Journal of Structural Engineering

Structural Identification: Opportunities and Challenges

--Manuscript Draft--

Manuscript Number:	STENG-1904R2
Full Title:	Structural Identification: Opportunities and Challenges
Article Type:	Forum
Section/Category:	Structural Identification
Corresponding Author:	Ahmet Emin Aktan, Ph.D. Drexel University Philadelphia, PA UNITED STATES
Corresponding Author E-Mail:	aaktan@drexel.edu
Order of Authors:	Ahmet Emin Aktan, Ph.D.
	James Brownjohn

Editor, Journals
ASCE

Dear Editor:

Please find attached a Forum Paper we were invited, together with Dr. James Brownjohn, to write and submit to a special issue of the Journal of Structural Engineering dedicated to Structural identification. Together with Dr. Brownjohn we submitted a draft for review, revisions to which were advised by the Editors. These revisions were made and several additional comments were received. We are now submitting the paper after its second revision.

Structural identification is a very important concept that will potentially help the civil engineering profession to understand the actual mechanical characteristics of constructed systems, incorporating the interactions between site, soil, foundations and the superstructure as well as their intrinsic and transient actions. Proper applications would lead to knowledge about the ground truth of as-constructed operating civil engineering products as opposed to empirical estimates of properties, performance and behavior during design. Given such a potential, structural identification is not a process but an art-form, requiring the leveraging of sufficient experience and expertise for modeling, field testing, interpreting the data and improvement of the models. Each of the writers has pioneered modeling, field testing and structural identification of a variety of constructed systems, each accumulating heuristics over 4 decades.

In this paper the writers first articulated the state-of-the-practice of civil engineering and the pressing reasons for greater applications of structural identification to properly selected constructed systems. They continue with the history of structural identification as well as the challenges and opportunities facing this art in the 21st Century. As the writers became the carriers of the torch following an earlier generation of visionaries who laid the foundations of this art, they believe that this paper would serve to distill their decades of experience and heuristics for the future generations. We are slightly over length and hope that you will accept the manuscript based on its potential benefits for the civil engineering profession.

With best regards,

A. E. Aktan and J. M.W. Brownjohn

Sincerely,

AEAktan

A. E. Aktan PhD

Structural Identification: Opportunities and Challenges

AE Aktan[1] and JMW Brownjohn[2]

The Intertwined Nature of Civil Engineering Systems in 2012

Civil engineer master builders have been constructing masterpieces for Millennia, long before the recent advent of Systems Engineering. However, since the 1950's the planning, financing, design, construction, operation, and maintenance of civil engineered -constructed - systems (buildings, bridges, airports, plants, tunnels, dams, antenna towers, storage tanks, power transmission towers, highways, railroads, pipelines, etc.) became the elements of highly complex, intertwined, and interdependent systems in dense urban areas. Such highly complex and multi-domain systems, termed ***infrastructures***, include government, education, healthcare, transportation, water, communication, energy, etc. (DHS 2010). As urban populations grew, demands for infrastructure services increased. Meanwhile the engineered elements of infrastructures aged and deteriorated, and their operational and structural capacity started to fall short of the demands. We started recognizing their fragility as the failure of one infrastructure element precipitated cascading consequential failures of additional elements from different infrastructures.

Failures of critical infrastructure due to natural or manmade hazards reiterate this connectivity. For example, on Jan 2, 1998, "*a century-old water main ruptured under lower Fifth Avenue in NY City, creating a car-swallowing, curb-to-curb sinkhole and watery chaos in a bustling neighborhood whose streets resembled Venice for a few hours. Then, as the rivers receded, a gas main broke and the crater spewed forth a tower of orange flames. No one was injured … but water damaged scores of lobbies,*

---

[1] Roebling Professor, Drexel University, Philadelphia, PA, USA
[2] Professor of Structural Dynamics, University of Sheffield, UK

storefronts and basements for blocks around, 40 residents were evacuated, hundreds of offices and businesses were closed, subways were halted, traffic was rerouted and gas, water, electric, steam heat and telephone services were disrupted for many (NY Times, Jan 3, 1998).

Three infamous 21st Century examples further demonstrate the unexpected cascading consequences of infrastructure failure:

- In the case of the World Trade Centre collapse on 9/11/2001, while airplane impact was a design consideration for the Towers, consequential explosion and fire associated with an airplane impact were neglected in the design. Catastrophic and disproportionate collapse of the Towers due to fire at the upper floors was completely unexpected. The NIST investigation (2005) into the collapses led to new code provisions.
- In the City of New Orleans on 8/31/2005 the storm surge due to Hurricane Katrina caused more than 50 breaches in drainage canal levees and also in navigational canal levees and precipitated the worst engineering disaster in the history of the United States. Such an event had been expected, but the neither the consequences nor the preparation needed for effective emergency response were properly estimated (ASCE, 2007).
- An hour after the 3/11/2011 Tohoku earthquake off the coast of Japan, the tsunami wave breached the protective walls at the Fukushima Nuclear Power Plant and destroyed the backup diesel power systems, leading to partial meltdowns at several reactors. The diesel generators were situated in a low spot on the assumption that the tsunami walls were high enough to protect against any likely tsunami. Subsequently ancient stone markers indicating higher Tsunami events were reported (CBS, 2011).

A Perspective on Infrastructure Performance in 2012

One question civil engineers ask after each hazard is how we can better prepare for mitigating risks arising due to the failures of infrastructures to perform. For a successful civil engineering education and practice in the 21st Century, we have to learn how to consider the society, the built environment and nature as an integrated ***complex multi-domain system*** even if we may only be designing a light-post. Civil engineers have to leverage information, simulation, experimental (sensor), and decision technology more effectively and in an integrative manner, so that we may leverage innovative paradigms such as ***lifecycle cost***, ***sustainability***, ***resilience, performance-based engineering, and risk-based asset management*** accounting for the multi-domain systems nature of infrastructures (Hansman et al. 2006; Gurian et al. 2009; Moon et al. 2009). While the empirical-heuristic knowledge base of civil engineering served us well until early 20th Century, in the 21st Century we have to make design, operation, maintenance, and renewal decisions based on complete scenarios and analyses by leveraging complete and mechanistic models of complex systems and by properly interpreting relevant, objective data.

