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Health Monitoring of a Truss Bridge using Adaptive Identification

James W. Fonda, *Student Member, IEEE*, and Steve E. Watkins, *Senior Member, IEEE*

Abstract—Integration of structural analysis, system identification, and sensor networks provide health monitoring capabilities that benefit many aspects of infrastructure management. This work presents an adaptive identification method based on Lyapunov methods for a truss structure. Lyapunov methods in the identification provide guaranteed convergence for the parameter estimation. Identification is carried out on a simulation model based on FEA methods. The FEA model offers realistic results from a truss structure and allows verification of the identification method for a rolling load case. A rolling load scenario provides use of realistic loading of a structure so that identification methods may be extended for field use. Estimation results show that convergence of health parameters is suitable though the use of the adaptive estimation. Also, results of simulations show that the adaptive estimation methods are able to track changes over time to provide monitoring of a degrading structure.

Index Terms—Sensor networks, strain sensing, structural monitoring, system identification, smart structures, adaptive

I. INTRODUCTION

Health monitoring of infrastructure components, such as bridge structures, is needed to assure proper maintenance, repair, and traffic management. Such management services all benefit from an integrated approach to structural analysis, sensor networks, and structural identification methods. Use of these methods can provide information on overall structural performance and on individual component performance. Management of large infrastructure networks can be aided through the use of on-line estimation and reporting of health parameters. Quantitative approaches using acquired field data offer improvement over qualitative and scheduled inspections.

Inspection and evaluation of the structural health of bridge structures has been traditionally based on “hands-on” visual inspection by experienced personnel. This process is time consuming and costly in transportation and time. Use of integrated processing combined with instrumentation can provide the long-term in-situ methods required by infrastructure components for intelligent monitoring.

Wireless systems and wired systems both provide data flow and control signal abilities for sensing and control operations. The use of these types of communication technologies as a networking medium for structures allows monitoring of many structures simultaneously. By “upgrading” the current system of structures, many benefits can be achieved. Monitoring for damage and other meaningful events in a structure’s life-cycle will provide visibility of structural health at all times. Expected extensions in service life will allow structures to recover more of the initial capital investment. These abilities improve the potential efficiency of the management, maintenance, and life-cycle costs of the structures. Such intelligent monitoring is particularly attractive due to the current demands of an aging bridge infrastructure.

Intelligent monitoring of structural systems involves providing visibility as well as decision making to structures. Sensing of structural variables such as temperature, pressure, displacement, and strain allow engineers to calculate estimates of load-induced deformations. Using the measured data the influence of estimated structural parameters on the safety of the structure can also be assessed. Improving sensor technology and low-power computing hardware continue to allow improved integration of these technologies into structural monitoring applications. Intelligent sensing methods can relay critical information back to key personnel. Use of integrated sensing, estimation, and communications provides the necessary components for structural identification methods to be implemented in an in-situ and on-line manner. Structural identification provides methods of identifying key parameters in structural systems to access the health of structures. Structural monitoring methods have developed from simple systems for data-logging into integrated systems for sampling, detection, and interpretation of data collected on structures. Structural monitoring systems therefore can become systems that incorporate methods to identify and report changes in the health of the instrumented structure or area in real-time.

Applications of sensing technology using distributed computing for sensing, control, identification, and health monitoring has been explored [1-6]. For instance, fiber optic sensor networks have shown to be reliable, long-term systems [7-11]. Higher level applications using embedded sensing and networking have been explored as well. The use of embedded systems for control and estimation for traffic-

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management and structural monitoring has been presented [12,13]. The performance of bridge structures can be characterized by specific parameters such as strength and stiffness. Methods to measure and estimate structural parameters in a meaningful way are needed. Use of structural monitoring is beneficial in the construction and repair phases of structural service. In particular, such technological aids can assist the personnel charged with annual repair schedules of large-scale and aging infrastructure. The impact of structural deficiencies on the annual GDP is also of concern [14]. Economic impact from deteriorating infrastructure can be wide reaching and includes not only the cost of repair but the costs of delays and closures on the transportation system. Traffic management is possible in which intelligent vehicles and intelligent roadways are combined. Related research has used structural identification methods for health and traffic monitoring [15-18] and adaptive filtering techniques have been used for traffic estimation/prediction applications.

