Monitoring case study: 2nd Jindo Bridge

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ABSTRACT: This case study summarizes the deployment and operation of a large scale wireless smart sensor network for structural health monitoring of the 2nd Jindo Bridge, a cable-stayed bridge connecting Jindo Island with the Korean Peninsula. The wireless monitoring system, initially installed in 2009, had been expanded over a 3-year deployment to over 100 wireless sensor nodes providing more than 600 channels of sensor data, making it the world's largest wireless network for bridge monitoring. This deployment has been extensively documented in the literature (Spencer et al., 2015; Rice et al., 2011; Jang et al., 2010).

Test Structure and Measured Data

Opening in 1984, the 1st Jindo Bridge is a cable-stayed bridge connecting the Korean peninsula and the Jindo Island; however, growing traffic demands quickly exceeded the load carrying capacity of the first bridge. The 2nd Jindo Bridge, which opened in 2005, is a streamlined steel box girder with a center span of 344 m supported by 60 parallel wire strand cables anchored to two diamond-shaped pylons. The bridge was to be instrumented with a continuous monitoring system that can autonomously estimate the various physical states of the bridge and serve as a testbed for evaluating wireless smart sensor network technology for structural health monitoring.

The objective of this deployment is long-term continuous monitoring of modal properties (natural frequencies, modal damping, and mode shapes), cable tension forces, and deck-cable interaction to determine structural performance.

The wireless monitoring system on the 2nd Jindo Bridge was initially installed in the summer of 2009. Seventy-one state-of-the-art wireless smart sensor (WSS) nodes with a total of 427 sensing channels were installed on the girder, the pylons, and the cables. Each node was comprised of the Imote2 processor board (including on-board CPU and radio transmitter), the ISM400 sensor board, and alkaline batteries. Measurements included 3-axes acceleration, plus temperature, humidity, and light. Combined with the ISHMP Services Toolsuite, these powerful nodes allow for synchronized data collection, aggregation, synthesis, and decision-making in real time.

The smart sensor nodes for the deck, pylons and cables were attached using different methods. The nodes were mounted to the steel deck and pylons using two magnets, each with a holding capacity of 10 kg, attached to the bottom of the enclosure. The nodes were mounted to the cables using two U-bolts and an aluminum mounting plate. These methods of mounting the sensors have proven to be fast, inexpensive, and secure.

Based on the success of the 2009 deployment, the monitoring system was extended to include 113 WSS nodes measuring a total of 659 channels of data in 2010 (see Figures 2), resulting in the world's largest wireless smart sensor network for SHM. The ISM400 sensor board was used on 100 nodes. A new highsensitivity accelerometer board (SHM-H board), which enables measurement of accelerations as low as 0.05mg, was used for 10 nodes. The remaining three nodes were connected to 3D ultrasonic anemometers to measure and collect wirelessly the speed and direction of wind on the bridge. Wireless strain measurement has also become available with the newly developed SHM-S sensor board. All 113 nodes were self–powered using solar or wind energy harvesting. Should any anomalies in the measured data be detected during the autonomous system operation, the base-station computers automatically email the research team so that appropriate action can be taken.

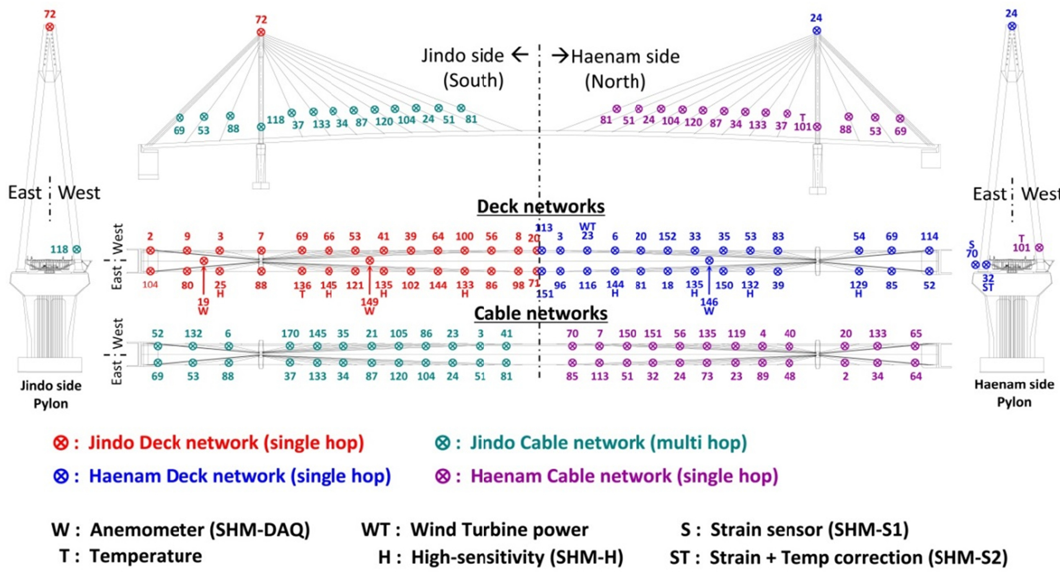

Figure 2: Sensor layout on the Jindo Bridge.