A new National Research Council Report (2011) noted that the absence of major earthquake in Urban USA has *lulled people into a false sense of security that the nation already is earthquake resilient. It noted a Los Angeles 7.8 magnitude earthquake simulation exercise and the staggering (simulated) consequent losses, and the lack of disaster resilience demonstrated by Hurricane Katrina.* Natural hazards with long return periods (500-2500 Years) and which are sometimes characterized as ***black swan events*** (Taleb 2010) are not the only concern related to infrastructure performance. In dense urban areas such as the Northeast Corridor in the US, transportation, water, power and communication are already failing to provide reliable and efficient operational performance under normal conditions

every day. There is ample concern for the safety and resiliency of the land transportation infrastructure under regular operating conditions **even without a natural or manmade hazard.**

The annual $200 Billion cost to the US economy of transportation system (Mineta 2006) compounded by other hidden costs due to poorly performing infrastructure far exceed the cost of a major earthquake or hurricane with a 475-Year return period. Unfortunately, transportation planning and funding in the US today appears to be driven by "deficit reduction" rather than innovative enhancement of infrastructure performance and mitigating hidden costs of such ***neon-***swan ***events*** (Zweig 2011) that are blindingly obvious and immensely important.

Many policy experts are advocating privatization mechanisms with users paying the cost of infrastructure services, such as Public-Private Partnerships (PPP) in order to finance future transportation funding. Primary requirements for attracting such investment are managing the risk of project delivery cost, lifecycle cost, and the reliability of performance, requiring a measurement of performance. Unfortunately, we still lack basic metrics for the valuation of infrastructure services and objective measures of performance.

Making effective investment and management decisions for multi-domain infrastructure systems is an increasingly complex challenge for which traditionally trained engineers are ill-equipped. ASCE's Vision 2025 (ASCE 2009) articulated the significance of the future civil engineer's role in this relation and recognizes that most of the built environment in our densely populated cities has reached and exceeded design life and capacity. We can no longer think of civil engineering as designers of new constructed systems but rather as the caretakers and maintainers of existing infrastructures – i.e. ***the architects of existing (and often geriatric) infrastructures – a role that is quite different from any that they have***

played in the past. This is a daunting challenge that the current practice of civil engineering and construction cannot expect to meet without renaissance. As development of printing technology facilitated the 15th Century *Renaissance*, ours will be facilitated through the applications of paradigms such as structural identification, health and performance monitoring, performance-based engineering, and asset management (Aktan et al, 2007; Moon et al. 2009).

Objectives

The term "structural identification" is an adaptation of the "system identification" concept from systems and control engineering to structural engineering of constructed systems. The term refers to a mechanistic "characterization" of a constructed system in terms of a physics-based analytical model.

Although civil engineers have been constructing both scaled physical and idealized physics-based analytical models for new design and construction since the Renaissance, they did not always realize the limited reliability of these. In fact, Galileo's failure to estimate correctly the stress distribution in a beam is a well-known example (Ballarini 2003). Through the later part of the 20th Century, many civil engineers used computers and structural analysis software to construct 3D FE models, expecting to obtain more reliable predictions of structural behavior. As it was well-known and articulated by many 20th Century master structural engineers (Pier Luigi Nervi, Robert Maillart and Hardy Cross, amongst others), it was the collaborative US-Japan earthquake engineering research in the 1980's that starkly revealed how typical approaches to modeling buildings fail to simulate critical behaviors of even highly idealized and symmetric 3D building systems (Bertero et al. 1984). Subsequent studies showed the importance of using experimental data measured in the field in order to seed analytical models to improve the reliability of simulations (Ghaffar and Housner 1976; Beck and Jennings 1980; Aktan and Farhey 1996;

Aktan et al. 1997; Aktan et al. 1998). These experiences revealed that discrepancies in the predicted versus measured global responses of a constructed system may easily exceed 500% and in the case of local responses may exceed 1000%.

Today, it is clear that our inability to predict structural performance is not due to a lack of computers or software, but a lack of our ability as civil engineers to model a given structure-foundation-soil (SFS) system ***completely*** such that all the critical kinetic and kinematic mechanisms are incorporated at the linear and nonlinear regimes. If such a ***complete*** physics-based model is constructed, simulations may be used to estimate a demand envelope for a given load effect. Case simulations point out that the structure may be loaded to its nonlinear limit states, the complete linear model serves as an excellent starting point to construct one for nonlinear simulations. ***Structural-identification provides a most effective way to improve reliability in computer modeling by reconciling experiment and analysis. St-Id may also help shape a realistic mind-model for all engineering and management disciplines since the concept leads us along a path to understand the reality of complex multi-domain infrastructure systems.***

The greatest challenge in successful applications of St-Id (Moon and Aktan 2006) have emerged as the systems integration requirements, requiring mastery in management, modeling and simulation, experimental arts, information technology, and decision-making. Unless we understand how infrastructures perform as complex systems we cannot expect to formulate effective policies, strategies and project-specific designs for improving their performance as systems. ***The authors' objective in writing this paper is to review the challenges that have to be overcome for successful applications of St-Id for serving condition, safety (vulnerability), serviceability, and reliability evaluation of a constructed system, as well as its health monitoring and management. The authors will further offer***

recommendations regarding how we may reach the future potential of St-Id in concert with additional systems engineering concepts for the sustainable management of multi-domain infrastructures.

Overview of Current Best Practice for St-Id

Since Prof. Yao and his colleagues published their pioneering ASCE work describing structural identification (Hart and Yao 1977; Liu and Yao, 1978), there has been extra-ordinary progress in computers, sensors, data acquisition hardware and software, and many St-Id applications. We recall that St-Id of constructed systems was first explored in conjunction with earthquake engineering research on the dynamics of buildings, nuclear facilities and dams by vibration generators, pioneered by Hudson in the early 1970's. Ghaffar's PhD dissertation at CALTECH (1976) advised by Housner, and their subsequent studies on the Golden Gate Bridge were early and remarkable efforts towards applications of structural identification. Subsequently, the earthquake engineering community became interested in using this concept for the identification of the dynamic characteristics of building structures from acceleration responses captured during earthquakes, and early studies on this theme were first reported by Yao (1979) and by Beck and Jennings (1980).

