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Structural monitoring and identification of civil infrastructure in the United States

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Abstract. Monitoring the performance and estimating the remaining useful life of aging civil infrastructure in the United States has been identified as a major objective in the civil engineering community. Structural health monitoring has emerged as a central tool to fulfill this objective. This paper presents a review of the major structural monitoring programs that have been recently implemented in the United States, focusing on the integrity and performance assessment of large-scale structural systems. Applications where response data from a monitoring program have been used to detect and correct structural deficiencies are highlighted. These applications include (but are not limited to): i) Post-earthquake damage assessment of buildings and bridges; ii) Monitoring of cables vibration in cable-stayed bridges; iii) Evaluation of the effectiveness of technologies for retrofit and seismic protection, such as base isolation systems; and iv) Structural damage assessment of bridges after impact loads resulting from ship collisions. These and many other applications show that a structural health monitoring program is a powerful tool for structural damage and condition assessment, that can be used as part of a comprehensive decision-making process about possible actions that can be undertaken in a large-scale civil infrastructure system after potentially damaging events.

Keywords: structural health monitoring; system identification; civil infrastructure systems; structural damage assessment

1. Introduction

Monitoring the performance, structural integrity and estimating the remaining useful life of civil infrastructures has been identified as a major objective in the civil engineering community in the United States (U.S.). This has been promoted by the fact that a significant portion of the U.S. infrastructure has exceeded its intended service life (U.S. Department of Homeland Security 2010). The aging and deterioration of America's infrastructure is reflected in the 2013 ASCE's Report Card, which highlights the need to improve the sustainability, resiliency, and ongoing maintenance of civil structures (American Society of Civil Engineers 2013). In addition to the deterioration from long term use, extreme events (such as earthquakes and hurricanes) pose a threat that can potentially result in sudden drops in the quality of the infrastructure. In this regard, it is desired to design resilient systems that show an increased robustness and capacity to recover after such drops in performance take place. The definition of two indices developed to quantity the resiliency and

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functionality of structures is shown in Fig. 1 (Cimellaro *et al*. 2010).

Currently, the state of structural integrity of the majority of civil structures is assessed by means of visual inspections and nondestructive evaluations (NDE) for local monitoring, performed by officials or private consulting engineers. Some NDE approaches for local evaluations include the use of ultrasonic and acoustic emissions, X-ray and Eddy currents, among others (Farrar *et al.* 2001). The main limitation of visual inspection and some of the traditional approaches is that they require access to the potentially damaged regions of the structure, which may be dangerous or not possible to access. Moreover, past disasters have shown that despite the best efforts of inspection officials, the prediction of a catastrophic structural failure remains a challenging task. An example of the difficulty to detect structural components in a critical condition is the recent collapse of the I-35W Bridge in Minneapolis.

A report from the National Transportation Safety Board (NTSB) concluded that despite that the I-35W Bridge was subjected to more frequent inspections than required by the National Bridge Inspection Standards, corrosion on the gusset plates had been underestimated by bridge inspectors (U.S. National Transportation Safety Board 2007, U.S. Department of Transportation 2010). The inspection results were attributed to the limited access inspectors had to the gusset plates; moreover, underestimation of corrosion was also found in bridges in other states. As a result, the NTSB concluded that visual methods alone are not capable of adequately evaluating the condition of gusset plates with section loss due to corrosion in tightly configured connections, or in connections where the members framing into the gusset plates are closely spaced. The cause of the collapse of the bridge was attributed to a design error combined with overload of the bridge (U.S. National Transportation Safety Board 2007).

Traditional approaches, such as visual inspection, are time consuming and leave the possibility for hidden undetected damage. These drawbacks have promoted the development of structural health monitoring over the past decades. Structural health monitoring (SHM) is the process of using continuous information obtained from an array of sensors deployed in a structural system, to infer in near real-time its state of structural integrity (damage diagnosis) and estimate its remaining useful life (damage prognosis) (Farrar and Worden 2007).

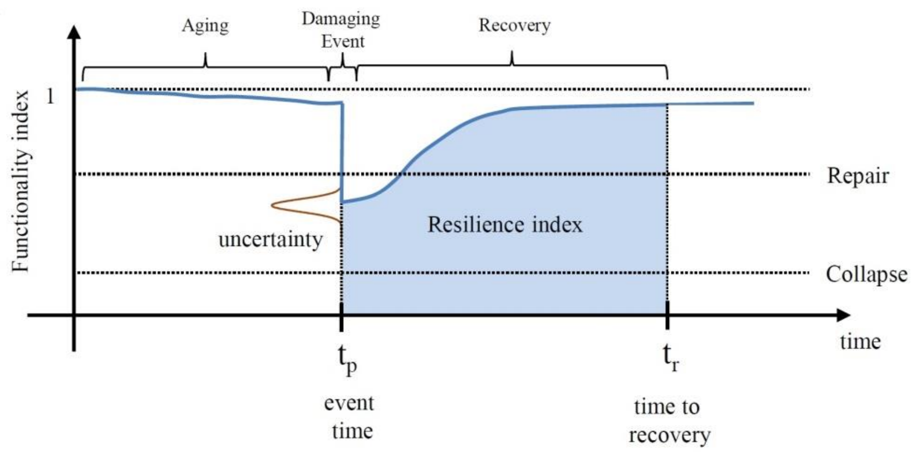

Fig. 1 Functionality and resiliency measures (Cimellaro *et al*. 2010)

Fig. 2 I-35 Bridge Collapse (Wills 2007)

