Internet-Enabled Wireless Structural Monitoring Systems: Development and Permanent Deployment at the New Carquinez Suspension Bridge

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Abstract: Dense networks of low-cost wireless sensors have the potential to facilitate prolific data collection in large and complex infrastructure at costs lower than those historically associated with tethered counterparts. While wireless telemetry has been previously proposed for structural monitoring, comparatively less research has focused on the creation of a complete and scalable data management system that manages the storage and interrogation of wireless sensor data. This paper reports on the development of a novel wireless structural monitoring system specifically tailored for large-scale civil infrastructure systems by architecturally combining dense wireless sensor networks with a suite of information technologies remotely accessible by the Internet. The architectural overview of the proposed Internet-enabled wireless structural monitoring system is presented including a description of its functional elements (for example, wireless sensors, database server, and application programming interfaces). The monitoring-system architecture proposed is validated on the New Carquinez (Alfred Zampa Memorial) Bridge in Vallejo, California. A permanent wireless monitoring system is installed consisting of 28 wireless sensor nodes collecting data from over 80 channels. The bridge sensor data are transferred by a wireless cellular connection to a remote database server where it is stored and available for interrogation by software clients granted access to the data. To illustrate the ability to autonomously process the bridge response data, the stochastic subspace identification method is used to extract accurate modal characteristics of the bridge that are used to update high-fidelity finite-element models of the bridge. The Internet-enabled wireless structural monitoring system proved to be scalable to a large number of nodes and has thus far proven stable and reliable over long-term use. **DOI: 10.1061/(ASCE)ST.1943-541X.0000609.**

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Introduction

Bridges are a vital infrastructure link within a nation's transportation system; in the case of the United States, there were 603,307 bridges in operation in 2009 (DOT 2009). In most modern vehicular transportation networks, bridges often control the throughput capacity of the system. Bridges are also the most expensive element of the system, costing an order of magnitude more than roads when calculated on a per-mile basis (Barker and Puckett 2007). The economic importance of bridges is underscored by the experience of regions that have witnessed bridge failures. For example, the collapse of the Interstate 35W (I-35W) bridge in Minneapolis, Minnesota, is estimated to have resulted in a total economic loss of $200 million to the greater Minneapolis metropolitan region (NIST 2008).

Because of their size, long-span bridges can be exposed to massive loads including dead (i.e., self-weight), traffic, wind, and earthquake loads. To better understand the complex dynamic behavior of long-span bridges under extreme loading events including strong winds and ground motions, structural monitoring systems are required to record bridge responses. In the United States, long-span bridges located in regions of known high seismicity have been installed with permanent trigger-based structural monitoring systems that record bridge accelerations during moderate to strong ground shaking. In California alone, more than 61 bridges have been instrumented through a joint partnership between the California Strong Motion Instrumentation Program (CSMIP) and the CALTRANS (Hipley 2001; California Geological Survey 2007). Many of California's long-span bridges are instrumented including the Golden Gate Suspension Bridge, San Francisco, California (76 sensors), and the Vincent Thomas Suspension Bridge, Long Beach, California (26 sensors). The motivation for installing these permanent structural monitoring systems is to provide a quantitative basis for evaluating

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how long-span bridges respond to spatially varying ground motion inputs. First, the seismic response of long-span bridges captured by permanent monitoring systems can verify design assumptions and lead to improved design methodologies. It should be noted that neither AASHTO nor CALTRANS design specifications provide guidance on the seismic design of bridges whose spans exceed 150 m (500 ft) (Liu et al. 2000); as a result, design verification is critically valuable. Second, permanent monitoring systems are routinely used to update finite-element models of the instrumented bridge. Accurate (updated) models are then used to rapidly evaluate the seismic response of the bridge using the ground motion records collected at the bridge site during a seismic event (Hipley 2001).

Although permanent monitoring systems have been successfully installed in the past, they largely remain limited to deployments in long-span bridges vulnerable to seismic activity. Because of the need to install hundreds of kilometers of coaxial wiring in the structure, the cost associated with system installations can be extremely high (Straser and Kiremidjian 1998). In addition, existing permanent monitoring systems typically contain tens of sensors, which are relatively low instrumentation densities given the size of the structures in which they are installed. Interest in permanent structural monitoring systems has grown in response to the bridge-engineering community's desire to implement more quantitative methods for structural health assessment [i.e., structural health monitoring (SHM)]. However, the low sensor densities in current use would prove inadequate for the identification of structural damage, which is a local phenomenon (Sohn et al. 2004). High installation costs and low sensor densities typically associated with tethered structural monitoring systems have driven interest in wireless structural monitoring systems (Straser and Kiremidjian 1998; Lynch 2002). Wireless sensors eliminate the extensive wiring that partially drive the cost of tethered monitoring systems high. An additional benefit of wireless sensors is the ease with which they can be moved or modularly added to after the initial installation of the wireless monitoring system. Since their conception, wireless sensors have rapidly matured to currently offer performance levels that approach that of tethered counterparts (Lynch 2007; Wang et al. 2007; Cho et al. 2008; Nagayama and Spencer 2009; Rice et al. 2010). Early efforts focused on testing the data-collection performance (e.g., accuracy) of wireless sensors in harsh field settings. Such efforts used short-term installation in short-span bridges for validation: Alamosa Canyon Bridge, New Mexico (Straser and Kiremidjian 1998; Lynch 2002; Taylor et al. 2009), Geumdang Bridge, Icheon, Korea (Lynch et al. 2006), Wright Bridge, New York (Whelan and Janoyan 2009), Yeondae Bridge, Icheon, Korea (Kim et al. 2010), and a short-span rail bridge in Illinois (Rice and Spencer 2008). More recently, the research community has begun to explore the deployment of wireless monitoring systems on long-span bridges, emphasizing the reliability of wireless communications over long distances and the robustness of devices deployed for long periods of time: Golden Gate Bridge (2,737 m), San Francisco (Pakzad et al. 2008; Pakzad 2010), Gi-Lu Bridge (240 m), Taiwan (Weng et al. 2008), Stork Bridge (124 m), Switzerland (Feltrin et al. 2010), and Jindo Bridge (484 m), Korea (Jang et al. 2010).

There remain a number of technological challenges that must be considered during the design of large-scale wireless structural monitoring systems (i.e., ones defined by a large number of sensing channels). Specifically, scalable monitoring-system architectures must be considered to ensure that the system has ample throughput for the amount of data collected. Undoubtedly, larger sets of raw data have the potential to provide the system end-user with more data from which information can be extracted (e.g., system identification, damage detection). However, copious amounts of data can also quickly overwhelm system end-users, leading to partial or total paralysis of their decision-making processes. Fortunately, a scalable monitoring-system architecture that facilitates automated data processing and information extraction can be realized through the adoption of information technologies that integrate sensor networks, data-acquisition systems, middleware tools, and data-processing services. Broadly defined as cyberinfrastructure, these technologies have been effectively used for data-driven discovery in a variety of scientific and engineering fields (National Science Foundation 2006). Similarly, cyberinfrastructure can be an enabling technology that enhances the scalability and functionality of bridge monitoring systems.

In this study, a hierarchically structured monitoring system is proposed with dense networks of low-cost wireless sensors installed at the lowest level of the system architecture and Internet-enabled information technologies employed at the higher levels to offer data storage and to facilitate automated data interrogation. Specifically, a powerful database system is at the core of the proposed architecture with application programming interfaces (APIs) defined to allow data interrogation clients to utilize bridge response data via the Internet. To validate the long-term performance of the cyber-enabled wireless structural monitoring system, the system was permanently installed on the New Carquinez (Alfred Zampa Memorial) Bridge (NCB). The role of the wireless monitoring system is to drive a model-updating process to ensure that the existing finite-element model of the bridge is suitable for the evaluation of the bridge immediately following a seismic event. The paper first describes the hierarchal design of the overall monitoring-system architecture. Next, the deployment of the system to the NCB is presented, followed by a description of the system identification methods implemented to autonomously process bridge response data for the extraction of modal information. Finally, the paper concludes with a summary of the key research findings and a discussion on the future research opportunities that remain.

Design of Internet-Enabled Wireless Monitoring System

To effectively monitor long-span bridges, the civil-engineering community has focused its research efforts on the design and validation of wireless sensors networks with the aim of potentially replacing wired structural monitoring systems with a lower-cost alternative. These efforts were successful in accelerating technology development to a point where today wireless sensors are rapidly approaching wired sensors in terms of both performance and reliability when installed in demanding field settings (Pakzad et al. 2008; Jang et al. 2010). Although installing larger numbers of sensors (wireless or wired) in a structure can provide extensive data for quantitative assessment of structural performance, issues such as how recorded response data are managed and processed have yet to be fully addressed to maximize the full potential of the data collected. Toward that end, this study explores the creation of a hierarchical monitoring system for civil infrastructure that combines the strengths of wireless sensors with the benefits of Internet-enabled information technologies.