Douglas and Reid (1982) were early pioneers in applying the St-Id concept to characterize the lateral response characteristics of an actual highway bridge by pull-release testing. Following the publication of the Proceedings of Natke and Yao's 1987 workshop "Structural safety evaluation based on system identification approaches (1988)," the concept eventually attracted the interest of large numbers of structural and earthquake engineering researchers. With the influence of International Modal Analysis Conferences (IMAC) starting in 1982, increasing numbers of mechanical, aerospace and civil engineering researchers became interested in taking advantage of vibration-based St-Id for testing and characterizing structures such as offshore towers, highway bridges, towers and buildings (Beck and Jennings 1980; Bonato et al. 1997; Aktan et al. 1997; Aoki and Sabia 2005; Liu et al. 2005; Nagayama et al. 2005; Gentile 2006; De Sortis and Paoliani 2007; Morassi and Stefano 2008; Conte 2009). In addition to these authors and others referenced later in this paper, we acknowledge significant contributions by Shinozuka (2005), Farrar (1994, 1999, 2003), DeRoeck (2001 (a), (b)), Sanayei (1997), Betti (2004), Hjelmstad (2009), DeWolf (1999) with their students and collaborators to structural system identification from engineering mechanics, computational mechanics and experimental mechanics perspectives.

It is a significant accomplishment that the ASCE Committee reached consensus on SIX essential Steps that have to be integrated in a complete and successful St-Id application to an actual, operating constructed system. The integration of these Six Steps would not be in any strict order, depending on the system, problems driving St-Id, etc:

1. **Clearly establish a business case,** in conjunction with the drivers and specific objectives for a St-Id application and identify any critical constraints that may challenge its success. Collect and evaluate all available legacy data and information including heuristic domain knowledge about the constructed system. Construct an e-warehouse that will serve as a library for all the legacy and new material. Use building information modeling (BIM) and bridge management systems (BMS) to serve as e-libraries.

   As very few owners, consulting engineers, and even large consulting companies may claim successful experiences with technology integration, it is both a challenge and a prerequisite to win an owners' and consulting engineers' support for access to for the St-Id of a constructed system. Many owners prefer to delegate professional engineering work to consultants, and a St-Id application will often have to be approved and supported by the consultant who may be in charge of the inspection, maintenance, repair, or management of a facility.

One obvious application for St-Id would have been in seismic instrumentation of buildings and bridges. For example the Strong Motion Instrumentation Programs by CA, USGS, Japan and Taiwan are currently NOT leveraging St-Id for optimum instrumentation design or reliable interpretation of strong motion data. With proper system design, informed by St-Id and complementing the typical accelerometer system with strain gauges and tilt-meters, the current investment into SMIP's may offer a greater payoff. The authors urge CSMIP, CALTRANS, USGS, US Army Corps and other agencies that are responsible for seismic instrumentation to explore the potential payoff from St-Id of a facility scheduled for seismic instrumentation.

Infrastructure owners may be motivated to leverage St-Id if an application promises to save a portion of repair, retrofit, or renewal funds or at least ascertain the effectiveness of renewal if designed in a traditional civil engineering approach. St-Id may even help show the retrofit is not necessary at all (Moyo et al. 2004). For these purposes, a mechanistic understanding of the existing constructed system and its characterization, by a calibrated computer model, are critical. St-Id could also assist when visual inspections reveal performance concerns for large, critical constructed systems. Vibrations, cracking, deformations and drifts that exceed thresholds and lead to serviceability concerns require that root causes are identified and mitigation strategies identified (Brownjohn et al. 2010; Moutinho et al. 2011). These are best identified through a St-Id application.

St-Id may be a means of establishing a quantitative and mechanistic baseline characterization for a newly constructed system similar to a **birth-certificate.** Documenting the baseline mechanical characteristics is invaluable and in fact essential in the case of performance-based engineering. In the case of innovative financing and project delivery of infrastructures through a Public-Private Partnership (PPP) arrangement, documenting the mechanical characteristics of a system as it changes hands from one party to another provides a strong business case for St-Id. As PPP becomes an increasingly preferred mechanism, we expect to see a much greater emphasis by financiers, owners, concessionaires, and insurers for relying on mechanistic models based on field data. This would become a major driver for increased numbers of state-of-the-art St-Id applications during construction, at commissioning, and after any event that may have an impact on the lifecycle. Finally, some major infrastructure owners and consultants have developed an appreciation of the value of St-Id especially in relation to retrofit design and historic preservation. Examples include NY City long span bridges such as the Brooklyn Bridge, the Henry Hudson Bridge, and the Throgs Neck Bridge.

2. **Study legacy data and information.** Observe the system in the field under different operational and environmental loading conditions and conceptualize the system for a-priori modeling.

Take advantage of practical measurements during field observations to capture as-is dimensions, material properties, and global structural characteristics such as natural frequencies and mode shapes. This step requires an ability to observe an actual full-scale system in the field, leverage heuristics, and decide on the characteristics, loading and response mechanisms – i.e. site, soil, foundation, load paths, displacement, deformation, and any concentrated distortion patterns; boundary, continuity, and movement systems - that should be incorporated in the a-priori model. Field observation offers the opportunity of reducing uncertainties about operational response levels, and help shape the model to allow inclusion of condition and performance deficiencies.

In the construction of a-priori models it is important to recognize that multiple models can represent a system (Goulet et al. 2010; Raphael and Smith 1998; Beven 2002). The model-builder has to have experience with constructed systems, as FE software will permit the construction of various models that may appear to simulate the geometry with fine resolution but still fall short of simulating the kinetics and kinematics. It is highly recommended to construct a model that can serve the objectives of St-Id at minimum necessary resolution. Mixed microscopic and element level models, representing critical details and regions in microscopic detail but represent less critical elements at an element level, may offer advantages.

3. Operational Monitoring and Controlled Experimentation.

There are several types of field experiments including: (a) ambient vibration testing (He et al. 2009; Brownjohn 2002; Brownjohn et al. 2011), (b) forced excitation testing (Brownjohn et al. 2003), (c) controlled load testing (Calcada et al. 2005), and (d) monitoring operational and environmental events (Catbas et al. 2008), with an St-Id campaign including one or more of these components with (a) or (b) more likely to be first, and (d) to run to the end. Application of (c) is already a requirement of a number of transportation agencies worldwide.

The a-priori model should be leveraged to design each type of experiment and especially the instrumentation required. Instrumentation should be designed to: (i) control the safe and successful execution of the experiment; (ii) test hypotheses regarding critical structural behaviors and the root causes of any condition issues; iii) immediately assure data quality; (iv) serve as the basis for the model refinement and calibration step.

The information provided by various experiments in (a) to (d) complements each other: Ambient vibration testing over a day to several weeks provides average values and variations in the frequencies, mode shapes, and damping of various modes. Monitoring operational and environmental events over several weeks to several months provide average magnitudes and bounds of inputs and responses due to live loads, wind, temperature, radiation, and other intrinsic force mechanisms (Brownjohn and Pan 2008). These two experiments may be performed simultaneously (Pakzad et al. 2008). However, controlled load testing at proof-load levels in conjunction with properly designed instrumentation and data acquisition remains a most definitive manner of measuring critical behaviors of medium-span bridge structures.