In particular, vibration-based SHM uses dynamic response measurements under the premise that they contain information about the dynamic properties of a system, which can be subsequently mapped to structural damage and integrity measures (Farrar *et al.* 2001). This premise is supported by research studies performed over the last decade (Inman *et al*. 2005, Naeim 2013). It is worth to point out that the purpose of SHM is not to completely replace traditional approaches. Traditional approaches have the advantage of using the engineering judgment of an expert and reliable non-destructive testing which is useful for examining the extent of local damage. Instead, SHM is a powerful additional tool to be used as part of a more comprehensive decision making process that includes risk analyses, repair/maintenance costs, expert opinions and past experience (Ettouney and Alampalli 2012). In essence, global vibration based structural health monitoring is used to detect the presence and approximate location of damage, followed by local NDE for determining the extent of damage. SHM and Structural identification is a topic of current interest in the United States (Moaveni *et al*. 2013).

2. Motivation for structural health monitoring programs

Application of a structural health monitoring (SHM) program in large-scale civil structures involves an economic cost that needs to be justified by some objectives to be fulfilled. Some of the outcomes that can be achieved by having an SHM program available include:

2.1 Assessment of structural performance and integrity for post-disaster decision making

Evaluation of the performance and the state of damage of a structure is of prime importance to prevent or reduce casualties and economic losses. As mentioned before, currently the evaluation of the majority of civil structures is performed using visual inspections and nondestructive tests that leave the possibility of hidden undetected damage. Moreover, these traditional approaches require knowledge of the potential damaged locations and that structural damage occurs near the outer surfaces of the structure (Farrar *et al.* 2001).

The limitations of traditional procedures were highlighted after the 1994 Northridge earthquake. Several studies revealed that visual inspections failed to detect numerous cracks and fracture at welded connections in a large number of buildings (Krawinkler 1996, Mahin 1998). Many of the fractured connections remained undetected for several months (Polidori *et al*. 1997). Because of the establishment of the California Strong Motion Instrumentation Program (CSMIP) after the 1971 San Fernando earthquake, strong-motion data and SHM of many structures that suffered damage during Northridge earthquake was available for post-earthquake damage assessment (Todorovska and Trifunac 2000, Ivanovic *et al.* 2000, Todorovska and Trifunac 2008). SHM can be crucial for post-earthquake evaluations.

After the performance and state of damage of a structure are assessed, the outcomes can be employed as part of a comprehensive decision-making process related to actions to be undertaken on the structure. This might involve, for example, the opening as is (do nothing), decommissioning or retrofit a structure before or after an event. It is essential to rapidly establish the condition of structures that are of vital importance to society, such as bridges, hospitals and fire departments, so the important follow up decisions can be made.

2.2 Design of earthquake-resistant structures (development and improvement of design codes provisions)

The outcomes of a structural monitoring program include the development and improvement of seismic codes provisions (Hamburguer 1997). For example, according to the California Strong Motion Instrumentation Program (CSMIP) the ground motion records from the 1994 Northridge earthquake indicated a much higher peak ground acceleration (PGA) at locations close to the fault than expected. The design codes such as the Uniform Building Code (UBC) were revised and now require designing buildings for larger seismic forces in near-fault zones. Other design provisions can be similarly adjusted based on the analysis of data from a sufficient number of structures.

2.3 Evaluation of new technologies for seismic protection and retrofitting

The evaluation of new technologies is an important application of structural monitoring programs. These technologies are aimed at reducing the impact of potentially damaging events (such as earthquakes and hurricanes), and repairing/retrofitting structures that have suffered structural damage (Kelly 1993, Celebi 1995, Pasala *et al*. 2013). The performance and effectiveness of seismic protection and retrofitting approaches is experimentally validated using strong-motion response obtained before and after the strengthening procedure takes place (Celebi and Liu 1996, Crosby *et al*. 2004, Soyoz *et al.* 2013).

For example, the base-isolated University of Southern California (USC) hospital building experienced strong motion during the 1994 Northridge earthquake. This structure was instrumented by the CSMIP and the available data was used to evaluate the performance of the base isolation system (Nagarajaiah and Sun 1995, Nagarajaiah and Xiaohong2000). Similarly, the performance of the base-isolation system of the Los Angeles Fire Command and Control building (FCC) was evaluated using system identification techniques after being strongly shaken by the 1994 Northridge earthquake (Nagarajaiah and Sun 2001).

The strong-motion records obtained by the CSMIP during the 1994 Northridge earthquake and the aforementioned studies (Nagarajaiah and Sun 1995, Nagarajaiah and Xiaohong 2000, Nagarajaiah and Sun 2001) confirmed for the first time the outstanding performance of base isolation in structures during strong earthquakes. A performance assessment study of the FCC building (Nagarajaiah and Sun 1995, Nagarajaiah and Sun 2001) found that the entry bridge over the isolation gap was damaged as a result of pounding at the base level, in the initial part of the ground motion and the base isolation performed well after the pounding ceased. The results from this study were accounted in the decision to retrofit the entry bridge.

2.4 Maintenance of civil structures

A proper maintenance program for civil infrastructure systems is of prime importance for safe operation conditions, to ensure that the service life is met or possibly extended, and to minimize the potential impacts of failure of some components of the system. A major challenge is to define a quantitative relationship between a maintenance program and its effect in the service life of a structure (Hawk 2003). Recent SHM applications to maintenance of civil structures have pointed to the use of non-invasive approaches that minimize inspection time and disruption of use. For this purpose a cost analysis is useful for quantifying the possible advantage of using a monitoring program (Ettouney and Alampalli 2012). Other issues are related to having limited resources and the fact that the aging of structures is usually a slow process that is initially not noticeable, resulting in deferring the maintenance program.