A detailed architectural overview of the proposed wireless monitoring system is presented in Fig. 1. The monitoring-system architecture is divided into two major layers: a lower layer consisting of low-power wireless sensor networks installed in the structure and an upper Internet-enabled layer offering a complete cyberinfrastructure framework for the management and interrogation of bridge response data. At the lowest layer, a dense network of wireless sensors is installed to record the environmental loading and corresponding response of the structure. In this study, the Narada

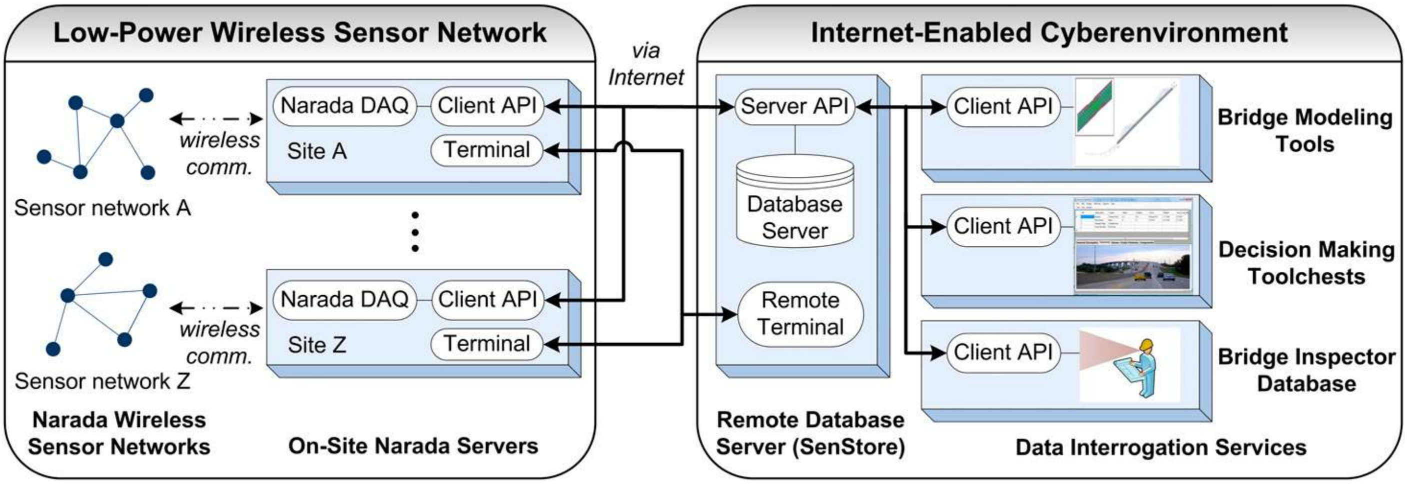

Fig. 1. Internet-enabled wireless structural monitoring system

wireless sensor node (Swartz et al. 2005) is adopted as the primary wireless sensor node. The wireless sensor network is designed to communicate its data to a server (termed the Narada server) that services the wireless sensor network; this server is installed in the structure and is used to temporarily store data and to prepare data for communication to the upper layer of the Internet-enabled wireless monitoring system. If a structure is spatially large, it may be necessary to divide the monitoring system into subnetworks and for each subnetwork to be serviced by its own wireless sensor network server. A wireless cellular modem is used to communicate between the wireless sensor network servers and the upper levels of the monitoring-system architecture. Bridge response data are centrally managed by the cyberenvironment using a database server termed SenStore that stores bridge information (e.g., geometrical descriptions of the structure, finite-element model information, and visual inspection reports) and sensor data in an object database. The database server publishes a well-defined set of client-server APIs that allows the wireless sensor network to authenticate its privileges to push data into the database. In a similar fashion, the API also allows software clients to authenticate their privileges to pull data out of the database for analysis using physical modeling and statistical inference tools (termed data interrogation services).

Low-Power Wireless Sensor Networks for Structural Monitoring

The wireless sensor network must achieve a number of operational requirements to be suitable for long-term (i.e., permanent) monitoring of civil infrastructure systems. First, the digital resolution of the wireless sensor network must be comparable to the resolution of traditional monitoring systems. Generally, wired monitoring systems rely upon analog-to-digital converters (ADCs) that have resolutions of 16 bits or higher. Second, the spatial scale of the structure to be instrumented requires the communication distance of the wireless sensor to be relatively long, potentially a few hundred meters in reliable line-of-sight range. Long-range communications will allow star network topologies to be used, which are easier to time synchronize and manage for high–data rate applications. Third, wireless sensors permanently deployed must be capable of operating for long periods (e.g., years, decades) without requiring battery replacement. Otherwise, the maintenance requirements associated with the wireless sensor network would eradicate all cost savings and operational conveniences offered by being wireless. Today, some of the established power-harvesting technologies such as photovoltaic cells can provide viable power solutions to keep unattended wireless sensors operational for long periods. Finally, the harsh operational environment of bridges requires wireless sensors to be physically robust when exposed to moisture, extreme temperature variations, and corrosive agents.

The Narada wireless sensor node previously developed at the University of Michigan is adopted and modified for long-term deployment in harsh field settings. Although a detailed overview of the hardware and software design of the Narada node is presented elsewhere (Swartz et al. 2005; Kim et al. 2010), this paper will describe how the node meets or is modified to meet the aforementioned operational requirements.

High-Resolution Data Collection

The Narada wireless sensor [Fig. 2(a)] is designed with an onboard ADC supporting high-speed data collection (up to 100 kHz) on four sensor channels. The resolution of the ADC is 16 bits, which is a widely used digitalization resolution for ambient response monitoring. The resolution typically ensures that low-amplitude ambient bridge vibrations (e.g., tower accelerations) can be accurately recorded.

Long-Range Communication

The Narada wireless node communicates on the 2.4-GHz IEEE 802.15.4 radio standard (IEEE 2006) using the Texas Instruments CC2420 transceiver. The output power of the CC2420 transceiver can be varied from 0 to -25 dB with the highest power setting (0 dB) achieving a nominal line-of-sight communication range of approximately 100 m. For a large structure, the use of short-range wireless communication requires the adoption of multihop communication schemes that move data from node to node until it arrives at a desired location. Many researchers have devised multihop network schemes for wireless structural monitoring systems including a pipeline communication scheme proposed by Pakzad et al. (2008) and single-sink multihop schemes by Nagayama et al. (2010). The disadvantage of multihop communication schemes is that they consume communication bandwidth and debilitate the total network throughput when dealing with large sets of data. To avoid the drawback of multihop communication protocols, an alternative option is to increase the output power of the transceiver to attain longer communication distances. Kim et al. (2010) proposed a power-amplified CC2420 transceiver [Fig. 2(b)] that can achieve line-of-sight

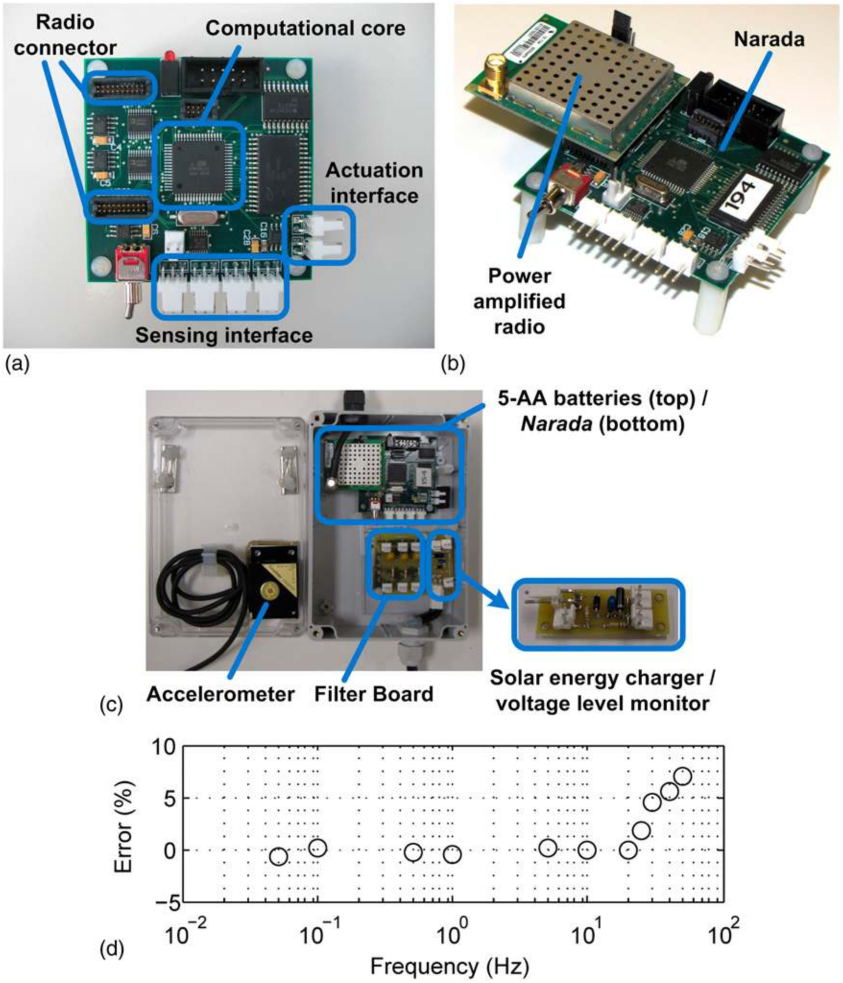

Fig. 2. Low-power Narada wireless sensor node for bridge monitoring: (a) main Narada circuit; (b) power-amplified IEEE 802.15.4 transceiver connected to the Narada node; (c) fully packaged Narada node in a plastic enclosure including solar power circuitry (rechargeable battery pack is not shown); (d) acceleration error associated with installing the accelerometer inside the wireless sensor packaging

communication ranges of over 500 m. The proposed radio integrates a 10-dB gain power amplifier that increases the output power of the radio. This output remains below the maximum power levels specified by the Federal Communication Commission (FCC) for the 2.4-GHz unlicensed radio band. To achieve this amplified output, the radio does consume an additional 6 mW of power during operation, but this increase is well within the power levels offered by solar cells that can be integrated with the Narada wireless sensor.

