Real-Time Estimation of the Structural Response using Limited Measured Data

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ABSTRACT

This study introduces an efficient procedure to estimate the structural response of a suspension bridge in real-time based on a limited set of measured data. Unlike conventional techniques, the proposed procedure does not employ mode shapes and frequencies. In this study, the proposed technique is used to estimate the response of a suspension bridge structure based on a set of strain gauge measurements. Finite element analysis is performed only once to set up the structural parameters, namely computed flexibility matrix, and computed hanger forces matrix. The response of the bridge was estimated without any additional finite element analysis using the computed structural parameters and the measured hanger strains. The Alfred Zampa Memorial Bridge, on Interstate 80 in California, was selected for this study. A high fidelity finite element model of the bridge was developed using the general purpose computer program ADINA. The proposed method has been proven to have the capability to estimate any type of structural response in real time based on the measured hanger strains, and provides an important part of an integrated Structure Health Monitoring (SHM) system for major bridges.

Keywords: SHM, real-time response, finite element, Alfred Zampa Memorial Bridge, suspension bridges

1. INTRODUCTION

An integrated Structure Health Monitoring (SHM) system for bridges is most effective with real-time evaluation of the bridge. However, there are two main obstacles to get real-time response: unknown nature of the traffic loads, and computational time. Analysis of high fidelity finite element models of bridges, which are necessary for reliable bridge-vehicle interaction evaluation, is computationally intense and cannot be performed in real-time. The traffic loads are unknown in their intensity, and distribution. The loading procedures that are defined by the codes are design loads and not real loading scenarios. Therefore, these loads cannot be used to estimate the real-time response of the bridge. The procedure proposed in this paper is independent of the finite element analysis and traffic load, and therefore, is ideal for real-time assessment of typical suspension bridges and arch bridges. Finite element analysis needs to be performed only once to obtain the structural parameters of the bridge. Then, measurements of suspenders will be used to estimate the response of the bridge in real-time. The measurements are strains in selected suspenders using strain gauges. This technique is not based on modal parameters (namely frequencies, mode shapes, and modal damping), it rather uses the measured displacements at the sensor locations. The strain gauges are very cost effective and can be easily installed and well-maintained on the suspenders. The effectiveness of the proposed procedure is presented in this paper using a high fidelity finite element model of Alfred Zampa Memorial Bridge.

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2. RESPONSE ESTIMATION PROCEDURE

Damage detection techniques are based on mode shapes and frequencies. Although other types of sensors can be used, the sensors are predominately accelerometers to estimate the "measured" frequencies and mode shapes. A finite element model of the bridge needs to be developed to obtain the "calculated" modal properties. Damage detection algorithms will be implemented to compare the measured and calculated values [1]. The objective in these techniques is to compute the dynamic characteristics of the bridge and compare them with those of the baseline conditions of the bridge.

An alternative approach, which is proposed in this paper, is to use a limited set of measured data (hangers strains in this paper) to estimate the structural response to the traffic loading in real-time. The real-time response estimate of a bridge can be obtained in the following five-step procedure, as shown schematically in Figure 2-1:

1. *One-time effort*: A finite element model of the bridge still needs to be developed to compute structural flexibility matrix [f]. If the number of sensors is [s], the size of this matrix is [sxs].
2. *One-time effort*: Compute response parameters of interest at all degrees-of-freedom (DOF) due to a unit force at each sensor location [H]. For a structure with [n] DOF, the size of this matrix is [nxs]. This is similar to three-dimensional influence line calculations for unit load at the sensor locations.
3. *Measurements (in real-time)*: obtain measured strain at each hanger and convert them to axial force vector [f^m] this is a [sx1] matrix.
4. *Estimated response (in real-time)*: compute the estimated response [H^e], which is a [nx1] vector, from equation blow:

   $H^e = Hf^{-1}f^m$
5. *Estimated C/D (in real-time)*: The demand to capacity for each element of the bridge can be computed in real-time.

