Inferring Dynamic Characteristics of a Bridge through Numerical Simulation and Low-Magnitude Shaking as a Global NDE Method

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ABSTRACT

Boundary conditions of a structure affect its response to dynamic excitations. In most highway bridge designs, the dynamic soil-structure interaction is not considered, with an underlying assumption that bridge piers have fixed-ends. Foundation flexibility, and more importantly radiation damping from the foundation, whether it is a shallow or deep foundation, can significantly influence the response of substructure/superstructure system. This may lead to deviations of the actual response compared to the design assumptions, depending on soil properties and geometrical and structural characteristics of the bridge. Low-magnitude shaking can be used as the means of evaluation of actual dynamic characteristics of a bridge. Moreover, numerical simulations of the same bridge with the same low-magnitude shaking load on the bridge can be used to model the dynamic response of the bridge, with the consideration of the dynamic soils structure interaction. In this paper, a comparison between the actual response of a bridge in Hamilton Township, New Jersey, and results from numerical simulations is presented. The shaking of the bridge was done using T-Rex, a large mobile shaker from NHERI Experimental Facility at University of Texas at Austin. The test setup, and results from both numerical simulations and field-testing are presented and discussed. Experimental results confirm that the FEM model developed is adequate to infer dynamic characteristics through the eigenmode analysis.

Keywords: DSSI, mobile shakers, SHM, modal analysis, St-Id

INTRODUCTION

In recent years, more attention has been paid to the development of more robust Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) techniques in order to assess infrastructure condition/performance. As a result, Structural Identification (St-Id), a subset of SHM/NDE, is an emerging field that utilizes a wide variety of sensing technologies and introduces cost-effective and safe approaches to quantitatively evaluate the condition/performance of existing infrastructure systems, and for the design of future infrastructure. Static/Quasi-Static SHM involves assessing the static response (displacement and rotations) of structures, namely bridges. However, considerable load levels are required to generate a noticeable response. On the other hand, a vibration-based SHM can help capture global characteristics related to the load carrying/transfer from the super- and substructure of bridges onto the foundation and, ultimately, surrounding soil. This is carried out by measuring the dynamic response of excited bridge at various locations and analyzing the measured response. Furthermore, highly-refined Finite Element Modeling of the same bridge can be developed and utilized in tandem with experimental results to better understand the dynamic behavior of bridges, and/or to confirm the design assumptions/parameters and expected behavior(1). In other words, the synergistic application of model- and vibration-based SHM/NDT is not implemented as a local damage detection method, but rather to assess an actual response to dynamic loads.

One of the most prevalent underlying assumptions in most dynamic analyses of bridges is the base fixity. However, it is evident from various research efforts that Dynamic Soil Structure Interaction (DSSI) effects can considerably alter the dynamic response of bridges (2, 3). The degree of variation of behavior, from the fixed-based assumption, when the DSSI is considered, and whether it is a detrimental or beneficial effect depends on several factors. Those include the rigidity ratio (ratio of the stiffness of the structure to the same of the soil-foundation system), the slenderness ratio (height of the structure to the base width ratio), type of the foundation, and the mass of the structure relative to the mass of the engaged soil-foundation system (4). There have been several attempts in previous research efforts to utilize either ambient vibrations, wind, or temperature changes to experimentally carry out the St-Id of bridges (5-7). Nevertheless, the response levels from such methods are insufficient to provide information about structure-foundation systems. Moreover, unintended composite action and engagement of nonstructural elements associated with the application of such methods can be challenging and entails significant extrapolation (8). Therefore, live-load testing on bridges using mobile shakers can be an advantageous approach to assess the effects of DSSI and infer dynamic features of bridges through modal analyses as a global NDE method. This serves two purposes: i) confirming design assumptions by analyzing a bridge and conducting model-based parametric studies, and ii) refining future designs of bridges with similar load conditions, geometry, and structure-foundation systems. The Natural Hazards Engineering Research Infrastructure (NHERI) mobile shakers can be employed to overcome uncertainties accompanying low-level conventional methods of St-Id, by shaking actual bridges in a controlled manner. Figure 1 illustrates the proposed shaking as part of SHM/NDT of bridges, as opposed to the conventional low-level methods.