Structural systems are normally use system identification analysis for construction quality assessment; however identification data can be used to interpret loading events throughout service life. System identification methods provide estimation of key performance parameters. System identification provides the means to calibrate a model of a physical system. For instance, acquired strain data can be used to estimate internal component stiffness. Monitoring of the loadings and over-loadings of a structure can be accomplished after identification of the strength for the structure. With a set of boundaries the use of alarm-driven reports may be accomplished. A set of alarms triggered can then be sent to a specified location such as an email address.

This work presents an adaptive identification method to provide useful health monitoring of a simple truss structure. A truss structure was used due to the number of aging in-service structures that still exist and due to ease of FEA analysis. Use of simulations will demonstrate the performance of the identification method proposed. Rolling loads are used in the simulations to provide a realistic case study of a structure that encounters traffic conditions. Use of adaptive system identification allows for an identification method that will provide accurate modeling where model structures are known.

II. SYSTEM IDENTIFICATION

A. Modeling and Identification of a Structure

System modeling is important in order to accomplish proper interpretation of readings from any system. Using models based on the sensor data provides the needed information to decipher what is happening at, or near, sensor locations. Use of these methods will allow the estimation of structural parameters so that guidelines for loading parameters can be set. Identification of the actual values that match our model structure to the physical system enables emulation of the movements in a graphical way within the constraints of the model used. Identified values are then used

to observe the movements of the structure based on recorded data. Also, the user may program loading scenarios that are simulated using identified parameter values.

Consider a truss bridge structure with frictionless pin connections that is instrumented with strain sensors on every element. Modeling and instrumentation parameter estimation can be applied to the structure as seen in block-diagram form in Fig. 1. Identification error is calculated between the output variable, in this case strain, and the model output, analytical strain. The error information is used to determine the needed parameters for the model calibration. Estimated parameters for the model are coefficients of the global-stiffness matrix based on the estimation of the cross sectional areas of the members of each element. The input is the load magnitude and position, $P(x,t)$.

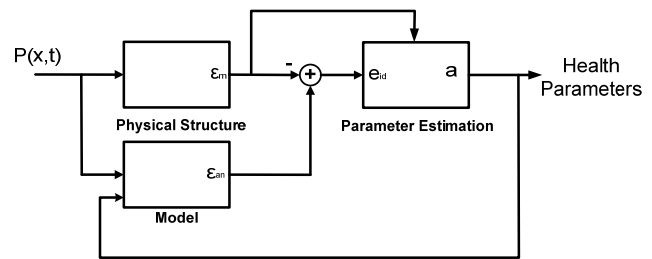


Fig.1 System identification overview where $P(x,t)$ is the loading function, ϵ_m is the measured strain, ϵ_{an} is the calculated strain, e_{id} is the identification error, and a is the cross sectional area of the members

Using this model, the system equations and an identification scheme provides the estimation of the cross sectional areas of the truss members. Adaptive identification is applied to the problem of truss health estimation.

III. TRUSS MODELING AND IDENTIFICATION

Adaptive identification and control methods have been used for many systems [19]. Adaptive methods can provide online estimation of dynamic uncertainties to provide both identification and control functionality. A stiffness analysis can model the structural behavior. Loss of stiffness, due to aging or damage, is determined by the identification system. A Lyapunov-based adaptive estimator for a scalar system is shown and is extended for a larger system.

A. Basic Modeling for Trusses

Structural mechanics for the analysis of the truss bridge is performed via matrix analysis methods. Matrix methods used the stiffness method for modeling and will be applied in this work for parameter estimation. Derivations of plane truss systems have been shown by several authors [20-22]. An example of the plane truss element and how the global stiffness matrix will relate the degrees of freedom (DOFs) to the output strains are now shown. Stiffness coefficients are used when relating the forces to the displacements to develop a relationship between the two.

The main structural element is the plane truss element for this application. Fig. 2 shows a system made up of plane-truss elements. The element is made up of a length of bar

that is fastened with smooth pins at each end. Each fastener is assumed to be frictionless and produce no moment at the end of the member. For this reason, the member will exist in only tension or compression in the model of the structure. The effect of fasteners is neglected, i.e. pin friction. Also the loading function $P(x,t)$ can be applied as a static or rolling load and will be discussed more Fig. 3.

