Transaction A: Civil Engineering
Vol. 17, No. 5, pp. 325–338

Invited/Review Article

Computational Earthquake Engineering of Bridges

T. Less[1] **and H. Adeli**[1,*]

Abstract. *A review of major research performed in the field of earthquake engineering of bridges during the past decade is presented with a focus on computational modeling. Topics covered include nonlinear simulation, hazard analysis, passive, active, and hybrid control of bridges, bridge damage studies, health monitoring of bridges, bridge management, and retrofitting of bridges. Important conclusions of interest to the bridge engineering community reported in the articles are noted.*

Keywords: *Bridge engineering; Bridge management; Earthquake engineering; Seismic hazard analysis; Health monitoring; Impact; Nonlinear simulation; Retrofitting; Vibrations control.*

INTRODUCTION

The purpose of this paper is to present a state-of-the-art review of the computational research performed in the field of earthquake engineering of bridges during the past decade. The focus of the review is on bridge structures and computational modeling as opposed to bridge components. Significant and representative computational research published since 2000 primarily in the following journals are reviewed: *Earthquake Engineering and Structural Dynamics, Journal of Structural Engineering, Journal of Bridge Engineering, Computer Aided Civil and Infrastructure Engineering, Engineering Structures, Earthquake Spectra, and Computers and Structures.* The review in each section is roughly presented chronologically. The decision to limit the review to these journals is based on their positions as key journals for computational earthquake engineering of bridges and limited space available for an article.

ANALYSIS AND SIMULATION

Nonlinear Simulations

Finite Element (FE) computing has become an increasingly powerful tool for bridge designers [1-6]. Research dealing with simulation methods and models involving large numbers of bridge elements, multiple loading situations, and complicated structures has progressed in a number of ways with the increasing power and availability of computers. Consolazio [7] uses neural networks [8-17] to accelerate the convergence of a preconditioned conjugate gradient iterative equation-solver for FE analysis of highway bridges consisting of steel girders and a concrete slab. Meng and Lui [18] investigate the effects of earthquake induced torsion on short span highway bridges with attention to asymmetry due to construction errors and accidental factors, and bridge deck rotation using vibration and earthquake response analysis. They conclude that for bridges with a small ratio of rotational to translational frequency, asymmetry can significantly affect the dynamic response. Linzell [19] presents results of the comparison of multiple FE models for curved steel bridges with experimental data obtained from nine full scale tests along with Monte Carlo simulations and conclude that, in general, the finite element models yield conservative results.

Cable-stayed bridges have received increasing attention in recent years, particularly in long span applications for reasons such as versatility and aesthetics [20-21]. A key issue in multi-span cable-stayed bridges is stabilization of the central tower(s) under extreme wind or seismic vibrations, since they cannot be anchored to an outer fixed support. A solution to this is the use of stabilizing cables which run from the top of the central tower(s) to a location on the deck

1. *Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, 470 Hitchcock Hall, 2070 Neil Avenue, Columbus, OH 43220, USA.*
*. *Corresponding author. E-mail: adeli.1@osu.edu*

Received 15 July 2010; accepted 23 August 2010

near the side towers. Ni et al. [22] investigate the effect of stabilizing cables on Ting Kau Bridge, a four-span cable-stayed bridge with central towers in Hong Kong, through a 3D FE analysis. The authors conclude that *"the longitudinal stabilizing cables are very effective in reducing the internal force in the central tower generated by longitudinal earthquake excitation, but insignificantly affect the seismic response in the bridge deck and side towers"*.

A relatively new option for bridge members are tubes of steel or composite materials filled with concrete. Shao et al. [23] present a parametric nonlinear beam-column method of analysis for these members based on cyclic load tests and note that steel tubes are preferable to composite tubes in hysteretic response, but composite tubes have a higher durability. Concrete Filled Tube (CFT) arch bridges have gained popularity in China in the past two decades where more than one hundred such bridges have been built [24]. A CFT arch rib is, however, heavier than the corresponding steel rib which means it attracts a larger level of earthquake force, especially in the out-of-plane (transverse) direction. Wu et al. [24] investigate CFT arch bridges by performing dynamic nonlinear 3D FE analysis of Second Saikai Bridge, the first CFT arch highway bridge in Japan, consisting of 2 CFTs with a 240-m main span and subjected to multiple earthquakes. The authors conclude that *"because the yielding elements of the arch rib increase, it is necessary for the analysis to consider the combined out-of-plane and longitudinal excitations"*.

Nielson and DesRoches [25] perform nonlinear 3D FE seismic response evaluation of single span, multispan simply supported and continuous multispan concrete girder bridges representative of the Southeastern and Central U.S. subjected to a synthetic ground motion for the Memphis area, and found that designing a bridge with continuous spans or with fixed or expansion steel bearings can escalate the seismic demand in columns, abutments, and bearings depending on the configuration of the bridge and earthquake intensity. Song et al. [26] propose a nonlinear inelastic analysis model using a softening plastic-hinge approach [27-30] for predicting the ultimate load-carrying capacity of steel cable-stayed bridges.

California Department of Transportation (CalTrans) defines *"ordinary and standard bridges"* as those using normal weight concrete, with span lengths less than 90 m, and located in areas with no liquefiable soil [31]. Gindy et al. [32] present a state space approach for deriving bridge displacements from acceleration measurements under vehicular loads. Caracoglia et al. [33] present a computer model for the simulation of the aeroelastic loading associated with lock-in from wind-induced vortex shedding for use in dynamic analysis of long-span bridges.

Research on nonlinear seismic analysis of bridges over the past decade has led to an increased understanding of vertical and near fault ground motion effects, bridge-cable interaction in cable-stayed bridges, bridge-train interaction under earthquake excitation, torsional behavior of bridges, and the seismic response of CFT arch bridges.

Impact Studies

Yuan and Harik [34] present an elastoplastic spring-mass model for the analysis of multi-barge flotillas colliding with bridge piers taking into account pier geometry and stiffness, and dynamic interaction between barges. Ulker et al. [35] study portable concrete traffic barriers under vehicular impact and provide a set of design guidelines. Sharma et al. [36] investigate the feasibility of developing a bridge bumper with several options of energy absorbing materials to minimize the physical injuries and protect bridges by absorbing the impact energy. Tsang and Lam [37] study the collapse of reinforced concrete columns in bridges by vehicle impact. Clark et al. [38] study the behavior of roll over protective structures (ROPS) (devices attached to heavy vehicles to provide protection during an accidental roll over) analytically and experimentally.

Hazard Analysis

Performance and probabilistic analyses are used to assess the socioeconomic repercussions of bridge damage states for use in bridge design and maintenance decisions. Hose et al. [39] present a parametric performance-based assessment method for RC bridges along with sample case studies. Probability-based assessment of bridges has been studied by Monti and Nisticò [40]. Fragility curves provide estimates of the probabilities of exceeding a particular limit state during a given level of ground motion intensity for an individual structure or a type of structures, and have been studied by Karim and Yamazaki [41].

Pan et al. [42] present fragility curves of Peak Ground Accelerations (PGA) for multispan continuous steel girder bridges indicative of those found in the Northeastern United States using 3D FE models subjected to 100 simulated seismic events. They conclude that *"bridges in New York State have reasonably low likelihood of collapse during expected earthquakes."* Banerjee and Shinozuka [43] present a nonlinear static procedure for developing fragility curves and seismic vulnerability assessment of bridges using the capacity spectrum method for identification of spectral displacement.

Wilson and Holmes [44] investigate the vulnerability of cable stayed bridges to seismic events during cantilevered construction using six 3D FE models simulating various stages of construction of the 675 m long Fred Hartman Bridge in Texas subjected to 12 seismic events. The authors debunk *"a common misconception that seismic loading during construction need not be considered because of the relatively short duration of construction."* They conclude that seismic vulnerability may be substantially greater for an incomplete bridge during construction than when the bridge is completed, especially during the final phases of construction, and the use of tie down cables are effective in reducing earthquake susceptibility.

Life cycle cost analysis and design of structures has been advanced recently as a more logical approach for design [45-46]. Kumar et al. [47] present a probabilistic approach for Life-Cycle Cost (LCC) analysis of corroding RC bridges in seismic regions.

Code Comparison

Based on a comparative study of seismic design of highway bridges carried out by the U.S. Federal Highway Administration and Japan's Public Works Research Institute, Yen et al. [48] and Park et al. [49] examine the differences between US (AASHTO) and Japanese design codes for RC bridge columns for simple two-span bridges using a design example and shake table tests. They found that while both codes are based on ultimate strength design the column designed according to US codes is smaller, more ductile, and has a larger reinforcement ratio and a longer period. The authors also conclude that the Japanese design will suffer a larger amount of damage, while the US based design will experience greater drift and residual displacement. Further, they note that "*The AASHTO column has spiral-type transverse reinforcement with closer spacings in contrast to the hoop-type transverse reinforcement with larger spacings for the JRA columns*" which explains the different behaviors.