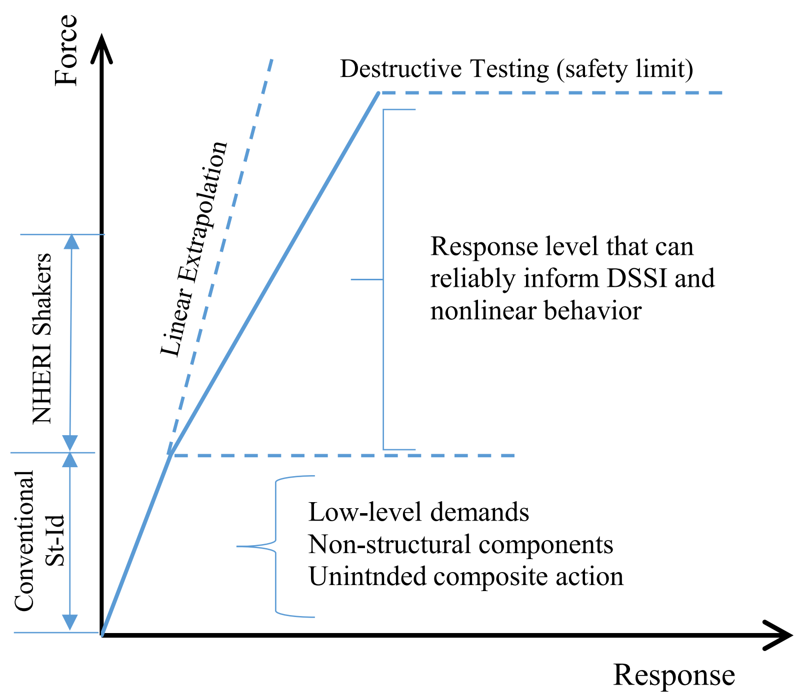


Figure 1: Comparison between conventional St-Id techniques with the proposed use of NHERI shakers.

In this paper, inferring dynamic characteristics of an actual bridge is carried out through an experimental program and numerical simulations. T-Rex, a large-amplitude mobile shaker from NHERI was used to shake an overpass bridge in Hamilton, NJ, vertically, transversely, and longitudinally. Multiple geophones were placed at various locations on the bridge to capture its dynamic response. In addition, modal analyses in 3D Finite Element Method (FEM) simulations of the bridge were conducted. The soil-foundation system was described by impedance functions to incorporate the effects of DSSI in the response. A comparison between some of the findings from the shaking of the bridge and the 3D FEM model results is presented. The results from the field have enhanced the reliability of simulation model predictions, and will in general lead to the enhancement of evaluation of nonlinear dynamic response of bridges.

EXPERIMENTAL STUDY

The objective of the study was to apply low-magnitude shaking to a bridge using T-Rex to capture the dynamic response and features, especially the resonant frequencies and their corresponding mode shapes. A low-magnitude shaking referred to herein is relative to the destructive testing limit described in Figure 1, or actual levels of seismic loads, rather than the much lower levels of conventional methods. The Hobson Avenue Bridge, a bridge over Interstate 195 in Hamilton Township, New Jersey was selected for the study. It is a 67.4 m [221 ft] 2-span steel girder jointed bridge with a three-hammerhead pier on a shallow continuous reinforced concrete (RC) footing. Figure 2 depicts various views of the bridge and the dimensions of the super- and substructure.

Figure 2: (a) Side view of Hobson Avenue Bridge. (b) Deck dimensions. (c) Substructure dimensions.

T-Rex, shown in Figure 3(a), is a mobile shaker from Infrastructure NHERI experimental facility at the University of Texas at Austin, which is capable of generating large dynamic forces in any of three directions (vertical, horizontal in-line, and horizontal cross-line). The response of the bridge can be monitored in real-time in a control room. The maximum force output is about 267 kN in the vertical mode and about 134 kN in each horizontal mode. However, the excitation amplitude was capped at 94 kN [21 kips] transversely and 48 kN [10. 8 kips] vertically to limit the response to 2.54 cm/s [1 in/s]. As shown in Figure 3a, airbags are used to isolate the shaker from the truck. The air bags act as a low pass filter, and transfer only the static force. If a free body of the T-Rex shaker is taken ignoring the hydraulic system, the only external dynamic force is the dynamic ground force, which is also the dynamic force output of T-Rex (9, 10). The response of the bridge can be monitored in real-time in a control room, as shown in Figure 3(b). The control room is moved off the bridge prior to testing.