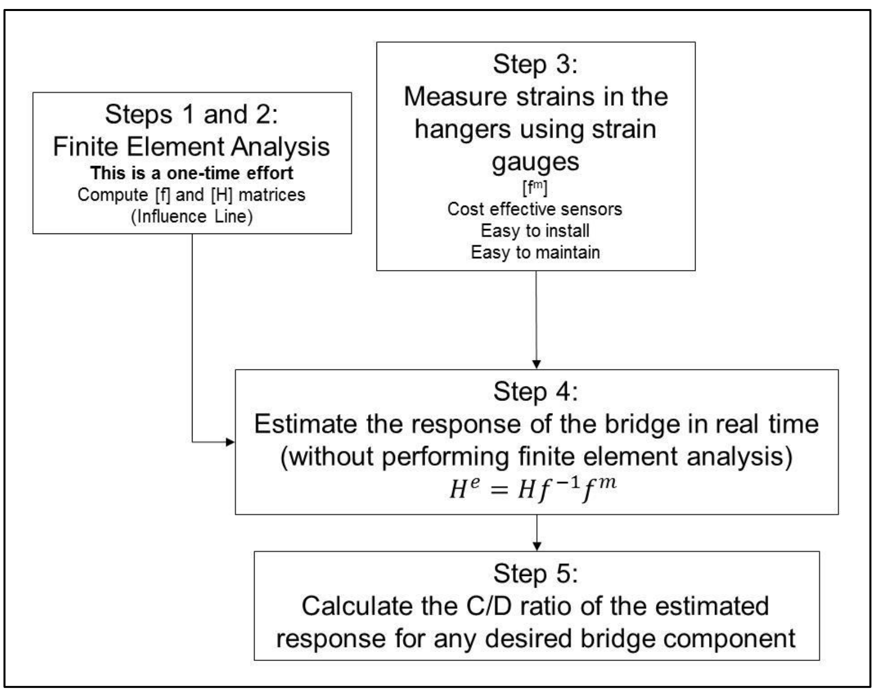

Figure 2-1: Flow chart showing the proposed technique

Using this technique, any response parameter can be estimated in real-time without any finite element analysis and without any knowledge about the traffic load. The estimated response can be compared with the corresponding capacity of the bridge component to estimate any damage or deficiency in the structure.

Obviously, the dynamic characteristics of the bridge will change in time and the finite element model needs to be calibrated [2] to represent the as-is conditions, as the bridge ages.

3. FINITE ELEMENT MODEL

The Alfred Zampa Memorial Bridge, also known as the New Carquinez bridge, is the first new suspension bridge built in the United States since 1973. The bridge connects Vallejo to Crockett in California (Figure 3-1). The length of the main span of the bridge and total length of the bridge are 728 m and 1056 m, respectively. The bridge includes two main concrete towers, two suspension cables and an orthotropic steel box girder deck. Cables are clamped to the deck at the middle of the span and anchored to the rock at both ends of the bridge. Concrete towers include two columns with two struts connecting them at the top of the columns and bottom of the deck. The deck is connected to the bottom struts with rocker links. Each tower is seated on top of two pile foundations.

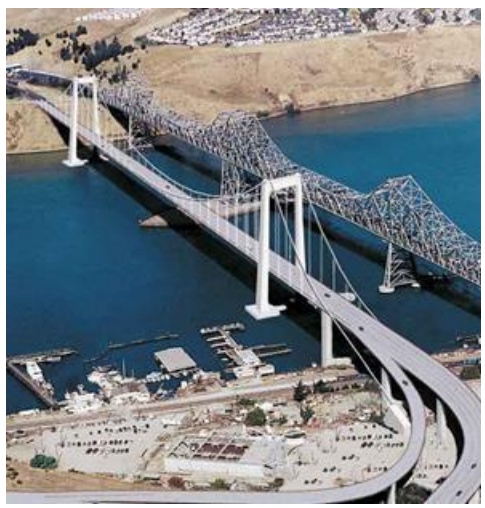

Figure 3-1: A view of the Alfred Zampa Memorial Bridge (courtesy of Metropolitan Transportation Commission)

A detailed finite element model of the bridge (Figure 3-2) was developed using ADINA computer program [3]. The towers, piers, foundation piles and main suspension cables were modeled with elastic beam elements. The suspension ropes were modeled with truss elements. Nonlinear force-displacement behavior was assigned to the 3D truss elements in order to accurately model the soil/rock properties around the piles. The steel box girder deck of the suspension bridge was modeled explicitly using multi-layer shell elements. The steel box girder deck of the suspension bridge was modeled using isotropic elastic shell elements and the ribs were modeled using orthotropic shell elements. A cross-section of the steel box girders and the bulkhead details are shown in Figure 3-3 . The construction sequence was included in the finite element model of the bridge using an in-house developed program SC-Cable [4]