Figure 3: Example of sensors deployed on the Jindo Bridge.

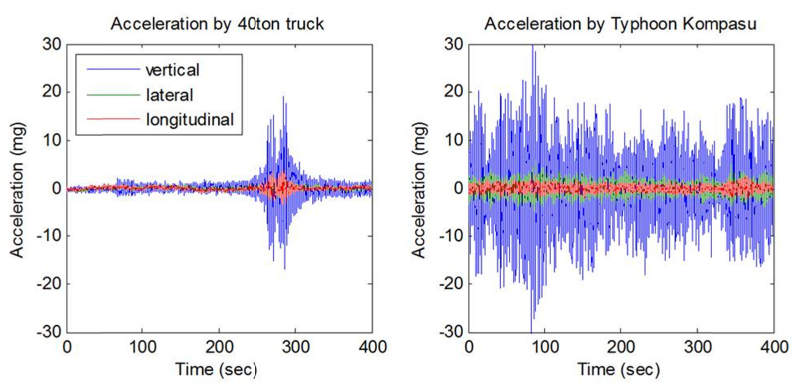

Figure 4: Acceleration response by 40-ton truck and Typhoon Kompasu.

The monitoring system can autonomously estimate various physical states of the bridge. For example, the modal properties (i.e., natural frequencies, modal damping, and mode shapes) can be obtained from the measured accelerations and utilized to refine the numerical model, to determine structural performance, and to find locations of possible fatigue damage. Cable tension force, one of the most important integrity measures for cable-stayed bridges, is estimated automatically using a vibration-based method. Deck-cable interaction, which may cause dynamic instability, also can be assessed. Aerodynamic and aeroelastic properties of bridges are estimated based on the synchronized wind speed and response data. The dense information enables comprehensive monitoring of the bridge's health.

In September 2010, Typhoon Kompasu hit the Korean Peninsula, with sustained wind speed of 54 m/s (195 km/h). During Kompasu, the vertical acceleration of the deck exceeded 20 mg, which is greater than the level of acceleration generated by a 40-ton truck (see Figure 4). Nonetheless, these accelerations were below the limit of 50mg proposed in the Korean Design Guidelines of Steel Cable-supported Bridges.

SHM Methodology and Results

The modal properties of the deck and pylons were obtained using the acceleration data. Utilizing an output-only modal analysis approach, nine vertical bending modes and one torsional mode were clearly identified from the vibration induced responses measured during the typhoon (see Figures 5-6). Compared with the identified modes using the data from an existing wired high-precision accelerometer on the bridge, the SHM system is found to provide highly accurate modal properties.

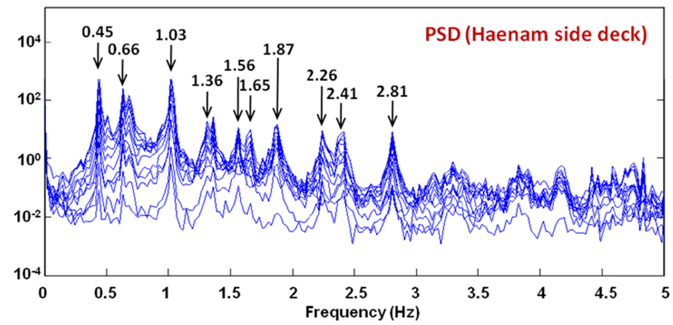

Figure 5: Power spectrum for bridge responses during Typhoon Kompasu.

The wind velocity fluctuations were measured with ultrasonic anemometers installed along the bridge. These data enable the estimation of spatial as well as temporal variation of the wind velocity along the bridge. The steady wind load coefficients and flutter derivatives were also obtained from a series of wind tunnel tests using a 1/36 scaled model of the deck section. The buffeting analyses results considering aerodynamic admittance effects show good agreement to the measured responses. This effort offers a significant enhancement in evaluating the aerodynamic safety and serviceability of bridges during strong winds by using synchronized simultaneous measurement of wind and acceleration data along the bridge.