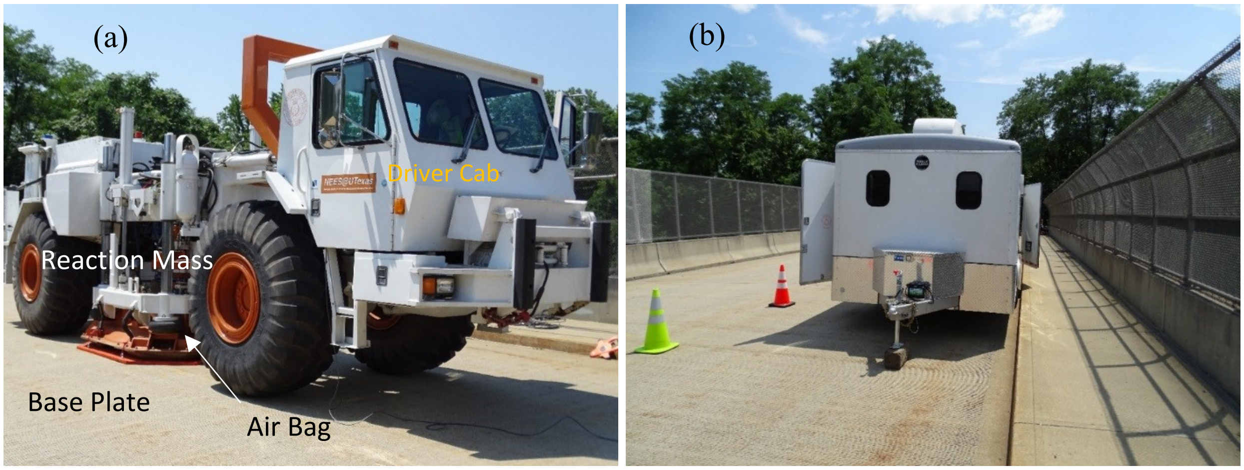


Figure 3: (a) T-Rex on bridge. (b) Control room to monitor response in real-time.

T-Rex can output an arbitrary waveform generated by an analog waveform generator. A linear chirp excitation was used to drive the T-Rex shaking during all the tests on the bridge. In the chirp function, the frequency of the load varies linearly from the start to end frequency during a given time period. The chirp function is a better option to limit the number of loading cycles, but might not always lead to full attainment of a steady state condition. In the current study, a linear chirp was conducted from 15 Hz to 1 Hz, with a total duration of 32 s and at a sampling rate of 200 Hz. The driving force was applied at several levels transversely, vertically, and longitudinally. Geophone and accelerometer arrays were placed at various locations on the deck. Figure 4 presents the locations of geophone arrays at the test site. The vertical, transverse, and longitudinal response was measured at each of the locations. A total of 45 geophones were employed in the current study to measure the response at the deck, bent, abutment, and ground. Figure 5 shows the installation of geophones and accelerometers at various locations on the bridge. In addition, a Multichannel Analysis of Surface Waves (MASW) test was carried out prior to shaking the bridge to estimate the soil system's shear wave velocity, which was found to be about 200 m/s down to about 15 m depth.

Figure 4: Geophone placement layout.