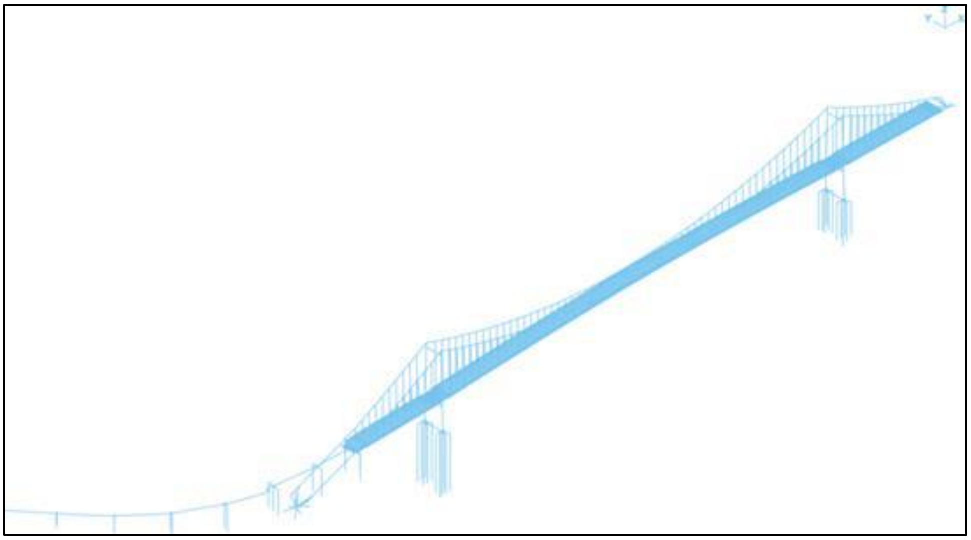

Figure 3-2: Finite element model of the Alfred Zampa Memorial Bridge

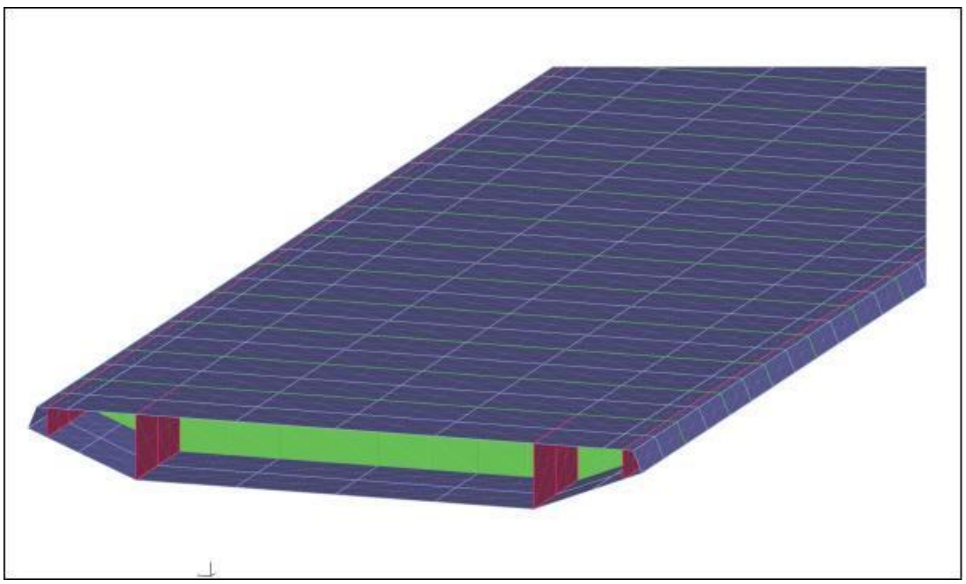

Figure 3-3: Finite element model of the deck

3.1 Finite Element Validation based in Modal Properties

A health monitoring system based on wireless sensors was designed and installed on the bridge to continuously measure its vibration response (Figure 3-4). Each sensing unit consists of a tri-axial accelerometer, an on-board analog-to-digital convertor for data collection, a Texas Instrument transceiver, and a rechargeable battery pack (Figure 3-5). Sensor data was collected by the closest server and transferred to a remote database via a wireless cellular modem. An internet-enabled cyber infrastructure framework handles transfer, maintenance and access to the data from the database server. The recorded accelerometer data was used to extract modal properties of the bridge. Table 3-1compares the frequencies of the bridge extracted from sensors data with those from the finite element model of the bridge. In general, there is good agreement between the measured and computed frequencies which shows the accuracy of the finite element model.