The NCHRP 483 report in life-cycle cost analysis outlines a set of guidelines that can be applied to the decision making process for the maintenance, repair/retrofit or selection of cost-effective alternatives for the preservation of bridges (Hawk 2003).

3. Application to structural damage and performance assessment

This section presents selected study cases where an SHM program has been employed to estimate structural damage and performance deficiencies in large-scale civil infrastructure systems. The advantage of having a monitoring program in place in these applications stem from the opportunity to evaluate the structure at different states of its lifetime. For example, if a structural deficiency is detected by SHM and a decision to repair the structure is made, the effectiveness of the approach employed to retrofit can be assessed by analyzing the response of the structure before and after the structural modification takes place.

3.1 Fred Hartman Bridge cables vibration

The Fred Hartman Bridge is a cable-stayed bridge located in La Porte, Texas. The bridge was opened to traffic in 1995, and with a cable-stayed portion of 754 m is one of the largest cable-stayed bridges in the United States. After the bridge operation started, it was noticed that the cables were experiencing excessive vibrations. A comprehensive monitoring program confirmed that the stays were subject to vibrations due to combined wind and rain effects (Zuo and Jones 2005).

To reduce the excessive vibrations two types of devices were installed: passive viscous dampers and cross-ties. To assess the effectiveness of the devices an SHM program was established in 1997. The program revealed that the dampers and cross-ties had been in general effective in suppressing rain/wind induced vibrations. It was also found that the higher modes effects are non-negligible and the dampers/cross-ties were less effective at reducing such effects (Zuo and Jones 2005).

3.2 University of Southern California Hospital base isolation system evaluation

The University of Southern California (USC) hospital is a base-isolated seven-story steel braced frames building. The isolation system of the USC hospital is made by a combination of lead-rubber bearings (elastomeric bearing with lead core) and elastomeric bearings. The building was instrumented by the California Strong Motion Instrumentation Program (CSMIP) (Shakal *et al*. 1994, Nagarajaiah and Sun 1995, Nagarajaiah and Xiaohong 2000).

Using the available strong-motion data it was shown that the USC hospital performed well and the base isolation was effective in reducing the response of the structure during the 1994 Northridge earthquake (Nagarajaiah and Sun 1995, and Nagarajaiah and Xiaohong 2000). Specifically, the base isolation reduced the peak roof acceleration to about 50% of the peak ground acceleration. The peak drift was less than 30% of the code specification and the structure responded elastically. Comparison of the computed response in the base-isolated and fixed-base structure indicated that the response would have been three times larger in the fixed-base case. This study was the first validation of the performance of a base isolated building subjected to a strong earthquake.

3.3 Fire command and control building pounding

The Los Angeles County Fire Command and Control (FCC) base-isolated building is a two-story steel frame structure with a high damping elastomeric bearing isolation system, located in the City Terrace area of East Los Angeles. The FCC building was instrumented by the California Strong Motion Instrumentation Program and experienced strong motion during the 1994 Northridge earthquake. The building experienced pounding at the entry bridge across the isolation gap at the base level.

The response of the structure and the impact force were successfully identified using parametric and non-parametric system identification (Nagarajaiah and Sun 1995, Nagarajaiah and Sun 2001). It was shown that the effectiveness of the base isolation was reduced due to the impact (pounding) effect, resulting in increased shear and drift demands. There was no structural damage, but the entry bridge over the isolation gap was damaged as a result of pounding at the base level, in the initial part of the ground motion and the base isolation performed well after the pounding ceased. The results from this study were accounted in the decision to retrofit the entry bridge.

3.4 Vincent Thomas Bridge cargo ship collision

The Vincent Thomas Bridge is a suspended steel truss bridge located in Los Angeles. The bridge was instrumented in 1981 with an array of 26 accelerometers deployed throughout the structure. On August 27, 2006 the bridge was struck by a large cargo ship, inducing moderate damage on the maintenance scaffolding at the main span. However, due to the strong collision impact, authorities were worried about the possibility of hidden structural damage that was not evident from the visual inspections.

The monitoring system previously installed in the bridge recorded the response before, during and after the collision took place. To evaluate the possibility of structural damage system identification techniques were used to estimate the dynamic properties of the structure before and after the collision (Yun *et al*. 2008). The results from the system identification process showed that there existed no significant structural damage.

3.5 Corrosion monitoring of the Manhattan Bridge

Corrosion control presents an important challenge in suspended and cable-stayed bridges maintenance. One of the main difficulties is that corrosion initiates in the interior of the cables, and thus it usually takes some time before the damage can be visually detected; at this point the reduction of cross section area in the cables might be severe. For this reason traditional approaches have been found to be deficient in finding critical locations in bridge cables that might be severely affected by corrosion. The use of an SHM program can aid in the early detection of corrosion damage and the accurate estimation of the extent of damage. This information can subsequently be employed in decision making strategies related to the maintenance of the bridge in order to ensure that its service life is met or possibly extended.

A recent comprehensive corrosion monitoring program of New York suspension bridges studied the corrosion process, and developed a methodology to accurately assess the condition of the cables (Betti *et al*. 2014). The methodology proposed in this study combines non-destructive testing with sensor measurements for monitoring the condition of high-strength steel wires typically used in suspension bridges. A comprehensive experimental program was undertaken to verify the methodology under different conditions that affect the corrosion process, such as temperature and humidity. The laboratory results were further validated using field measurements from the Manhattan Bridge. It was shown that the proposed methodology has the capability to provide accurate information about the interior environment in the cables. Thus, the system can be employed to detect the onset of corrosion, enabling to perform early maintenance to delay its further propagation.