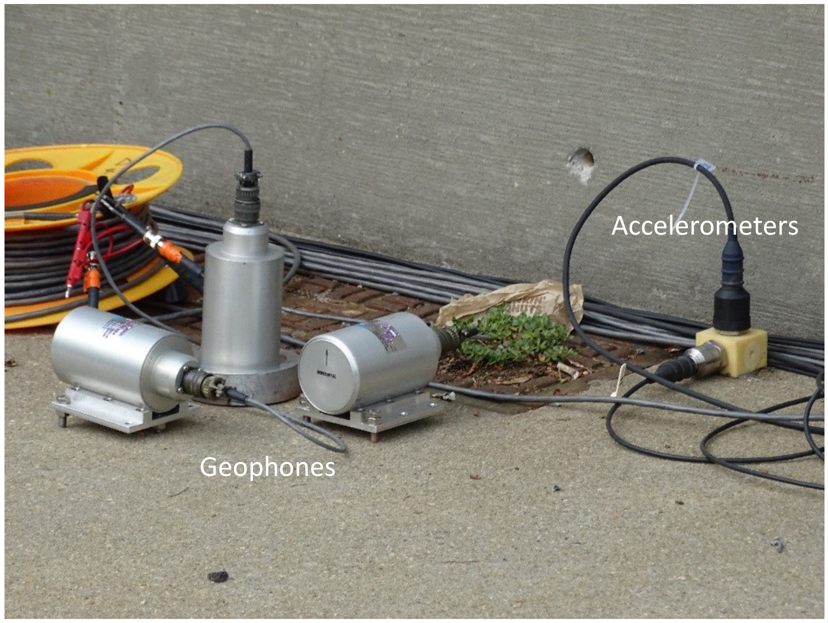


Figure 5: Geophone and accelerometer arrays used to capture the dynamic response.

NUMERICAL STUDY

Prior to the shaking of the bridge, FEM models were developed to simulate and capture the effects of DSSI on dynamic response. COMSOL Multiphysics software was used to produce the 3D FEM simulations of the bridge response due to the chirp signal type dynamic loading. Initially, eigenmode studies were conducted to estimate the resonant frequencies (mode shapes) of the bridge, which are independent of the load amplitude. The eigenvectors were scaled with respect to the mass matrix to obtain the participation factors and expected peak responses. Following the testing, the model was adjusted and expanded to conduct time history and frequency domain studies. Figure 6 presents the main elements of the 3D model developed in COMSOL. It is very closely matching the geometry and dimensions of the actual bridge. The restraints at the ends of the bridge were imposed to reflect simply-supported bridge conditions. The soil-foundation system (SFS) was incorporated in the 3D model by a system of translational and rotational frequency-dependent springs placed at the bottom of the pier footing defined in Cartesian and spherical coordinates, respectively, utilizing the closed-form representations of dynamic impedances developed by Gazetas (11).

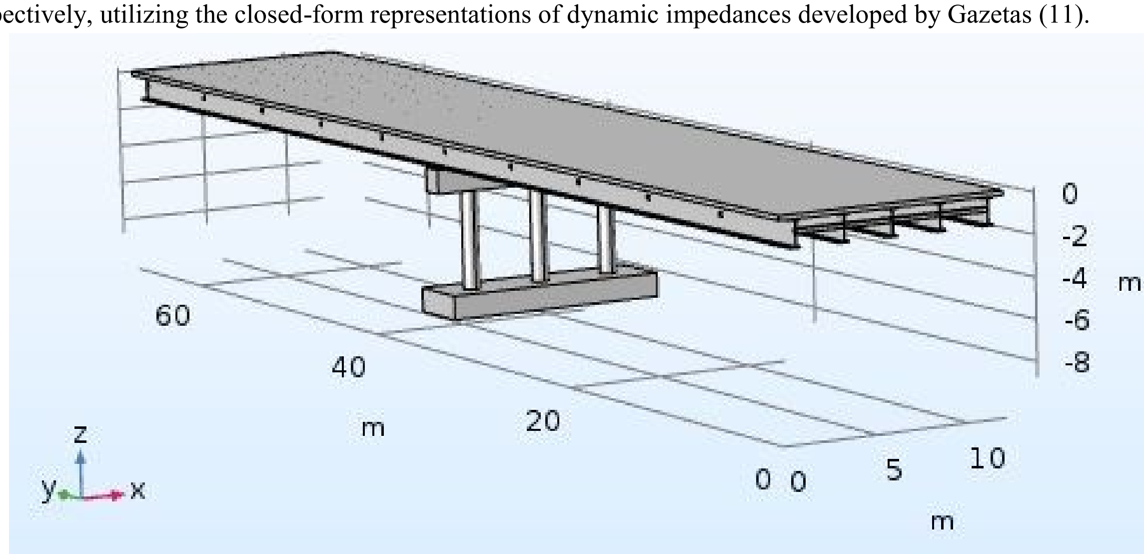


Figure 6: Perspective of the Hobson Avenue Bridge model.

RESULTS

Table 1 presents the results of the eigenmode analysis of the FEM model for the fixed-base and SFS(DSSI)-incorporated cases. The imaginary part is indicative of energy loss due to damping and energy decay rate for each cycle. As expected, the resonant frequencies for each eigenmode are higher for the fixed-base compared to the SFS-incorporated model. It is also observed that higher energy losses are incurred as frequency increases in both models. Mass Participation Factors (MPFs) for each mode in each direction. The magnitude of the MPF in a direction indicates the predominant mode of vibration, allowing the identification of the mode shape, or compliance.

