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NONLINEAR TRACKING OF DYNAMIC PROPERTIES IN A STRUCTURE FROM SERVICE CONDITION TO COLLAPSE

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Abstract. Observation of dynamic properties in a bridge that was subjected to distortion caused by movements of the surrounding soil, was made over several months. Along with high-sensitivity measurements, crack mapping and deflections were also reported to monitor damage evolution at several instances of soil movement. Also, deep soil monitoring to assess the global mechanism of massive movement, was implemented. Structural behaviour was calculated based on construction drawings and verified with actual data collected during more than ten different instances, at which damage was progressively evidenced in the structure. As part of this research time-frequency distribution through Fourier and Hilbert transformations among others, was used to enhance understanding of the damage mechanism and to confirm the most probable scenario that finally took the bridge to out-of-service condition. This paper presents data and signal processing to track damage evolution by means of a nonlinear model as an improved version of the traditional linear one, which was proved to lack of capabilities to arrive at conclusions consistent with real bridge conditions. Data interpretation was confirmed with structural analyses and direct on-field visualization, to suggest a reliable monitoring, to track bridge condition from the initial stage to its critical condition that required final removal.

1 INTRODUCTION

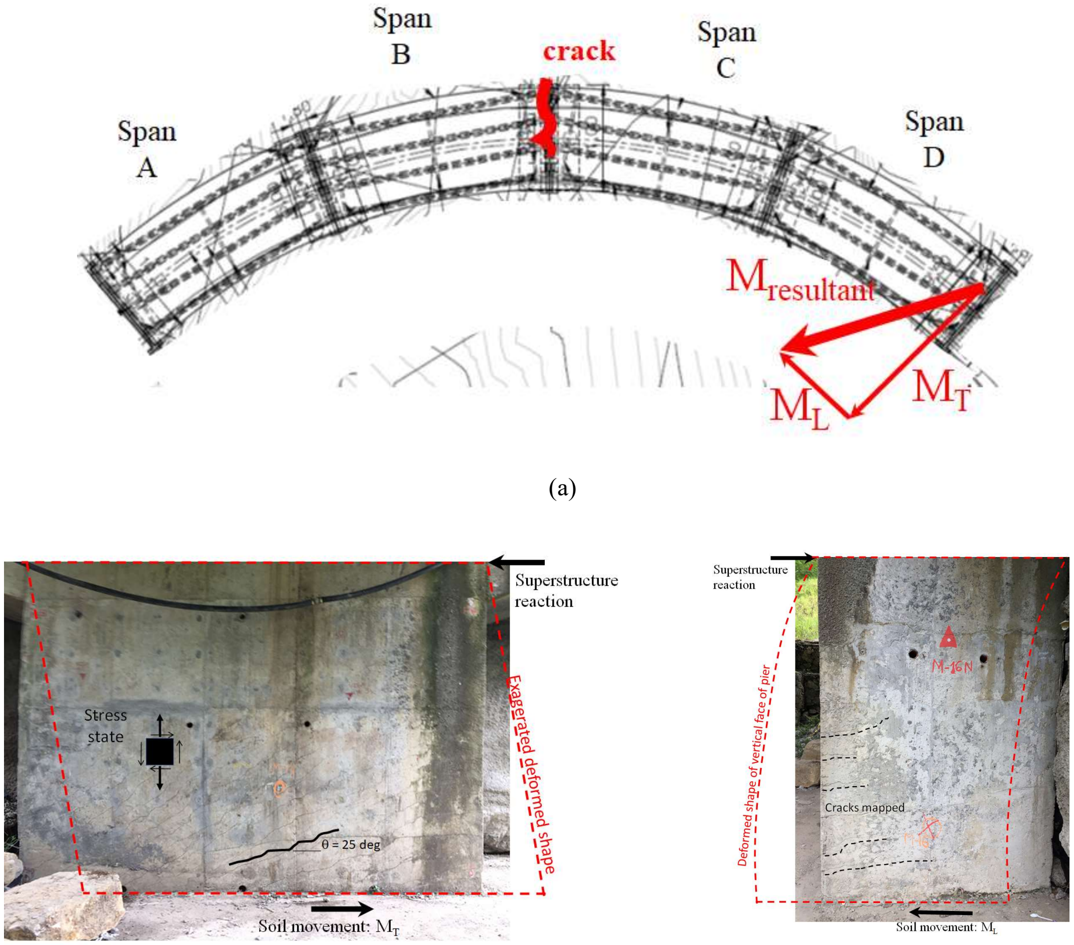
Continuous monitoring of a bridge subjected to progressive damage up to the point of being taken out of service, is seldom available. This is due either because this type of situation is not common within a practical time frame, or because bridges are not regularly monitored with permanent instrumentation [1]. In order to collect meaningful information from instrumentation installed on a structure, both type of sensors and their location are important. However, it is even more important to know what specific processing scheme is adequate to identify potential damage in the structure. While selection of sensors and their location may be based on a reasonable monitoring design, identification of damage depends on the effectiveness of the processing technique selected from a wide range of options available in the literature [2]. While several robust damage detection techniques are available, sensitivity of any specific technique to damage in a given bridge is to be tested for the specific purpose. In general terms, a given technique based on small-amplitude observations can be either linear or nonlinear for an assumed elastic behaviour of the structure. The linear-elastic perspective is the traditional option and cost-effective in general [3], but precision may be sacrificed for sake of simplicity. This article explores sensitivity of damage in a bridge to small-amplitude vibrations recorded as the damage evolves, from the perspective of a non-linear elastic concept rather than from the linear-elastic approach typically used in the literature for civil applications.