VIBRATION CONTROL

Passive Control

Systems which lessen structural response by absorbing energy without feedback can be referred to as passive systems. These include Friction Pendulum Bearings (FPBs), seismic isolation using bearings or dampers made from various materials, Tuned Mass Dampers (TMDs), energy absorbing braces, and rocking piers. FPB systems have been studied by Abrahamson and Mitchell [50]. Constantinou et al. [51] present multiple configurations for a so-called toggle-brace system which combines conventional bracings with dampers. Roussis et al. [52] examine seismic isolation systems. Poovarodom et al. [53], and Chen and Kareem [54] study TMDs and their application.

From 1983 to 2004, twelve bridges in Iceland were base-isolated with Lead Rubber Bearings (LRBs). Bessason and Haflidason [55] describe the recorded response of Thjorsa River Bridge in Iceland, an arch truss bridge with an 83-m long span that is base-isolated with LRBs, to the 2000 South Iceland earthquakes ($M = 6.5$ and 6.6). They found that while the bridge is located rather close to the epicenter of the earthquakes (5 km and 16 km), the base isolation was effective in preventing serious damage and that traffic across the bridge was able to resume immediately after the earthquake. Liao et al. [56] compare the response of regular and LRB isolated 3-span continuous RC box girder bridges subjected to the near and far field records of the Chi Chi Taiwan earthquake and conclude that the PGA is the most important factor in determining the response of isolated bridges, and that during near-field earthquakes the base shear reduction from the use of bridge isolation is limited.

Choi et al. [57] investigate the use of rubber elastomeric bearings with prestrained wires of nickel titanium Shape Memory Alloy (SMA) as an alternative to conventional LRBs in a 3-span continuous steel girder bridge subjected to two different earthquakes. The results of cyclic deformation tests and nonlinear modeling show that the SMA rubber bearings perform better than the conventional bearings. The deck and relative displacements for the SMA bearings were greater than conventional bearings at low peak gravitational acceleration, but were reduced at high accelerations due to the strain hardening properties. Andrawes and DesRoches [58] study the effects of ambient temperature on SMA bearing behavior using a nonlinear dynamic FE model of a 417-m 18-span RC concrete box girder bridge subjected to 4 different earthquakes and conclude that the SMA bearings perform significantly better in limiting displacement at higher ambient temperatures.

Carden et al. [59] investigate buckling-restrained transverse braces in steel truss bridges which "*consist of a yielding steel core embedded inside a grout-filled tube such that it is restrained against all but the highest modes of buckling when in compression*" as ductile end cross frames. They perform shake table studies on an 18-m long two-girder single span bridge model subjected to the 1940 El Centro earthquake and conclude that buckling-restrained braces are superior to X angle braces.

In summary, a good number of papers have been published on the application of passive vibration control systems in bridges with a focus on seismic isolation designs, particularly LRBs, FPBs, and more recently, SMA bearings. Only representative papers were reviewed in this section.

Active, Semi-Active and Hybrid Control

Systems used to control bridges requiring power and a control algorithm can be classified as active, semi-active, or hybrid control depending on the exact methods employed. Active control normally requires significant amounts of energy to power systems such as hydraulic actuators to control the bridge response [60-76]. Semi-active systems require substantially less energy, such as Magneto-Rheological dampers (MR) or semi-active friction or stiffness dampers, and can be effective during a power outage (they can work with batteries). But the line between active and semi-active control systems is becoming fuzzy as increasingly more powerful batteries are developed. Hybrid control refers to the combination of semi-active or active control with passive control systems.

Xu et al. [77] propose using decentralized non-parametric neural network control of cables with actuators to influence the response of a cable stayed bridge. Semi-active control has been investigated by a number of other researchers [78,79]. Ruangrassamee and Kawashima [80] investigate nonlinear and pounding effects in bridges with hybrid control. Park et al. [81] discuss active control of cable-stayed bridges using a hierarchical fuzzy logic method [82-95] which is used as a supervisor, called Fuzzy Supervisor Control (FSC), for individual linear quadratic Gaussian control (LQG) of hydraulic actuators and apply the technique to the Bill Emerson Memorial Bridge subjected to 3 different earthquakes. Lee and Kawashima [96] study nonlinear behavior of a hybrid system consisting of variable dampers as a semi-active system and base isolation in a five-span continuous RC bridge subjected to near fault ground motions of the 1999 Chi-Chi, Taiwan, earthquake, with a Linear Quadratic Regulator (LQR) control modified with a time-delay compensation.

MR dampers are dampers filled with a fluid that respond to an applied magnetic force by reversibly changing to a semi-solid state with controllable properties [97]. Liu et al. [98] compare energy minimization, Lyapunov, fuzzy logic and variable structure system fuzzy logic control algorithms for use with MR dampers using shake table tests of a 1/12 scale model of a highway bridge with fail-safe MR dampers and conclude that the fuzzy logic and variable structure system fuzzy logic algorithms are preferable due to low energy requirements and implementation ease. Kim and Adeli [21] present vibration control of cable-stayed bridges under various seismic excitations using the robust wavelet-hybrid feedback LMS (Least Mean Squared) algorithm developed by Adeli and Kim [99]. Ok et al. [100] study semi-active control of cable-stayed bridges with magneto-rheological dampers using fuzzy logic as a control algorithm and applied it to the Bill Emerson Memorial Bridge.

In summary, bridge control using active, semi-active and hybrid systems is not widely used, however with the continued development of more efficient control systems, this technology could become a powerful tool for bridge designers, especially in long span, flexible bridges.

BRIDGE DAMAGE STUDIES

Per ASCE [101] and the U.S. Department of Transportation index, 26.9% (161,892 of 600,905) of bridges in the United States are structurally deficient or obsolete, leading to the increased risk of damage and the growing importance of damage identification.

Wallace et al. [102] examine over thirty highway bridges in Taiwan primarily consisting of prestressed RC I-girders on RC columns with or without bearings that were damaged during the 1999 Chi-Chi, Taiwan earthquake including twelve collapsed bridges. They found that the damage to the bridges was predominantly due to near fault effects. They also report that poor structural arrangements including short piers controlled by shear failure, insufficient transverse or vertical reinforcement, eccentric connections, and inadequate foundation performance contributed to bridge damage.

Imbsen et al. [103] evaluate the damage to bridges in Turkey after the 1999 Kocaeli earthquake ($M = 7.4$), mainly composed of continuous decks on short simple-span RC girders supported by elastomeric bearings on stiff RC columns with pile foundations and small seat width. The authors report in general good performance for bridges in the region, with one modern bridge collapse, which was caused by fault rupture, out of approximately one-hundred bridges in the area of extensive building damage. Other problems identified were damage to expansion joints due to pounding and inadequate capacity of transverse shear keys. The authors also note that the Bolu Viaduct which uses a passive energy dissipation system suffered only minor damage.

Torkamani and Lee [104] perform linear dynamic analysis of the 189 m tension tied arch Birmingham Bridge with a steel deck in Pittsburgh using the normal mode method subjected to the 1940 El Centro Earthquake, and conclude that "*steel deck tension-tied arch bridges may be subjected to severe damage and potential failure under high intensity seismic motions*". Chang et al. [105] studied the damage to the Chi-Lu single-pylon cable-stayed bridge with two 120-m spans during the 1999 Chi-Chi earthquake in Taiwan. At the time of the earthquake, the bridge was under construction and near completion with parts of the deck yet to be installed. The authors report a vertical crack in the pylon from the roadway to the level of the lowest cables and severe damage to the deck possibly due to unsymmetrical behavior of the incomplete bridge.

Bolton et al. [106] study the change in the modal properties of a 2-span continuous concrete box girder bridge damaged during an earthquake using a linear 3D FE model and the incremental single-input, multiple-output force response test method [107] to estimate the modal properties of the bridge before and after the Hector Mine Earthquake in California ($M = 7.1$). Ranf and Eberhard [108] present a strategy for prioritizing bridge inspections after an earthquake based on construction date and type of bridge using fragility curves as opposed to distance from epicenter, and note that movable bridges are particularly vulnerable.

Estimation of financial loss due to earthquake excitation is directly linked to structural response and damage to a bridge, which can be approximated by the likelihood that a design parameter will be exceeded. The work published in this area is mostly based on collection of data and reducing and presenting them in some form of linear or nonlinear regression model. Some are deterministic, others are based on the probability theory. Bradley et al. [109] propose a log-log hyperbolic model to fit the probabilistic seismic hazard analysis data for New Zealand regions taking into account the probability of overloading during a seismic event.