3.6 Retrofit of the Santa Clara County office building

The Santa Clara County office is a 13-story steel moment-resisting frame building located in San Jose, California. The building was subjected to strong vibrations due to three strong earthquakes (Morgan Hill, Mt. Lewis and Loma Prieta) that caused non-structural damage. In 1994 the building was retrofitted with visco-elastic dampers. Ambient vibrations tests were performed before and after retrofitting to study the effect of the retrofit approach in the fundamental modes of vibration. Using system identification approaches it was found that the retrofit chiefly resulted in an increase in the effective stiffness and damping of the structure (Celebi and Liu 1996). Evaluation of the effect of retrofitting a structure is an important application that can be successfully tackled using an SHM program and structural identification.

4. Modal identification of civil infrastructure systems

A major outcome of an SHM program is the capability to assess the performance and condition of civil infrastructure systems. For this purpose a reliable prediction of the response (demands) of the system under different operating conditions is needed. To predict the response of structural systems an analytic model (such as a finite element model) is developed. Discrepancies between the measured and predicted response arise due to modeling assumptions/idealizations, uncertainties in failure mechanisms, material properties, boundary conditions, among others.

In order to minimize the response prediction error and enhance the predicting capability of structural models, the parameters of the model need to be chosen in an optimal way, a subject known as system identification. Vibration-based system or structural identification is the process of using dynamic response measurements to estimate the parameters that define a model class of a system of interest (Kijewski-Correa *et al*. 2008). The parameters usually used in applications are the vibration frequencies, mode shapes and damping ratios. Changes in the model parameters can be further employed after a potentially damaging event as a measure of structural damage (Farrar *et al.* 2001).

We now present a brief review of the main techniques typically applied in the identification of large-scale civil infrastructure systems.

4.1 Peak amplitude method (peak-picking)

The peak amplitude method is the simplest approach for identification of structural systems (Bishop and Gladwell 1961). In this approach the natural frequencies are obtained from the peaks of the magnitude of the complex frequency response or the transfer function. The damping ratios are computed from the sharpness of the peaks, usually using the half-power bandwidth method. The modes of vibration are estimated from the ratio of the amplitude of the response at different degrees of freedom. This method assumes that the damping matrix is diagonalizable, and provides reliable results if the structure is lightly damped and the modes are well separated (Bishop and Gladwell 1961).

4.2 Frequency Domain Decomposition (FDD)

The frequency domain decomposition is an extension of the peak amplitude method to cases where the input is a (unknown) broadband stationary excitation with a constant power spectral density matrix. Similarly to the peak amplitude method, the modes are assumed to be well separated with small damping. A singular value decomposition of the output power spectral density is used to compute the response autocorrelation functions, which in turn yield the damping ratios and natural frequencies, while the mode shapes are obtained from the singular vectors (Brincker *et al*. 2000).

4.3 Eigensystem Realization Algorithm (ERA) and the Natural Excitation Technique (NExT-ERA)

The Eigensystem Realization Algorithm (ERA) is an approach for system identification of linear systems. The objective of ERA is to obtain a minimum realization of the matrices $(\mathbf{A}, \mathbf{B}_1, \mathbf{C})$ of a state-space model from vibration data (Juan and Pappa 1985). For this purpose a singular value decomposition of the generalized Hankel matrix (formed from free vibration response measurements) is employed. Two indicators are usually used to discriminate computational modes that may result from numerical truncations, measurement noise and nonlinearity: the modal amplitude coherence and modal phase collinearity (Juan and Pappa 1985).

Natural Excitation Technique (NExT-ERA)

The need to use the free response of the structure (or input/output data) in order to apply the ERA is a limitation for its application in large-scale infrastructure systems, when the possibility of using an actuator to excite the structure is not available. For structural systems subjected to broad-band stationary excitations a modified form referred to as the natural excitation technique (NExT) was developed (James III *et al.* 1993); this approach operates using only output measurements (operational modal analysis). The NExT algorithm is based on the fact that the cross-correlation of the response at two coordinates has the same functional form of the impulse response. Thus, the cross-correlation functions (which can be estimated from the output data) can be used to form the Hankel matrix used in ERA (NExT-ERA). A modified version of the algorithm (MNexT-ERA) was recently developed to use multiple measurements as reference coordinates to compute the cross-correlation functions (He *et al*. 2009).

4.4 Stochastic Subspace Identification (SSI)

The stochastic subspace identification (SSI) algorithm is an output-only approach developed for applications where the main components of the input excitations cannot be measured. In this method the unmeasured input (w) and the measurement noise (v) are assumed to be white noise processes. The Hankel matrix discussed in the ERA is formed using the output data and partitioned in two upper/lower Hankel matrices. A singular value decomposition of the projection of the partitioned Hankel matrices yields the observability and controllability matrices, from which the state-space realization is estimated (Van Overschee and De Moor 1996).

5. SHM programs in large-scale civil infrastructure systems in the U.S.

In this section we review some of the recent structural health monitoring programs that have been established in the United States. The programs involve the instrumentation of major high-rise buildings, bridges and dams throughout the country, with special attention to seismic prone regions. The major instrumented bridges with SHM systems are listed in Table 1. Instrumentation in bridges usually consists of displacement transducers, strain gauges and accelerometers. In a specific project basis, additional instrumentation might include a global positioning system (GPS), anemometers, corrosion sensors, cable tension force sensors, among others.