4. Data Archival, Quality Assurance, Processing, Pattern Extraction, Modeling and Interpretation.

This category has two sub-divisions, with the first three activities representing the basic minimum requirement and of themselves requiring an excellent computational engineering and IT background. Metadata and data need to be checked for quality assurance and archived prior to processing, preferably during the experiment, to catch and rectify mistakes in-situ.

Processing of dynamic and static data for extracting the mechanical properties of a system and patterns require a good signal processing and structural dynamics background. Technology advances in modal analysis facilitate on-site analysis of dynamic data for type (a) and (b) tests that can advise changes in experimental strategy in near real-time.

Pattern extraction, development of meta-models and interpretation are specialized fields that represent one of the most significant challenges for St-Id (Cross et al. 2010; Moaveni et al. 2009). This activity cannot be carried out in isolation since the coordination, quality testing, and reality checking of any products from this Step, especially the physical interpretation of the data in relation to structural behavior and performance, require continuity, feedback, and iteration between all of the steps 1-4.

5. Selecting, Calibration and Validation of Physics-Based Model(s).

Applied mechanics experts may worry that such a model cannot represent a structure-foundation-soil (SFS) system that may be nonlinear, non-observable and non-stationary. In fact a constructed system is never entirely observable or stationary, and many critical parameters and mechanisms are clouded by not only random but epistemic uncertainty (Oberkampf 2005).

Nevertheless, a calibrated and validated physics-based linear model for scenario analysis and decision-making is an essential St-Id tool for addressing structural engineering problems. Structural engineers are well-aware that a constructed system cannot be strictly linear, yet many limit states (e.g. excessive vibration) may occur within the linear performance range.

The real challenge (and art) in St-Id an art is to know how and when to smear rationally all the nonlinearity and non-stationary characteristics of a system into a linearized, physics-based model that is suitable for the objectives of the St-Id application, while retaining a healthy degree of skepticism until the model is proven reliable.

The size, resolution, and sophistication of a physics-based model depends on the objectives of St-Id, the consequences of the uncertainty in estimating demands, capacity, and vulnerability, and on the critical failure modes of a SFS system. This model can never be unique or fully representative. However, with reliable and well interpreted performance data, it should be possible to leverage heuristics and reach a reasonable level of confidence in the ability of a model to represents important characteristics of the actual constructed system. This requires structural and geotechnical specialists to work more closely and adapt each other's technologies for model validation.

While many exercises focus on variability of model parameters, the most critical problem in St-Id is to ascertain that a model is ***complete***. It must incorporate all the critical force distribution mechanisms and the kinematics depending on boundary conditions, soil-foundation characteristics, and deformation patterns of elements or groups of elements. Incompleteness due to epistemic uncertainty (in addition to difficulty in 3D conceptualization) is often the most significant source of model error, and it is extremely difficult to identify such errors unless each step of St-Id is coordinated and performed as a continuum.

Identifying a model that is complete is a challenge in every discipline. We should ideally explore an infinite space of possibilities then rule out spaces of variables for which the model is not compatible with observations. In fact the best we can do is to find a model that is ***compatible*** with measurement data and noise levels as well as with the application.

We inject some caution: The calibrated or updated model should be a projection of complete behavior on the space of observable signals and information. In that sense it can be dangerous to attempt to apply it to gain new knowledge that it does not contain (Brown 1985). This is analogous to the danger of extrapolating from data that are only robust to interpolation**.**

6. **Decision-Making**

Step 6 involves leveraging the calibrated model for scenario analyses, evaluating, and prioritizing decisions regarding the performance and/or condition concerns, and/or retrofit and renewal design. Critical risks due to probable non-performance of the system at any limit-state should be identified in this stage. Critical hazards, vulnerabilities, and probable failure modes need to be identified, validated and documented as an objective overview of the health of a system in order to strengthen the business case for St-Id.

The key to a successful culmination of St-Id is therefore whether the calibrated model proves suitable for comprehensive scenario simulations – especially related to the safety and stability of failure of the facility due to various manmade and natural multi-hazards. Reliably simulating phenomena such as blast, fire, impact, accident, flood as well as operational and serviceability concerns may require more than one model or one software package. Finally, during each of the Steps 1-6, coordinators of St-Id should be leveraging heuristics to a maximum, and Step 6 should certainly include the owners and managers of the system.

Implications of the Overview for Best Practices

A successful outcome of St-Id very much depends on each of the steps being accomplished successfully ***within a continuum*** as opposed to in isolation. In the past there have been attempts to carry out these six steps sequentially by different specialists working like a tag team. These efforts have not been as successful as applications where the entire cycle would be coordinated by the same person, allowing for iteration of the whole cycle or parts of it. Such a person would have experience in the six steps and be able to integrate mind-model views of the same system from:

- Owner/operator

- Consulting engineer
- Modeler - integrating analytical, mathematical, numerical and computational modeling
- Experimentalist - designing and executing field experiments to capture the critical system behaviors
- Risk and reliability analysis and optimization expert to judge and correlate analysis and experiment
- Expert manager to integrate empirical-heuristic knowledge with the objective-mechanistic insight from St-Id to make informed management decisions

Present day civil engineering courses provide very little training for such a role. Hence one of the major challenges in introducing the St-Id approach advocated here is to advise accreditation agencies worldwide that they should require universities to switch from a culture of structural engineering teaching focusing on designing for new structures to one of maintaining and managing our existing infrastructures. This fits perfectly within the popular ethos of resilience and sustainability. We can also show students and engineers they can have more fun figuring out how an existing structure works than designing a new one.

It is important to identify requirements for St-Id to provide sufficient payoff. First, the owner/manager of a constructed system should be entirely convinced of the necessity of St-Id for making prudent management decisions. Second, the St-Id team of *coordinator* and specialists must be available and should possess the empirical-heuristic knowledge that can only come from experience over many decades of field work on actual constructed systems. If these requirements are not met it is best not to expect much from St-Id. Even when the second requirement is met and a large investment is made in St-Id, confidence bounds in identifying such parameters as global flexibility, mode shapes, local deformations, movements and reactions of a large system such as a long-span bridge can only be as good as 75%-90%. Hence operators/owners are justified to be skeptical, reinforcing the need to identify clearly, situations when a payoff can be had from St-Id:

1. When we step outside the bounds of applicability of codes and design for innovative structural forms and/or new construction methods and materials, we have to rely on St-Id to mitigate the risks due to epistemic uncertainty.
2. When we have an existing constructed system whose operation is vital for the well-being of an urban region, and the system is exhibiting distresses and performance concerns such as excessive vibrations, cracks, spalls, etc. then St-Id should pay off.
3. In the case of constructed systems that may be managed as a fleet, e.g. simple highway overpasses designed and constructed with highly similar materials, St-Id of a select sample may help manage a much larger population more effectively.