HEALTH MONITORING OF BRIDGES

Currently an increasing number of bridges are being outfitted with strain gauges, deflection gauges, accelerometers, dynamic weight-in-motion sensors, and temperature sensors for health monitoring purposes. This is especially true for long span, high priority bridges, and instrumentation already in place has resulted in response records for these bridges under earthquake excitations, especially in the Far East countries of Japan, China and South Korea.

Algorithmically, the problem of health monitoring of bridges is akin to the system identification problem which has a long history of research [110,111]. System identification can be divided into parametric system identification where the parameters of the structure such as stiffness and damping are identified and non-parametric system identification techniques. Neural networks have found many applications in various disciplines of civil engineering over the past two decades [112-136]. Huang and Loh [137] present a neural network-based non-parametric method for nonlinear system identification of bridges using the Nonlinear Auto Regressive Moving Average with Exogenous (NARMAX) approach [138] and apply it to a five-span continuous pre-stressed box-girder bridge located in Taiwan subjected to several different earthquake ground motions.

Pridham and Wilson [139,140] present a modal parameter estimation technique for linear structures employing stochastic subspace identification, expectation maximization algorithm, and the Monte Carlo simulation, and apply it to Quincy Bayview Bridge, a 542-m cable-stayed bridge in Illinois. Arici and Mosalam [141] study modal system identification of bridges using Monte Carlo simulations, linear FE models of 2 continuous multispan bridges subjected to real and simulated earthquake data, and applying a sensitivity analysis, and conclude that for health monitoring purposes "*only the first three modal frequencies and the 1st mode shape*" need be used for the particular type of bridges studies.

Bozdag et al. [142] perform vibration analysis of New Galata Bridge, a 480-m long bascule bridge with a movable central span of 75 m using data from strain gauges and accelerometers, and a dynamic FE analysis, and discovered that "*the first several natural frequencies of flaps are in the earthquake frequency range, especially at the unlocked situation*" which could cause failure of the bridge. Nagayama et al. [143] present a method of modal identification using natural excitation technique, eigensystem realization algorithm, and inverse analysis of structural properties, and apply it to Hakucho Bridge, a 1380-m steel box girder suspension bridge in Japan, using data from ambient vibrations to identify modes and changes in the structure. Çelebi [144] presents an overview of the real-time structural health monitoring system implemented on the cable-stayed Bill Emerson Memorial Bridge using a broadband network and accelerometers.

With a focus on the use of a smaller number of sensors, Zhou et al. [145] evaluate different vibration-based damage detection methods for bridges based on changes in the fundamental mode shape, curvature, and flexibility using 3D dynamic FE models and experimental results on a half-scale model of a single span concrete slab on steel girder bridge deck monitored with accelerometers and strain gauges and conclude that methods based on changes in the mode shape and flexibility methods performed better than other methods in the absence of experimental data. However the accuracy for all techniques was significantly reduced if the damage was located near the supports. Zhu et al. [146] discuss identification of flutter derivatives of a long-span self-anchored suspension bridge using wind tunnel studies and computational fluid dynamics. Mondal and DeWolf [147] describe a computer-based remote monitoring system for the temperature monitoring of an eleven span segmental, post-tensioned concrete box-girder bridge.

Siringoringo and Fujino [148] present parametric system identification of long cable-stayed bridges in the Tokyo Bay area with main span lengths in the range 455-570 m using accelerograms from the 2004

Niigata earthquake. He et al. [149] identify the modal parameters through wind-induced vibration response of Vincent Thomas Bridge, a suspension bridge located in San Pedro near Los Angeles, California, using the data-driven stochastic subspace identification method. Carden and Brownjohn [150] apply "*covariance-driven stochastic subspace identification*" and fuzzy clustering algorithm [151,152] to data obtained from a 3-span post-tensioned concrete box girder bridge with a main span of 30 m. Belli et al. [153] present model based evaluation of reinforced concrete bridge decks with defects using ground penetrating radar and a computational scheme for interpretation of scanned images.

Ren et al. [154] study wavelet packet [155,156] energy changes to assess the integrity of shear connectors in slab on girder bridges using a 1:3 scaled model of a single span RC bridge. Ni et al. [157] study damage identification of Ting Kau cable-stayed bridge by defining a relative flexibility change index. Soyoz and Feng [158] report wireless vibration monitoring of a three-span 111-m long concrete bridge instrumented with 13 acceleration sensors, with the goal of identifying changes in the bridge structure over a five-year period. Cruz and Salgado [159] evaluate *six damage detection methods for vibration monitoring of reinforced concrete bridges*.

Research in this area needs to be developed further for reliable real time health monitoring and remote damage identification of bridges.

BRIDGE MANAGEMENT

There are around 600,000 bridges in the U.S. [160] which are managed by states and counties depending on their jurisdictions. Commercial bridge management systems such as Pontis [161] are used by different highway agencies with limited success. Research on development of effective bridge management systems has been reported by a number of researchers.

Sirca and Adeli [162] and Waheed and Adeli [163] present a methodology and an intelligent decision support system to help bridge engineers convert a Working Stress Design (WSD)-based bridge rating to the Load Factor Design (LFD)-based rating with little human effort using Case-Based Reasoning (CBR) [164]. Hammad et al. [165] describe a mobile model-based bridge lifecycle management system developed in Java that links data about the entire lifecycle stages of a bridge including design, construction, inspection, and maintenance to a 4D virtual model of the bridge. Elbehairy et al. [166] present a bridge repair management system that attempts to minimize the life-cycle cost of repair of seven bridge components: deck, superstructure, substructure, bearings, joints, overlay, and finishing by integrating both project-level and network-level decisions. They use genetic algorithms as their optimization approach [165-172].

RETROFITTING

Steel truss and RC bridges have been popular bridge options for decades, though some of the older designs fail to meet current code requirements for seismic loads. In order to rectify the deficiencies the bridge may need to be retrofitted as an alternative to complete replacement. Many different retrofit systems have been developed and evaluated such as structural fuse systems [173-174], ductile end frames [175], jackets comprised of steel or composite materials [176-178], base isolation as described in the control section of this paper, link slabs [179], SMA restrainers [180] and ground-level beams [181].

Paultre et al. [182] study the effects of retrofits to Beauharnois Bridge, a suspension bridge in Canada with a main span of 177 m. The retrofits included replacing the bridge deck with an orthotropic slab on steel trusses, and adding cable stays which change the bridge to a hybrid cable-stayed-suspension structure. Ingham [183] describes the seismic retrofit of the historic Million Dollar Bridge in Alaska that was damaged during the 1964 Prince William Sound earthquake. The retrofit consisted of replacement of a damaged pier and seismic isolation using FPBs. Zanardo et al. [184] study the application of FRP retrofit techniques for short RC arch bridges using FE models subjected to both single and multiple accelerograms applied at different piers. They report that using FRP with concrete overlays to increase section thickness is "*the most workable solution*" to retrofit such bridges.

Murphy and Collins [185] propose the retrofit of suspension bridges with friction and hysteretic dampers along the suspended span through the simulation of the FE model of a suspension bridge with a 655 m main span subjected to six synthetic earthquakes typical of those occurring in Central and Eastern U.S. Uang et al. [186] investigate the shear links and orthotropic deck used in the retrofitting of the same bridge employing large scale cyclic tests and nonlinear FE analysis and found that "*for capacity design, the overstrength factor (1.25) as specified in the AISC Seismic Provisions is significantly lower than that measured (1.83 to 1.94) and is, thus, non-conservative for the links tested.*"

A common problem with older bridge columns is lack of confinement and resistance to spalling when subjected to shear forces typically developed during major seismic events. Solutions to this problem involve retrofitting these columns with concrete or steel jackets. Haroun and Elsanadedy [187] study behavior of cyclically loaded squat RC bridge columns retrofitted with jackets made of different composite materials, and conclude that composite jackets are effective and do not modify the load distribution and reaction of the structure, an advantage over conventional steel jackets. Cheng et al. [188] investigate the use of carbon FRP composite jackets as a retrofit method for hollow columns using full scale tests and conclude that carbon FRP jackets are an effective repair and retrofit method for hollow sections.

CONCLUDING COMMENTS

Notable advances in the field of earthquake engineering of bridges have been made in the past decade, especially in the form of improved bracing systems, connections, passive energy dissipation systems such as base isolation, active and hybrid control systems, and retrofitting of existing bridges incorporating recently developed materials such as composites and SMA. Enhanced models of different types of bridges, components and their interactions using finite element and nonlinear analyses are continuously being developed to better simulate actual behavior and component interaction. Innovations in efficient component and system design and bridge management systems have led to lower cost and safer structures.