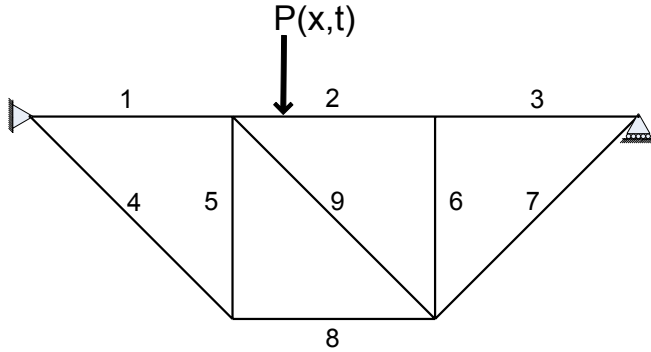


Fig.2 Example of a plane truss system with loading function $P(x,t)$

B. Plane Truss Elements and Simulation

Truss elements differ from frame elements which may have rotations about the joints that produce moments in the member. Due to this the forces in the truss member are along its axial direction with its interactions with the other members determined by their connectivity; each joint in the structure then having two degrees of freedom (DOF).

The plane element stiffness matrix K^e is the first step in assembling the model. The equation is found in several standard structural analysis texts and is given in (1) where E , A , and L are the Young's Modulus, the cross sectional area, and the length of the truss element respectively [20-22].

$$K^e = \frac{EA}{L} \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (1)$$

$$K_g^e = TK^eT^T \quad (2)$$

$$T = \begin{bmatrix} \cos \theta & \sin \theta & 0 & 0 \\ -\sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & \cos \theta & \sin \theta \\ 0 & 0 & -\sin \theta & \cos \theta \end{bmatrix} \quad (3)$$

The rotation matrix operation can be applied to each truss element and summed to produce the global stiffness matrix for a truss structure. The matrix T is a coordinate transform from the local to the global system where the angle θ is the angle made from the x axis in the global system. Once the formation of the element stiffness matrices in the global

system is calculated it is time to formulate the global stiffness matrix.

The code number method [20] allows an algorithm to identify the connectivity of the truss system without a visual reference. Code numbers for the assembly of global stiffness matrices provides a fast and easy method for a computer program to label and analyze a truss structure. Code numbering is based on labeling the unconstrained DOF first and then remaining support reactions last. Assignment of the code numbers is quite easy if a visual inspection of the structure is performed. In this process a set of information is formed that describes the connectivity of the structure and how it reacts to loading. The process ends when all constrained and unconstrained DOF have been assigned. Next, the FEA model that is used to perform the analysis will be shown.

Use of the structural stiffness matrix, K_g , to solve for the displacements makes for a useful and quick solution. Now the structure may be placed in a simulation that develops the behavior at static points or in a dynamic nature if needed. FEA simulation will help to reveal how the structure should behave and allow development of an identification scheme.

C. System Identification

A priori information about the physical structure is needed to provide a proper model. For the modeling of a truss system, a stiffness analysis adapted to the state space approach was chosen due to the capability to incorporate dynamics. A global stiffness matrix, K_g , is obtained for the truss and using K_g states of the system are related to the outputs. The states are the displacements and the outputs are strains. B_o is a transform matrix that takes advantage of the known geometry of the structure to relate the global displacements to the strains on the members. As seen in Fig.1 the identification scheme uses the model for the structure and measured values from a physical structure to complete the identification loop.

The truss behavior, as given by the state space method, is simulated using the joint positions of the structure as the state variables. The member strains are directly related to the joint displacements and are used as the outputs of the system model. This ordinary differential equation takes the form of the familiar mass-spring-damper. Using (4) and dropping the damping term, C , and the acceleration term for a static measurement we arrive at (5). Equation 6 shows the relationship between the displacements, x , and the strains, ϵ . The relationship among x , F , and K_g , is the global-stiffness matrix. Further development of the system leads to a transformation of displacements, x , to strains, ϵ , to allow comparable results to the structure. B_o provides the displacement-to-strain transformation.

$$\ddot{x} = K_g x + C\dot{x} - F(x, t) \quad (4)$$

$$\ddot{x} = -K_g x + F(x, t) \quad (5)$$

$$\epsilon = B_o x \quad (6)$$

Vector and matrix driven system are necessary to model higher order states space systems. The matrix system representation accommodates the multi-input multi-output (MIMO) nature of the truss structure. The inputs are the forces applied at the joints, or panel points, of the truss and the outputs are the strains on each member.

