Multiple Reference Impact Testing for Bridge Assessment with Drop Hammer

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Abstract. A new drop hammer was designed and used for multiple reference impact testing of two bridges. The drop hammer utilizes a multiple-rebound control system for successfully applying a single impact with repeatable high-level force for bridge testing. Signal analysis results indicate that the drop hammer provides a higher signal-noise ratio and a better coherence even when the response signals are subject to pollution due to traffic on the bridge. Modal flexibility was computed by using the impact data from the drop hammer, and meaningful deflected shapes could be generated demonstrating the potential of the envisioned structural assessment system.

Introduction

According to the U.S. Federal Highway Administration, over 33% of the 604,485 bridges in the US are more than 50 years old, among which 43% are either structurally deficient or functionally obsolete [1]. Given the scale of this problem and the potential enormous cost, wholesale replacement is not realistic. This places significant emphasis on proper diagnosis/prognosis and effective intervention. 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 [2].

In order to realize a rapid impact test on a bridge without stopping the traffic on all lanes, a Global Structural Assessment (GSA) system is envisioned to rapidly perform Single Impact Multiple Output (SIMO) testing. The GSA system utilizes a trailer equipped with an impact device and is pulled by a small truck along a lane or the centerline of a bridge. It is hypothesized that the GSA system will execute a series of independent SIMO tests as it traverses a bridge, each test delivering an impact and capturing the responses of the structure through an array of sensors in the vicinity of the impact. While each SIMO test may be processed independently to obtain local flexibility coefficients as well as the deflection basins along the measurement points, it may also be possible to artificially stitch multiple SIMO tests together and process them in an integrated manner to obtain more complete flexibility information [3].

The impact force envisioned for the GSA system would have magnitudes between 13 and 26 tons and would deliver impacts with a high degree of repeatability. Such a large level of impact force is considered desirable in order to provide a higher signal-noise ratio for a test and possibly mitigate the influence of noise due to any traffic during the impact. Further it was important to deliver a single sharp impact. In this paper, a GSA system based on a drop hammer with rebound control, and its applications for impact testing of two bridges named as Bridge A and Bridge B are reported. Test results demonstrated the feasibility of the concept, and show that the drop hammer was more robust and reliable in comparison to a traditional instrumented sledge hammer.

Rebound Controlled Drop Hammer

A Rebound Controlled Drop Hammer is designed to provide large sufficient robust impact force for the bridge test. 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 [3]. 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.1). 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 [4].

Bridge A Test

Bridge A was built in 1983 in New Jersey, US. Each direction of the bridge 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. A series of fatigue cracks, bearing and joint deterioration and very high vibration amplitudes under traffic loads were observed.

Data acquisition and instrumentation layout. Truck load test was conducted on the Southbound Span 2 to measure the deflection basin of this bridge. Several controlled static-load tests with 3 empty, 3 full and 6 full trucks were positioned on the bridge and displacement were captured through 12 displacement transducers. The displacement sensors were located on Southbound Span 2 in a rectangular grid (Fig. 2). These locations coincide with other modalities of instrumentation including strains and accelerations. Distributed data acquisition was used for field test, and 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 [3].

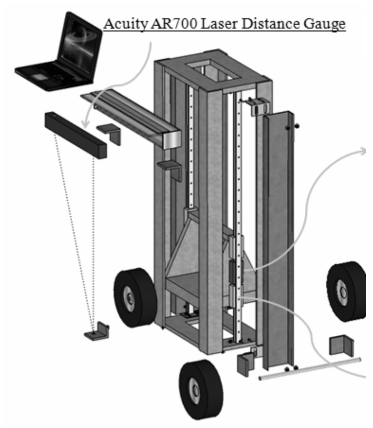


Fig. 1 Rebound Controlled Drop Hammer.