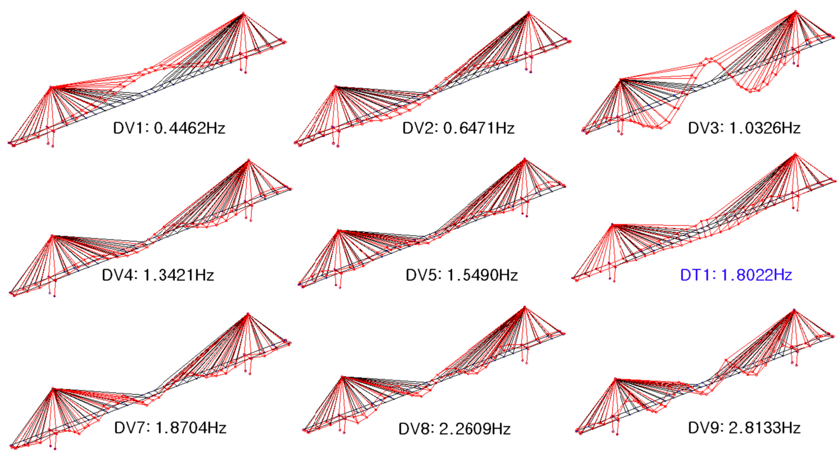

Figure 6: Identified mode shapes below 3 Hz.

The tensions in the bridge's stay cables were obtained autonomously using vibration data, combined with the known cable properties (i.e., length, weight, stiffness, etc.). In this approach, the vertical acceleration was used primarily to estimate the tension, while longitudinal and lateral accelerations helped to delineate the modes unique to the cable (as opposed to the deck and pylon). Estimated tensions during the typhoon were compared with the design tensions and those obtained in the previous routine inspection. As shown in Figure 7, the current cable tensions are close to their design values and have changed little from the 2008 inspection, which confirms the integrity of the bridge. Thus, continuous monitoring of this important health indicator is facilitated.

In addition to continuously monitoring the bridge structure, the WSS network monitors itself. For example, the battery power system is assessed periodically, including the charging current from the solar panel and the battery voltage. Should the battery voltage in a specific node become too low (e.g., due to too many cloudy days), the node is put into a deep sleep until the batteries can be charged and the node brought safely back online.

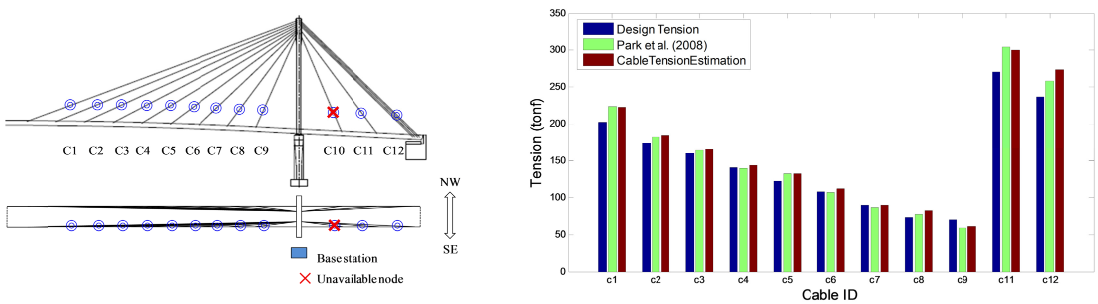

Figure 7: Comparison of estimated cable tensions.

Lessons Learned

Smart sensing technology for structural health monitoring is an important field that is coming of age. Combining civil engineering knowledge with developments in sensor technology and network/information management has provided a solution that is a robust and significantly lower-cost (approximately $10 per channel) alternative to traditional wired monitoring systems. Indeed, a WSS provides an important new tool to help engineers address the many challenges of managing civil infrastructure.

Acknowledgements

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References

[1] Spencer, B. F., Jr., Jo, H., Mechitov, K. A., Li, J., Sim, S. H., Kim, R. E., Cho, S., Linderman, L. E., Moinzadeh, P., Giles, R. K., and Agha, G. A. (2015). “Recent advances in wireless smart sensors for multi-scale monitoring and control of civil infrastructure.” *Journal of Civil Structural Health Monitoring*, DOI: 10.1007/s13349-015-0111-1.

[2] Cho, S., Jo, H., Jang, S., Park, J., Jung, H. J., Yun, C. B., Spencer, B. F., Jr., and Seo, J.W. (2010). “Structural health monitoring of a cable-stayed bridge using wireless smart sensor technology: data analyses.” *Smart Structures and Systems*, 6(5): 461-480.

[3] Sim, S. H., Li, J., Jo, H., Park, J. W., Cho, S., Spencer Jr, B. F., & Jung, H. J. (2014). A wireless smart sensor network for automated monitoring of cable tension. Smart Materials and Structures, 23(2), 025006.

[4] Jang, S., Jo, H., Cho, S., Mechitov, K. A., Rice, J. A., Sim, S. H., Jung, H. J., Yun, C. B., Spencer, B. F., Jr., and Agha, G. A. (2010). “Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation.” *Smart Structures and Systems*, 6(5), 439–460.

[5] Rice, J. A., Mechitov, K. A., Sim S. H., Spencer, B. F., Jr., and Agha, G. A. (2011). “Enabling framework for structural health monitoring using smart sensors.” *Structural Control and Health Monitoring*, 15(8), 574–587.