The matrix B_o is determined by the location of each available strain on the members. The transformation is simplified for the case of the plane truss system the assumption that only axial forces are present. The nodal displacements are related by the truss geometry and connectivity to the strains as given in (7). The matrix has a non-zero B_k for each member. The basic form for the k-th member, i.e. the member between the i-th and j-th nodes, is shown in the (7). Parameters are member length, L_k , the angles of the member to the x-axis and the y-axis, θ_x , and θ_y , respectively [23]. If nodes are not connected by a member, the transformation is concatenated with zeros.

$$B_k = \frac{1}{L_k} \begin{bmatrix} -\cos(\theta_x) & -\cos(\theta_y) & \cos(\theta_x) & \cos(\theta_y) \end{bmatrix} \quad (7)$$

Note that the dynamic behavior of the truss is handled by (5). This is opposed to a static analysis where the second order term is neglected.

D. Parameter Estimation

Parameter estimation for truss structures for a known configuration must be based around a parameter that will reveal health conditions. The FEA development shown above depends on an accurate global stiffness matrix for the case shown above. Therefore, the estimation of the stiffness parameters will be the main goal of the system identification that will now be discussed. Equations 8 and 9 are used to setup an error system that was also seen in Fig. 1.

$$\varepsilon_{an} = B_o (\text{inv}(\hat{K}_g(\bar{a})))F \quad (8)$$

$$e_{id} = \varepsilon_{an} - \varepsilon_m \quad (9)$$

The error information is used to determine the needed parameters for model calibration. The estimated variables are the cross sectional areas of the members and are given as the \bar{a} vector. Using strain readings, the proper model, and an adaptive update, the cross sectional areas are found to provide strength information about the truss structure. In particular, the axial stiffness values for each member may be extracted as K_{11}^e , which is an entry in the stiffness matrix of each member in the system. In the next section, the adaptive update law is shown using Lyapunov methods.

Lyapunov methods provide a design methodology that guarantees convergence of an uncertainty in the presence of a properly modeled system. Beginning with the scalar dynamic system shown in (10), the plant estimator shown in (11), and the error system in (12) a scalar adaptive identification method will now be shown. A time-derivative on the error system shows the result of (13) and (14). In (15)

and (16) the parameter errors are defined, using these and substituting arriving at (17). Next, a Lyapunov candidate is chosen in (18) and its derivative is shown with substitutions in (19). Finally, the parameter updates are chosen by setting terms in (19) to zeros and solving. The update shown in (20) results in updating of the \hat{a} parameter, which in this case will calibrate the scalar entries in the truss system. Extension of the scalar system is done by using a scalar update for each element of the truss where the error is the strain error and the measured error as the state in the update.

$$x = ax + ku \quad (10)$$

$$\hat{x} = \hat{a}\hat{x} - \hat{k}u \quad (11)$$

$$e = \hat{x} - x \quad (12)$$

$$\dot{e} = \dot{\hat{x}} - \dot{x} = (\hat{a}\hat{x} - \hat{k}u) - (ax + ku) \quad (13)$$

$$\dot{e} = (\hat{a} - a)x + a(\hat{x} - x) + (\hat{k} - k)u \quad (14)$$

$$\phi = \hat{a} - a \quad (15)$$

$$\varphi = \hat{k} - k \quad (16)$$

$$\dot{e} = ae + \phi\dot{\hat{x}} + \varphi u \quad (17)$$

$$v = \frac{1}{2}(e^2 + \phi^2 + \varphi^2) \quad (18)$$

$$\dot{v} = e\dot{e} + \phi\dot{\phi} + \varphi\dot{\varphi} = e(ae + \phi\dot{\hat{x}} + \varphi u) + \phi\dot{\phi} + \varphi\dot{\varphi} \quad (19)$$

$$\dots = ae^2 + \phi\dot{\hat{x}}e + e\varphi u + \phi\dot{\phi} + \varphi\dot{\varphi}$$

$$\phi\dot{\phi} + \phi\dot{\hat{x}}e \rightarrow \dot{\phi} = ex \quad (20)$$

$$\varphi\dot{\varphi} + e\varphi u \rightarrow \dot{\varphi} = eu \quad (21)$$

IV. SIMULATION RESULTS

In this section simulation results will be presented. After a brief description of simulation setup an overview of the parameters used in this work and results will be shown.