Due to the increased use of health monitoring systems and the huge amount of data they produce research will continue on development of more effective approaches for automated real-time damage detection and health monitoring of bridges. Research on semi-active and hybrid control of structures, so-called smart structures, has the potential to yield more efficient bridge structures. Newer computing paradigms and technologies, such as case-based reasoning, genetic algorithms, and wavelet signal processing will find additional applications in bridge engineering.

REFERENCES

1. Adeli, H., Gere, J. and Weaver, W. Jr. "Algorithms for nonlinear structural dynamics", *Journal of Structural Division*, ASCE, **104**(ST2), pp. 263-280 (1978).
2. Yu, G. and Adeli, H. "Object-oriented finite element analysis using EER model", *Journal of Structural Engineering*, ASCE, **119**(9), pp. 2763-2781 (1993).
3. Adeli, H. and Kumar, S. "Distributed finite element analysis on a network of workstations - algorithms", *Journal of Structural Engineering*, ASCE, **121**(10), pp. 1448-1455 (1995).
4. Kumar, S. and Adeli, H. "Distributed finite element analysis on a network of workstations - implementation and applications", *Journal of Structural Engineering*, ASCE, **121**(10), pp. 1456-1462 (1995).
5. Yu, G., Tzeng, G.Y., Chaturvedi, S., Adeli, H. and Zhang, S.Q. "A finite element approach to global-local modeling in composite laminate analysis", *Computers and Structures*, **57**(6), pp. 1035-1044 (1995).
6. Moaveni, B., Conte, J.P. and Hemez, F.M. "Uncertainty and sensitivity analysis of damage identification results obtained using finite element model updating", *Computer-Aided Civil and Infrastructure Engineering*, **24**(5), pp. 320-334 (2009).
7. Consolazio, G.R. "Iterative equation solver for bridge analysis using neural networks", *Computer-Aided Civil and Infrastructure Engineering*, **15**(2), pp. 107-119 (2000).
8. Villaverde, I., Grana, M. and d'Anjou, A. "Morphological neural networks and vision based simultaneous localization and mapping", *Integrated Computer-Aided Engineering*, **14**(4), pp. 355-363 (2007).
9. Panakkat, A. and Adeli, H. "Recurrent neural network for approximate earthquake time and location prediction using multiple seismicity indicators", *Computer-Aided Civil and Infrastructure Engineering*, **24**(4), pp. 280-292 (2009).
10. Pande, A. and Abdel-Aty, M. "A computing approach using probabilistic neural networks for instantaneous appraisal of rear-end crash risk", *Computer-Aided Civil and Infrastructure Engineering*, **23**(7), pp. 549-559 (2008).
11. Panakkat, A. and Adeli, H. "Neural network models for earthquake magnitude prediction using multiple seismicity indicators", **17**(1), pp. 13-33 (2007).
12. Zou, W., Chi, Z. and Lo, K.C. "Improvement of image classification using wavelet coefficients with structured-based neural network", *International Journal of Neural Systems*, **18**(3), pp. 195-205 (2008).
13. Nemissi, M., Seridi, H. and Akdag, H. "The labeled systems of multiple neural networks", *International Journal of Neural Systems*, **18**(4), pp. 321-330 (2008).
14. Schneider, N.C. and Graupe, D. "A modified lamstar neural network and its applications", *International Journal of Neural Systems*, **18**(4), pp. 331-337 (2008).
15. Savitha, R., Suresh, S. and Sundararajan, N. "A fully complex-valued radial basis function network and its learning algorithm", *International Journal of Neural Systems*, **19**(4), pp. 253-267 (2009).
16. Khashman, A. "A neural network model for credit risk evaluation", *International Journal of Neural Systems*, **19**(4), pp. 285-294 (2009).
17. Ghosh-Dastidar, S. and Adeli, H. "Spiking neural networks", *International Journal of Neural Systems*, **19**(4), pp. 295-308 (2009).
18. Meng, J.Y. and Lui, E.M. "Torsional effects on short-span highway bridges", *Computers and Structures*, **75**(6), pp. 619-629 (2000).
19. Linzell, D.G. "The role of computer models in full-scale bridge laboratory tests", *Computer-Aided Civil and Infrastructure Engineering*, **16**(6), pp. 431-443 (2001).
20. Adeli, H. and Zhang, J. "Fully nonlinear analysis of composite girder cable-stayed bridges", *Computers and Structures*, **54**(2), pp. 267-277 (1995).

21. Kim, H. and Adeli, H. "Wavelet hybrid feedback-LMS algorithm for robust control of cable-stayed bridges", *Journal of Bridge Engineering*, **10**(2), pp. 116-123 (2005).

22. Ni, Y.Q., Wang, J.Y. and Lo, L.C. "Influence of stabilizing cables on seismic response of a multispan cable stayed bridge", *Computer-Aided Civil and Infrastructure Engineering*, **20**(2), pp. 142-153 (2005).

23. Shao, Y., Aval, S. and Mirmiran, A. "Fiber-element model for cyclic analysis of concrete-filled fiber reinforced polymer tubes", *Journal of Structural Engineering*, **131**(2), pp. 292-303 (2005).

24. Wu, Q., Yoshimura, M., Takahashi, K., Nakamura, S. and Nakamura, T. "Nonlinear seismic properties of the second Saikai Bridge, a concrete filled tubular (CFT) arch bridge", *Engineering Structures*, **28**(2), pp. 163-182 (2006).

25. Nielson, B.G. and DesRoches, R. "Seismic performance assessment of simply supported and continuous multispan concrete girder highway bridges", *Journal of Bridge Engineering*, **12**(5), pp. 611-620 (2007).

26. Song, W.K., Kim, S.E. and Ma, S.S. "Nonlinear analysis of steel cable-stayed bridges", *Computer-Aided Civil and Infrastructure Engineering*, **22**(5), pp. 358-366 (2007).

27. Adeli, H. and Chyou, H. "Plastic analysis of irregular frames on microcomputers", *Computers and Structures*, **23**(2), pp. 233-240 (1986).

28. Park, H.S. and Adeli, H. "A neural dynamics model for structural optimization - application to plastic design of structures", *Computers and Structures*, **57**(3), pp. 391-399 (1995).

29. Adeli, H. and Mabrouk, N. "Optimum plastic design of unbraced frames of irregular configuration", *International Journal of Solids and Structures*, **22**(10), pp. 1117-1128 (1986).

30. Adeli, H. and Manomaiphibul, T. "On the plastic design of braced frames", *International Journal of Civil Engineering for Practicing and Design Engineers*, **5**(9), pp. 815-848 (1986).

31. CalTrans "Seismic design criteria", SDC-2006, California Department of Transportation, Sacramento, California (2006).

32. Gindy, M., Vaccaro, R., Nassif, H. and Velde, J. "A state-space approach for deriving bridge displacement from acceleration", *Computer-Aided Civil and Infrastructure Engineering*, **23**(4), pp. 281-290 (2008).

33. Caracoglia, L., Noè, S. and Sepe, V. "Nonlinear computer model for the simulation of lock-in vibration on long-span bridges", *Computer-Aided Civil and Infrastructure Engineering*, **24**(2), pp. 130-144 (2009).

34. Yuan, P. and Harik, I.E. "One-dimensional model for multi-barge flotillas impacting bridge piers", *Computer-Aided Civil and Infrastructure Engineering*, **23**(6), pp. 437-447 (2008).

35. Ulker, M.B.C., Rahman, M.S., Zhen, R. and Mirmiran, A. "Traffic barriers under vehicular impact: from computer simulation to design guidelines", *Computer-Aided Civil and Infrastructure Engineering*, **23**(6), pp. 465-480 (2008).

36. Sharma, H., Hurlebaus, S. and Gardoni, P. "Development of a bridge bumper to protect bridge girders from overheight vehicle impacts", *Computer-Aided Civil and Infrastructure Engineering*, **23**(6), pp. 415-426 (2008).

37. Tsang, H.H. and Lam, N.T.K. "Collapse of reinforced concrete column by vehicle impact", *Computer-Aided Civil and Infrastructure Engineering*, **23**(6), pp. 427-436 (2008).

38. Clark, B.J., Thambiratnam, D. and Perera, N.J. "Dynamic impact analysis of a roll over protective structure", *Computer-Aided Civil and Infrastructure Engineering*, **23**(6), pp. 448-464 (2008).

39. Hose, Y., Silva, P. and Frieder, S. "Development of a performance evaluation database for concrete bridge components and systems under simulated seismic loads", *Earthquake Spectra*, **16**(2), pp. 707-715 (2000).