Table 1 Major instrumented bridges in the U.S.

Name	**Year Opened**	**Location**	**Type**
Golden Gate Bridge	1937	San Francisco, CA	Suspension
Vincent Thomas Bridge	1964	Los Angeles, CA	Suspension
Commodore Barry Bridge	1974	Pennsylvania/New Jersey	Truss
Sunshine Skyway Bridge	1987	Terra Ceia, FL	Cable-stayed
Fred Hartman Bridge	1995	La Porte, Tx	Cable-stayed
Bill Emerson Memorial Bridge	2003	Missouri/Illinois	Cable-stayed
Alfred Zampa Memorial Bridge	2003	Vallejo, CA	Suspension
Saint Anthony Falls I-35W Bridge	2008	Minneapolis, MN	Post-tensioned concrete box girder

Table 2 Major instrumented buildings in the U.S.

Name	Location	Stories	Sensors*
One Rincon Hill Tower	San Francisco, CA	62	72
Transamerica Tower	San Francisco, CA	60	21
Office Building (CSMIP 24629)	Los Angeles, CA	54	20
Office Building (CSMIP 24602)	Los Angeles, CA	52	20
Century City, 2029 CPE	Los Angeles, CA	44	42
One Bell Center	St Louis, MO	43	24
Chevron Building	San Francisco, CA	40	24
Crowne Plaza Hotel	Seattle, WA	34	15
Los Angeles City Hall	Los Angeles, CA	32	27
Pacific Park Plaza	Emeryville, CA	30	30
Federal Deposit Insurance Corporation	San Francisco, CA	22	30
Hilton Hotel	Anchorage, AK	20	15
Robert B Atwood Bldg	Anchorage, AK	20	53
New Federal building	San Francisco, CA	18	36
Frontier Building	Anchorage, AK	14	36
Caltech Millikan Library	Pasadena, CA	9	36

*Uni/bi-directional accelerometers deployed throughout the structure

A list of the major buildings with an SHM system are listed in Table 2. Typically the instrumentation in buildings consists of a set of accelerometers located at the first story, the roof and a limited number of intermediate stories (Celebi 1995, Huang *et al.* 2012). On a specific project basis additional instrumentation might include displacement transducers and strain gauges.

Most of the instrumented structures in the previous tables are included as part of the U.S. National Center for Engineering Strong Motion Data (CESMD) and the data is available to the public through their website http://strongmotioncenter.org.

5.1 U.S. National Center for Engineering Strong Motion Data

The Center for Engineering Strong Motion Data (CESMD) is a cooperative effort between the United States Geological Survey (USGS) and the California Geological Survey (CGS) to integrate earthquake strong-motion data from the California Strong Motion Instrumentation Program (CSMIP), the USGS National Strong Motion Project, and the Advanced National Seismic System (ANSS).

The CESMD contains records of more than 300 structures including buildings, bridges and dams. After a strong earthquake occurs, the collected records are processed and disseminated to engineers, seismologists, building officials, state and local governments and emergency personnel. All processed data are available from the U.S. National Center for Engineering Strong Motion Data at http://strongmotioncenter.org which includes over 10,000 records from past events. The CESMD is the largest instrumentation program in the United States.

5.2 Chicago full-scale monitoring program

The Chicago full-scale monitoring program was a cooperative effort between the University of Notre Dame, the Boundary Layer Wind Tunnel Laboratory (University of Western Ontario) and Skidmore, Owings & Merrill LLP, established to study the behavior of high-rise buildings subjected to wind-induced vibrations. The program focuses on the evaluation of vibration serviceability (occupant perception/comfort) and the investigation of the dynamic properties of high-rise buildings identified from vibration data. For this purpose the performance of three buildings in Chicago was studied by comparing the prediction from finite element and wind tunnel models to system identification results under different operating conditions (Kijewski-Correa *et al.* 2006).

The structural system of the three buildings studied consisted of a steel tube-type system (for two of the buildings) and a reinforced concrete shear wall system (for the third building). Each building was instrumented using four accelerometers placed as two orthogonal pairs located in opposite corners at the highest story. A global positioning system (GPS) was also installed to measure the dynamic displacement of the buildings. Since the study was focused on wind-induced vibrations, two ultrasonic anemometers were installed in the tallest of the three buildings to measure the wind speed and direction.

The main conclusions of the program are (Kijewski-Correa 2009):

- Accelerometers are not sufficient to monitor structures in high winds regions:
  Monitoring of civil structures in the United States have focused to regions with moderate/high seismic hazard. In general the earthquake response of building structures can be effectively captured by accelerometers (usually deployed at different height throughout the structure). However, the response of high-rise buildings subjected to wind-induced vibrations has two significant components that are difficult to capture by accelerometers: a mean (static) component and a low frequency (background) component. Thus, to monitor high-rise buildings accelerometers need to be combined with displacement measurements.

- Dynamic properties show amplitude dependence under wind loads:
  The effect of vibration amplitude on the identified frequencies and damping ratios was studied. Based on the results for the different buildings it was concluded that the lateral deformation mechanism rather than material controls the dynamic parameters, with the amplitude dependence effect being more pronounced in systems whose primary lateral deformation mode is dominated by shear. This is in agreement with other studies that have focused in identification of dynamic properties from earthquake records (Bernal *et al*. 2012).