2 BRIDGE DESCRIPTION

The bridge used for the current study is an infrastructure curved-in-plan prestressed concrete bridge, located in soil under massive movement conditions derived from changing environmental conditions. The bridge was monitored with temporal instrumentation installed on the bridge at several instances during over a year time frame. Given that climate and environmental conditions are of a great interest nowadays in the literature, this paper focusses on the study of evolution in mechanical properties of the bridge during its progressive damage. The bridge consists of simply-supported spans with lengths between 25 m and 30 m and superstructure length-to-depth ratios of about 17. The bridge was provided with deep foundation consisting of pile groups under each pier. Figure 1 a, b and c, show the plan-view of the bridge, longitudinal elevation view and transverse elevation view of one of the piers of the bridge, respectively. These figures illustrate the general movement of the surrounding soil M_T and their component effects along longitudinal M_L and transverse direction M_T, at one of the piers of the bridge with extensive concrete cracking. Stress calculation for the pier shown in Figure 1 was based on Mohr's circle according equations 1 and 2, along with the forces estimated from the soil movement recorded with survey. Such stresses, are consistent with crack inclination shown in Figure 1(b) and concrete tensile resistance of the pier calculated based on concrete cylinders tested. The crack marked up in Figure 1(a) on the pavement surface opened up to 3 cm over the full monitoring time, and it was observed in full depth of the concrete slab but with apparent permanent contact between adjacent slab portions. Figures 1(b) and 1(c) show exaggerated deformed shapes corresponding to mainly shear and mainly bending respectively, considering the dominant deformation type along each of the main horizontal directions of the pier. It can be seen that movement of surrounding soil turns into relative distortion of the bridge, due to lateral restraining provided by other piers that are not within the soil movement and connect as a whole through the continuous slab.

$$\theta_p := \frac{1}{2}\cdot\mathrm{atan}\left(\frac{2\cdot\tau_{xy}}{\sigma_x - \sigma_y}\right) \tag{1}$$

$$\sigma_1 := \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\;2}} \tag{2}$$



(a)

(b)

(c)