40. Monti, G. and Nisticò, N. "Simple probability-based assessment of bridges under scenario earthquakes", *Journal of Bridge Engineering*, **7**(2), pp. 104-114 (2002).

41. Karim, K.R. and Yamazaki, F. "Effect of earthquake ground motions on fragility curves of highway bridge piers based on numerical simulation", *Earthquake Engineering and Structural Dynamics*, **30**(12), pp. 1839-1856 (2001).

42. Pan, Y., Agrawal, A.K. and Ghosn, M. "Seismic fragility of continuous steel highway bridges in New York state", *Journal of Bridge Engineering*, **12**(6), pp. 689-699 (2007).

43. Banerjee, S. and Shinozuka, M. "Nonlinear static procedure for seismic vulnerability assessment of bridges", *Computer-Aided Civil and Infrastructure Engineering*, **22**(4), pp. 293-305 (2007).

44. Wilson, J.C. and Holmes, K. "Seismic vulnerability and mitigation during construction of cable-stayed bridges", *Journal of Bridge Engineering*, **12**(3), pp. 364-372 (2007).

45. Sarma, K.C. and Adeli, H. "Life-cycle cost optimization of steel structures", *International Journal for Numerical Methods in Engineering*, **55**(12), pp. 1451-1462 (2002).

46. Adeli, H. and Sarma, K., *Cost Optimization of Structures - Fuzzy Logic, Genetic Algorithms and Parallel Computing*, Wiley, West Sussex, United Kingdom (2006).

47. Kumar, R., Gardoni, P. and Sanchez-Silva, M. "Effect of cumulative seismic damage and corrosion on the life-cycle cost of reinforced concrete bridges", *Earthquake Engineering and Structural Dynamics*, **38**(7), pp. 887-905 (2009).

48. Yen, W.P., Cooper, J.D., Park, S.W., Unjoh, S., Terayama, T. and Otsuka, H. "A comparative study of U.S.-Japan seismic design of highway bridges: I. design methods", *Earthquake Spectra*, **19**(4), pp. 913-932 (2003).

49. Park, S.W., Yen, W.P., Cooper, J.D., Unjoh, S., Terayama, T. and Otsuka, H. "A comparative study of U.S.-Japan seismic design of highway bridges: ii. shake-table model tests", *Earthquake Spectra*, **19**(4), pp. 933-958 (2003).

50. Abrahamson, E. and Mitchell, S. "Seismic response modification device elements for bridge structures development and verification", *Computers and Structures*, **81**(8-11), pp. 463-467 (2003).

51. Constantinou, M.C., Tsopelas, P., Hammel, W. and Sigaher, A.N. "Toggle-brace-damper seismic energy dissipation systems", *Journal of Structural Engineering*, **127**(2), pp. 105-112 (2001).

52. Roussis, P.C., Constantinou, M.C., Erdik, M., Durukal, E. and Dicleli, M. "Assessment of performance of seismic isolation system of bolu viaduct", *Journal of Bridge Engineering*, **8**(4), pp. 182-190 (2003).

53. Poovarodom, N., Kanchanosot, S. and Warnitchai, P. "Application of non-linear multiple tuned mass dampers to suppress man-induced vibrations of a pedestrian bridge", *Earthquake Engineering and Structural Dynamics*, **32**(7), pp. 1117-1131 (2003).

54. Chen, X. and Kareem, A. "Efficacy of tuned mass dampers for bridge flutter control", *Journal of Structural Engineering*, **129**(10), pp. 1291-1300 (2003).

55. Bessason, B. and Haflidason, E. "Recorded and numerical strong motion response of a base-isolated bridge", *Earthquake Spectra*, **20**(2), pp. 309-332 (2004).

56. Liao, W.I, Loh, C.H. and Lee, B.H. "Comparison of dynamic response of isolated and non-isolated continuous girder bridges subjected to near-fault ground motions", *Engineering Structures*, **26**(14), pp. 2173-2183 (2004).

57. Choi, E., Nam, T.H. and Cho, B.S. "A new concept of isolation bearings for highway steel bridges using shape memory alloys", *Canadian Journal of Civil Engineering*, **32**, pp. 957-967 (2005).

58. Andrawes, B. and DesRoches, R. "Effect of ambient temperature on the hinge opening in bridges with shape memory alloy seismic restrainers", *Engineering Structures*, **29**(9), pp. 2294-2301 (2007).

59. Carden, L.P., Itani, A.M. and Buckle, I.G. "Seismic performance of steel girder bridges with ductile cross frames using buckling-restrained braces", *Journal of Structural Engineering*, **132**(3), pp. 338-345 (2006).

60. Saleh, A. and Adeli, H. "Parallel algorithms for integrated structural and control optimization", *Journal of Aerospace Engineering*, **7**(3), pp. 297-314 (1994).

61. Saleh, A. and Adeli, H. "Parallel eigenvalue algorithms for large-scale control-optimization problems", *Journal of Aerospace Engineering*, ASCE, **9**(3), pp. 70-79 (1996).

62. Adeli, H. and Saleh, A. "Optimal control of adaptive/smart bridge structures", *Journal of Structural Engineering*, **123**(2), pp. 218-226 (1997).

63. Saleh, A. and Adeli, H. "Robust parallel algorithms for solution of the riccati equation", *Journal of Aerospace Engineering*, **10**(3), pp. 126-133 (1997).

64. Adeli, H. and Saleh, A. "Integrated structural/control optimization of large adaptive/smart structures", *International Journal of Solids and Structures*, **35**(28-29), pp. 3815-3830 (1998).

65. Saleh, A. and Adeli, H. "Optimal control of adaptive/smart building structures", *Computer-Aided Civil and Infrastructure Engineering*, **13**(6), pp. 389-403 (1998).

66. Saleh, A. and Adeli, H. "Optimal control of adaptive building structures under blast loading", *Mechatronics*, **8**(8), pp. 821-844 (1998).

67. Kim, H. and Adeli, H. "Hybrid feedback-least mean square algorithm for structural control", *Journal of Structural Engineering*, **130**(1), pp. 120-127 (2004).

68. Kim, H. and Adeli, H. "Hybrid control of smart structures using a novel wavelet-based algorithm", *Computer-Aided Civil and Infrastructure Engineering*, **20**(1), pp. 7-22 (2005).

69. Kim, H. and Adeli, H. "Hybrid control of irregular steel highrise building structures under seismic excitations", *International Journal for Numerical Methods in Engineering*, **63**(12), pp. 1757-1774 (2005).

70. Kim, H. and Adeli, H. "Wind-induced motion control of 76-story benchmark building using the hybrid damper-tuned liquid column damper system", *Journal of Structural Engineering*, **131**(12), pp. 1794-1802 (2005).

71. Hentschel, M. Wulf, O. and Wagner, B. "A hybrid feedback controller for car-like robots - combining reactive obstacle avoidance and global replanning", *Integrated Computer-Aided Engineering*, **14**(1), pp. 3-14 (2007).

72. Shih, M.C and Wang, T.Y. "Active control of electro - rheological fluid embedded pneumatic vibration isolator ", *Integrated Computer-Aided Engineering*, **15**(3), pp. 267-276 (2008).

73. Jiang, X. and Adeli, H., Neuro-genetic algorithm for nonlinear active control of highrise buildings", *International Journal for Numerical Methods in Engineering*, **75**(7), pp. 770-786 (2008).

74. Suresh, S., Kannan, N., Sundararajan, N. and Saratchandran, P. "Neural adaptive control for vibration suppression in composite fin-tip of aircraft", *International Journal of Neural Systems*, **18**(3), pp. 219-231 (2008).

75. Liu, M. and Zhang, S. "An LMI approach to design H_∞ controllers for discrete-time nonlinear systems based on unified models", *International Journal of Neural Systems*, **18**(5), pp. 443-452 (2008).

76. Chen, J.P., Webster, R.S., Hathaway, M.D., Herrick, G.P. and Skoch, G.J. "High performance computing of compressor rotating stall and stall control", *Integrated Computer-Aided Engineering*, **16**(2), pp. 75-89 (2009).

77. Xu, B., Wu, Z.S. and Yokoyama, K. "Neural networks for decentralized control of cable-stayed bridge", *Journal of Bridge Engineering*, **8**(4), pp. 229-236 (2003).

78. Erkus, B., Abé, M. and Fujino, Y. "Investigation of semi-active control for seismic protection of elevated highway bridges", *Engineering Structures*, **24**(3), pp. 281-293 (2002).

