85	-0.53	-0.62	-0.64	-0.46
Relative error (%)	10%	7.61%	5.36%	**-31.92%**	-12.28%	-12.20%

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

Figure 12. Pier cap crack under girder 1

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REFERENCES

FHWA.(2011).National Bridge Inventory. *U.S. Department of Transportation, Federal Highway Administration*.

ASCE. (2011). Structural identification of constructed systems: a state-of-the-art report. *ASCE-SEI Structural Identification of Constructed Systems Committee*, Reston, Va.

Aktan, A.E., Catbas, N., Turer,A. and Zhang. Z F.(1998). Structural identification: Analytical aspects. *Journal of Structural Engineering*, **124:7**, 817-829.

Catbas, F.N. and Aktan, A,E.(2002). Condition and damage assessment: issues and some promising indices. *Journal of Structural Engineering*, **128:8**, 1026-1036.

Catbas, F.N., Brown, D.L and Aktan, A.E. (2004). Parameter estimation for Multiple-Input Multiple-Output modal analysis of large structures. *Journal of Engineering Mechanics*, **130:1**, 921-930.

Catbas, F.N., Brown,D,L. and Aktan, A.E. (2006). Use of modal flexibility for damage detection and condition assessment: Case studies and demonstrations on large structures. *Journal of Structural Engineering*, **132:11**, 1699-1712.

Hogue,T.D., Aktan, A.E. and Hoyos, A.(1991). Localized identification of constructed facilities. *Journal of Structural Engineering*, **117:1**, 128-148.

Raghavendrachar, M. and Aktan. A.E.(1992). Flexibility by multireference impact testing for bridge diagnostics. *Journal of Structural Engineering*, **118:8**, 2186-2203.