Each structure that is to be evaluated must have a loading pattern developed. This pattern may be constructed with static or dynamic inputs. Rolling load patterns provide a more realistic loading scenario and may be provided in a real-time manner. Use of a camera and a wireless sensor network on a structural system can provide the sensory information for the identification algorithm. A smart camera with a load-approximating algorithm based on vehicle size can estimate the rolling-load pattern. This pattern in turn can be correlated with the strain readings from the structure.

Previously discussed adaptive identification methods are now evaluated in simulation. Use of rolling loads to simulate a steady-state traffic pattern is used for simulation results. The truss is subjected to a rolling load of a particular frequency that has a constant load with a slight sinusoidal variance added. This scenario gives a reasonable loading parameter that might be seen on a one-way bridge.

Input forces for DOF loading are calculated by the free body diagram of a piece of bridge decking, shown in Fig. 3, and using equations of mechanical equilibrium. The use of the decking and the equilibrium equations results in two

equations that will be the amount of force required to be exerted to hold the load for a piece of decking, resulting in (22). These equations give the information to load the DOFs of the structure. The entries are determined by the position of the load on the structure and which piece of decking is under load.

$$R_1 = \frac{P \cdot x}{L} \quad R_2 = \frac{P \cdot (L - x)}{L} \quad (22)$$

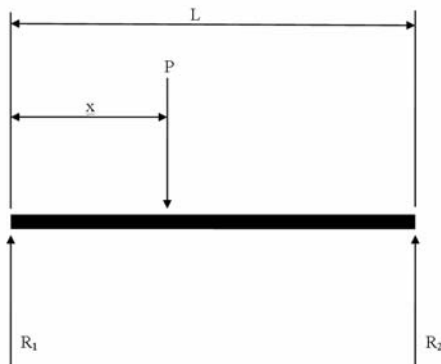


Fig.3 Free body diagram of loaded decking and reactions

Now simulation results are shown for the parameters discussed above. Rolling loads are introduced to the structure at a constant speed and traffic frequency. The automobiles are approximated by an appropriate scaled weight with a slight sinusoidal variance added to it. Simulations were performed with this system and results are now shown for the selected truss members. In Fig. 4 the parameter estimations are shown. As the figure shows the estimations converge to the nominal value of 1.0 in² in a short period of time and then are able to track new changes in conditions. This convergence of the parameters demonstrates the adaptive estimation method's ability to provide online monitoring for tracking damages in real time.

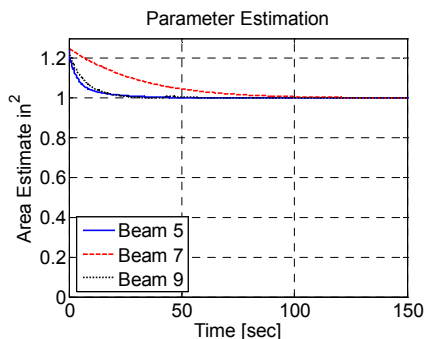


Fig.4 Estimation Results for Undamaged Structure

Next a simulation was performed where one element of the truss structure was damaged. For this simulation one member is simply decreased in strength before the estimation begins. Fig. 5 show that the adaptive method is able to identify which beam element is damaged. This simulation was also performed for two and three damaged

and those results are shown in Fig. 6 and Fig. 7. A 1.2-in² upper bound is used as a starting point; this type of value can be estimated from blueprints. The estimation results for the other undamaged truss members, i.e. beams 1, 2, 3, 4, 6, and 8, converge to 1.0 in² and show no change for these damage cases. As seen in Fig. 4 the parameters converge in a short time showing that the estimations can be formed in near real time.