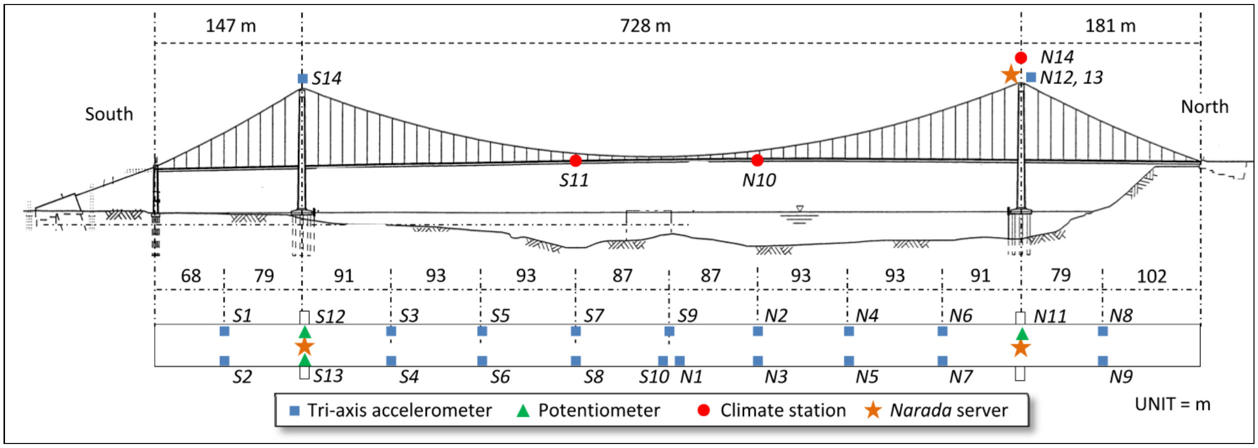

Figure 3-4: Bridge instrumentation

Figure 3-5: structural health monitoring components

Table 3-1: Measured and computed frequencies of the bridge

Mode number	1	2	3	4	5
Measured Frequencies	0.194	0.260	0.351	0.413	0.487
FE Frequencies	0.195	0.256	0.347	0.394	0.459

4. SIMULATION OF THE MEASUREMENTS AND VALIDATION OF THE PROCEDURE

For the purpose of this study 22 strain gauges were virtually installed on the hangers on the east and the west sides of the bridge (total of 44). Currently, there is no physical installed strain gauge on the hangers. Therefore, all the measurements need to be simulated using the detailed finite element developed for this bridge. Simulated measurement, estimated response and actual response were all computed for a pre-defined traffic load. This does not limit the generality of this procedure, because the estimated response is computed independent of the loading scenario.

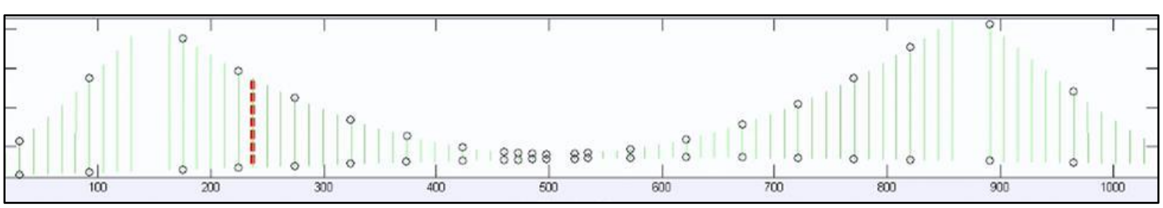

Figure 4-1: Location of strain gauges on the hangers

4.1 Simulated Sensor Reading -- Virtual Measurements

Since, measurements at the hangers are not available; they can be simulated through the detailed finite element model. Since it has been clearly shown that the computed and measured frequencies are very close, and since the measured and computed hanger forces are showed to be very similar, the finite element model was used as a "virtual measurement tool" to simulate sensor readings. To show the accuracy of the proposed procedure, this simulated sensor reading were used in the absence of the measurements at the hangers. Obviously, when sensors are installed and their readings are available, there is no need to simulate sensor readings.