5.3 High-rise building in San Francisco (One Rincon Hill Tower)

The One Rincon Hill Tower is a 62-story residential building located in downtown San Francisco. The building height (foundation to roof) is about 618 feet, and its construction was completed in 2008. The tower is the first building in California to have a liquid tuned mass damper (Huang *et al*. 2012). The vertical load system consists of post-tensed flat slabs supported by reinforced concrete shear walls and columns. The lateral force resisting system consists of a reinforced concrete ductile core wall system with additional reinforced concrete outrigger columns (see Fig. 3). The outrigger columns are connected to the core with steel buckling-restrained braces. The lateral force resisting system was designed using a performance-based seismic design procedure (Klemencic *et al*. 2006).

The structure was instrumented by deploying a sensors array in the central core wall at different stories. In a first phase 36 accelerometers were installed by CSMIP. In a second phase USGS/NSMP joined in the instrumentation of the building in a cooperative effort, adding 36 new accelerometers. The location of the total 72 accelerometers is shown in Fig. 4. The building description and the sensor layout for the building are included in the Center for Engineering Strong Motion Data (CESMD). Strong motion data obtained after a strong earthquake is made available immediately through the CESMD website. This data can be used to perform a post-earthquake damage assessment. Based on ambient vibration data the fundamental period of the building is 3.3 seconds. Additional information about this project can be found in Huang *et al.* (2012).

5.4 Golden Gate Bridge

The Golden Gate Bridge is located at the entrance of the San Francisco Bay, and was opened to traffic in 1937. The total length of the bridge is 2790 m, with a main span of 1280 m. The structure consists of suspended steel trusses supported by braced steel towers.

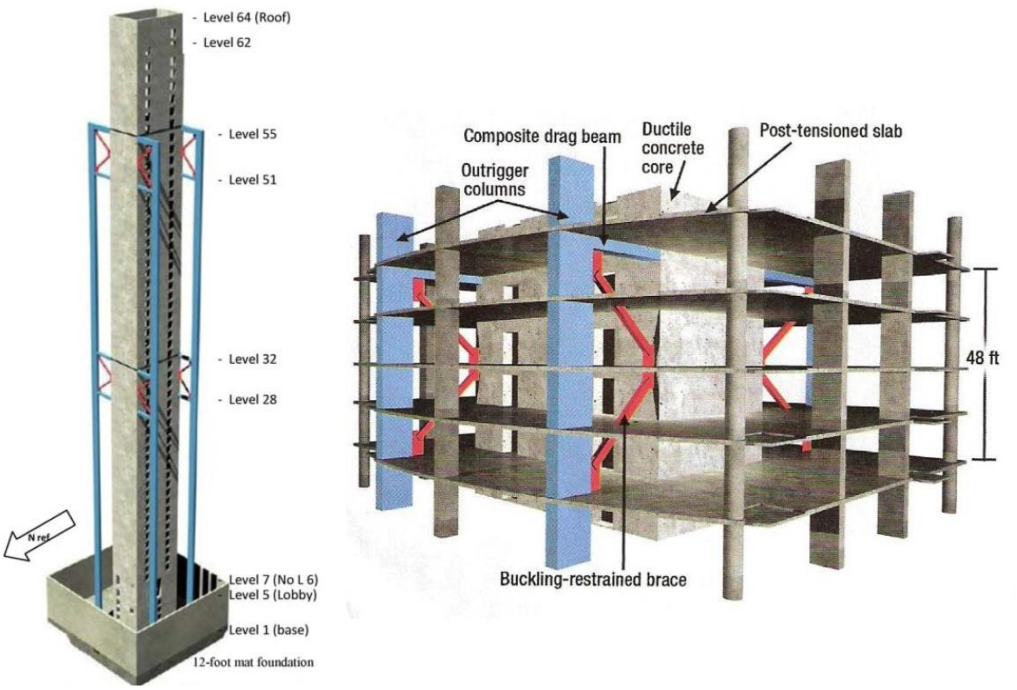

Fig. 3 One Rincon Hill Tower structural system (Huang *et al*. 2012)

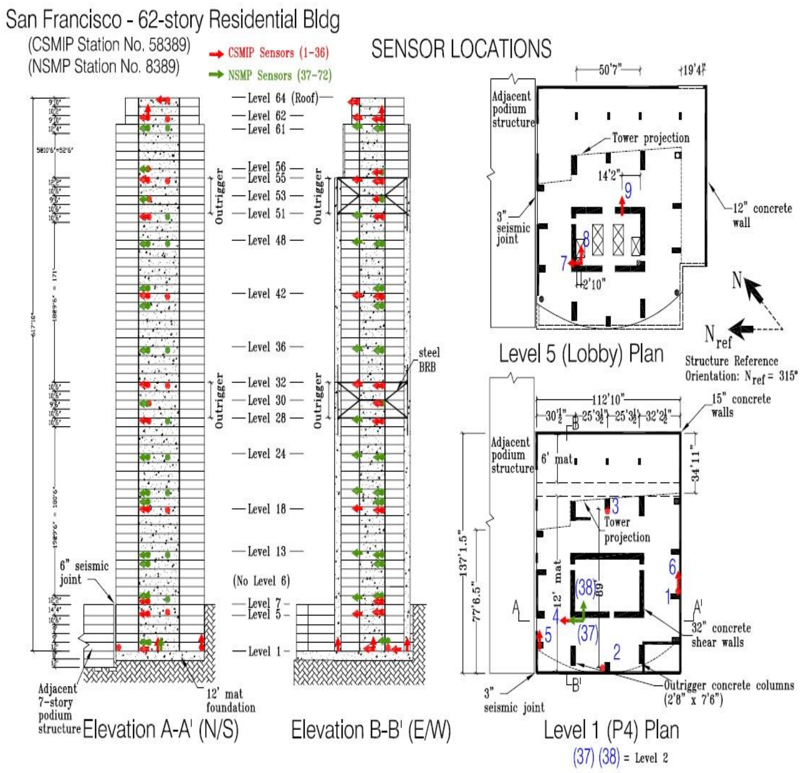

Fig. 4 One Rincon Hill Tower instrumentation (http://www.strongmotioncenter.org)