Table 1: Eigenfrequencies obtained from FEM simulation of SFS(DSSI)-incorporated and fixed-base models

Frequency (Hz) – DSSI	Frequency (Hz) – Fixed	Mode No#
2.6814+0.13748i	2.8299+0.14929i	1
3.2798+0.18909i	3.2900+0.19000i	2
3.6832+0.23083i	3.6912+0.23055i	3
4.2029+0.28946i	4.2262+0.29196i	4
4.7694+0.36681i	4.8301+0.37142i	5
6.1213+0.57771i	6.1623+0.58507i	6
6.8398+0.71598i	6.8616+0.71863i	7
8.3588+1.0551i	8.3797+1.0603i	8
9.1409+1.2599i	9.1598+1.2640i	9

Table 2: MPF in each direction for the DSSI-incorporated model

Mode No#	MPF_x	MPF_y	MPF_z
1	1.542	69.253	2.7642
2	3.5646	0.369	0.47626
3	3.3658	0.3836	806.95
4	641.39	1.0472	6.8149
5	598.17	0.7138	1.2181
6	1.1691	16.337	6.2724
7	0.37801	0.3633	214.05
8	0.013057	8.7602	0.08168
9	0.015426	0.1665	15.784

Figure 7 presents a surface plot of the velocity amplitude for each mode shape obtained. It is evident that mode #4 and #5 are the most predominant modes from the normalized amplitudes and MPFs, and they represent the transverse motion of the bridge, predominantly due to rocking. To confirm the results from FEM, response spectra due to the actual shaking of the bridge from various locations were examined at various load levels. It is noteworthy that not all mode shapes predicted from the FEM could be inferred from the testing due to a low response magnitude. Figure 8 presents response spectra from selected locations under a load magnitude of 53.4 kN [12 kips]. As observed from Figure 8(a), the bridge exhibited two different transverse mode shapes at 4.41 Hz and 4.64 Hz. This is attributed to the rocking of the foundation. Moreover, the vertical response in Figure 8(b) reveals vertical/out of plane mode shapes. Modes #6 and #7 were not identified in the current study since the peak response was localized at the abutments, as shown in Figure 7. The error in the resonant frequencies obtained from the FEM models for both cases for modes #4 and #5, relative to the field test, was used to assess the applicability of the DSSI model. The error was 4.76% and 0.25% for the DSSI model, and 4.08% and 0.5% for the fixed-base, respectively. Mode #5 is a transverse mode and it was the predominant mode of vibration by inspecting the response from the testing and FEM models. Hence, it is desired that the FEM model captures this mode as close as possible to more accurately describe the dynamic response and resulting stresses. Therefore, it can be deemed that the DSSI-incorporated FEM model matches the test results better than the fixed-base model. This is also supplemented by the overall error estimated from the other modes.