4.2 Estimated Responses

The "estimated responses" were obtained using the simulated sensor readings as described in Section 2.

4.3 Actual Response

The "actual responses" were obtained from finite element analysis of the detailed model and compared with the "estimated responses" to show the accuracy of the procedure. Actual responses are calculated for the validation only and they do not need to be computed in a real-time monitoring of a bridge.

4.4 Implementation of the Procedure to a 2D Model

Before using a more complex detailed model of the bridge, the procedure was used to estimate the deflections of a two-dimensional model of the Alfred Zampa Memorial Bridge. The bridge model was subjected to a series of traffic loading scenarios as shown in Figure 4-2 through Figure 4-4. The deflected shape, which was computed using finite element analysis ("actual response"), was compared with the estimated deflection of the bridge using the proposed procedure. As discussed earlier, the estimation procedure has no knowledge of the traffic load and the only required data for it is the hanger strains, which comes from measurements ("simulated sensor reading"). The procedure accurately estimates the response for all the scenarios. Comparison of other response parameters is shown in the detailed 3D model.

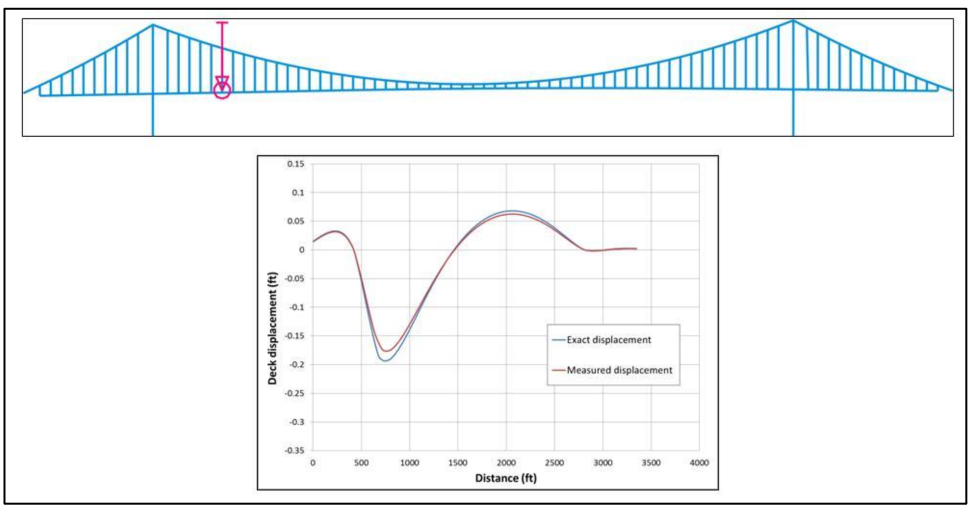

Figure 4-2: Superstructure displacement due to one load -- estimated versus actual

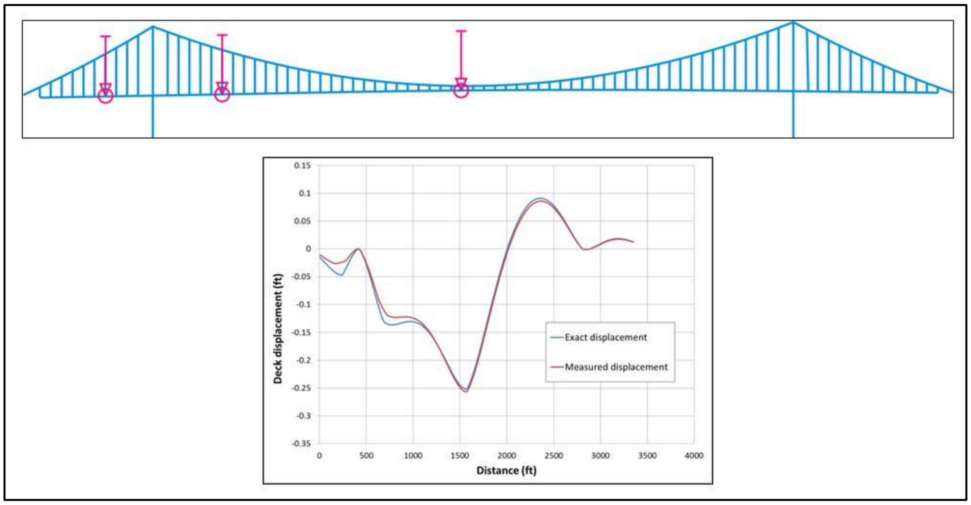

Figure 4-3: Superstructure displacement due to three loads -- estimated versus actual