The value in a properly executed St-Id would be a more reliable and complete conceptualization of i) the performance of a constructed system ii) its critical regions and behavior mechanisms (e.g. force paths and kinematics), and iii) its critical loading scenarios and the estimation of its failure modes under extreme events. St-Id would also support formulation of strategies for effectively mitigating performance deficiencies. Given that even well executed St-Id may cost between $50K and $1M depending on the size, complexity and resolution; the potential for saving insurance and replacement costs, the criticality of the functions of a constructed system, and expected lifecycle must all be factored into the cost-benefit analysis when making a business case for St-Id.

Towards System-Identification of Complex Multi-Domain Systems

The current state of the art on St-Id of constructed systems has been documented in a Report by the ASCE SEI Committee on St-Id of Constructed Systems (ASCE-SEI 2011). This report contains an overview of more than 15 contemporary St-Id applications, including those of tall and midrise buildings, towers, suspension bridges, long-span arch and truss bridges, and movable bridges. A wide range of experimental tools, from ambient vibration, wind, seismic monitoring, forced excitation, impact, and truck-loading have been used. Physics-based models of various resolutions, including macroscopic, element level and microscopic Finite Element models were used for the simulation of these constructed systems. Many other applications that leveraged non physics-based models have also been discussed and referenced in the ASCE Report.

As evidenced by the applications to real buildings, bridges, and towers detailed in the ASCE SEI Committee Report by Kijewski-Correa and Kareem, Omrani and Taciroglu, Ni, Moaveni, He and Conte, Zhang, Pan, Prader and Moon, Pakzad and Fenves, Yun and Masri, Fujino, Siringoringo and Nagayama, Goulet and Smith, Catbas and Gul, Schlune, and Plos and Gylltoft, we may estimate the existence of more than two dozen centers of excellence in the world that can presently do justice to the challenges of St-Id applications to large constructed systems. Meanwhile, there is increasing evidence that modeling and simulation of just constructed systems are often insufficient to reach reliable decisions for architecting and managing our built environment.

Management of multi-domain systems require decision-making at the confluence of natural, social, and engineered domains, and no matter how reliable we may model the engineered components of infrastructures, we still need to incorporate social factors such as politics, policy, economy, sustainability, etc. in most decisions. It follows that whether we may expand the St-Id concept to the system-identification of complex multi-domain systems such as infrastructures becomes a highly important question.

As an example of a complex multi-domain system, consider the highway transportation infrastructure. Many engineers and users may envision this system as comprised of roads, bridges, signs and traffic. However, as Fig. 1 provides a depiction of the actual system comprised of complex, mixed and intertwined layers of ***Human, Natural*** and ***Engineered*** Systems and Elements. The Human systems would include societal (history, culture, values, politics, policy, economy), organizational, institutional (as well as corporations), and individuals. Natural systems include climate, weather, geology-soil, water, air, plants, and animals. Engineered systems include manufactured elements such as autos, signals, lights, signs, ITS cameras and communications, enforcement, and security systems. Finally, constructed elements include pavements, bridges, retaining walls, drainage structures, embankments, sound-barriers, sign structures, etc. The system is highly dynamic, non-stationary, and multi-scale; affected by phenomena and mechanisms at microscopic thru macroscopic length scales as well as along a very long frequency bandwidth, from under 0.1Hz thru Giga-Hertz levels. Such systems need to be explored and mapped with all sub-systems and elements from various domains, along with the intersections, interdependencies, and interactions between these at various performance limit states and time. Contributions by Sussman (2005) towards a process for studying such systems, which he has termed: "***Complex, Large-Scale, Interconnected, Open, Socio-technical (CLIOS) Systems"*** are noteworthy.

Figure 1 shows how little means we have for knowing how to perturb and control such a CLIOS system optimally and effectively (through policy, planning, financing, revenue generation and management paradigms, decisions and actions) so that we may get outcomes which we desire such as acceptable performance levels in conjunction with minimum lifecycle cost. The hypothesis is that if we are able to model and identify such a system, with its most critical human, natural, and engineered elements, we may formulate planning, financing, revenue, operational, and maintenance/preservation management policies that may offer an optimum performance of the entire system for maximum lifecycle benefit/cost. Given the considerable debate that is currently ongoing for various financing, revenue, and ownership mechanisms for critical infrastructures, especially regarding the financing of essential infrastructure services, a clear understanding of the system would be invaluable in order to identify cause-and effect relationships that may result from various acceptable options for such decisions. Policy and planning would be founded on a much more realistic and objective understanding of the entire system rather than driven by political convenience.

It is especially challenging to understand and model various human systems such as organizations, corporations, institutions, and individuals as well as their communication and decision-making processes. Various investigators have proposed macro-modeling approaches based on economic and network models. There have also been simulations of individuals and populations based on “agent models” (Kai et al. 1998; Sharpanskykh and Stroeve 2011; Hersey 2001; Bonabeau 2001). Organizational and process models have also been proposed (Popova and Sharpanskykh 2008). For example, Figure 2 depicts a stakeholder influence diagram for evaluating how various institutional and policy decisions may impact management decisions for a toll-bridge system (Jackson et al. 2011). The fact remains that the state of practice for reliable modeling and simulation of multi-domain systems, especially the Human systems and elements within these systems is in its infancy. Coordinated research and demonstrations by multi-disciplinary teams, including social scientists, economists, finance and business managers as well as a new generation of civil and environmental multi-domain systems engineers are urgently needed for enabling sound and prudent policy decisions regarding infrastructures.

Conclusions:

Structural-system identification after four decades came of age as a mature civil engineering concept applicable to any constructed system (provided a sound business case can be made for it). The concept requires a coordinated, integrative multi-disciplinary effort, bringing together most of civil engineering sub-disciplines in addition to electrical and mechanical engineering expertise. Application of the concept to a constructed system results in a characterization of the system through a physics-based (mechanistic) model. An infinite number of models can be constructed to represent a constructed system at many levels of detail (resolution) and complexity (distributed, nonlinear and/or stochastic). **The challenge is to pick the minimum levels of resolution and complexity justified for a given system and the objectives driving the St-Id.** The remainder of the St-Id is then focused on making this model "complete" and error-free, then to assign confidence bounds for simulations of the system subjected to the scenarios relevant to the St-Id application objectives.

