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Structural Identification of an Old Bridge by Multiple Reference Impact Test Method

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Abstract. Experimental data was collected for structural identification (St-Id) of an old bridge: (1) static displacement and strain measurements taken under proof-load level, and; (2) multi-reference impact test (MRIT) data from one of the spans of a three span, cast-in-place reinforced concrete (RC) T-beam Bridge. MRIT was used to generate the modal data for computation of modal flexibility and displacement profiles. The St-Id procedure used during this application was designed to mitigate epistemic uncertainty in the data interpretation process. Successful results from MRIT demonstrated the reliability of applications for bridge condition assessment based on impact testing.

Introduction

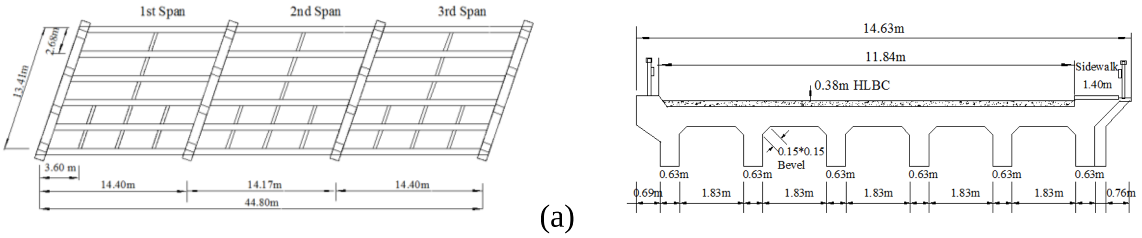
During the last 30 years, the state of the art in structural identification (St-Id) of constructed systems has advanced significantly and dozens of applications to many large and complex structural systems have been demonstrated. The ASCE St-Id of Constructed Systems Committee recommends the following six steps [1]: (1) clearly defining the objectives for St-Id followed by observation and conceptualization of the entire structural-foundation-soil system by site visits and study of all legacy data/information, including sampling and testing materials; (2) a priori analytical modeling; (3) uncontrolled and/or controlled experiments; (4) processing and interpretation of data; (5) model-experiment correlation; and, (6) utilization of the insight gained during Steps (1)-(5) in conjunction with the field-calibrated model for simulations and decision-making. Through these steps, bridge engineers may accomplish a true integration of experiment and analysis, as well as information technology and decision sciences.

Step 3 of St-Id may leverage controlled experiments such as static load applications, ambient monitoring, dynamic force applications or a combination of these. Doebling et al. and Sohn et al. provide an overview of the vibration-based applications conducted during the previous 15 years while the state-of-the-art report by the ASCE Structural Identification of Constructed Systems Committee (2011) provides an up-to-date description of the spectrum of experimental methods used in St-Id[2~3]. Forced vibration testing (FVT) is a powerful method for experimenting with constructed systems and it is the only test method capable of providing an estimate of modal mass and modal flexibility. Different FVT methods include rotating eccentric mass exciters, electro-dynamic shakers, transient testing, MRIT, and step relaxation.

Due to its ease of application, multi-reference impact testing (MRIT), which was first developed in the 1970's offers the greatest utility for bridge condition assessment since it may be executed relatively quickly [4]. Successful MRIT test was conducted on HAM-42-0992 highway bridge [5]. The continuous, 3-span steel-stringer Seymour Bridge was another earlier and successful demonstration of the application of MRIT for condition assessment, and excellent correlation was accomplished between the deflection profiles obtained from modal flexibility and deflections measured under truck loads [6]. The primary challenge in its application however, is that aged and deteriorated highway bridges are often characterized by non-linear and non-stationary behaviors that are often not observable, and these attributes violate the underlying assumptions of modal analysis. As a result, careful design and execution of the experiments and on-site validation of measurement quality and interpretation is required to understand the limits of a linear, stationary representation of the system.