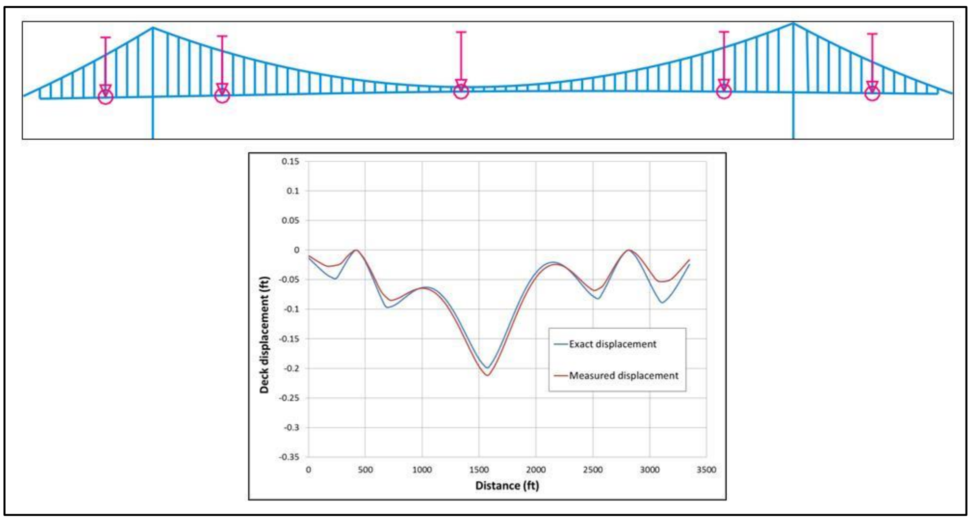

Figure 4-4: Superstructure displacement due to five loads -- estimated versus actual

4.5 Implementation of the Procedure on a 3D detailed model

With the preliminary study using 2D model, the procedure was applied to the detailed three-dimensional model of the Alfred Zampa Memorial Bridge. A graphical user interface (GUI) was developed to show the estimated response and the comparison with the actual response. The actual response does not need to be computed in a real-time monitoring of a bridge and it was included in this GUI for validation purposes only. The hanger forces were estimated and are presented in Figure 4-5 for both the west and the east side hangers. The color-coded graphics shows the intensity of axial force in each hanger as the traffic loading is moving on the bridge. Also shown in the same figure, is the comparison between the "estimated hanger forces" (dashed line) and "actual hanger forces" (solid line) for a selected hanger, which is identified in red at the west side hangers. Similar comparison was made for the forces in the cables in Figure 4-6. Any other response parameters can be easily estimated using this GUI. These results show that the proposed method has the capability to accurately estimate any type of structural response in real time based on the measured hanger strains.

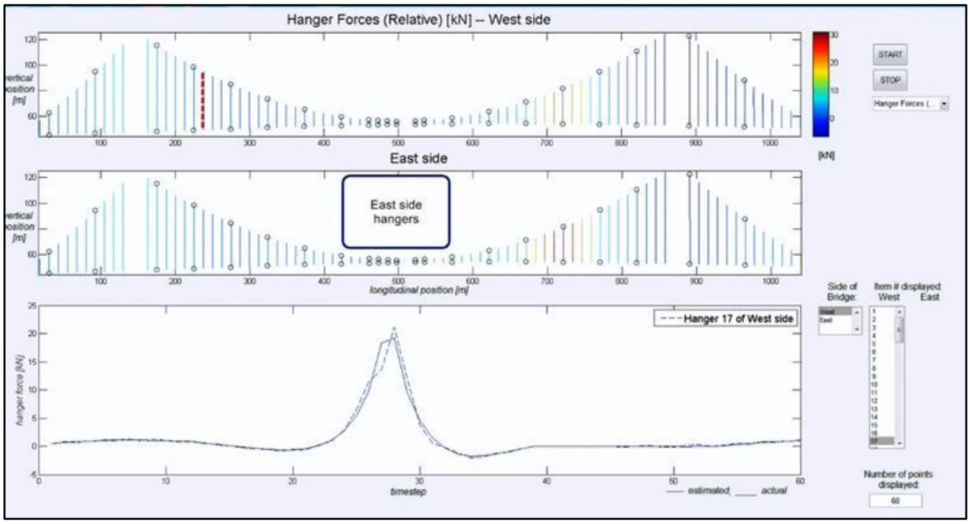

Figure 4-5: Hanger forces at hanger due to traffic load – estimated versus actual