Given that the single most critical barrier to confidence in simulations involving constructed systems is the ***epistemic uncertainty*** associated with the as-is mechanical characteristics and various capacities of the system, its foundations and soil, as well as its remaining lifecycle, and the demands anticipated during this period, the authors do not endorse unnecessary sophistication in modeling or in trying to simulate randomness in those common parameters in a FE model without an abundance of data required for characterizing randomness. The single most important requirement is to make the model and simulations ***sufficiently complete***, i.e. incorporating all of the critical mechanisms that may govern the kinetics and kinematics as well as proper choice of the scenarios that will be simulated by the model given the drivers of the application.

The challenge of constructing a "***sufficiently complete***" model brings to us the necessity of incorporating heuristics about the type of constructed system and anything that is known about the specific system being identified. Also critical will be the ability to observe and conceptualize a constructed system – requiring the model builder to actually see, touch, and observe the system for days if not weeks; in addition to studying plans, drawings and other documentation and leveraging visualization tools for completely conceptualizing the 3D geometry.

Recommendations:

The authors recommend that skilled groups that have demonstrated expertise in St-Id of constructed systems remain connected, and continue demonstrating best practices while exploring ways to improve the reliability to be expected from St-Id applications through round-robin studies. One such study has been initiated by the authors by leveraging a common highway bridge in NJ, under FHWA and NJDOT's support and auspices (A. Aktan et al., unpublished LTBP report 2011).

There is an urgent need to increase the number of civil engineering academic programs that are capable of demonstrating and teaching St-Id.-We urge the numerous civil engineering programs to develop field research capabilities and include St-Id as a component of their curricula in the near future. We also urge that accreditation agencies such as ABET (USA) and JBM (UK) require inclusion of St-Id in civil engineering curricula. Given that measurements, experiments, data interpretation, analysis and design are all already expected to be included in the elements of a modern civil engineering curriculum, their teaching could be linked using the St-Id concept for a more rewarding student experience (Yao 1996).

Federal government agencies such as NIST, NSF, FHWA and others should consider St-Id as an important enabler for meaningful technology integration and generation of fundamental knowledge. The more applications reveal hidden behaviors and common blind-spots in modeling constructed systems, the more we will be able to characterize constructed systems with mechanistic models of improved confidence. The risks associated with modeling critical constructed systems without any understanding of the confidence in the simulations have become too great in dense urban areas where the consequence of failures and even delays in a project have become unacceptable.

A final recommendation regards urban infrastructure rejuvenation, which is an essential element and in fact a driver of urban rejuvenation. Presently there is no established integrated systems approach to infrastructure planning, feasibility, sustainability analysis, design, construction, operation, and management, providing an opportunity to map the St-Id concept for modeling entire infrastructures in manners that may be validated. Current infrastructure modeling approaches are generally macroscopic, e.g. network and macro-economic models, while there have been efforts towards simulating the human and organizational elements of infrastructures for transportation planning, none of which approaches have matured or been properly validated.

Structural engineers should coordinate research in integrative modeling of infrastructures along with their societal, organizational and individual human elements, nature and environment in addition to their engineered systems. This will require use of actual transportation (highway, airport, rail, transit, etc.), water and power distribution networks as real-life laboratories. ‘Infrastructure’ is becoming a pressing “hot” research area and structural engineers need to seize opportunities to steer research funding agencies and foundations towards funding real-life field laboratories for research, education, and demonstrations of infrastructure modeling and system-identification. Experience from such live laboratories will develop understanding of complex, multi-domain (CLIOS) systems, empowering structural engineers to transform management decision-making based on realistic scenario simulations.

References

Abdel-Gaffar, A.M. (1976). “Dynamic analyses of suspension bridge structures and some related topics” PhD dissertation, Civil Engineering Department, California Institute of Technology.

Aktan, A.E., Farhey, D.N., Helmicki, A.J., Brown, D.L., Hunt, V.J., Lee, K.L. and Levi, A., “Structural Identification for Condition Assessment: Experimental Arts,” Journal of Structural Engineering, ASCE, Vol. 123, No. 12, Dec., 1997.

Aktan A.E., Catbas, N., Turer, A., and Zhang, Z. (1998). “Structural identification: analytical aspects” Journal of Structural Engineering **124**(7).

Aktan, A.E. and Farhey, D. (1996). “Condition and reliability assessment of constructed facilities” ACI SP **162**, 73-92.

Aktan, A.E., Ellingwood, B., Kehoe, B. (2007). “Performance-based engineering of constructed systems. Forum Paper” Journal of Structural Engineering **133**(3) FORUM.

Aoki, T., Sabia D. (2005). “Structural identification and seismic performance of brick chimneys, Tokoname, Japan” Structural Engineering and Mechanics **21**(5), 553-570.

ASCE-SEI (2011). “A State-of-the-Art report by the ASCE-SEI Committee on Structural Identification of Constructed Facilities” ASCE, in press.

Ballarini, R. (2003). “The Da Vinci-Euler-Bernoulli Beam Theory?” Mechanical Engineering. <http://memagazine.asme.org/web/Da_VinciEulerBernoulli_Beam.cfm> (July 26, 2012).

Banan, M-R., Hjelmstad, K.D. (2009). “Identification of Structural Systems from Measured Response” Civil Engineering Studies SRS-579, College of Engineering, University of Illinois at Urbana-Champaign.

Beck, J. L., and Jennings, P.C. (1980). “Structural Identification Using Linear Models and Earthquake Records” Earthquake Engineering and Structural Dynamics, **8**, 145-160.

Bertero, V. V., Aktan, A. E., Charney, F. A. and Sause, R. (1985). “Earthquake Simulator Tests and Associated Analytical and Correlation Studies of a 1/5 Scale Replica Model of a Full Scale, 7-Story R/C

Frame-Wall Structure," Publication SP-84, "Earthquake Effects on Reinforced Concrete Structures, U.S.-Japan Research," American Concrete Institute.

Beven, K. (2002). "Towards a coherent philosophy for modeling the environment" Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, **458**, 2465-2484.

Bonabeau, E. (2001). "Agent-based modeling: methods and techniques for simulating human systems" In Proceedings of National Academy of Sciences **99**(3): 7280-7287.