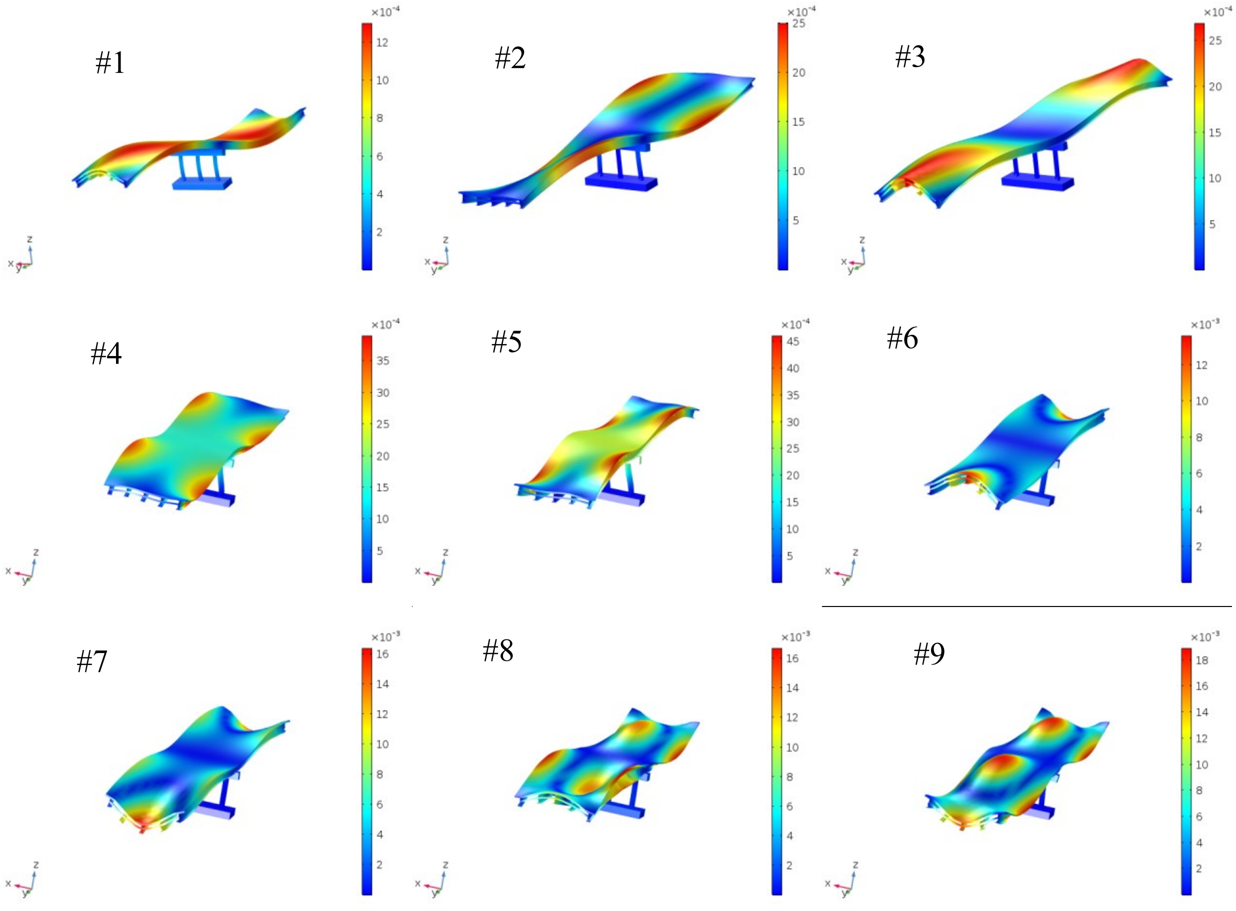
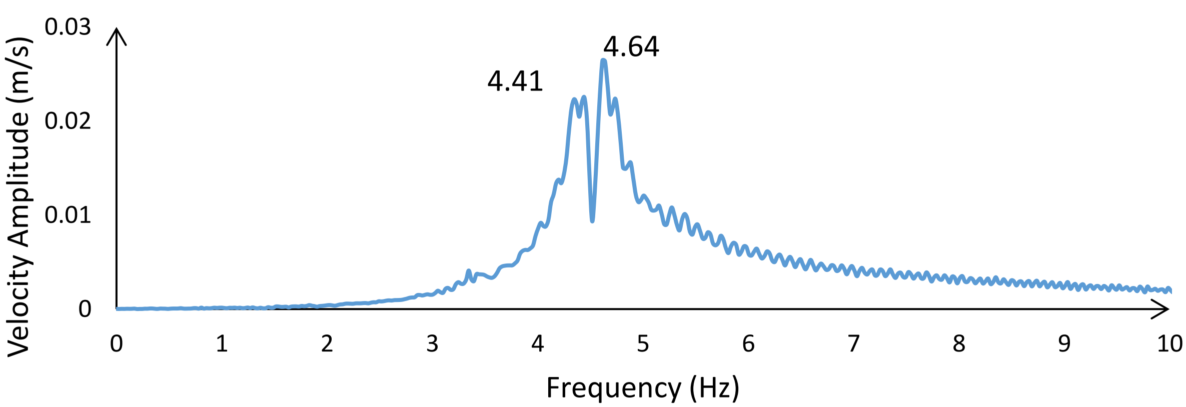