Bridge Description

The Bridge is constructed in 1930. It is a three span, simply supported RC T-beam bridge with 18^o skew. Each span is approximately 14.40m long, with a width (along the skew with sidewalk) of 14.63m. There are six girders along each span with dimensions of 1.22m×0.61m, with a transverse diaphragm along the width in the middle and on the downstream side of the span. Two additional partial diaphragms increase the stiffness and the mass on one side as shown in the plan in Fig.1.



(a) (b)

Fig. 1 The Bridge: (a) Girder Plan; (b) Cross-section.

The bridge is a cast-in-place RC test specimen represented a far more challenging un-symmetric superstructure system with skew, and was covered by an asphalt overlay. There was extensive deterioration of the asphalt as well as the concrete deck under the asphalt. The high level of damping obscured a successful identification of many of the poles in the FRF, biasing modal flexibility calculation. In addition, the re-distribution of the truck loading caused large differences in ULS from modal flexibility and static test results, a phenomenon not observed before. Whether MRIT based St-Id can be successful in the case of such a structure given its highly damped and closely coupled modes, was considered to be a highly challenging case to validate the applicability of MRIT as an experimental method as well as the overall linearized St-Id process itself.

St-Id of Bridge

Static Instrumentation. The static instrumentation of the first span of the Bridge included 40 sensors to capture any opening or progression of the existing cracks, beam rebar strains, vertical displacements and any settlements at the bearings. Since the first span was the most accessible span from the underside, a majority of the gages were located under this span.

Static Truck Load Test. In the static load test, the loads were applied using six special dump trucks capable of being loaded up to a total of 44.64 tons each. The bridge was loaded incrementally from positioning three empty trucks to six fully loaded trucks for a total of 270 tons without any damage or distress. On average, each of the front-wheel tire loads were approximately 4.5 tons and the back-wheel tire loads were approximately 8.9 tons.

Based on the vertical displacement measurements, it was concluded that the continuity between spans was negligible since no deformation occurred in the span adjacent to the loaded span. The displacement response of the bridge was generally linear, with a small amount of softening. No significant nonlinearity was present in global responses. The displacement profiles at ¼, ½ and ¾ points along the first span and under the full truck load is shown in Fig. 2. As expected, the largest response was at the mid-span (-3.20mm), with proportionally smaller responses at ¼ and ¾ spans. As a result of the skew, the response at ¼-span is slightly larger than at ¾-span. The maximum recorded steel strain was 150 microstrain at axis c-4.

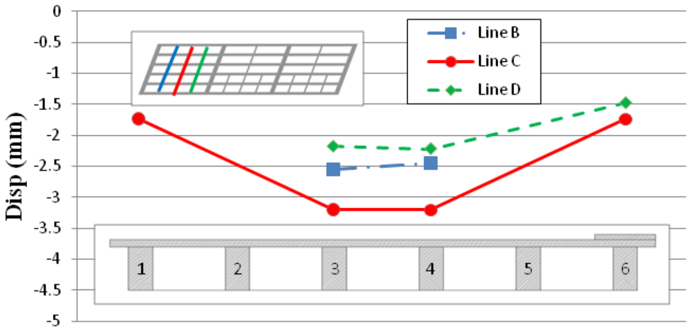


Fig. 2 Measured displacement results in the 1st span

Modal Test by MRIT. In MRIT, the responses to a dynamic impact force are measured and the Frequency response functions (FRF) are computed to yield modal parameters. The instrumentation layout can be found in Fig.3. The identified modal frequencies between 0~60 Hz are shown in Table 1, including the MAC values between the mode shapes calculated by two different methods. Mode shapes 1 through 6 and the 9 through 12 from all three methods correlate very well, with MAC values above 0.9. The bridge exhibits high damping, evident in Figs. 4 ~ 5. In Fig. 4 the response signal quickly decayed in 0.16s~0.22s, and the damping ratios in Table 1 identified by different modal analysis methods also reveal very high damping ratios exceeding 5% in many cases.