Solar-Powered Operation

The eradication of wires does have the disadvantage of eliminating the primary power source for sensors installed in a wired monitoring system. For long-term deployments (e.g., years, decades), a comprehensive power solution must be created for unattended wireless sensors. The solution must include both hardware components (e.g., energy harvesters) as well as sensor usage strategies that minimize power consumption (e.g., use of low-power sleep modes). Although many power-harvesting technologies have been proposed, this study chooses to utilize a solar energy solution. The Narada wireless sensor is designed with a rechargeable battery pack that can be charged by a photovoltaic cell. The benefit of using solar energy is the wide selection of solar panels currently available in the market. The selected panel is a monocrystalline solar panel with a power rating of 3.3 W and a maximum power voltage of 9 V [Fig. 3(d)]. The panel is also relatively small with a footprint area of 24 × 20 cm. To maximize the amount of energy collected, the panel is installed on a tilted frame that tilts the panel at a steep angle (50°) to receive more energy in the winter; the tilted installation also keeps the surface of the solar panel clean. Integrated into the design of the Narada node [Fig. 2(c)] is a custom-designed circuit that charges a rechargeable battery pack using the solar cell output. To monitor the voltage level of the battery pack, the custom-designed charging circuit also provides the Narada node with a means of measuring the battery pack voltage. It should be noted that the life expectancy of the rechargeable battery pack is finite. Eventually, recharge fatigue on the battery will diminish its ability to hold a full charge; at that time, the battery pack would need to be replaced.

Low-Power Sleep Mode

To ensure the Narada wireless sensor never fully depletes its battery energy before it can be replenished by the solar cell, the node operates in a duty-cycled fashion, oscillating between a sleep state (215 mW) and an active state (375 mW). The active state is where the node is collecting data and wirelessly transmitting data. The sleep state power is larger than other wireless sensors proposed with structural monitoring, because the microcontroller is powered down but the radio is fully powered. This approach to reducing the power consumption of the node ensures that the node can reliably establish

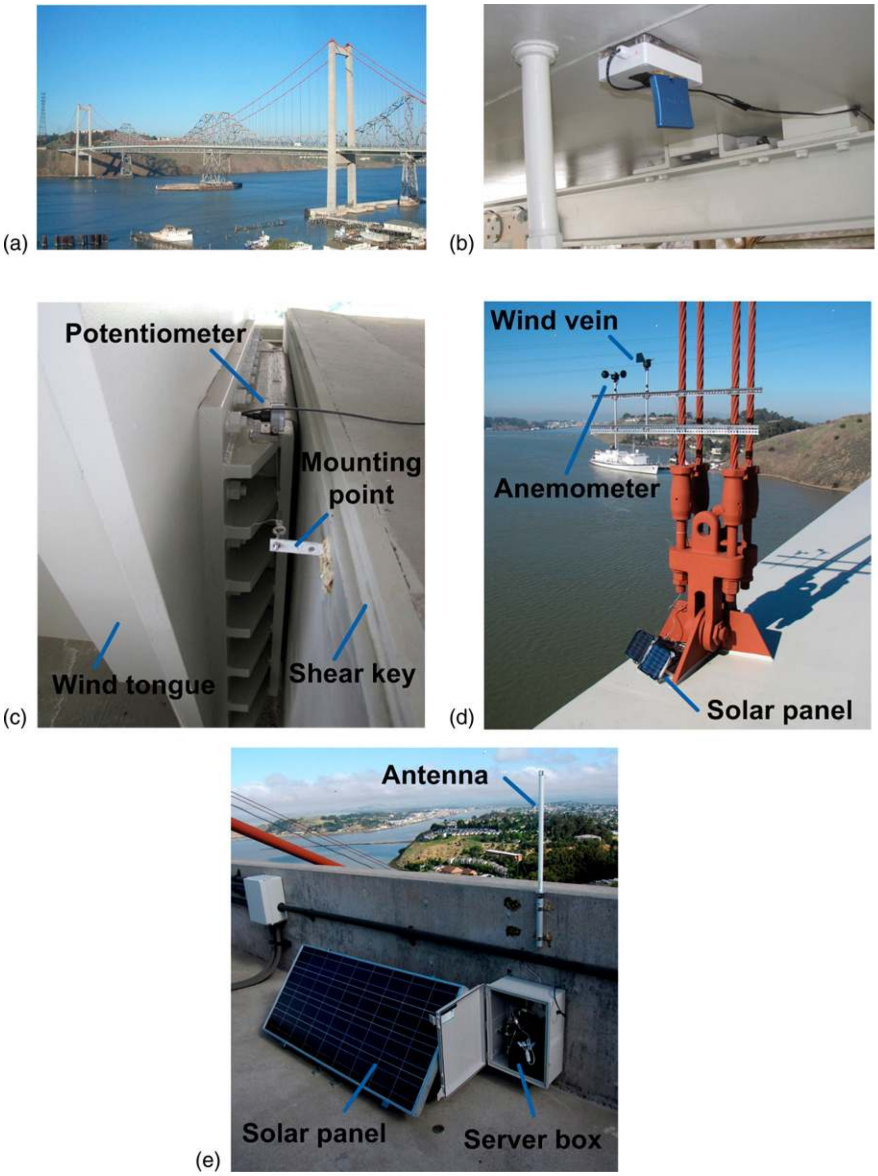

Fig. 3. (a) View of the NCB bridge from Crockett, California; (b) Narada sensor node magnetically mounted to the bottom surface of the main steel orthotropic deck; (c) installation of potentiometer at the north tower shear key; (d) installation of climate sensors (vane and anemometer shown) and solar panel at one of the bridge hangers; (e) Narada server, solar panel, and antenna anchored to the top of the north concrete tower

connectivity with the Narada server at all times. As proposed in other studies, greater reductions in the sleep power requirements can be achieved if the radio is also powered off. However, this strategy would require the node turning the radio on at set times agreed upon with the server. This would prevent remote users (e.g., bridge owners) from accessing the wireless monitoring system and controlling its activities except when the radio is awake. If it is conservatively assumed that there is only 2.5 h of diffuse daylight per day, then a duty cycle of 20% or less is feasible. However, significantly more daylight (including direct sunlight) is expected, allowing for much larger duty cycles.

Hardened Packaging

The wireless sensor node is packaged in a polycarbonate National Electrical Manufacturers Association (NEMA)-rated waterproof enclosure that protects the wireless sensor electronics from the outdoor elements [Fig. 2(c)]. Three rare-earth magnets, each with a 222-N (50-lb) force capacity, are screw-mounted to the enclosure base to allow the wireless sensor node to be magnetically mounted to any flat metallic structural surface. The use of magnets for installing the wireless sensors simplifies their installation, because special surface treatment is not needed. An additional benefit is that it protects structural surfaces that have been painted with anticorrosion coatings from aggressive bonding agents (e.g., epoxy). Included inside the enclosure is a Narada wireless sensor node with an extended range CC2420 radio interfaced, triaxial accelerometer (MEMSIC CXL02TG3), rechargeable battery pack (7 V), and power-harvesting circuit. All electrical components (i.e., everything except the triaxial accelerometer) are securely fastened by screws to plastic sheets layered in the enclosure. The antenna for the extended-range radio and the solar panel are kept outside of the enclosure to allow for appropriate placement on-site. The wires used to interface the antenna and panel to the wireless sensor circuits are passed into the enclosure through grommet holes. To ensure the enclosure remains waterproof, silicon chalk is injected into the grommet holes.

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The triaxial accelerometer is epoxy-bonded to the bottom surface of the enclosure immediately above one of the magnets on the outer enclosure surface. To verify that this approach to accelerometer installation does not introduce errors in the acceleration measurements, the packaging was tested on a modal shaker in the laboratory. The enclosure was magnetically attached to the surface of the modal shaker just as it would be on the bridge. Under varying sinusoidal excitation, the output of the accelerometer is compared with the output of a second accelerometer epoxy-bonded directly to the shaker. The error in measured amplitude is plotted as a function of frequency as shown in Fig. 2(d). The results indicate that the enclosure perfectly transfers accelerations below 25 Hz without distortion; after 25 Hz, the enclosure acts as a mechanical filter attenuating the measurement. Given that long-span bridges like the NCB exhibit low-frequency dynamics, the approach to accelerometer installation is sufficiently accurate.

The network of Narada wireless sensors installed in the bridge communicates directly with a Narada server located at the bridge site. The Narada server is intended to serve as the point of connection between the network of wireless sensors on the lower level of the monitoring-system architecture and the cyberinfrastructure framework on the upper level. The Narada server operates on an industrial grade, low-power single-board computer (SBC) running Linux. The SBC is approximately $10 \times 10 \times 2$ cm and permits fanless operation over a temperature range from -40 to 85°C. The server communicates with the Narada wireless sensor nodes using a CC2420 transceiver that has a 9-dBi omnidirectional antenna attached. The Narada nodes each employ a 6-dBi unidirectional antenna; the antenna must be pointed in the general direction of the Narada server. With this configuration of antennas, stable wireless communication between the nodes and a server is experienced for communication ranges exceeding 500 m. The connection between the Narada server and the remote database server is established via a wireless cellular modem interfaced to the universal serial bus (USB) port of the Narada server. A sealed lead-acid battery (12 V, 35 Ah) is used to power the SBC server; the battery is charged by a 110-W, 12-V solar panel (multicrystalline silicon photovoltaic). An off-the-shelf solar controller with low-voltage disconnection and pulse-width modulation regulation is implemented to control the charging of the battery and to avoid overheating the battery during charging.