Bonato, P., Ceravolo, R., and De Stefano, A. (1997). "The use of wind excitation in structural identification" Proc. Conference: 2nd European and African Conference on Wind Engineering, Genoa, June 22-26, 1997.

Brown, T.A. (1985). "A unified approach to the identification of dynamic behaviour using the theory of vector spaces" PhD Thesis, University of Bristol, UK.

Brownjohn, J.M.W. (2002). "Ambient vibration studies for system identification of tall buildings" Earthquake Engineering and Structural Dynamics **32**, 71-95.

Brownjohn, J.M.W. (2007). "Structural health monitoring of civil infrastructure." Philosophical Transactions A, Royal Society 365(1851),589-622.

Brownjohn J. M. W., Carden E. P., Goddard C. R., and Oudin, G.(2010). "Real-time performance monitoring of tuned mass damper system for a 183 m reinforced concrete chimney" Journal of Wind Engineering and Industrial Aerodynamics. **98**(3) 169-179.

Brownjohn, J.W.W., De Stefano, A., Xu, Y.-L., Wenzel, H., and Aktan, A.E. (2011). "Vibration-based monitoring of civil infrastructure: challenges and successes" Journal of Civil Structural Health Monitoring. **2**(1), 79-95.

Brownjohn, J.M.W., Magalhaes, F., Caetano, E., and Cunha, A. (2010). "Ambient vibration re-testing and operational modal analysis of the Humber Bridge" Engineering Structures **32**(8).

Brownjohn, J.M.W., Moyo, P., Omenzetter, P., Lu, Y. (2003). “Assessment of highway bridge upgrading by dynamic testing and finite element model updating” Journal of Bridge Engineering, 8(3), pp162-172.

Brownjohn, J.M.W., Pan TC. (2008). “Identification of loading and response mechanisms from ten years of performance monitoring and structural analysis of a 280m office tower.” ASCE Journal of Performance of constructed Facilities 22(1), pp24-34.

Calcada, R., Cunha, A., and Delgado, R. (2005). “Analysis of Traffic-Induced Vibrations in a Cable-Stayed Bridge. Part I: Experimental Assessment” Journal of Bridge Engineering 10(4), 370-385.

Catbas F.N.; Susoy, M.; Frangopol, D.M. (2008). “Structural health monitoring and reliability estimation: Long span truss bridge application with environmental monitoring data” Engineering Structures **30**(9), 2347-2359.

Committee on National Earthquake Resilience--Research, Implementation, and Outreach; Committee on Seismology and Geodynamics; National Research Council (2011). “National Earthquake Resilience: Research, Implementation, and Outreach” The National Academies Press, ISBN-10: 0-309-18677-3, 244 pages, 2011.

Cross, E., Worden, K., Koo, K.Y.,and Brownjohn, J.M.W. (2010). “Modelling Environmental Effects on the Dynamic Characteristics of the Tamar Suspension Bridge” IMAC XXVIII, Jacksonville, Florida, USA, 1-4 February.

De Sortis, A., Paoliani, P., (2007). “Statistical Analysis and Structural Identification in Concrete Dam Monitoring” Engineering Structures **29(1)** 110-120.

Douglas, B.M., Reid, W.H., (1982). “Dynamic tests and system identification of bridges” Journal of Structural Engineering **108**(10), 2295-2312.

Farrar, C.R., Baker, W.E., Bell, T.M., Cone, K.M., Darling, T.W., Duffey, T.A., Eklund, A., and Migliori, A. (1994). “Dynamic characterization and damage detection in the I-40 bridge over the Rio Grande,” LA--12767-MS, 1994 Jun 01.

Farrar, C.R., Doebling, S.W. (1999). "Structural health monitoring at Los Alamos National Laboratory" IEEE Colloquium on Condition Monitoring: Machinery, External Structures and Health (Ref. No. 1999/034).

Franco, G., Betti, R., and Lus, H. (2004). "Identification of Structural Systems Using an Evolutionary Strategy," J. Eng. Mech. 130, 1125.

Gentile, C. (2006). "Modal and structural identification of a RC arch bridge" Structural Engineering and Mechanics 22(1), 53-70.

Goulet J.A., Kripakaran, P., Smith, I.F.C. (2010). "Multimodel structural performance monitoring" Journal of Structural Engineering 136(10), 1309-1318.

Gurian, P.L., Aktan, A.E., Montalto, F., and Moon, F. (2009). "Research priorities for infrastructure asset management." Speaker's Journal on Pennsylvania, ISBN 0-9667794-4-4, 9, 43 – 54. (COMMONWEALTH: A Journal of Political Science).

Hansman, R.J., Magee, C., de Neufville, R., Robins, R., Roos, D. (2006). "Research agenda for an integrated approach to infrastructure planning, design and management." International Journal of Critical Infrastructure, 2 (2/3), 146-159.

Hart, G.C. and Yao, J.T.P. (1977). "System identification in structural dynamics" Journal of Engineering Mechanics, **103**(6), 1089-1104.

He, X., Moaveni, B., Conte, J.P. Elgamal, A., Masri, S. (2009). "System identification of Alfred Zampa Memorial Bridge using dynamic field test data" Journal of Structural Engineering **135**(1), 54-66.

Hersey P., Blanchard, K.H., Johnson, D.E. (2001). "Management of organizational behavior: leading human resources" Academic Internet Pub Inc.

Hudson, D.E. (1970). "Dynamic Tests of Full-Scale Structures" Chapter 7 in Earthquake Engineering, Wiegel, R. (Ed.) - Prentice Hall.

Jackson, E., et al. (2011). “*Implementing Knowledge Management Practices for Infrastructure Management*” Project Report Vol. Drexel University, Philadelphia, PA: Department of Civil, Architectural, and Environmental Engineering.

Kai, N., et al. (1998). “TRANSISM traffic flow characteristics” TRANSIMS Report Series, USDOT and USEPA, Los Alamos National Laboratory, LA-UR 97-3531.

Liu H., Yang Z.H., Gaulke M.S. (2005). “Structural identification and finite element modeling of a 14-story office building using recorded data” Engineering Structures **27**(3) 463-473.

Liu, S. C., Yao, J. T. P. (1978). Structural identification concept. Journal of Structural Engineering**, 104**(12), 1845-1858.

Mineta, N. (2006). “National strategy to reduce congestion on America’s transportation network” USDOT <http://isddc.dot.gov/OLPFiles/OST/012988.pdf> (July 26, 2012).