Figure 1: Study Bridge

3 NONLINEAR BEHAVIOUR OF THE BRIDGE

Figure 2 shows the 3D finite element model built in Sap2000 [4] used to study the bridge. In this model frame elements were used to represent piers, piles, and beams, whereas shell elements were used for slabs, abutments, and footings. The model was built linear elastic with concrete modulus of elasticity according to standard formulations [5] to represent the bridge in the pristine condition, and before it was subjected to distortions caused by soil movements. Therefore, tracking of dynamic properties of the bridge over time because of cracking, thus, to detect damage, was executed by considering the undamaged condition estimated by means of the numerical model. Sequence of observed damage in the bridge was as follows: i) first initial cracking was caused on the pier elements due to lateral displacement, ii) once the relative movement between substructure and superstructure closed gaps by bearing contact between beams and seismic stoppers, lateral distortion is pass on to the superstructure slab, iii) additional soil movement turns into superstructure slab damage because the slab connects all the piers in the bridge that have different lateral movement amounts. This latter stage of damage, opposite to affecting mainly lateral natural frequencies of the bridge by cracking of piers, has the potential to affect vertical frequency of the superstructure spans of the bridge.

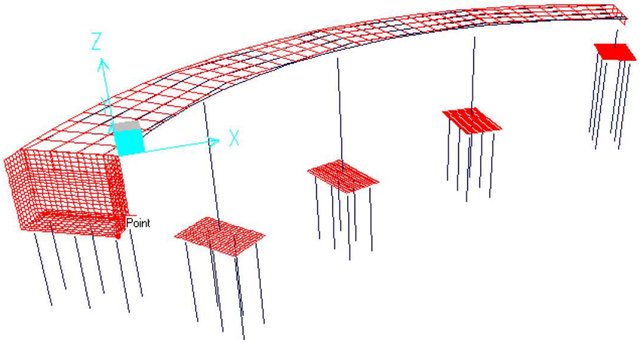


Figure 2: Full 3D Bridge model

Because of the crack at midpoint of the bridge shown in Figure 1(a), span C (and also span B) is more prone to exhibit stiffness degradation than span A located at a more distant location from the crack. Comparison of vibration spectra measured at spans A and C is shown in Figure 3. It can be seen in Figure 3 that frequency spectra for spans A and span C have a similar dominant frequency at about 5.8 Hz, that is marked up as an upper limit labeled as f_{up} in the figure. Also, an additional dominant frequency of about 4.4 Hz marked up as f_{bot} is shown in the vibration of span C, but such frequency is not observed in the undamaged span A. Future observation of vertical frequencies of the slab spans of the bridge by means of finite-element modeling, indicate that based on the stiffness degradation caused by the crack of the slab in Figure 1(a), the lower (f_{bot}) and upper bound frequencies (f_{up}) marked in Figure 3 correspond to different stage of damage as illustrated in Figure 4.