Cyberinfrastructure Framework

The cyberinfrastructure framework that constitutes the upper level of the wireless monitoring-system architecture is designed to manage the transmission and storage of bridge data. It is also designed to provide a secure but convenient means of accessing data. At the core of the cyberinfrastructure framework is a remotely accessible database server (named SenStore) that has been designed to store all data and information pertaining to a monitored bridge. Temporal data (e.g., sensor readings) are stored in hierarchical data format (HDF5) files, whereas bridge metadata (e.g., bridge geometric details, structural details, location and type of sensors) is stored in a structured query language (SQL) object database. The format HDF5 is an open-source file format optimized for storing numerical data and has been developed and maintained by the HDF Group (Champaign, Illinois). The database schema is designed to also transparently link the bridge metadata with finite-element models and bridge-inspection data including inspector reports, photos, and videos. This approach of storing bridge sensor data and historical inspection data in a single database system provides bridge owners with a comprehensive and complete repository for bridge management.

The SenStore database server provides remotely accessible object-oriented APIs that allow clients to transparently access data on the server. The server can handle concurrent calls from multiple clients and can manage data from multiple sensor networks on a single bridge or from bridges located at different sites (Fig. 1). The APIs are implemented using ZeroC Ice, an open-source software product, which includes support for several programming languages (e.g., Java, C++, C#) and includes software tools for implementing servers, clients, and secure shell (SSL) encryption. In the proposed system architecture, the Narada server located at the bridge represents a client that can access SenStore through a wireless cellular network connection (Fig. 1). The Narada server client has privileges at the SenStore server to store wireless sensor data into the SQL/HDF5 database. System end-users using a remote client (e.g., web portal) can configure and operate the Narada wireless sensor network deployed on the bridge through the SenStore server. System end-users can also implement data interrogation services that query the remote SenStore server via the client API.

Field Validation at the New Carquinez Bridge

New Carquinez (Alfred Zampa Memorial) Bridge

The proposed structural monitoring system is implemented on the NCB. The NCB is a long-span suspension bridge that crosses the Carquinez Strait and is managed by CALTRANS [Fig. 3(a)]. The bridge carries four lanes of westbound traffic on Interstate 80 from Vallejo, California, on the north side of the bridge to Crockett, California, on the south side. The bridge was constructed in 2003 at a total cost of $240 million as a replacement for the original Carquinez Bridge, which was constructed in 1927 (Bay Area Toll Authority 2011). There is a separate steel cantilever truss bridge (constructed in 1958) that carries eastbound Interstate 80 traffic. More than 19 million vehicles cross the westbound and eastbound bridges annually.

The main structural components of the NCB are two concrete towers, a steel orthotropic box girder, two anchorages, and two suspension cables. The main span (i.e., the span between the north and south towers) of the bridge is 728 m, and the total bridge length is 1,056 m (Fig. 4). The bridge is equipped with apparatuses for maintenance and inspection such as traveler rigs on the main and wing spans, elevators inside the concrete towers, and power outlets throughout the two towers. As a relatively new bridge in operation for less than 10 years, there are no major structural deficiencies yet reported for the bridge; none are anticipated in the near future either. The CSMIP has installed a permanent wired seismic monitoring system in the bridge consisting of 70 channels of acceleration collected from force-balanced accelerometers installed inside the bridge girder and within the link beams of the concrete towers. The system also monitors the wind profile from an anemometer installed at the center of the main span and relative girder longitudinal displacement collected from displacement sensors installed on the girder. The CSMIP monitoring system is a trigger-based system that is designed to trigger once seismic motion is detected; CSMIP personnel also have the ability to turn the system on upon demand.

Preliminary Testing

Prior to the installation of the permanent wireless system, the performance of the Narada wireless sensor nodes were evaluated on the NCB through a series of short-term deployments carried out in 2009. These deployments sought to evaluate the quality of the wireless communication channel and the sensitivity of the Narada nodes for ambient acceleration measurements. The quality of service on the wireless communication channel was evaluated for three2 communication scenarios: (1) between locations along the main deck and the top of the towers, (2) between the tower and locations along the underside of the main deck, and (3) inside the girder. Long-distance communication could be established between the top of the north tower and a Narada node placed 700 m away on the top surface of the main deck. A similar communication range was achieved underneath the bridge girder. For example, a receiver that was placed on the south tower link beam was able to reliably communication with Narada nodes magnetically mounted to the bottom surface of the girder [Fig. 3(b)] up to 540 m away. Inside the girder, the wireless signal performed poorly, achieving a maximum range of only 50 m. This was attributable to the large steel diaphragms inside the girder that enclose the node (i.e., Faraday cage) and prevent the signals from escaping. Based on these findings, placement of the receiver on the top of the towers communicating with Narada nodes on the top of the bridge deck would provide the best performance for the wireless communication channel. However, CALTRANS preferred that Narada nodes not be placed on the top surface of the bridge because of the possibility of pedestrian vandalism. As such, the underside of the bridge girder was determined to be the best location for the installation of the permanent wireless monitoring system.

To verify the measurement accuracy of the Narada node, two tests were carried out. First, a Narada node with a triaxial accelerometer (MEMSIC CXL02TG3) was installed side-by-side with one of the CSMIP accelerometers previously installed on the interior of the main girder. As shown in Fig. 5(a), the vertical accelerations of the bridge deck collected by both monitoring systems (i.e., wireless Narada and wired CSMIP) are in strong agreement. When converted to the frequency domain using a Fourier transform, the corresponding Fourier output spectra in the frequency range of interest (< 1 Hz) are also in strong agreement [Fig. 5(b)]. Discrepancies do exist between the Narada and CSMIP accelerometers at frequencies much greater than 1 Hz, but these discrepancies will not affect the system identification analysis to be conducted provided that the first ten modes of the bridge are below 1 Hz. The second test focused on the quality of the measured girder acceleration when the Narada

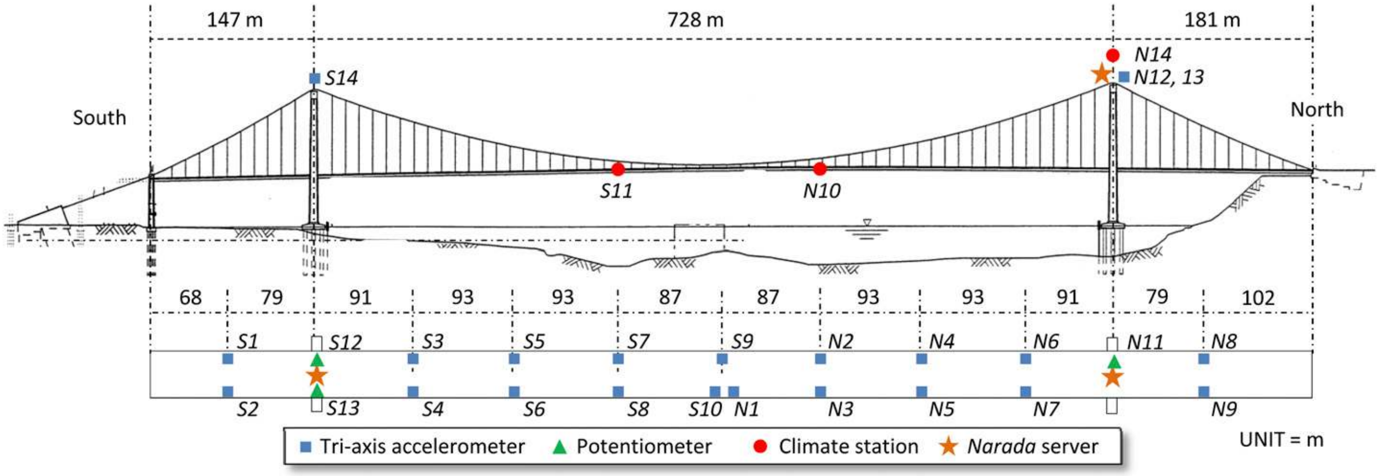

Fig. 4. Long-term wireless monitoring system installed on the NCB: sensor types and locations

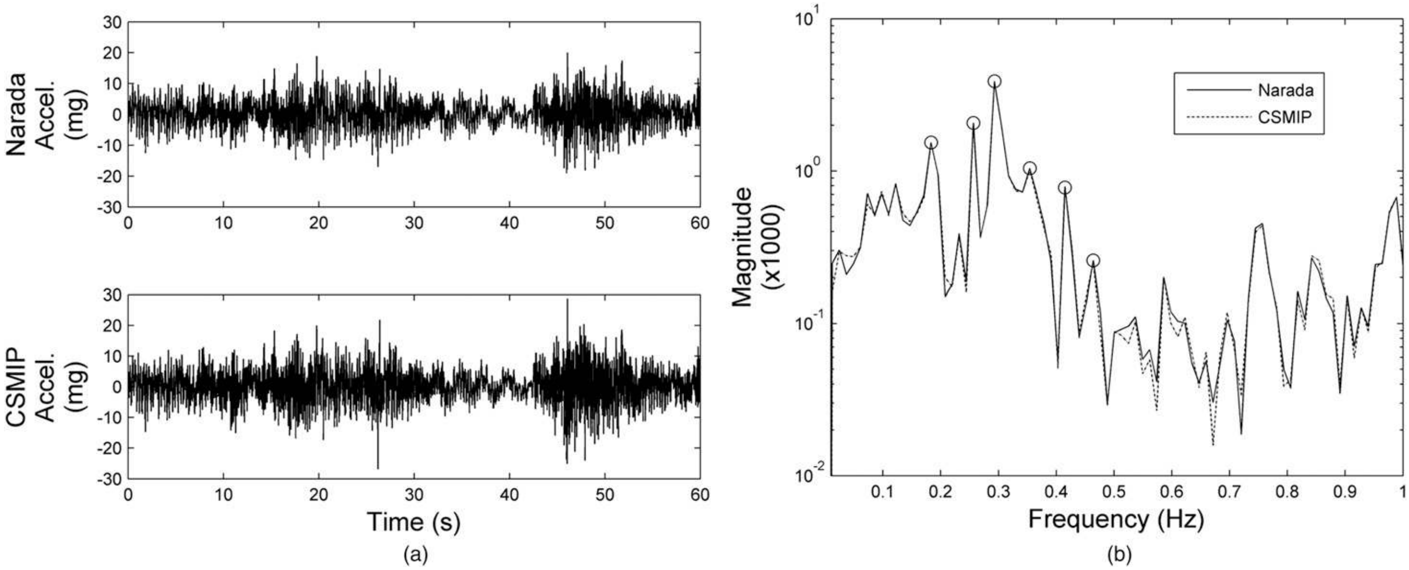

Fig. 5. Accelerometer comparison: (a) measured acceleration response (20 Hz) from the wireless (top) and wired (bottom) accelerometers; (b) corresponding Fourier spectra from 0 to 1 Hz (with the first six modal peaks identified)