Figure 7: Modes shapes of the bridge obtained from FEM simulation



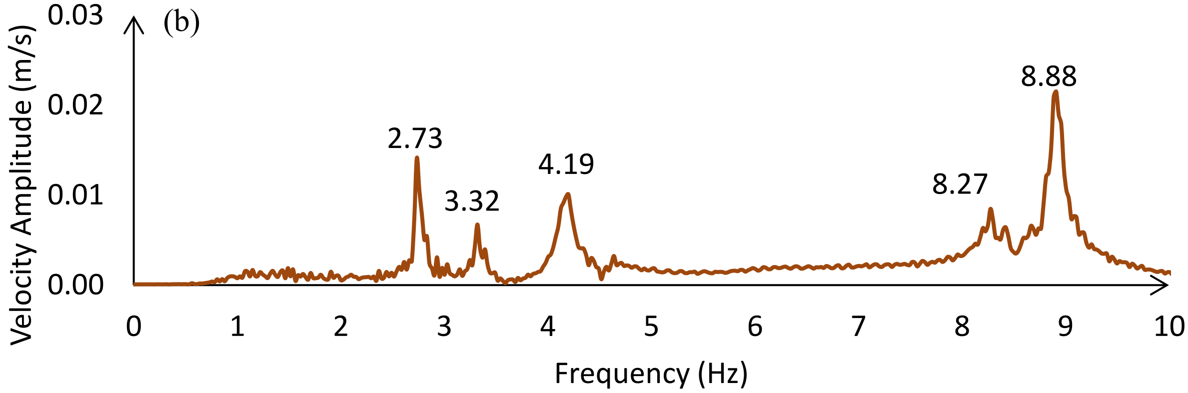
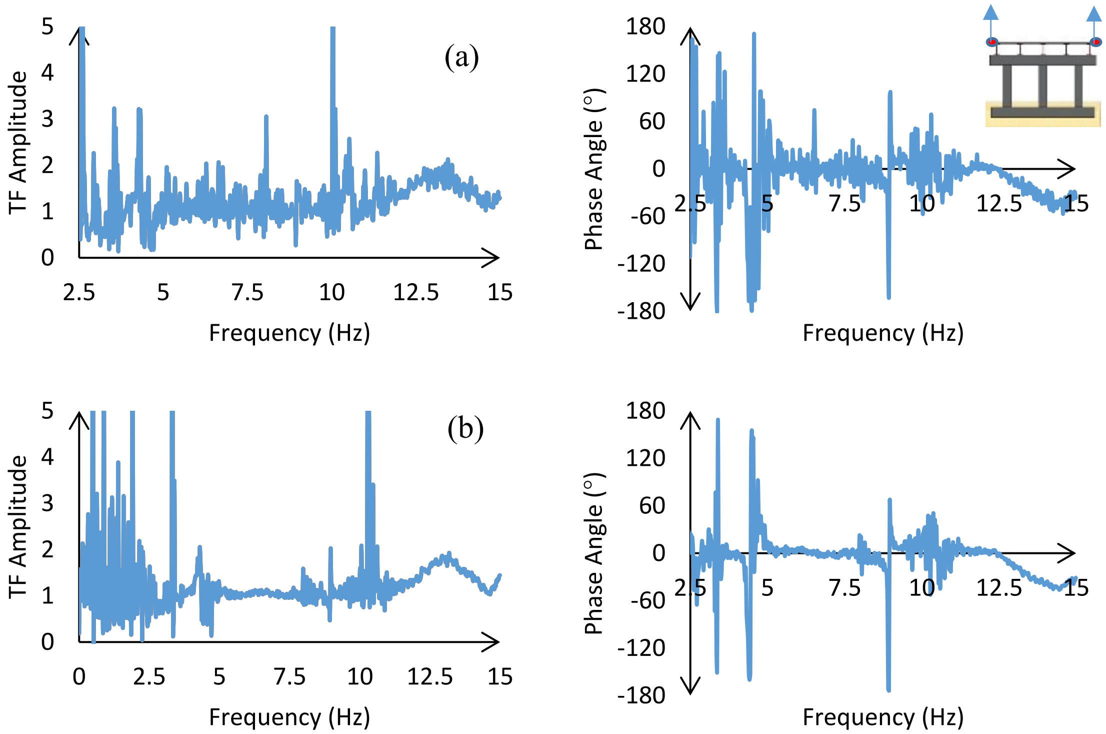


Figure 8. (a) Transverse response above pier east due to transverse loading, (b) Vertical response at midspan-east due to vertical loading.