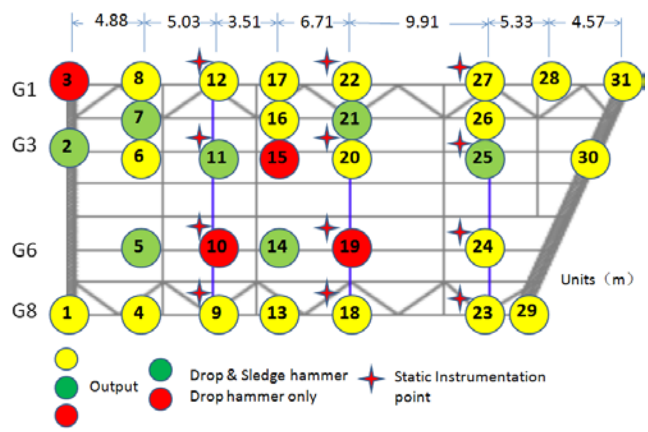
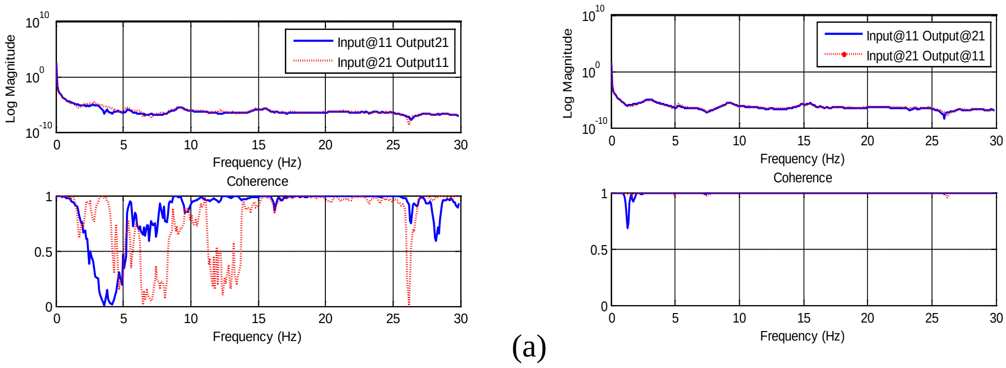


Fig. 2 Instrumentation of Southbound Span 2

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.3, revealing that the drop hammer provided robust coherence and reciprocity while the sledge hammer reciprocity and coherence were poor.



(a) (b)

Fig. 3 Reciprocity provided by (a) Drop Hammer and (b) Sledge Hammer

Modal flexibility and truck load surface calculation. The first 9 modes within 0-20 Hz are shown in Fig.4. The CMIF method was utilized for modal parameter identification and the singular value plot that was used for CMIF analysis is shown in Fig.5 (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.5 (b), revealing the promise of rapid impact testing under high level repeatable impacts for objective condition evaluation of typical bridge structures.

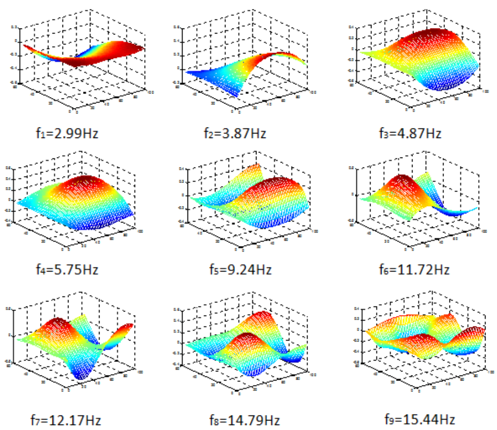


Fig. 4 Analysis results for the first 9 modes for the South bound span2.

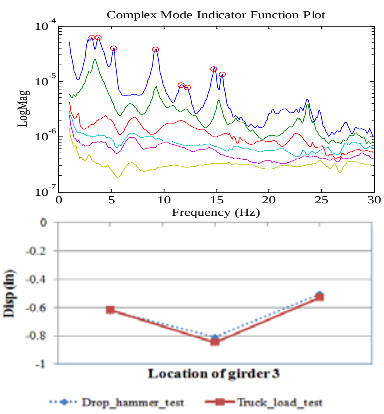


Fig. 5 (a) CMIF singular value plot; (b) Correlation of displacements measured under truck-loads and simulated by modal flexibility along Girder 3.

Bridge B Test

The Bridge B is also located in New Jersey, US. It consists of three spans and carries four lanes of traffic in each direction. It has a roadway width of 12.80m from curb to curb and concrete sidewalks are present on each side of the bridge with widths of 10.67m. Each span consists of a reinforced concrete deck on seven simply supported rolled steel I-beams with partial-length welded bottom flange cover plates spaced at 2.18m. The substructure was composed of reinforced concrete abutments and hammerhead type piers. The test segment of the bridge consisted of one half of a single span. Traffic control allowed the two lanes included in the test segment to be blocked from traffic, while allowing traffic to proceed on the other two lanes.

Hammer Impact Test. The local impact test was conducted by using a Drop Hammer. The southbound lanes of the 1st span of the bridge were selected for the impact test by traffic control. A dynamic signal acquisition module (National Instruments NI9234) with a reconfigurable control and acquisition system (CompactRIO) was used to collect the dynamic data. The ModalView software developed by ABSignal Inc. was utilized for signal processing, frequency analysis and modal analysis. 25 PCB 393A-03 accelerometers were installed on the top surface of the deck. The sensor layout, which consisted of 21 accelerometers, was designed to ensure that a relatively dense and regular distribution of responses was captured spatially (Fig. 6). Three additional sensors were roved around with the impact device to capture the acceleration at the driving point by using various averaging techniques [5].