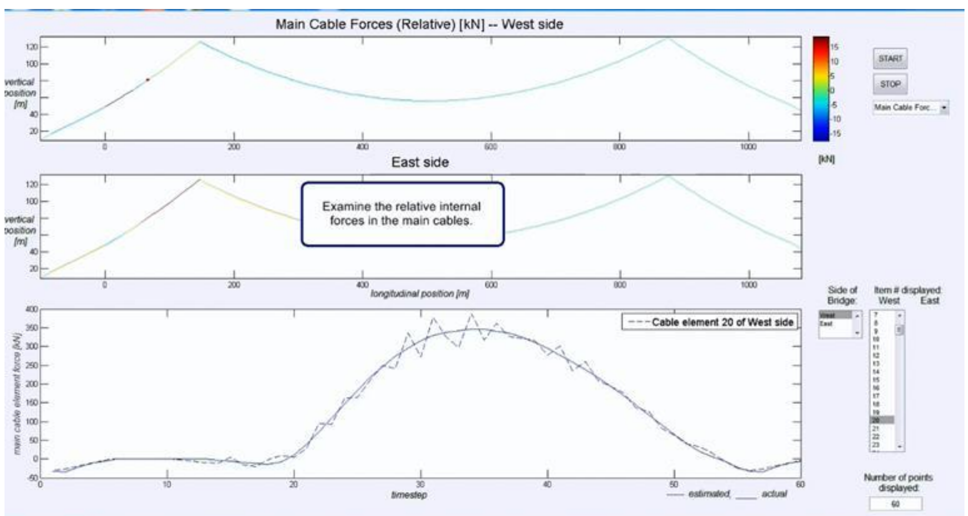

Figure 4-6: Cable forces due to traffic load - estimated versus actual

5. CONCLUSIONS

A procedure was proposed to estimate the response of the bridge in real-time, which is independent of the finite element analysis and traffic load, and therefore, is ideal for real-time assessment of typical suspension bridges and arch bridges. The proposed procedure uses a limited set of measurements (for instance, hanger forces) to estimate any response of the bridge (bridge deformation, cable forces, etc.). This procedure was implemented for the Alfred Zampa Memorial Bridge.

The finite element model of the Alfred Zampa Memorial Bridge was used to simulate the measurements in this study. The FE model was validated based on the experimental modal properties obtained from ambient vibration test. The maximum error between measured and numerical modal frequencies was less than 6%.

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REFERENCES

[1] I. Talebinejad, H. Sedarat, A. Emami-Naeini, A. Krimotat, Jerome Lynch "Implementation of Damage Detection Algorithms for the Alfred Zampa Memorial Suspension Bridge", SPIE smart structures/NDE, San Diego, March 9-13, 2014.

[2] A.A.Mosavi, I. Talebinejad., H. Sedarat, Y. Zhang, P. Hipley, E. Thometz, V. Vince, J. Lynch, U Using field measured ambient-induced vibration responses for Finite Element Model Calibration of the Carquinez Bridge , Seventh National Seismic Conference on Bridge and Highways (7NSC), Bridge Resilience for earthquake and other natural hazards, Oakland, May 20-22, 2013.ADINA R& D, Theory and Modeling Guide, Vol. I. Watertown, MA: ADINA Solids & Structures, 2009.

[3] ADINA R& D, Theory and Modeling Guide, Vol. I. Watertown, MA: ADINA Solids & Structures, 2009.

[4] Hassan Sedarat , Alexander Kozak , Joyce Lee , Alex Krimotat , Vince Jacob , Steve Mitchell, Efficient Techniques in Finite Element Analysis and Seismic Evaluation of Suspension Bridges, Seventh National Seismic Conference on Bridge and Highways (7NSC), Bridge Resilience for earthquake and other natural hazards, Oakland, May 20-22, 2013.