79. Agrawal, A.K., Yang, J.N. and He, W.L. "Applications of some semiactive control systems to benchmark cable-stayed bridge", *Journal of Structural Engineering*, **129**(7), pp. 884-894 (2003).

80. Ruangrassamee, A. and Kawashima, K. "Control of nonlinear bridge response with pounding effect by variable dampers", *Engineering Structures*, **25**(5), pp. 593-606 (2003).

81. Park, K.S., Koh, H.M., Ok, S.Y. and Seo, C.W. "Fuzzy supervisory control of earthquake-excited cable-stayed bridges for a seismically excited cable-stayed bridge", *Engineering Structures*, **27**(7), pp. 1086-1100 (2005).

82. Sarma, K. and Adeli, H. "Fuzzy discrete multicriteria cost optimization of steel structures", *Journal of Structural Engineering*, **126**(11), pp. 1339-1347 (2000).

83. Adeli, H. and Karim, A. "Fuzzy-wavelet RBFNN model for freeway incident detection", *Journal of Transportation Engineering*, **126**(6), pp. 464-471 (2000).

84. Karim, A. and Adeli, H. "Comparison of the fuzzy-wavelet RBFNN freeway incident detection model with the California algorithm", *Journal of Transportation Engineering*, **128**(1), pp. 21-30 (2002).

85. Adeli, H. and Jiang, X. "Neuro-fuzzy logic model for freeway work zone capacity estimation", *Journal of Transportation Engineering*, **129**(5), pp. 484-493 (2003).

86. Adeli, H. and Jiang, X. "Dynamic fuzzy wavelet neural network model for structural system identification", *Journal of Structural Engineering*, **132**(1), pp. 102-111 (2006).

87. Smith, J.F. and Nguyen, T.H. "Autonomous and cooperative robotic behavior based on fuzzy logic and genetic programming", *Integrated Computer-Aided Engineering*, **14**(2), pp. 141-159 (2007).

88. Sabourin, C. Madani, K. and Bruneau, O. "Autonomous biped gait pattern based on fuzzy-CMAC neural networks", *Integrated Computer-Aided Engineering*, **14**(2), pp. 173-186 (2007).

89. Jiang, X. and Adeli, H. "Dynamic fuzzy wavelet neuroemulator for nonlinear control of irregular high-rise building structures", *International Journal for Numerical Methods in Engineering*, **74**(7), pp. 1045-1066 (2008).

90. Stathopoulos, A., Dimitriou, L. and Tsekeris, T. "Fuzzy modeling approach for combined forecasting of urban traffic flow", *Computer-Aided Civil and Infrastructure Engineering*, **23**(7), pp. 521-535 (2008).

91. Perusich, K. "Using fuzzy cognitive maps to identify multiple causes in troubleshooting systems", *Integrated Computer-Aided Engineering*, **15**(2), pp. 197-206 (2008).

92. Rigatos, G.G. "Adaptive fuzzy control with output feedback for H-infinity tracking of SISI nonlinear systems", *International Journal of Neural Systems*, **18**(4), pp. 305-320 (2008).

93. Jin, X.L. and Doloi, H. "Modelling risk allocation decision-making in PPP projects using fuzzy logic", *Computer-Aided Civil and Infrastructure Engineering*, **24**(7), pp. 509-524 (2009).

94. Villar, J.R., de la Cal, E. and Sedano, J. "A fuzzy logic based efficient energy saving approach for domestic heating systems", *Integrated Computer-Aided Engineering*, **16**(2), pp. 151-163 (2009).

95. Haidar, A.M.A., Mohamed, A., Al-Dabbagh, M., Aini Hussain, A., and Masoum, M. "An intelligent load shedding scheme using neural networks & neuro-fuzzy", *International Journal of Neural Systems*, **19**(6), pp. 473-479 (2009).

96. Lee, T.Y. and Kawashima, K. "Semiactive control of nonlinear isolated bridges with time delay", *Journal of Structural Engineering*, **133**(2), pp. 235-241 (2007).

97. LORD Corporation "What is magneto-rheological (MR) fluid?" http://www.lord.com /Home/MagnetoRheologicalMRFluid/ MRFluidTechnology/WhatisMR/tabid/3772/ Default.aspx (2008).

98. Liu, Y., Gordaninejad, F., Evrensel, C.A., Wang, X. and Hitchcock, G. "Comparative study on vibration control of a scaled bridge using fail-safe magneto-rheological fluid dampers", *Journal of Structural Engineering*, **131**(5), pp. 743-751 (2005).

99. Adeli, H. and Kim, H. "Wavelet-hybrid feedback-least mean square algorithm for robust control of structures", *Journal of Structural Engineering*, **130**(1), pp. 128-137 (2004).

100. Ok, S.Y., Kim, D.S., Park, K.S. and Koh, H.M. "Semi-active fuzzy control of cable-stayed bridges using magneto-rheological dampers", *Engineering Structures*, **29**(5), pp. 776-788 (2007).

101. American Society of Civil Engineers (ASCE) "Report card for america's infrastructure: bridges", http://www.infrastructurereportcard.org/fact-sheet/br idges (2009).

102. Wallace, J.W., Eberhard, M.O., Hwang, S.J., Moehle, J.P., Post, T., Roblee, C., Stewart, J.P. and Yashinsky, M. "Highway bridges", *Earthquake Spectra*, **17**(S1), pp. 131-152 (2001).

103. Imbsen, R.A., Roblee, C.J., Yashinsky, M., Berilgen, M.M. and Toprak, S. "Impact on highway structures", *Earthquake Spectra*, **16**(S1), pp. 411-435 (2001).

104. Torkamani, M.A.M. and Lee, H.E. "Dynamic behavior of steel deck tension-tied arch bridges to seismic excitation", *Journal of Bridge Engineering*, **7**(1), pp. 57-67 (2002).

105. Chang, K.C., Mo, Y.L., Chen, C.C., Lai, L.C. and Chou, C.C. "Lessons learned from the damaged Chi-Lu cable-stayed bridge", *Journal of Bridge Engineering*, **9**(4), pp. 343-352 (2004).

106. Bolton, R., Sikorsky, C., Park, S., Choi, S. and Stubbs, N. "Modal property changes of a seismically damaged concrete bridge", *Journal of Bridge Engineering*, **10**(4), pp. 415-428 (2005).

107. Ewing, D.J., *Modal Testing: Theory and Practice*, Research Studies Press, Letchworth, UK (1984).

108. Ranf, R.T. and Eberhard, M.O. "Post-earthquake prioritization of bridge inspections", *Earthquake Spectra*, **23**(1), pp. 131-146 (2007).

109. Bradley, B.A., Dhakel, R.P., Cubrinovski, M., Mander, J.B. and MacRae, G.A. "Improved seismic hazard model with application to probabilistic seismic demand analysis", *Earthquake Engineering and Structural Dynamics*, **36**(14), pp. 2211-2225 (2007).

110. Adeli, H. and Jiang, X., *Intelligent Infrastructure - Neural Networks, Wavelets and Chaos Theory for Intelligent Transportation Systems and Smart Structures*, CRC Press, Boca Raton, Florida (2009).

111. Puscasu, G. and Codres, B. "Nonlinear system identification based on internal recurrent neural networks", *International Journal of Neural Systems*, **19**(2), pp. 115-125 (2009).

112. Adeli, H. and Hung, S.L. "A concurrent adaptive conjugate gradient learning algorithm on MIMD machines", *Journal of Supercomputer Applications*, MIT Press, **7**(2), pp. 155-166 (1993).

113. Hung, S.L and Adeli, H. "Parallel backpropagation learning algorithms on cray Y-MP8/864 supercomputer", *Neurocomputing*, **5**(6), pp. 287-302 (1993).

114. Hung S.L. and Adeli, H. "A parallel genetic/neural network learning algorithm for MIMD shared memory machines", *IEEE Transactions on Neural Networks*, **5**(6), pp. 900-909 (1994).

115. Hung, S.L. and Adeli, H. "Object-oriented back propagation and its application to structural design", *Neurocomputing*, **6**(1), pp. 45-55 (1994).

116. Adeli, H. and Hung, S.L. "An adaptive conjugate gradient learning algorithm for effective training of multilayer neural networks", *Applied Mathematics and Computation*, **62**(1), pp. 81-102 (1994).

117. Adeli, H. and Park, H.S. "Counter propagation neural network in structural engineering", *Journal of Structural Engineering*, ASCE, **121**(8), pp. 1205-1212 (1995).

118. Adeli, H. and Park, H.S. "A neural dynamics model for structural optimization - theory", *Computers and Structures*, **57**(3), pp. 383-390 (1995).

119. Adeli, H. and Park, H.S. "Optimization of space structures by neural dynamics", *Neural Networks*, **8**(5), pp. 769-781 (1995).