node is installed beneath the girder [Fig. 3(b)]. Interestingly, some minor variation was discovered between the measured accelerations even when Narada nodes are located as far as 50 cm apart. This observation revealed that the measured acceleration can be amplified and filtered by the local dynamics of the bottom girder plate. To eliminate this local influence on the global acceleration response, the Narada nodes must be installed immediately below the internal steel diaphragms used to stiffen the bridge deck. The suspenders connect to the main girder at the girder diaphragms; as a result, accelerations measured at these locations will accurately capture the global dynamic response of the bridge.

Long-Term Wireless Sensor Deployment

The permanent installation of the system on the NCB was initiated in October 2010 with the wireless monitoring system fully installed by January 2011. Fig. 4 presents the layout of the Narada wireless sensor network. In total, 19 Narada nodes (denoted as nodes S1–S10 and N1–N9) with triaxial accelerometers (MEMSIC CXL02TG03) included in their enclosure were magnetically installed on the underside of the main girder [Fig. 3(b)]. The Narada wireless sensors installed on the main girder were configured to record the vertical, lateral, and horizontal accelerations of the girder. On the top of the towers, three Narada nodes with triaxial accelerometers were mounted (denoted as nodes S14, N12, and N13). For the tower accelerometers, all three accelerometer channels available were recorded (i.e., vertical, longitudinal, and transverse). Three Narada nodes (denoted as N11, S12, and S13) with potentiometers (Celesco SP2–50) were installed to measure the longitudinal displacement between the wind tongue of the girder and the tower shear key [Fig. 3(c)]. Three additional nodes were installed in the bridge (denoted as S11, N10, and N14) that contained an anemometer (NRG Systems 40H), wind vane (NRG Systems 200P), solid-state temperature sensor (National Semiconductor LM35DT), and humidity sensor (TDK Corporation CHS-UPS). Wind speed was computed by the Narada node based on the square voltage wave output by the anemometer; a frequency-converting circuit was implemented to increase the range of measurable wind speed up to 75 m/s. The wind vane and anemometer are presented in Fig. 3(d). Another attractive feature of the monitoring system is its ability to monitor the power level of the battery pack. Specifically, one of the ADC channels on each Narada node is used to measure the voltage in its battery pack. In total, 28 Narada units were installed on the NCB with 81 channels of data collection (Table 1).

Table 1. Summary of the New Carquinez Bridge Wireless Monitoring System Channels

Sensor type	Narada nodes	Description	Total channels
Triaxial accelerometer (MEMSIC CXL02TG3)	22	Vertical acceleration (22) Horizontal acceleration (22) Narada node battery level (22)	66
Potentiometer (Celesco SP2–50)	3	Relative displacement (3)	3
Climate station (NRG Systems 40H & 200P, National Semiconductor LM35DT, TDK CHS-UPS)	3	Wind speed (3) Wind direction (3), temperature (3), humidity (3)	12
Total	28	—	81

The size of the NCB required the wireless monitoring system to be divided into three subnetworks each serviced by one Narada server. Narada nodes N1 through N11 communicate to the Narada server installed on the link beam of the north tower. Similarly, Narada nodes S1 through S13 communicate to the Narada server of the south tower. Finally, a Narada server is installed on the top of the north tower [Fig. 3(e)] to operate a subnetwork consisting of Narada nodes N12, N13, N14, and S14. Splitting the monitoring system into three subnetworks introduces a challenge when time synchronizing the entire monitoring system. Each wireless sensor subnetwork is accurately synchronized by its Narada server using a synchronization beacon method (all units synchronize to a single beacon packet transmitted by the server). However, the three servers must also be synchronized with each other. Toward this end, the network time protocol native to Linux is used to accurately synchronize the servers to a common time basis. The collocated sensors (S10 and N1) were used to verify the accuracy of the time synchronization process with accuracies below 500 μs found experimentally.

Implementation of the New Carquinez Bridge Cyberenvironment

Fig. 6 shows the schematics of the complete cyberenvironment implementation. The Narada servers are configured to collect sensor data either upon a set schedule or when a user demands it. In the implementation of the monitoring system on the NCB, the monitoring

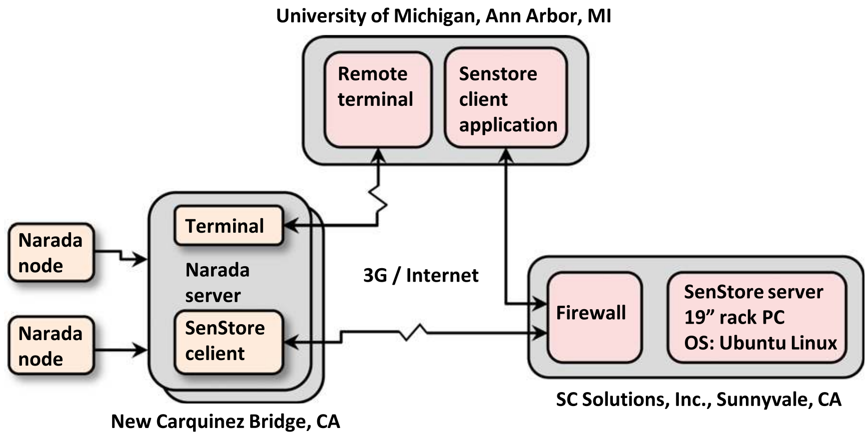

Fig. 6. Implementation of the cyberenvironment for the NCB wireless monitoring system

system is configured to collect data every 4 h for a continuous 8 min at 20 Hz. When not collecting data, the Narada wireless sensor nodes are kept in their sleep state to preserve their limited battery supplies. Sensor data collected by each Narada server is then communicated into a remote SenStore server via the Internet using a third-generation (3G) cellular modem. The cyberenvironment utilizes the SenStore client interface to send the data periodically to the SenStore server application. The SenStore server is implemented on a Linux server located off-site in Sunnyvale, California, in the offices of SC Solutions. The sensor data are stored by the SenStore server and can be accessed by any client application with the proper security credentials. It should be noted that the Narada servers installed on the NCB can also be remotely controlled from the University of Michigan using the remote terminal feature in Linux (Ubuntu). This feature allows the research team to easily check on the status of Narada nodes and to upgrade the Narada server when software updates are available. The cyberenvironment has been working successfully without any problems since February 2011.

Labor and Cost for Deploying System at Large-Span Bridges

The deployment of the wireless monitoring system on the NCB was an opportunity to truly assess the costs associated with the installation of a wireless monitoring system. The suitability of the NCB deployment for this purpose was enhanced by the fact that the installation cost associated with the wired CSMIP seismic monitoring system is known. The installation of the wireless monitoring system consisted of three parts: installation of the Narada servers, installation of the individual Narada nodes (including their solar panels), and the adjustment of the Narada node antennas to ensure reliable communication with the server. The installation of each Narada server took about 2 h using a team of three engineers; this includes the time to transport the server supplies to their installation locations. The installation of each Narada node took at most 1 h. This required the movement of the pneumatic rig underneath the main deck to the installation location (approximately 20 min) and the installation of the solar panel, the stringing of a 60-m electrical wire from the panel to the Narada node, and the magnetic attachment of the Narada node to the girder surface (approximately 40 min). Two engineers were needed to conduct the installation of each node. Before moving to the next location, the quality of the wireless communication channel between the node and server was checked. The most challenging part of the entire system installation was the establishment of stable wireless communication between nodes and the server. To ensure the communication channel is reliable, the unidirectional antenna of each Narada node was adjusted to avoid obvious line-of-sight obstacles (e.g., deck drainage pipes, the traveler rig rails) and to maximize the radio signal strength indicator (RSSI). The team (two engineers) installing the Narada nodes was also responsible for adjusting the node antennas for reliable communication. The cost associated with the installation of each Narada node ($1,470) and server ($1,620) is documented in Table 2. The installation of the 28 Narada nodes and the three Narada servers resulted in a total cost of $46,020; amortized over 81 sensor channels, the total system cost on a per-channel basis is only $568. If the cost of the SenStore server ($20,000) is included, the per-channel cost of the monitoring system is only $815. In comparison, the installation of the CSMIP monitoring system on long-span bridges in California costs approximately $8,000 per channel. Of this cost, approximately $2,500 is associated with hardware and $6,500 is associated with the installation of sensors and wiring in the bridge. This is one order of magnitude greater than the NCB wireless monitoring system.