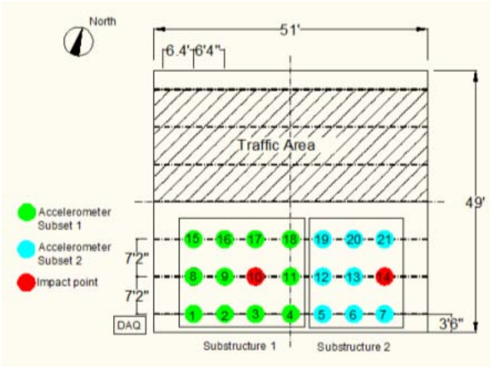


Fig.6 Instrumentation layout for the bridge B test

Signal Processing and Modal Analysis. The drop hammer had a force level of around 80 kN which induced a peak bridge response of around 2.05g. The raw time histories were preprocessed by adding the rectangular and exponential windows to eliminate the effects of leakage. The windowed time histories are then transformed into auto and cross power spectra using a 16,384 point FFT.

SISO, SIMO and MIMO Modal Analysis. The GSA system will provide a series of independently obtained SIMO tests as it traverses a bridge, with each test delivering an impact and capturing the response of the structure through an array of sensors in the vicinity of the impact. In this paper, four scenarios of the modal flexibility analysis were conducted to simulate the GSA working status. Four typical scenarios are designed including SISO, SIMO, MIMO, and global cases. All four scenarios are used to develop the modal flexibility coefficient at point 10 for comparative purposes. The identified modal flexibility coefficients of point 10 for different cases are listed in Table 1.

Table 1 Modal flexibility coefficient at point 10 in different cases (m/N)

Global	SISO	SIMO	MIMO
1.36e-08	1.32e-08	1.33e-08	1.35e-08

Finite Element Modeling and Validation. After modal flexibility has been obtained, the next challenge is to evaluate the reliability of each modal coefficient shown in Table 1. In the envisioned application of the GSA system, time/cost requirements limit the application of the truck load test on the bridge.

In this case, a truck load test was not conducted. Without the static test, an a priori FE model was developed to provide a reference for the comparison of modal flexibility (Fig. 7). The first 9 modes within are shown in Fig.8. Along with physical properties of the different bridge components, the boundary conditions are generally considered to have significant influence on the modal parameters of the FE model. Therefore, four different boundary conditions were modeled including pin-pin, pin-roller, fixed-fixed and spring-spring. To extract the static flexibility coefficients a unit load was applied at point 10 and the resulting displacements corresponded to the flexibility coefficient (Table 2). While this approach to evaluating the accuracy of the modal flexibility estimates is admittedly not as convincing as a static truck load test, it does provide a very promising independent correlation with the impact tests.

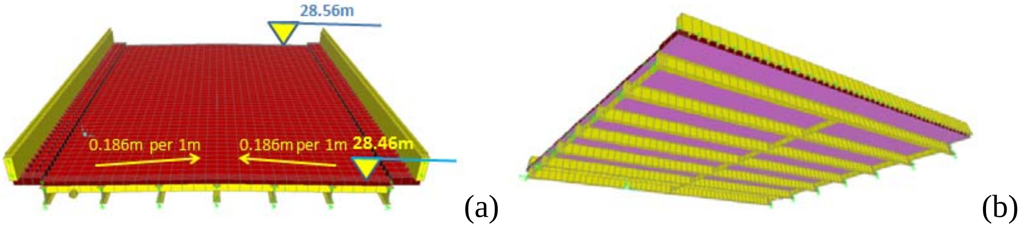


Fig. 7 Finite element model for the 1st span of bridge B (a) Top view (b) Bottom view