120. Adeli, H. and Park, H.S. "Fully automated design of superhighrise building structure by a hybrid AI model on a massively parallel machine", *AI Magazine*, **17**(3), pp. 87-93 (1996).

121. Park, H.S. and Adeli, H. "Distributed neural dynamics algorithms for optimization of large steel structures", *Journal of Structural Engineering*, ASCE, **123**(7), pp. 880-888 (1997).

122. Adeli, H. and Karim, A. "Neural network model for optimization of cold-formed steel beams", *Journal of Structural Engineering*, ASCE, **123**(11), pp. 1535-1543 (1997).

123. Adeli, H. and Karim, A. "Scheduling/cost optimization and neural dynamics model for construction", *Journal of Construction Management and Engineering*, ASCE, **123**(4), pp. 450-458 (1997).

124. Adeli, H. and Wu, M. "Regularization neural network for construction cost estimation", *Journal of Construction Engineering and Management*, ASCE, **124**(1), pp. 18-24 (1998).

125. Adeli, H. and Samant, A. "An adaptive conjugate gradient neural network - wavelet model for traffic incident detection", *Computer-Aided Civil and Infrastructure Engineering*, **15**(4), pp. 251-260 (2000).

126. Senouci, A.B. and Adeli, H. "Resource scheduling using neural dynamics model of Adeli and Park", *Journal of Construction Engineering and Management*, ASCE, **127**(1), pp. 28-34 (2001).

127. Samant, A. and Adeli, H. "Enhancing neural network incident detection algorithms using wavelets", *Computer-Aided Civil and Infrastructure Engineering*, **16**(4), pp. 239-245 (2001).

128. Sirca, G. and Adeli, H. "Neural network model for uplift load capacity of metal roof panels", *Journal of Structural Engineering*, **127**(11), pp. 1276-1285 (2001).

129. Adeli, H. and Kim, H. "Cost optimization of composite floors using the neural dynamics model", *Communications in Numerical Methods in Engineering*, **7**, pp. 771-787 (2001).

130. Karim, A. and Adeli, H. "CONSCOM: An OO construction scheduling and change management system", *Journal of Construction Engineering and Management*, **125**(5), pp. 368-376 (1999).

131. Tashakori, A.R. and Adeli, H. "Optimum design of cold-formed steel space structures using neural dynamic model", *Journal of Constructional Steel Research*, **58**(12), pp. 1545-1566 (2002).

132. Karim, A. and Adeli, H. "Radial basis function neural network for work zone capacity and queue

estimation", *Journal of Transportation Engineering*, **129**(5), pp. 494-503 (2003).

133. Dharia, A. and Adeli, H. "Neural network model for rapid forecasting of freeway link travel time", *Engineering Applications of Artificial Intelligence*, **16**(7-8), pp. 607-613 (2003).

134. Hooshdar, S. and Adeli, H. "Toward intelligent variable message signs in freeway work zones: a neural network approach", *Journal of Transportation Engineering*, **130**(1), pp. 83-93 (2004).

135. Ahmadkhanlou, F. and Adeli, H. "Optimum cost design of reinforced concrete slabs using neural dynamics model", *Engineering Applications of Artificial Intelligence*, **18**(1), pp. 65-72 (2005).

136. Sirca, G. and Adeli, H. "Cost optimization of prestressed concrete bridges", *Journal of Structural Engineering*, ASCE, **131**(3), pp. 380-388 (2005).

137. Huang, C.C. and Loh, C.H. "Nonlinear identification of dynamic systems using neural networks", *Computer-Aided Civil and Infrastructure Engineering*, **16**(1), pp. 28-41 (2001).

138. Chen, S. and Billings, S.A. "Representation of nonlinear systems: the NARMAX model", *International Journal of Control*, **49**, pp. 1013-1032 (1989).

139. Pridham, B.A. and Wilson, J.C. "Identification of base-excited structures using output-only parameter estimation", *Earthquake Engineering and Structural Dynamics*, **33**(1), pp. 133-155 (2004).

140. Pridham, B.A. and Wilson, J.C. "A reassessment of dynamic characteristics of the Quincy Bayview bridge using output-only identification techniques", *Earthquake Engineering and Structural Dynamics*, **34**(7), pp. 787-805 (2005).

141. Arici, Y. and Mosalam, K.M. "Statistical significance of modal parameters of bridge systems identified from strong motion data", *Earthquake Engineering and Structural Dynamics*, **34**(10), pp. 1323-1341 (2005).

142. Bozdag, E., Sunbuloglu, E. and Ersoy, H. "Vibration analysis of new galata bridge-experimental and numerical results", *Computers and Structures*, **84**(5-6), pp. 283-292 (2005).

143. Nagayama, T., Abe, M., Fujino, Y. and Ikeda, K. "Structural identification of a nonproportionally damped system and its application to a full-scale suspension bridge", *Journal of Structural Engineering*, **131**(10), pp. 1536-1545 (2005).

144. Çelebi, M. "Real-time seismic monitoring of the new cape girardeau bridge and preliminary analyses of recorded data: an overview", *Earthquake Spectra*, **22**(3), pp. 609-630 (2006).

145. Zhou, Z., Wegner, L.D. and Sparling, B.F. "Vibration-based detection of small-scale damage on a bridge deck", *Journal of Structural Engineering*, **133**(9), pp. 1257-1267 (2007).

146. Zhu, Z., Gu, M. and Chen, Z.Q. "Wind tunnel and computational fluid dynamics study of identification of flutter derivatives of a long-span self-anchored suspension bridge", *Computer-Aided Civil and Infrastructure Engineering*, **22**(8), pp. 541-554 (2007).

147. Mondal, P. and DeWolf, J.T. "Development of computer-based system for the temperature monitoring of a post-tensioned segmental concrete box-girder bridge", *Computer-Aided Civil and Infrastructure Engineering*, **22**(1), pp. 65-77 (2007).

148. Siringoringo, D.M. and Fujino, Y. "System identification applied to long-span cable-supported bridges using seismic records", *Earthquake Engineering and Structural Dynamics*, **37**(3), pp. 361-386 (2008).

149. He, X., Moaveni, B., Conte, J.P. and Elgamal, A. "Modal identification study of Vincent Thomas Bridge using simulated wind-induced ambient vibration data", *Computer-Aided Civil and Infrastructure Engineering*, **23**(5), pp. 373-388 (2008).

150. Carden, E.P. and Brownjohn, J.M.W. "Fuzzy clustering of stability diagrams for vibration-based structural health monitoring", *Computer-Aided Civil and Infrastructure Engineering*, **23**(5), pp. 360-372 (2008).

151. Ghosh-Dastidar, S. and Adeli, H. "Wavelet-clustering-neural network model for freeway incident detection", *Computer-Aided Civil and Infrastructure Engineering*, **18**(5), pp. 325-338 (2003).

152. Jiang, X. and Adeli, H. "Fuzzy clustering approach for accurate embedding dimension identification in chaotic time series", *Integrated Computer-Aided Engineering*, **10**(3), pp. 287-302 (2003).

153. Belli, K. Wadia-Fascetti, S. and Rappaport, C. "Model based evaluation of bridge decks using ground penetrating radar", *Computer-Aided Civil and Infrastructure Engineering*, **23**(1), pp. 3-16 (2008).

154. Ren, W.X., Sun, Z.S., Xia, Y., Hao, H. and Deeks, A.J. "Damage identification of shear connectors with wavelet packet energy: laboratory test study", *Journal of Structural Engineering*, **134**(5), pp. 832-841 (2008).

155. Jiang, X. and Adeli, H. "Wavelet packet-autocorrelation function method for traffic flow pattern analysis", *Computer-Aided Civil and Infrastructure Engineering*, **19**(5), pp. 324-337 (2004).

156. Jiang, X., Mahadevan, S. and Adeli, H. "Bayesian wavelet packet denoising for structural system identification", *Structural Control and Health Monitoring*, **14**(2), pp. 333-356 (2007).

157. Ni, Y.Q., Zhou, H.F., Chan, K.C. and Ko, J.M. "Modal flexibility analysis of cable-stayed Ting Kau Bridge for damage identification", *Computer-Aided Civil and Infrastructure Engineering*, **23**(3), pp. 223-236 (2008).

158. Soyoz, S. and Feng, M.Q. "Long-term monitoring and identification of bridge structural parameters", *Computer-Aided Civil and Infrastructure Engineering*, **24**(2), pp. 82-92 (2009).

159. Cruz, P.J.S. and Salgado, R. "Performance of vibration-based damage detection methods in bridges", *Computer-Aided Civil and Infrastructure Engineering*, **24**(1), pp. 62-79 (2009).