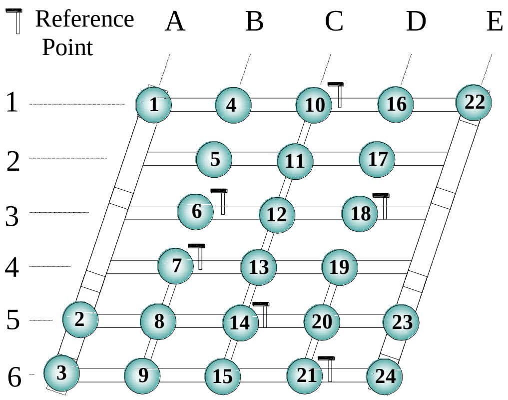


Fig.3 Dynamic instrumentation layout for the 1st span

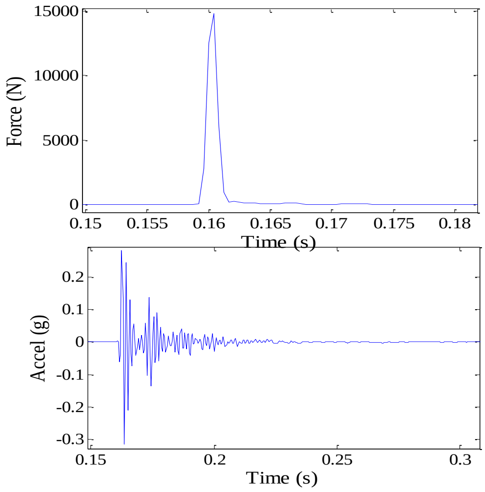


Fig. 4 Typical hammer impact force and response signal in time domain

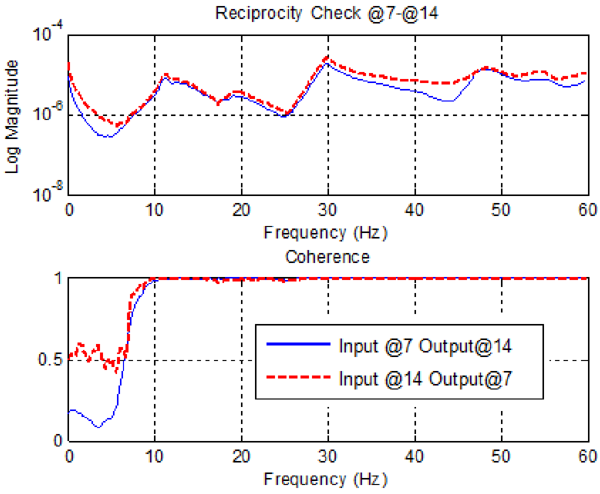


Fig. 5 Typical reciprocity check between reference points different

Table 1 Frequencies and Mode Shape MAC comparisons from different algorithms

	CMIF		PolyMAX		SSI		MAC Comparison		
	Freq(Hz)	Damp.(%)	Freq(Hz)	Damp (%)	Freq(Hz)	Damp (%)	C and P	C and S	P and S
1	11.185	6.30%	11.216	5.20%	11.141	6.36%	0.9799	0.9782	0.9801
2	12.952	13.33%	13.033	7.35%	12.988	7.08%	0.9384	0.9916	0.9652
3	12.999	9.90%	15.380	9.16%	15.564	8.37%	0.9490	0.9518	0.9963
4	18.074	7.28%	17.676	2.72%	17.538	3.91%	0.9919	0.9804	0.9928
5	18.927	6.42%	18.966	4.79%	18.995	5.74%	0.9981	0.9974	0.9993
6	29.707	2.69%	29.697	2.92%	29.669	3.05%	0.9992	0.9979	0.9982
7	37.760	6.48%	38.190	5.15%	37.858	4.79%	0.4531	0.9895	0.4752
8	40.848	8.48%	39.779	11.21%	/	/	0.8151	/	/
9	45.480	6.44%	45.401	4.90%	45.298	4.69%	0.9510	0.9876	0.8993
10	47.608	2.59%	47.773	5.96%	47.576	2.73%	0.8055	0.9907	0.7340

Note: C—CMIF, P---PolyMAX, S---SSI

Finite Element (FE) Model. The FE model was constructed in Stand7, which is a commercially available FE software package. In total, the model was comprised of 1946 beam elements (including spring elements), 6808 shell elements, 2080 link elements and 56000 degrees of freedom. As shown in Fig. 6, the model used frame elements to represent the beams, diaphragms and piers of the structure, and shell elements represented the deck.