Table 2. Installation Costs of the Narada Wireless System on the NCB

Component	Cost
Narada node	
Narada with radio	$150
Enclosure and assembly	$60
Unidirectional antenna	$20
5 AA rechargeable batteries	$5
3.3-W solar cell with mounting	$20
10-m (30-ft) power cable	$15
Accelerometer (3 axis)	$1,000
Labor (2 work hours @ $100/h)	$200
Total	$1,470
Narada server	
PC/104 server	$400
Narada radio	$200
Deep-cycle 12-V battery	$60
12-V DC/5-V DC converter	$10
Omnidirectional antenna	$100
110-W solar panel	$250
Labor (6 work hours @ $100/h)	$600
Total	$1,620

Response Data Obtained by the Internet-Enabled Wireless Monitoring System

The vertical accelerations of the northernmost portion of the main bridge girder are plotted in Fig. 7. The data were collected for 480 s using a 20-Hz sampling frequency early in the morning on February 3, 2011. The 20-Hz sample rate was selected based on a preliminary modal analysis of the bridge that found the first ten global vibration modes to be well below 1 Hz [Fig. 5(b)]. The vibration source of the NCB girder is the vehicular and wind loads. For example, the high-amplitude accelerations witnessed in Fig. 7 are associated with heavy truck traffic. The maximum acceleration in the vertical direction was found to be dependent upon the traffic condition, achieving maximum amplitudes between 100 and 150 mg under routine truck loading during the daytime hours. The climate condition at the NCB was also concurrently measured using the climate sensors mounted on the main deck at sensor nodes S11, N10, and N14. The wind speed and the air temperature as measured on February 3, 2011, at the same time as the acceleration data presented in Fig. 7, are presented in Fig. 8(a); as can be seen, the wind speed varied between 5 and 20 m/s, whereas the ambient temperature was steady at approximately 8.5°C. The relative displacement between the steel girder and the towers in the longitudinal direction were similar at both the north and south towers [Fig. 8(b)]. The maximum relative displacement was found to depend on the wind and traffic conditions with maximum displacements of 3–5 cm typically measured. The displacement records can also be used to monitor the expansion and contraction of the bridge girder under extreme temperature variations.

Data Interrogation Methods

Completed in 2003, the NCB is a relatively young bridge that has been in operation for less than 10 years. Structural deterioration and damage is not anticipated for the NCB because of its normal environment and loading condition. Rather, the bridge is located in a highly seismic area of the country and is vulnerable to strong ground motion. This has motivated the installation of the CSMIP

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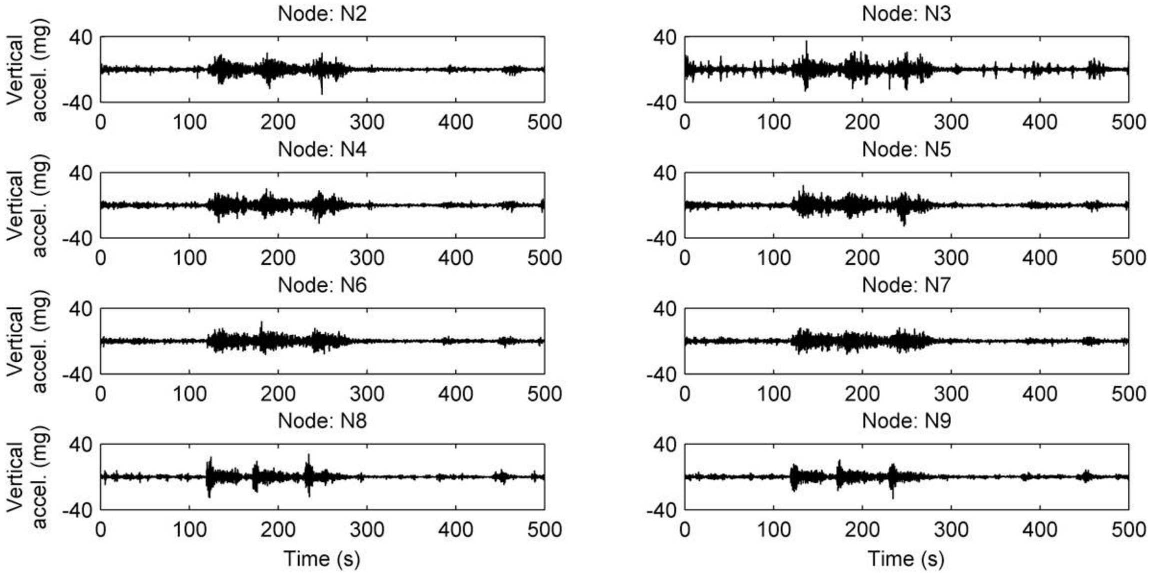

Fig. 7. Response data for NCB collected at 20 Hz on February 3, 2011 (early morning): girder vertical accelerations at selected locations

system permanently installed in the NCB. The CSMIP system is a trigger-based structural monitoring system that is designed to record structural response data when ground motion is detected. The objective of the CSMIP system is to assess the spatial variations of strong ground motion during earthquakes, to quantify structural response characteristics based on measured strong ground motions, and to calibrate the analytical model of the bridge (Liu et al. 2000).

Similar to the CSMIP monitoring system, the wireless structural monitoring system deployed on the NCB in this study is not intended to serve as a SHM system. Rather, it is deployed to understand variations in bridge properties attributable to environmental factors including temperature and wind and to provide ambient response data from which modal characteristics (e.g., modal frequencies and mode shapes) can be regularly derived. The modal characteristics of the bridge are valuable for the updating and refinement of the high-fidelity finite-element model maintained by the bridge owner. Finite-element models are often an integral component of the evaluation of a bridge immediately following an earthquake. Specifically, strong ground motions recorded at the bridge foundation can be used as the input to the model for the prediction of the seismic response of the bridge. Postevent damage can then potentially be identified through an analysis of bridge displacements and component stresses predicted by the finite-element model. To this end, the NCB data set collected in the SenStore server was automatically processed to extract the modal characteristics of the bridge and to identify variations in those characteristics attributable to variations in the bridge environmental parameters. Furthermore, tools that automatically evaluate the reliability of the wireless sensors nodes were developed.

Evaluation of Wireless Sensor Reliability

A major objective of the study is to evaluate the long-term performance and reliability of the Narada wireless sensors nodes deployed. A software tool was written to access the SenStore server as a client and to evaluate the status of each sensor node. The sensor diagnostic tool queries the database to determine when each sensor node logs its data into the database. In addition, the time history data deposited in SenStore is analyzed to determine if a sensor has exhibited behavior associated with a faulty sensor (e.g., outputting a static signal such as 0 V, high levels of measurement noise, excessive drifting). A table within the SenStore SQL database is updated to reflect the status of each sensor by attributing the sensor to one of three states: available, available but potentially faulty, or not available. Once the table in the SQL database is updated, the client graphically reports the status of each sensor for any time period the end-user specifies (Fig. 9).

Since the completion of the wireless monitoring system on the NCB in February 2011, the system has been temporarily paused three times to allow for system upgrades and modification. The first review occurred in mid-February 2011; the objective of this review was to check on the wireless sensors, to modify the unidirectional antennas of Narada nodes that had intermittent connectivity issues, and to replace the battery recharge circuit included in the Narada nodes. During this review, the plastic enclosures of the wireless sensors were opened. Unbeknownst at the time, a high level of moisture was trapped inside the enclosures during this repair because of the damp winter climate in February. The moisture trapped inside the enclosures eventually caused the majority of the wireless sensors to stop operating by late February 2011. In late April 2011, all of the Narada nodes were investigated to diagnose the cause of their loss; the condensation of moisture in the node enclosures was identified as the cause. Interestingly, all of the nodes had fully charged batteries that further proved the issue was associated with the wireless sensor circuit exposed to moisture. In response to this identified detriment, all of the Narada nodes were dried and repackaged with desiccant packs to ensure long-term dryness. Since that time, the monitoring system exhibited improved reliability with all of the sensors working properly. In mid-July, a third review of the monitoring system was conducted to replace two of the Narada nodes that had exhibited connectivity issues. Upon their replacement, the loss of connectivity was attributed to the disconnection of the solar panel from the nodes leading to the eventual depletion of their battery packs. Since that time, the wireless monitoring systems has been operating without incident.

Extraction of New Carquinez Bridge Modal Properties by Output-Only System Identification

Output-only system identification techniques are widely used in civil engineering for the estimation of the modal properties of a structure using ambient excitations. Although input-output system