Transfer functions were evaluated to assess the effect of changing the load magnitude. Figure 9 illustrates the Transfer Functions (TFs) between the east and west sides of the bridge above the pier at several load levels of vertical shaking. As the power input increased, the TF clearly increased, evident by the reduction in undulations in both the amplitudes and phase angles, due to a higher signal-to-noise ratio. This allows for a clearer identification of resonant frequencies, promoting the use of shakers, as opposed to conventional methods that rely on ambient vibrations, wind, or temperature changes.



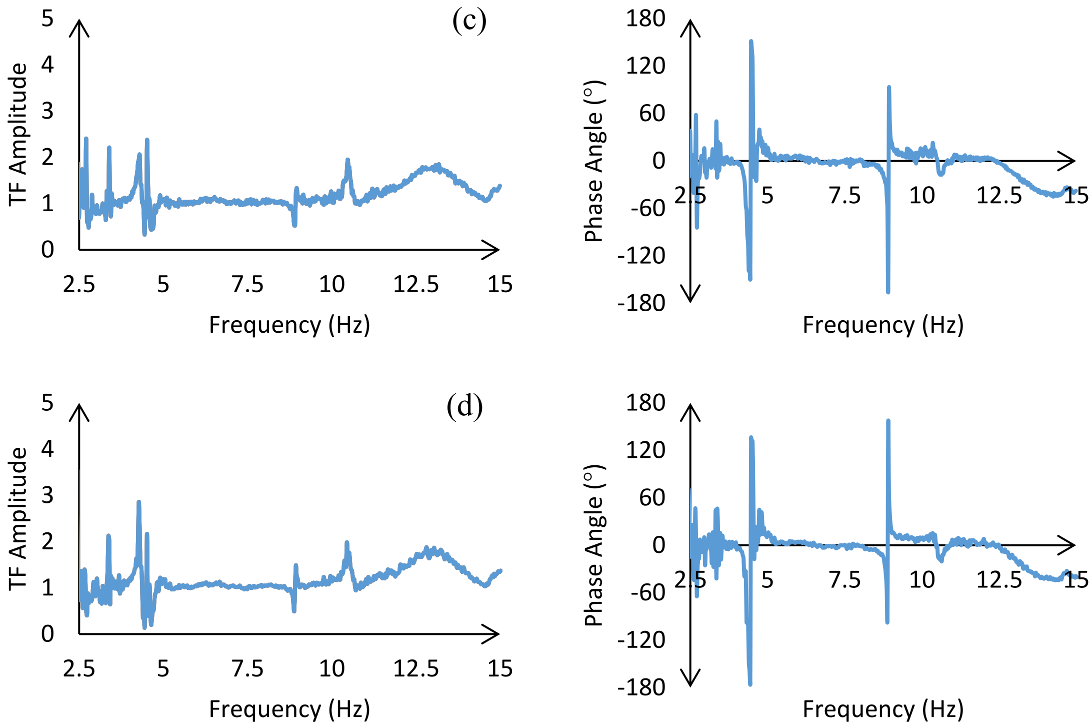


Figure 8. Transfer functions and phase angles of vertical response between east and west side of the deck above the pier due to vertical load @(a) 13.3 kN [3 k]. (b) 26.7 [6 k]. (c) 40 kN [9 k]. (d) 53.4 kN [12 k].

CONCLUSIONS

In the current study, a holistic approach to infer dynamic characteristics of an actual bridge by shaking it using a mobile shaker (T-Rex) and FEM element modelling as a combination of vibration- and model-based SHM/NDT. In addition, 3D finite element models were developed to compare the eigenmodes with and without incorporating the DSSI-effect. Results from the current study serve as a basis for further investigations. The primary findings presented in this paper are:

- Mobile shakers are an effective SHM or global NDE tool to assess the dynamic response of bridges, as opposed to the conventional St-Id, in combination with FEM models.
- From the experimental frequency sweep, the tested bridge exhibited two different dominant modes of transverse vibration at 4.41 and 4.64 Hz. The experimental results confirm that the FEM model presented in was adequate.
- The DSSI-incorporated model showed an overall better accuracy in terms of capturing the resonant frequencies of the bridge than the fixed base model.
- Increasing the load magnitude leads to clearer transfer functions and phase angle measurements, allowing a better identification of dynamic characteristics such as resonant frequencies.

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