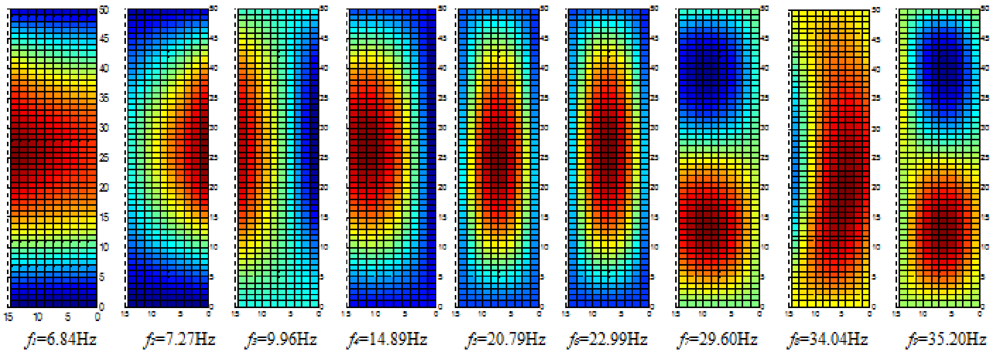


Fig. 8 Measured first 9 modes in global test by drop hammer

Table 2 Static flexibility coefficient at point 10 in different boundary conditions (m/N)

	Pin-Roller	Pin-Pin	Fix-Fix	Spring-Spring
Static flexibility	1.31e-08	7.71e-09	7.08e-09	1.30e-08

Substructure integration. After confirming the successful identification of the modal flexibility coefficient at point 10, the proposed substructure integration procedure was employed to stitch together two independent SIMO tests. As seen in Fig 6, two substructure tests were performed at point 10 and point 14, each surrounded with a subset of sensors to measure the response of each substructure. Therefore, two SIMO substructure analyses were conducted to extract the local modal flexibility. The first 9 modes were selected using Peak Picking from the CMIF singular value plot, shown in Fig.9 (a), (b), obtained from the CMIF algorithm. The global modes are then assembled as shown in Fig.10. It is shown that the natural frequencies of the two substructures are similar and only vary by a maximum of 2%. The majority of the mass normalized mode shapes can be constructed by simply connecting the two substructures.

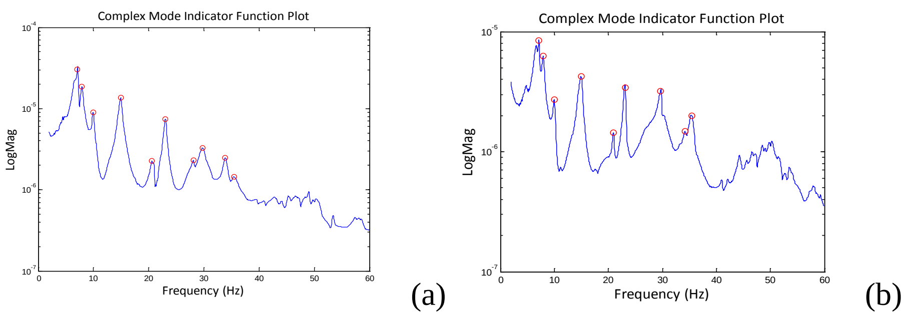


Fig. 9 (a) Peak-Picking in CMIF SV figure for Substructure 1 and (b) Peak-Picking in CMIF SV figure for substructure 2

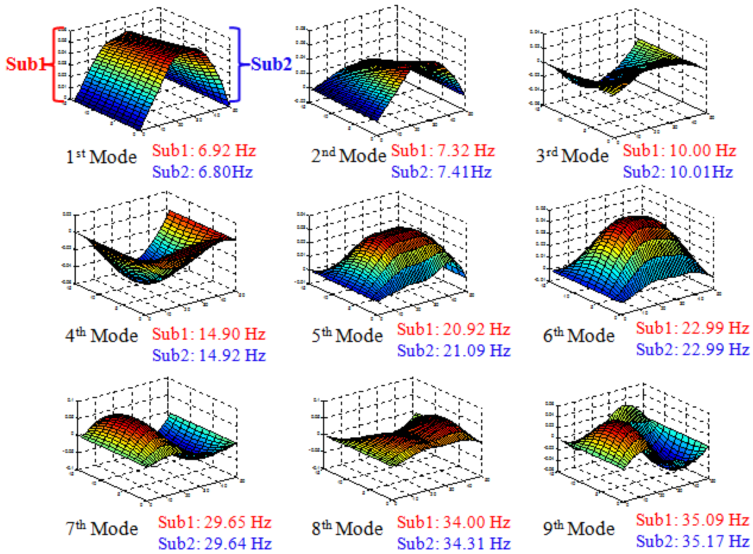


Fig. 10 Mode shapes integrated by the two substructures

Conclusions

A rebound controlled 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 two bridges. Even when the response signals were polluted by traffic noise, the rebound controlled 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 such as the integration or patching of several SIMO test results to serve as a MIMO test. Eventually such GSA systems may become an essential prelude to visual inspections, directing the inspector to possible areas of concern implied by any anomalies or changes in flexibility.

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