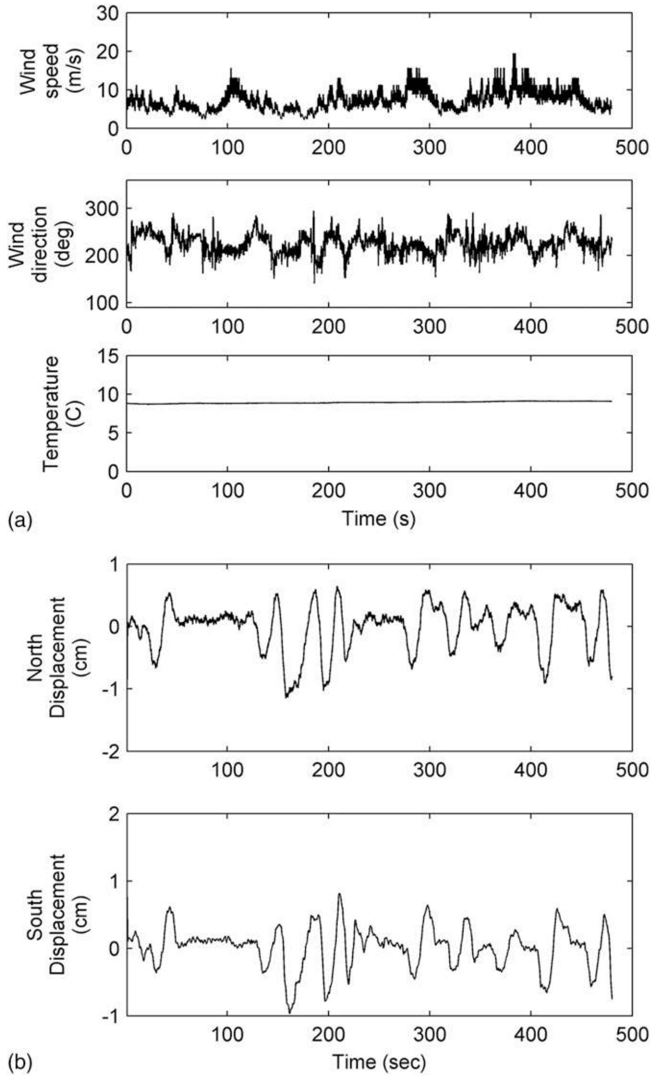

Fig. 8. Environmental and NCB response data collected at 20 Hz on February 3, 2011 (early morning): (a) wind speed, wind direction (relative to the western compass direction), and temperature; (b) relative displacement between the steel girder (wind tongue) and towers (concrete shear key) in the longitudinal direction

identification methods are known to be more accurate, the lack of a controlled and measurable excitation source prevents their use in many structural monitoring applications. A variety of output-only system identification methods are available in both the time and frequency domain for modal parameter estimation. In the frequency domain, the frequency-domain decomposition (FDD) technique (Brincker et al. 2001) is one widely used method. Time-domain methods are also available including the Ibrahim time-domain method (Ibrahim and Pappa 1982) and the natural excitation technique (NeXT) method (James et al. 1996). More recently, the stochastic subspace identification (SSI) technique has grown in popularity (Van Overschee and De Moor 1994). In this study, the SSI method is used to estimate the modal properties of the NCB. The SSI technique is a computationally expensive system identification method but provides highly accurate mode shapes and modal damping ratios. For interested readers, the mathematical formulation of the SSI technique and its application to various full-scale structural systems can be found in Verhaegen (1994), Peeters and Roeck (1999, 2001), and Kim and Lynch (2011).

Prior to the use of the SSI method, low-pass filtering was applied to the NCB vertical acceleration data set, because the frequency range of interest for the main deck is lower than 1 Hz. Utilizing off-line data processing, a forward-reverse filter was implemented for the purpose of zero-phase distortion; specifically, a seventh-order Butterworth infinite impulse response (IIR) filter with a cutoff frequency of 2 Hz was applied. In addition, the acceleration data were down-sampled from 20 to 2 Hz to increase the numerical efficiency of the SSI analysis. Implementation of the SSI algorithm entails a priori determination of two user-defined parameters: (1) the number of block rows of the past output in the block Hankel matrix and (2) the model order (i.e., the dimension of the Kalman filter state sequence). Theoretically, the number of block rows should be larger than the model order (Van Overschee and De Moor 1993). As a result, the selection of the model order is a significant parameter that controls the quality of the SSI results. Even though the model order can be determined from the number of significant singular values of the measured system output, stabilization plots are used to select an appropriate model order.

The filtered and down-sampled data sets were prepared separately for the south and north data sets. Then, SSI analyses were conducted with these two data sets for 12 different model orders (18–216 using a model order increment of 18). For each SSI analysis, modal parameter estimation was conducted to extract mode shapes and modal damping ratios. Structural modes with large modal

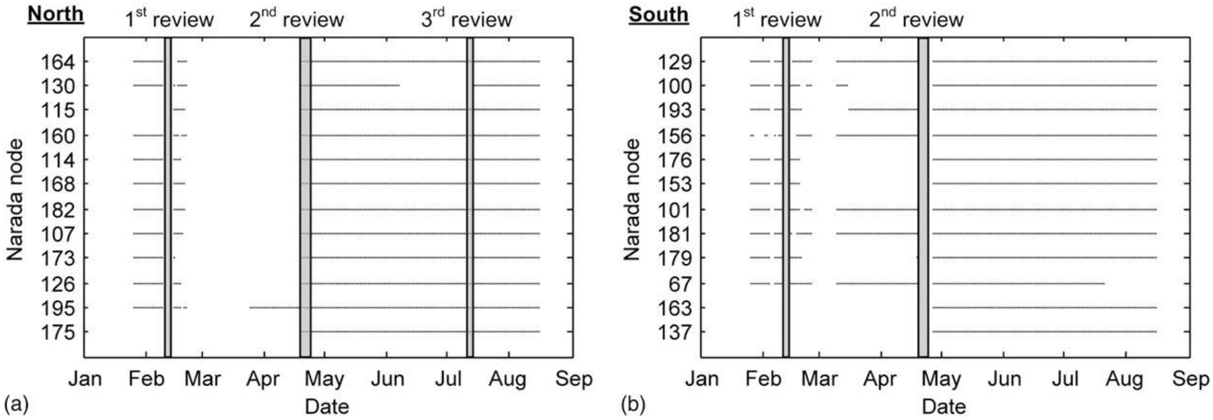

Fig. 9. Sensor diagnostic client reporting the sensor availability in the (a) north and (b) south networks from February to August 2011 (the black dot for each node denotes the availability of the wireless sensor node)

damping ratios (i.e., more than 10%) were eliminated, because such damping ratios would not be realistic for an actual structural system. The results were plotted on stabilization plots [Figs. 10(a and b)] to determine an appropriate model order. Three to seven dominant modes are evident in the stabilization plots between 0 and 0.6 Hz. As the model order increased, higher-order structural modes were easier to identify, while modal damping ratios converged to more reasonable levels (i.e., lower damping ratios below 10%). When the model order was larger than 144, seven structural modes were consistently estimated with reliable damping ratios. As can be seen in Fig. 10(b), the extracted modal damping ratios were less stable than the modal frequency, but this is a common occurrence for lightly damped structures (Hong et al. 2011). A final model order of 180 was selected for subsequent SSI analyses.

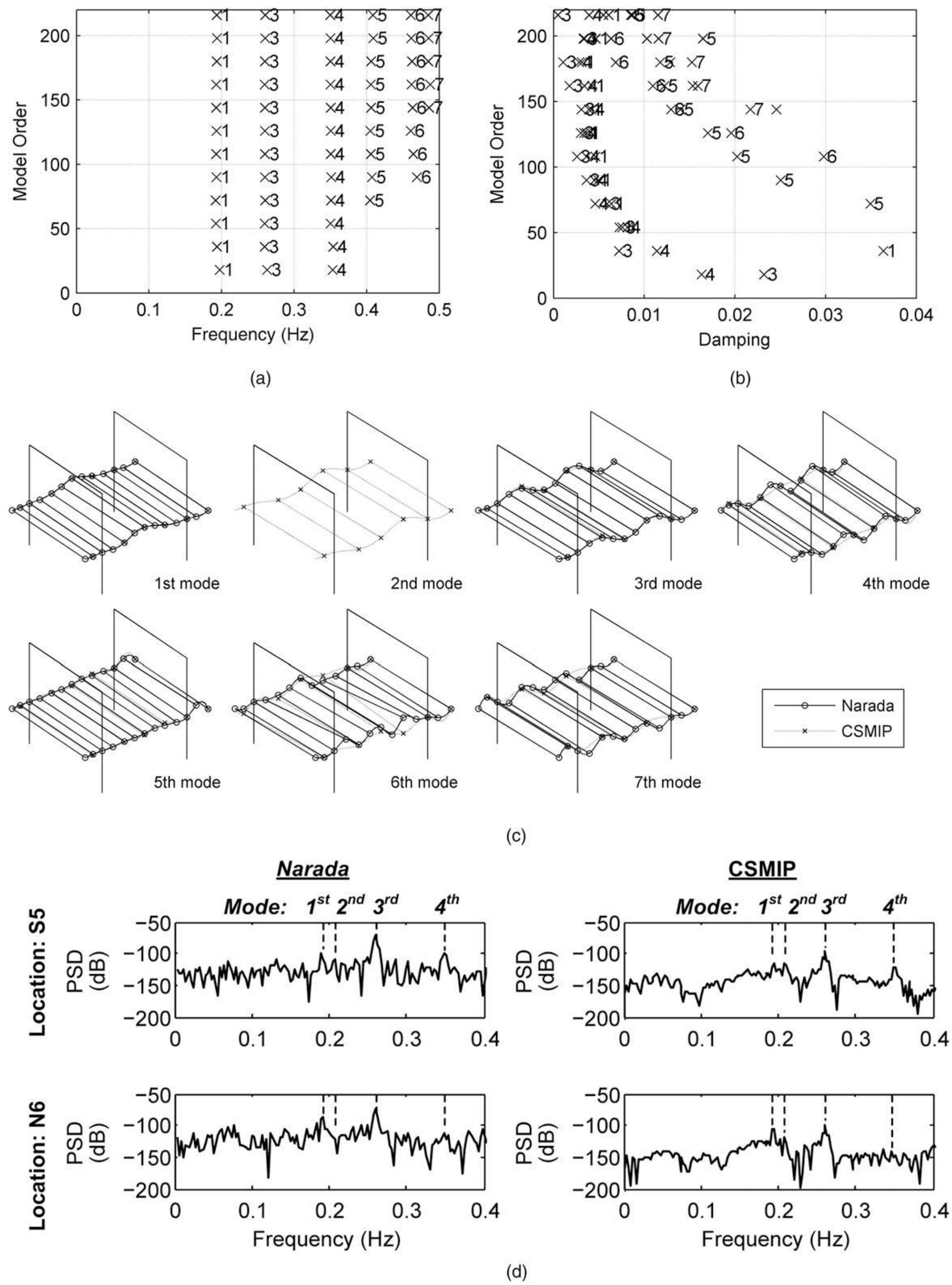

Fig. 10. Estimated NCB modal parameters by SSI: (a) modal frequency; (b) damping ratio; (c) extracted mode shape using Narada and CSMIP data sets; (d) PSD comparison at locations most excited by the second mode (S5 and N6 in Fig. 5)

The modal properties estimated by SSI from the Narada and CSMIP data sets were consistent [Fig. 10(c)]; only the second mode was not identifiable from the Narada data set. Table 3 summarizes the identified modal frequencies for the NCB ranging from 0.19 (mode 1) to 0.49 Hz (mode 7). The first four modes and the seventh mode were identified as pure bending modes; the fifth and sixth modes had more irregular shapes than the other mode shapes. To evaluate how well the SSI-derived modes correlated between different data sets, the modal assurance criteria (MAC) proposed by Allemang and Brown (1982) was used. When comparing the Narada and CSMIP-derived modes, strong correlation was found for the first four modes (except the second mode, which was absent from the Narada data set) with nearly equal modal frequency and high MAC values close to 1 (Table 3).