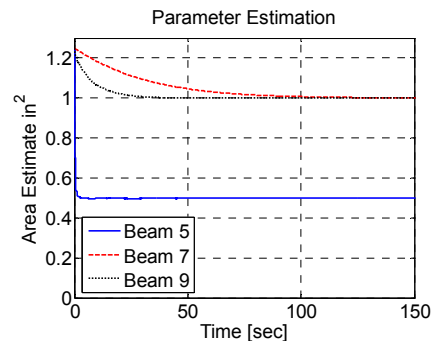


Fig.5 Estimation Results for Single Damaged Beam. Beam 5 has a reduced cross-sectional area

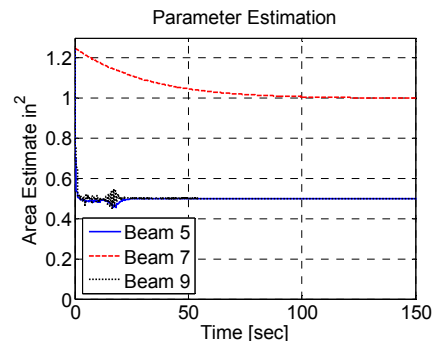


Fig.6 Estimation Results for Two Damaged Beams

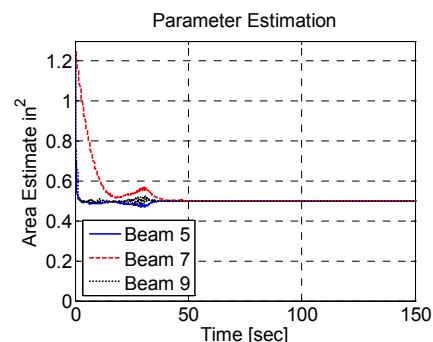


Fig.7 Estimation Results for Three Damaged Beams

Next a simulation of a damaged member that is slowly failing is shown. These results are shown in Fig 8. For these results element 5 is made to fail linearly over time, e.g the cross sectional area is gradually reduced. The results of the simulation show that the adaptive method provides an online identification of a fatiguing system over time. This type of identification is the most important to repair scheduling. While the ability to catch failures at any instant is important, the ability to estimate a time-to-failure is vital to health management for infrastructure.

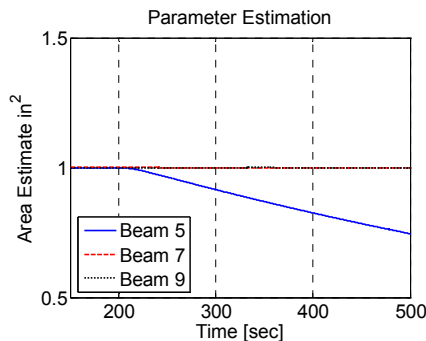


Fig.8 Fatiguing Beam Estimation Results

V. CONCLUSION

Sensor networks, structural analysis, and system identification can assist in the management and maintenance of instrumented structures. These intelligent systems offer benefits for bridges and other infrastructure throughout the life-cycle. Improvements in maintenance alone on the roadway systems can reduce the total long-term costs for the structure. Based on age, total volumetric amount of traffic to date, and detected defects, performance, economic viability and safety can be quantitatively weighted. The truss approach can be applied to truss bridges, power-line towers, and other support structures. Extensions can be applied to other bridge types and terrestrial emplacements. Embedded sensor networks and dedicated processing systems give smart or intelligent capabilities that are vastly superior to qualitative evaluation, temporary monitoring, or even simple sensor instrumentation. The filtering mathematics are similar to those used for estimation of traffic parameters.

In addition to improving management of infrastructure, intelligent roadway structures may enhance capabilities of intelligent vehicles and transportation systems. With status information on and on-line communication from the roadway, vehicles, users, and managers of the transportation network can integrate intelligent vehicles and intelligent roadways. Networks of intelligent structures can contribute to traffic management by improving available information on traffic conditions and in the environment. Improvements in condition awareness on the roadway systems can provide new options in intelligent transportation.

In this work an adaptive parameter estimation technique for truss structures was presented. Simulations show that for a realistic rolling load the results of the parameter estimation converge in a timely manner and are capable of tracking changing parameters as the structure degrades. Use of such techniques should be tested on laboratory structures to investigate viability for field deployment. These techniques can be applied to previously collected data to bring an estimation up-to-date then the estimation switched to an on-line method. Future extensions can include application of in-situ monitoring to traffic management as well as the health and performance monitoring for management, maintenance, and repair of reinforced concrete and other composite structures via FEA modeling to allow the adaptive parameter estimation to be validated for those structure types.

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