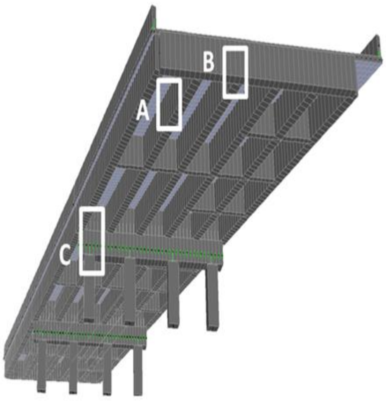
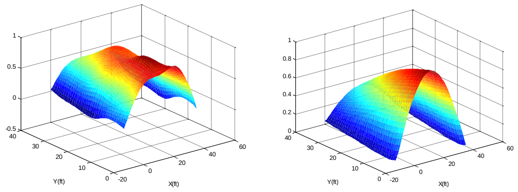
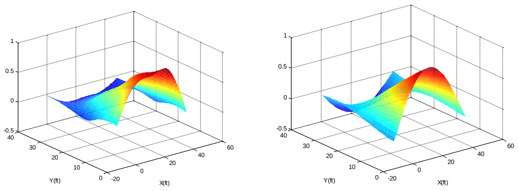
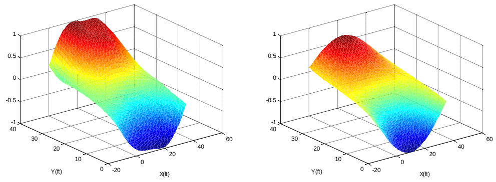
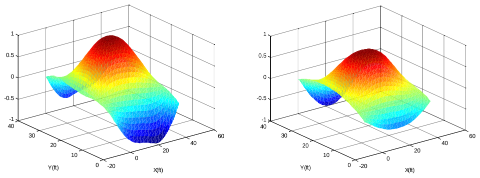
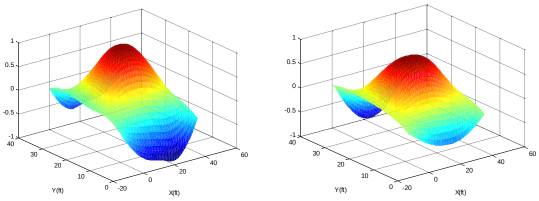
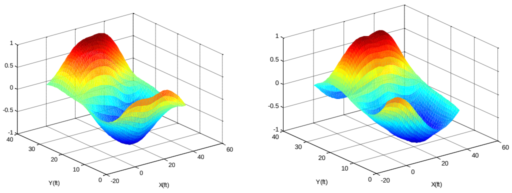
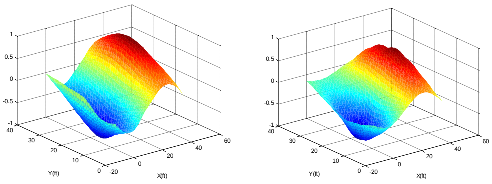
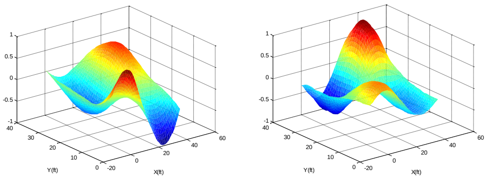
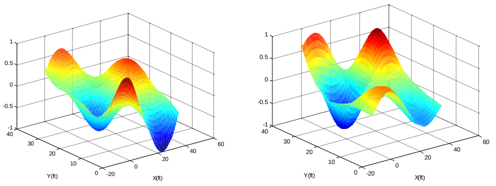
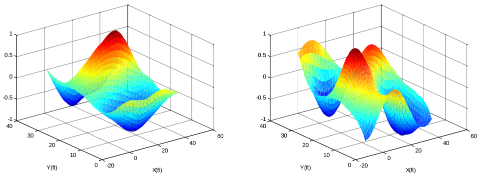