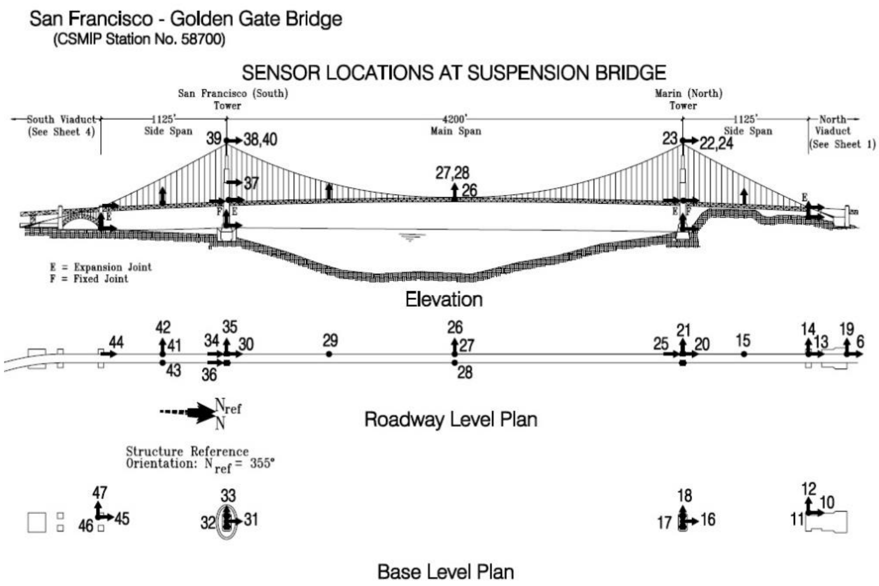

Fig. 5 Golden Gate bridge instrumentation (http://www.strongmotioncenter.org)

The instrumentation of the bridge consists of 69 accelerometers and 4 relative displacement sensors, and a free-field station on the south side of the bridge. In addition, more recently, a wireless sensor network consisting of 320 sensors was temporarily deployed in the structure (Pakzad *et al.* 2008).

Identification under ambient vibration studies have been performed to estimate the dynamic characteristics of the bridge (Abdel-Ghaffar and Scanlan 1985a, Abdel-Ghaffar and Scanlan 1985b).

5.5 Vincent Thomas Bridge

The Vincent Thomas Bridge is a suspended steel truss bridge located in Los Angeles. The total length of the bridge is 1847 m with a main span of 457 m, and it was opened to traffic in 1964. The structure consists of suspended steel trusses supported by braced steel towers. The bridge is located in the seismic active Southern California region. The bridge was retrofitted between 1996 and 2000, including the incorporation of about forty-eight nonlinear passive viscous dampers (Ingham *et al*. 1997).

An instrumentation program on the bridge was initiated in 1981 with the installation of 26 accelerometers. The modal parameters have been previously identified using data from the 1987 Whittier earthquake and the 1994 Northridge earthquake (Smyth *et al.* 2003).

5.6 Bill Emerson Memorial Bridge

The Bill Emerson Memorial Bridge is a cable-stayed bridge located across the Mississippi river between Cape Girardeau, Missouri, and East Cape Girardeau, Illinois. The bridge total length is 1205 m with a main span of 350 m. The Bill Emerson Memorial bridge is located approximately 50 miles from New Madrid (Missouri), an active seismic region where strong earthquakes have occurred in the past. For example, in 1811-1812 three earthquakes of magnitudes 7.0-8.0 took place, with strong aftershocks of magnitudes up to 7.4 (Chen *et al*. 2007).

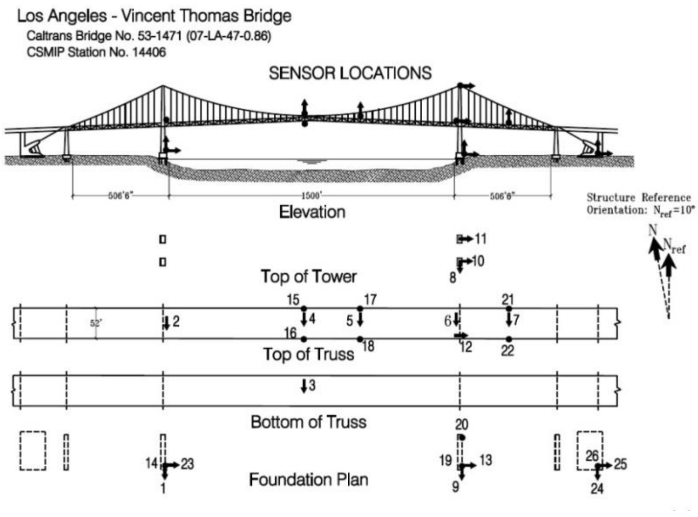

Fig. 6 Vincent Thomas bridge instrumentation (http://www.strongmotioncenter.org)

Fig. 7 Bill Emerson Memorial bridge (http://en.wikipedia.org)

Due to its close location to an active seismic region the bridge was instrumented by the Missouri Department of Transportation in April 2005 (Hartnagel *et al.* 2006). The real-time seismic monitoring system has a total of 84 accelerometer channels deployed throughout the structure and a free-field station close to the bridge.