160. Memmott, J. "Highway bridges in the united states-an overview", U.S. Department of Transportation Research and Innovative Technology Administration, SR-003, Washington, DC (2007).

161. Federal Highway Administration (FHWA), Pontis, Version 4.0 Technical Manual Report, U.S. Department of Transportation, Washington, DC (2001).

162. Sirca, G.F., Jr. and Adeli, H. "Case-based reasoning for converting working stress design-based bridge ratings to load factor design-based ratings ", *Journal of Bridge Engineering*, **10**(4), pp. 450-459 (2005).

163. Waheed, A. and Adeli, H. "Case-based reasoning in steel bridge engineering", *Knowledge-Based Systems*, **18**(1), pp. 37-46, (2005).

164. Karim, A. and Adeli, H. "CBR model for freeway work zone traffic management", *Journal of Transportation Engineering*, ASCE, **129**(2), pp. 134-145 (2003).

165. Hammad, A., Zhang, C., Hu, Y. and Mozaffari, E. "Mobile model-based bridge lifecycle management system", *Computer-Aided Civil and Infrastructure Engineering*, **21**(7), pp. 530-547 (2006).

166. Elbehairy, H., Hegazy, T. and Soudki, K. "Integrated multiple-element bridge management system", *Journal of Bridge Engineering*, **14**(3), pp. 179-187 (2009).

167. Adeli, H. and Cheng, N.-T. "Augmented Lagrangian genetic algorithm for structural optimization", *Journal of Aerospace Engineering*, **7**(1), pp. 104-118 (1994).

168. Adeli, H. and Cheng, N.-T. "Concurrent genetic algorithms for optimization of large structures", *Journal of Aerospace Engineering*, **7**(3), pp. 276-296 (1994).

169. Dridi, L., Parizeau, M., Mailhot, A. and Villeneuve, J.P. "Using evolutionary optimisation techniques for scheduling water pipe renewal considering a short planning horizon", *Computer-Aided Civil and Infrastructure Engineering*, **23**(8), pp. 625-635 (2008).

170. Cheng, T.M. and Yan, R.Z. "Integrating messy genetic algorithms and simulation to optimize resource utilization", *Computer-Aided Civil and Infrastructure Engineering*, **24**(6), pp. 401-415 (2009).

171. Kang, M.W., Schonfeld, P. and Yang, N. "Prescreening and repairing in a genetic algorithm for highway alignment optimization", *Computer-Aided Civil and Infrastructure Engineering*, **24**(2), pp. 109-119 (2009).

172. Rodriguez, A. and Reggia, J. "A distributed learning algorithm for particle systems", *Integrated Computer-Aided Engineering*, **16**(1), pp. 1-20 (2009).

173. Sarraf, M. and Bruneau, M. "Ductile seismic retrofit of steel deck-truss bridges I: Strategy and modeling", *Journal of Structural Engineering*, **124**(11), pp. 1253-1262 (1998).

174. Sarraf, M. and Bruneau, M. "Ductile seismic retrofit of steel deck-truss bridges II: Design applications", *Journal of Structural Engineering*, **124**(11), pp. 1263-1271 (1998).

175. Itani, A.M., Bruneau, M., Carden, L. and Buckle, I.G. "Seismic behavior of steel girder bridge superstructures", *Journal of Bridge Engineering*, **9**(3), pp. 243-249 (2004).

176. Saiidi, M.S., Martinovic, F., McElhaney, B., Sanders, D. and Gordaninejad, F. "Assessment of steel and fiber reinforced plastic jackets for seismic retrofit of reinforced concrete columns with structural flares", *Journal of Structural Engineering*, **130**(4), pp. 609-617 (2004).

177. Chang, S.Y., Li, Y.F. and Loh, C.H. "Experimental study of seismic behaviors of as-built and carbon fiber reinforced plastics repaired reinforced concrete bridge columns", *Journal of Bridge Engineering*, **9**(4), pp. 391-402 (2004).

178. Pantelides, C.P., Ward, J.P. and Reaveley, L.D. "Behavior of R/C bridge bent with grade beam retrofit under simulated earthquake loads", *Earthquake Spectra*, **20**(1), pp. 91-118 (2004).

179. Caner, A., Dogan, E. and Zia, P. "Seismic performance of multisimple-span bridges retrofitted with link slabs", *Journal of Bridge Engineering*, **7**(2), pp. 85-93 (2002).

180. DesRoches, R. and Delemont, M. "Seismic retrofit of simply supported bridges using shape memory alloys", *Engineering Structures*, **24**(3), pp. 325-332 (2002).

181. Pantelides, C.P., Alameddine, F., Sardo, T. and Imbsen, R. "Seismic retrofit of state street bridge on interstate 80", *Journal of Bridge Engineering*, **9**(4), pp. 333-342 (2004).

182. Paultre, P., Proulx, J. and Begin, T. "Dynamic investigation of a hybrid suspension and cable-stayed bridge", *Earthquake Engineering and Structural Dynamics*, **29**(5), pp. 731-739 (2000).

183. Ingham, T.J. "Analysis of the million dollar bridge for seismic retrofit", *Computers and Structures*, **81**(8-11), pp. 673-67 (2003).

184. Zanardo, G., Pellegrino, C., Bobisut, C. and Modena, C. "Performance evaluation of short span reinforced concrete arch bridges", *Journal of Bridge Engineering*, **9**(5), pp. 424-434 (2004).

185. Murphy, T.P. and Collins, K.R. "Retrofitting suspension bridges using distributed dampers", *Journal of Structural Engineering*, **130**(10), pp. 1466-1474 (2004).

186. Uang, C.M., Seible, F., McDaniel, C. and Chou, C.C. "Performance evaluation of shear links and orthotropic bridge deck panels for the New San Francisco-Oakland bay bridge", *Earthquake Engineering and Structural Dynamics*, **34**(4-5), pp. 393-408 (2005).

187. Haroun, M.A. and Elsanadedy, H.M. "Behavior of cyclically loaded squat reinforced concrete bridge columns upgraded with advanced composite-material jackets", *Journal of Bridge Engineering*, **10**(6), pp. 741-748 (2005).

188. Cheng, C.T., Mo, Y.L. and Yeh, Y.K. "Evaluation of as-built, retrofitted and repaired shear-critical hollow bridge columns under earthquake-type loading", *Journal of Bridge Engineering*, **10**(5), pp. 520-529 (2005).

BIOGRAPHIES

Thomas Less is a Graduate Student in the Department of Civil and Environmental Engineering at The Ohio State University and Project Engineer at Barr & Prevost Engineering, where he performs bridge and structural design.

Hojjat Adeli is the Abba G. Lichtenstein Professor of Civil Engineering at The Ohio State University. A contributor to 76 different research journals, he has authored/co-authored over 450 papers in various fields of computer science, engineering, mathematics and medicine since 1976 when he received his Ph.D. from Stanford University at the age of 26. He has authored/co-authored fourteen books and edited fourteen books. In 1995, he wrote Machine Learning - Neural Networks, Genetic Algorithms and Fuzzy Sets (published by John Wiley and Sons), the first authored book that covers and integrates the three main areas of soft computing. His recent books include Intelligent Infrastructure - Neural Networks, Wavelets and Chaos Theory for Intelligent Transportation Systems and Smart Structures (CRC Press, 2009) and Automated EEG-based Diagnosis of Neurological Disorders - Inventing the Future of Neurology (CRC Press, 2010). He also holds a United States patent. He is the quadruple winner of The Ohio State University Lumley Outstanding Research Award. In 1998 he received The Ohio State University's highest research honor, the Distinguished Scholar Award "in recognition of extraordinary accomplishment in research and scholarship". In 2005, he was elected Honorary/Distinguished Member of American Society of Civil Engineers: "for wide-ranging, exceptional and pioneering contributions to computing in many civil engineering disciplines and extraordinary leadership in advancing the use of computing and information technologies in civil engineering throughout the world". In 2007, he received The Ohio State University, College of Engineering, Peter L. and Clara M. Scott Award for Excellence in Engineering Education as well as the Charles E. MacQuigg Outstanding Teaching Award. In 2008, he was elected a Fellow of the American Association for the Advancement of Science (AAAS), "for distinguished contributions to computational infrastructure engineering and for worldwide leadership in computational science and engineering as a prolific author, keynote speaker and editor-in-chief of journals". He received the Outstanding Civil Engineer award from the American Society of Civil Engineers Central Ohio Section in 2009. He is the founder and Editor-in-Chief of the international journals Computer-Aided Civil and Infrastructure Engineering and Integrated Computer-Aided Engineering and the Editor-in-Chief of International Journal of Neural Systems.