Fig. 6 Finite element model

Model Updating. The modes identified by the CMIF method were chosen to calculate the modal flexibility. In extracting modal flexibility from MIMO test results, the first 10 modes were used. A modal flexibility to static flexibility convergence analysis for the modal grid points on girders 3, 4 and 6 were performed. The Strand7 software, through an Application Programming Interface (API), interfaces with Matlab to make use of the many toolboxes available (statistical, optimization, etc.) for updating FE models. Under the six truck load test, the tensile strain in the reinforced concrete beams exceeded the strain at which cracking begins. As such, the beams exhibited substantial cracking, especially in the middle portion of the bridge. As a result, the parameter identification was carried out using six average crack height parameters y, corresponding to the six primary girders.

In the case of mode shapes the correlation is not as successful as the correlation of frequencies. The 1st-5th and 7th-8th mode shapes have higher MAC values (generally above 0.8) while the 9th -12th modes have lower MAC values, perhaps because the cubic interpolation functions proved too coarse for these higher modes. The authors note that the modes which have lower MAC values will have less influence on the modal flexibility, as discussed in relation to the modal flexibility convergence study presented. The 10 identified modes after interpolation using the cubic interpolation method are shown in Table 2 in 3D view. As shown in Fig.7, the measured Truck Load Surface (TLS) for girder 3 matches the deflection from modal flexibility very well.

Table 2 Comparison of the interpolated modes by measurement and calculated modes by FE model (In each group, left figure is the measured mode shape and right figure is the calculated mode shape)

 f_{1st_FE} =11.564 Hz (Δf=3.28%, MAC_{1st} =0.9763)	 f_{2nd_FE} = 12.970 Hz (Δf=0.14%, MAC_{2nd} =0.9621)
 f_{3rd_FE}= 13.784 Hz (Δf=5.69%, MAC_{3rd} =0.9663)	 f_{4th_FE}= 19.153 Hz (Δf=5.63%, MAC_{4th} =0.9497)
 f_{5th_FE}= 19.397 Hz (Δf=2.42%, MAC_{5th} =0.9614)	 f_{6th_FE}= 31.319 Hz (Δf=5.15%, MAC_{6th} =0.7184)
 f_{7th_FE}= 38.294 Hz (Δf=1.39%, MAC_{7th} =0.8300)	 f_{8th_FE}= 40.637 Hz (Δf=0.52%, MAC_{8th} =0.9310)
 f_{9th_FE}= 45.393 Hz (Δf=0.19%, MAC_{9th} =0.4885)	 f_{10th_FE}= 46.682 Hz (Δf=1.98%, MAC_{10th} =0.6304)

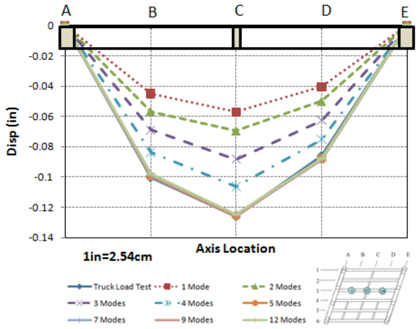


Fig .7 TLS convergence study of deflections for Girder 3

Discussions and Conclusions

This paper demonstrated how the writers leveraged St-Id for objective condition assessment and load capacity rating of an 80-year old reinforced concrete bridge which lacked design or construction plans and was posted. To perform St-Id reliably at full operating stress levels, the bridge was loaded by proof-level loads and over 40 displacement and strain responses were captured. In addition, a dynamic impact test was performed to evaluate the validity of modal analysis on this bridge with an uncommon, highly un-symmetric distribution of mass and stiffness in addition to skew. Strand7 API strategy could automatically perform model updating for a complicated finite element model. Finally , the results of modal flexibility correlate measured TLS's very well indicated that the advantage of multiple reference impact performance for bridge condition assessment.

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