The objective of the SHM program was to assess the performance of the bridge for design earthquakes using updated (identified) finite element models. The identified frequencies using peak picking are compared to the calibrated finite element model. The identified model was used to compute the factor of safety of the cables when the bridge is subjected to past earthquake records.

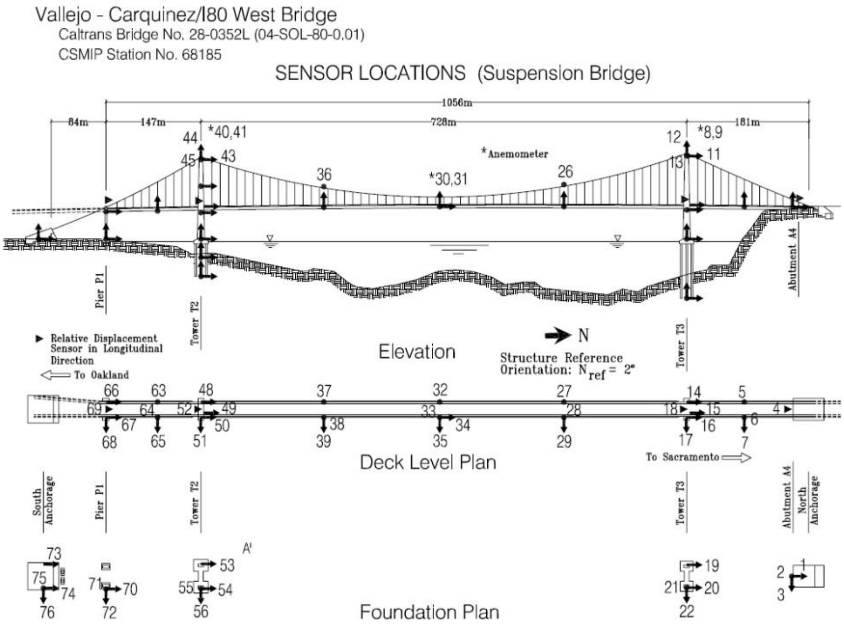

Fig. 8 Alfred Zampa bridge instrumentation (http://www.strongmotioncenter.org)

5.7 Alfred Zampa Memorial Bridge (New Carquinez)

The New Carquinez Suspension Bridge is a suspension bridge between Vallejo and Crockett, California. The bridge total length is 1056 m with a main span of 730 m. The bridge was instrumented in 2004 with 76 sensors on the suspension bridge and 27 sensors on the approach.

A comprehensive system identification study was carried out under ambient and forced vibration (He *et al*. 2009). For this purpose the natural excitation technique - eigensystem realization algorithm (MNEXT-ERA), the stochastic subspace approach (SSI) and the enhanced frequency domain decomposition (EFDD) algorithms were employed.

6. Conclusions

The aging and deterioration of the United States civil infrastructure system have promoted the development of structural health monitoring programs to monitor, in near real-time, the performance of structures and estimate their remaining useful life. This paper presented a review of the major structural monitoring programs that have recently taken place in the United States, focusing on the integrity and performance assessment of large-scale structural systems. Several practical applications where response data from a monitoring program have been used to detect and correct structural deficiencies were highlighted. These include:

i) *Structural damage assessment of civil infrastructure systems:* With the establishment of the California Strong Motion Instrumentation Program (CSMIP) after the 1971 San Fernando earthquake, strong-motion data of many bridges and buildings that suffered damage during Northridge earthquake is available for post-earthquake damage assessment. The limitations of traditional procedures were highlighted after the 1994 Northridge earthquake. Several studies revealed that visual inspections failed to detect numerous cracks and fracture at welded connections in a large number of buildings. Many of the fractured connections remained undetected for several months. SHM can thus be crucial to detect hidden structural damage and for post-earthquake evaluations.

ii) *Excessive wind and rain induced vibration of cables in cable-stayed bridges:* In this application an SHM program is used to evaluate the severity of the structural deficiency, and to assess the effectiveness of corrective measures. This application of SHM was undertaken on the Fred Hartman Bridge to study the performance of passive dampers and cross-ties in reducing the cables vibration.

iii) *Evaluation of the effectiveness of advanced technologies for seismic protection and retrofitting:* Strong-motion data is useful to assess the operation performance of advanced seismic protection devices during an earthquake. For example, after the 1994 Northridge earthquake response data collected by the CSMIP was used to validate the performance of base isolation systems in structures subjected to strong earthquakes for the first time.

iv) *Impact damage assessment in bridges due to ship collisions:* In 2006 the Vincent Thomas Bridge was struck by a large cargo ship, leaving authorities worried about the possibility of hidden structural damage that was not evident from the visual inspections. Vibration data from an SHM system obtained before, during and after the event was used to determine that the bridge suffered no structural damage.

v) *Corrosion monitoring of cable-stayed bridges:* Monitoring the corrosion of cables is a challenging task because the corrosion process starts inside the cable, and due to the effect of temperature and humidity. A recent comprehensive corrosion monitoring program of New York suspension bridges studied the corrosion process, and developed a methodology to accurately assess the condition of the cables. It was shown that the proposed methodology has the capability to provide accurate information about the interior environment in the cables using SHM information.

The applications and outcomes of an SHM system demonstrate that it is a powerful and essential tool, to be used as part of a comprehensive decision-making process for civil infrastructure systems during their operation and shortly after extreme events. This decision-making process is aimed at responding to the society demand of ensuring the public safety, and minimizing the time to recovery of structural systems of vital importance, such as bridges, hospitals and fire departments after an event disrupts their operation.

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