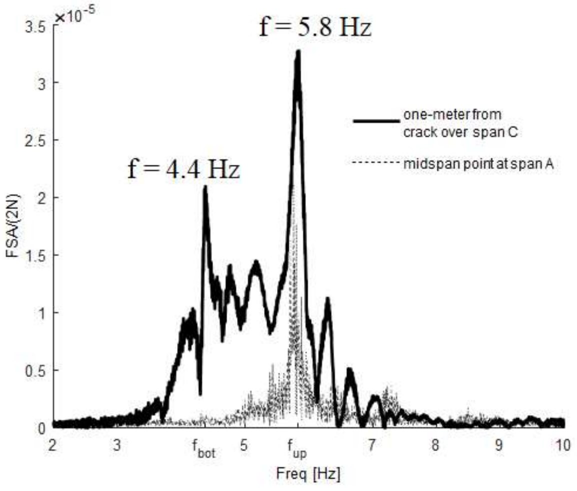


Figure 3: Full 3D Bridge model

Figure 4 shows the models built for an isolated portion of the superstructure used to estimate vertical frequencies measured in the bridge as shown in Figure 3. Figure 4(a) shows the components included (slab and beams). Figure 4(b) shows both edges of the slab restrained to represent the continuous connecting condition to adjacent slabs for the undamaged condition, thus, when no crack had been formed. Figure 4(c) has a portion of one of the edges free in rotation to represent the crack observed in the bridge as shown in Figure 1(a). Eigenvalues obtained for the model with the two boundary conditions shown in Figures 4(b) and 4(c), indicate that slab fundamental natural frequencies are 4.9 Hz and 6.1 Hz for the cracked and uncracked conditions respectively. These estimated frequencies are in average within 8% difference of frequencies f_{bot} and f_{up} measured during monitoring of span C as shown in Figure 3, which is the span adjacent to the crack. Despite additional tuning that may be achieved in model results by selecting other modulus of elasticity value, this comparison suggests that span C is exhibiting frequencies corresponding to damage and undamaged condition. One possible mechanism for the alternating frequency behavior, it may be that depending on amplitude of vibration, contact along the crack varies as it opens and closes based on concrete interlocking between adjacent slab portions. This variation in the contact provides different degrees of slab continuity. Such slab behavior has an upper-bound frequency corresponding to full continuity condition similar to that of the undamaged condition as that exhibited by span A (Figure 3), and a lower-bound frequency associated to free contact along the crack length as that estimated with modeling (4.9 Hz according to Figure 4).

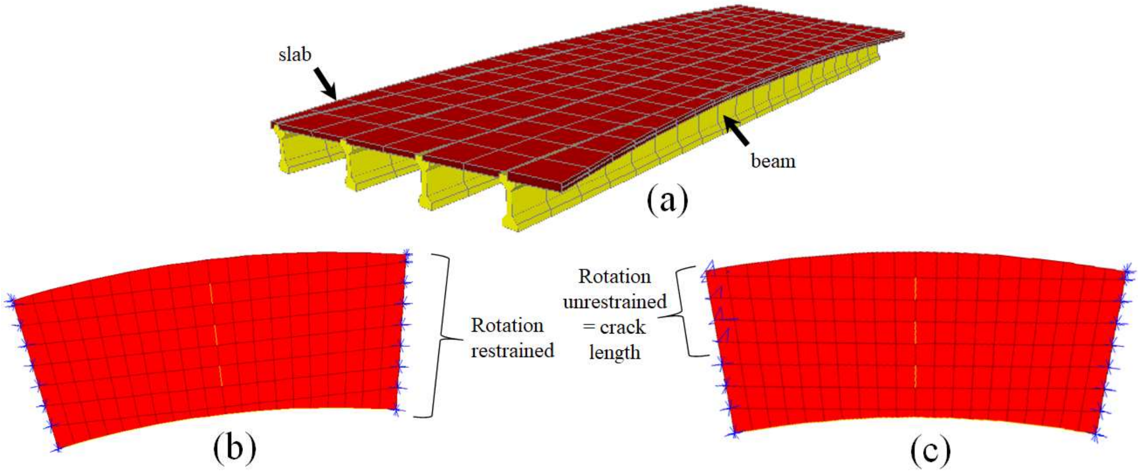


Figure 4: Numerical modeling for superstructure

12 CONCLUSIONS

- Observations on a bridge by collecting small-amplitudes vibrations during different instances of damage, has been made by comparing with a finite element model built assuming pristine conditions.

- Comparison between direct measurements of vibrations on similar slab spans, allow identification of a frequency lower than the undamaged-condition frequency. This additional frequency corresponds to the effect of a wide crack exhibited at the midportion of the bridge.
- Consistent with previous observation, vibration of slab span away from such crack did not have frequency component associated to the damage condition.
- Nonlinear evaluation of vibrations of the bridge are to provide additional insight on the mechanism that led to participation of different fundamental frequencies in the same slab span.

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