The absence of the second mode from the Narada data set was further studied. In total, eight different CSMIP data sets collected every 6 h over a two-day period were analyzed. Only in two CSMIP data sets could the second mode be accurately identified; incidentally, both of those data sets occurred in the early morning at 3 a.m. (local time). At the frequency of the second mode, the SSI results for the Narada data set showed some indication of the mode's existence, but the mode was eliminated during the model-order selection process because of its inconsistency and distorted mode shape. The power spectrum density (PSD) function derived from the Narada acceleration data set was compared with that of a CSMIP acceleration data set that included the second mode [Fig. 10(d)]. The PSD functions were specifically compared at sensor locations corresponding to the peaks in the second mode shape (e.g., Narada units S5 and N6 in Fig. 4). In the CSMIP PSD function, the peak corresponding to the second mode was (barely) identifiable, whereas in the Narada data set, the higher noise floor suppresses the peak. It is suspected that this is because of the location of the Narada wireless sensor node on the bottom surface of the main girder where local vibrations in the girder plate are possible.

The modal properties estimated by SSI analysis were found to be close to those reported by others who have conducted similar studies (Conte et al. 2008; He et al. 2009; Nayeri et al. 2009; Hong et al. 2011). For example, Conte et al. (2008) conducted a modal analysis of the NCB through dynamic testing using a tethered sensor network before the bridge opened. He et al. (2009) expanded on that study by applying different system identification methods to the same data set. Conte et al. (2008) and He et al. (2009) both identified the asymmetric bending mode as the second mode (the mode the Narada network was unable to identify). Hong et al. (2011) also applied the SSI method to a CSMIP data set obtained from the NCB in 2008; they reported the same second asymmetric mode as the first mode. Interestingly, the fifth mode extracted from the Narada data set has only the north half of the girder excited; this is consistent with the results reported by Hong et al. (2011).

Comparison between a Finite-Element Model and the Modal Characteristics

A high-fidelity model of the NCB has been developed by SC Solutions, using *ADINA*, a commercial finite-element modeling tool well-suited for the dynamic analysis of nonlinear structures. The model was based on the as-built drawings provided by CALTRANS and provides a realistic and reliable mathematical representation of the real structure. The theoretical modal frequencies and mode shapes have been computed from *ADINA* after the application of the bridge dead load in the model. The modal characteristics of the NCB predicted by *ADINA* were compared with the modal characteristics obtained by SSI analysis of the Narada acceleration data sets (Fig. 11). As summarized in Table 3, the modal frequencies and mode shapes predicted by *ADINA* were in strong agreement with those obtained experimentally from the wireless monitoring system; in particular, high MAC values were obtained for the pure bending modes including the first, third, fourth, and seventh modes. A currently progressing effort is the construction of a fully automated model-updating methodology for the *ADINA* model based on modal characteristics extracted from the real-time measurements.

Conclusions

The cyber-enabled wireless SHM system proposed in this paper has been designed for monitoring large and complex civil-engineering structures such as long-span bridges. The system adopts a hierarchical architecture with low-cost solar-powered wireless sensor nodes (Narada) deployed on the lowest level of the system. The Narada wireless sensor has attributes ideally suited for structural monitoring including high-resolution analog-to-digital conversion and long-distance communications. On the upper level of the monitoring-system architecture, a complete cyberinfrastructure framework is implemented based on a versatile database server termed SenStore. SenStore is designed to serve as a comprehensive repository for both bridge response data and bridge metadata such as bridge geometric details and material properties. The SenStore database publishes defined client-server APIs that allow clients to interact with the data stored in the database in a secure and reliable manner. Software tools that automate the interrogation of bridge data for information extraction (e.g., system identification, damage-detection analysis) would be provided access to the database as SenStore clients. As such, the cyberenvironment is designed to support computational efforts aimed toward the translation of the enormous amounts of data collected from the bridge into meaningful information for bridge decision makers.

The wireless monitoring system has been permanently deployed at the NCB in Vallejo, California. A total of 28 Narada wireless sensors collecting 81 channels of data have been in service since February 2011. The majority of the channels are dedicated to the

Table 3. Summary of System Identification Results

	Frequency (Hz)			Mode shape modal assurance criteria	
Mode	Narada	California Strong Motion Instrumentation Program	Finite-element model	Narada versus California Strong Motion Instrumentation Program	Narada versus finite-element model
1	0.193	0.194	0.212	0.996	0.956
2	—	0.205	—	—	—
3	0.260	0.261	0.271	0.960	0.969
4	0.350	0.351	0.365	0.937	0.973
5	0.407	0.413	0.412	0.843	0.525
6	0.465	0.455	0.492	0.101	0.085
7	0.487	0.484	0.502	0.889	0.913

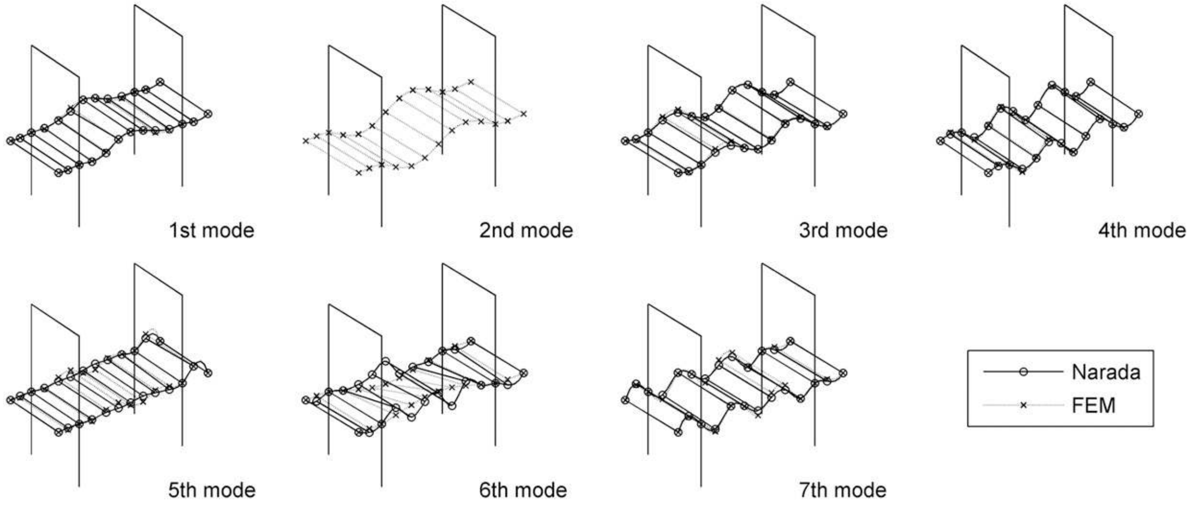

Fig. 11. Mode shape comparison between Narada and the *ADINA* model

measurement of bridge accelerations (girder and towers), but the climate (temperature, wind speed, wind direction, and humidity) and displacements are also measured. The Narada wireless sensors installed in the NCB have been in service since February 2011. Aside from an issue of moisture trapped in the Narada enclosures, the wireless monitoring system has proven to be physically robust and has exhibited reliable communication even over long distances (e.g., over 500 m). In addition, the wireless sensor data were found to be equivalent to identical data collected by a traditional tethered monitoring system permanently installed on the bridge for seismic monitoring applications. Using NCB acceleration response data collected by SenStore, SSI was performed to derive a model from which the NCB modal properties could be extracted. Modal properties including modal frequency, modal damping ratio, and mode shape have been found to be in agreement with those extracted from the wired seismic monitoring system as well as those predicted by a high-fidelity finite-element model of the bridge. The only limitation of the wireless monitoring system was its inability to extract the second mode of the NCB. The higher noise floor of the Narada wireless sensors is found to be the likely culprit for the absence of the second mode from the wireless monitoring-system data set.

Ongoing research efforts are focused on the development of application packages targeting the potential uses of the data sets obtained from the wireless structural monitoring system. Furthermore, the reliability of the sensors deployed on the NCB continues to be closely monitored. In particular, the quality of wireless communications on the NCB and the long-term performance of the rechargeable battery packs are being closely tracked. Other power-harvesting devices are also being explored including harvesters that derive energy from the vibrations of the bridge. In addition, more wireless sensor nodes are being planned for installation in a second phase of deployment including sensors to monitor the vibrations of the main suspension cable and the hangers.

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