Moaveni, B., Conte, J.P., Hemez, F.M. (2009). “Uncertainty and sensitivity analysis of damage identification results obtained using finite element model updating” Journal of Computer Aided Civil and Infrastructure Engineering, **24**(5), 320-334.

Moon, F. Aktan, A.E. (2006). “Impacts of epistemic uncertainty on structural identification of constructed systems” Shock and Vibration Digest, **38**(5).

Moon, F., A.E. Aktan, F. Jalinoos, S. Jin. (2009). “Leveraging Technology for Performance Based Bridge Engineering, Materials Evaluation,” Journal of ASNT, Sep 2009.

Morassi, A., Stefano, T. (2008). “Dynamic Testing for Structural Identification of a Bridge” Journal of bridge engineering **13**(6), 573-585.

Moutinho C., Cunha A., Caetano E. (2011). “Analysis and control of vibrations in a stress-ribbon footbridge.” Structural Control and Health Monitoring **18**(6) 619-634.

Moyo, P., Brownjohn, J.M.W. Omenzetter, P. (2004). "Highway bridge live loading assessment and load carrying capacity estimation using a health monitoring system" Structural Engineering and Mechanics **18** (5), 609-626.

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

Natke, H.G., Yao, J.T.P. (1987). "Structural Safety Evaluation Based on System Identification" Springer-Verlag, Wien, New York.

Oberkampf, W.L. (2005). "Uncertainty Quantification Using Evidence Theory, Presentation for: Advanced Simulation and Computing Workshop, Error Estimation, Uncertainty Quantification, and Reliability in Numerical Simulations" August 22-23, 2005, Stanford University <http://www.stanford.edu/group/cits/pdf/lectures/oberkampf.pdf>.

Pakzad, S.N., Fenves, G.L., Kim, S., Culler, D.E. (2008). "Design and implementation of scalable wireless sensor network for structural monitoring" Journal of Infrastructure Systems. 14, 89.

Peeters, B., and Guido DeRoeck. (2001). "One-year monitoring of the Z24-Bridge: environmental effects versus damage events," Earthquake Engng Struct. Dyn. 2001; 30:149.

Peeters, B., and Guido DeRoeck. (2001). "Stochastic System Identification for Operational Modal Analysis: A Review," J. Dyn. Sys., Meas., Control -- December 2001 -- Volume 123, Issue 4, 659.

Popova, V., and Sharpanskykh, A. (2008). "Process-oriented organisation modelling and analysis" Enterprise Information systems **2**(2):157–176.

Raphael, B., I. Smith, I.F.C. (1998). "Finding the right model for bridge diagnosis" Artificial Intelligence in Structural Engineering, Lecture Notes in Computer Science **1454**, 308–319.

Sanayei, M., Imbaro, G.R., McClain, J.A.S. and Brown, L. (1997) "Structural Model Updating Using Experimental Static Measurements," *Journal of Structural Engineering*, Vol. 123, No. 6, June 1997, pp. 792-798.

Sharpanskykh, A., Stroeve, S.H. (2011)." An agent-based approach for structured modeling, analysis and improvement of safety culture" Computational and Mathematical Organization Theory **17**, 77–117.

Shinozuka, M., and Ghanem, R. (1995) "Structural System Identification. II: Experimental Verification" *Journal of Engineering Mechanics*, Vol. 121, No. 2, pp. 265-273.

Sohn, H., Farrar, C. R., Hemez, F. M., Czarnecki, J. J. (2003) "A Review of Structural Health Review of Structural Health Monitoring Literature 1996-2001" LA-UR-02-2095, 2010 Jun 03.

Sussman, J.M. , Sgouridis, S.P., Ward, J.L. (2005). "New Approach to Transportation Planning for the 21st Century: Regional Strategic Transportation Planning as a CLIOS Process" Transportation Research Record **1931**, 89-98.

Taleb, N.N. (2010). "The Black Swan: The Impact of the Highly Improbable (Second edition)" Random House Publishers.

Yao, J.T.P. (1996). "On Civil Infrastructure Systems and Engineering Education Viewpoint" Journal of Infrastructure Systems, **2**(1), EDITORIAL. 17-24.

Yao, J.T.P, (1979). "Damage assessment and reliability evaluation of existing structures" Engineering Structures **1**(5)s 245-251.

Zhao, J. and DeWolf, J.T. (1999). "Sensitivity Study for Vibrational Parameters Used in Damage Detection," J. Struct. Eng, 125, 410.

URLs:

ASCE (2009) "Vision 2025" The Roadmap to Achieve the Vision, <http://content.asce.org/vision2025/index.html> (July 26, 2012).

CBS (2011) “Ancient stone markers warned of tsunamis” The Associated Press. http://www.cbsnews.com/stories/2011/04/06/501364/main20051370.shtml

Hudson, D.E. (1961). “A New vibration exciter for dynamic tests of full scale structures. California Institute of Technology” unpublished <http://resolver.caltech.edu/CaltechEERL:1961.EERL.1961.001>

ASCE (2007): THE NEW ORLEANS HURRICANE PROTECTION SYSTEM: What Went Wrong and Why, A Report by the American Society of Civil Engineers Hurricane Katrina External Review Panel, http://web.archive.org/web/20080624204644/http://www.asce.org/files/pdf/ERPreport.pdf

NIST (2005)” Final Reports from the NIST World Trade Center Disaster Investigation” <http://www.nist.gov/el/disasterstudies/wtc/wtc_finalreports.cfm> (Jan 4, 2012).

NY Times (1998).” Water Main Ruptures, Creating A Huge Sinkhole on Fifth Avenue”

McFadden, R. D. (1998). “Water Main Ruptures, Creating A Huge Sinkhole on Fifth Avenue” <http://www.nytimes.com/1998/01/03/nyregion/water-main-ruptures-creating-a-huge-sinkhole-on-fifth-avenue.html> (Jan. 21’ 2012).

U.S. Department of Homeland Security (2010). “DHS| Critical Infrastructure” DHS. <http://www.dhs.gov/files/programs/gc_1189168948944.shtm> (May 15, 2012).

Zweig, J. (2011) “Forget About Black Swans, the One Floating Ahead is Neon” http://online.wsj.com/article/SB10001424053111904233404576462410143674364.html (July 26, 2012).

http://en.wikipedia.org/wiki/National_Infrastructure_Reinvestment_Bank

http://en.wikipedia.org/wiki/2011_T%C5%8Dhoku_earthquake_and_tsunami#Nuclear_power_plants

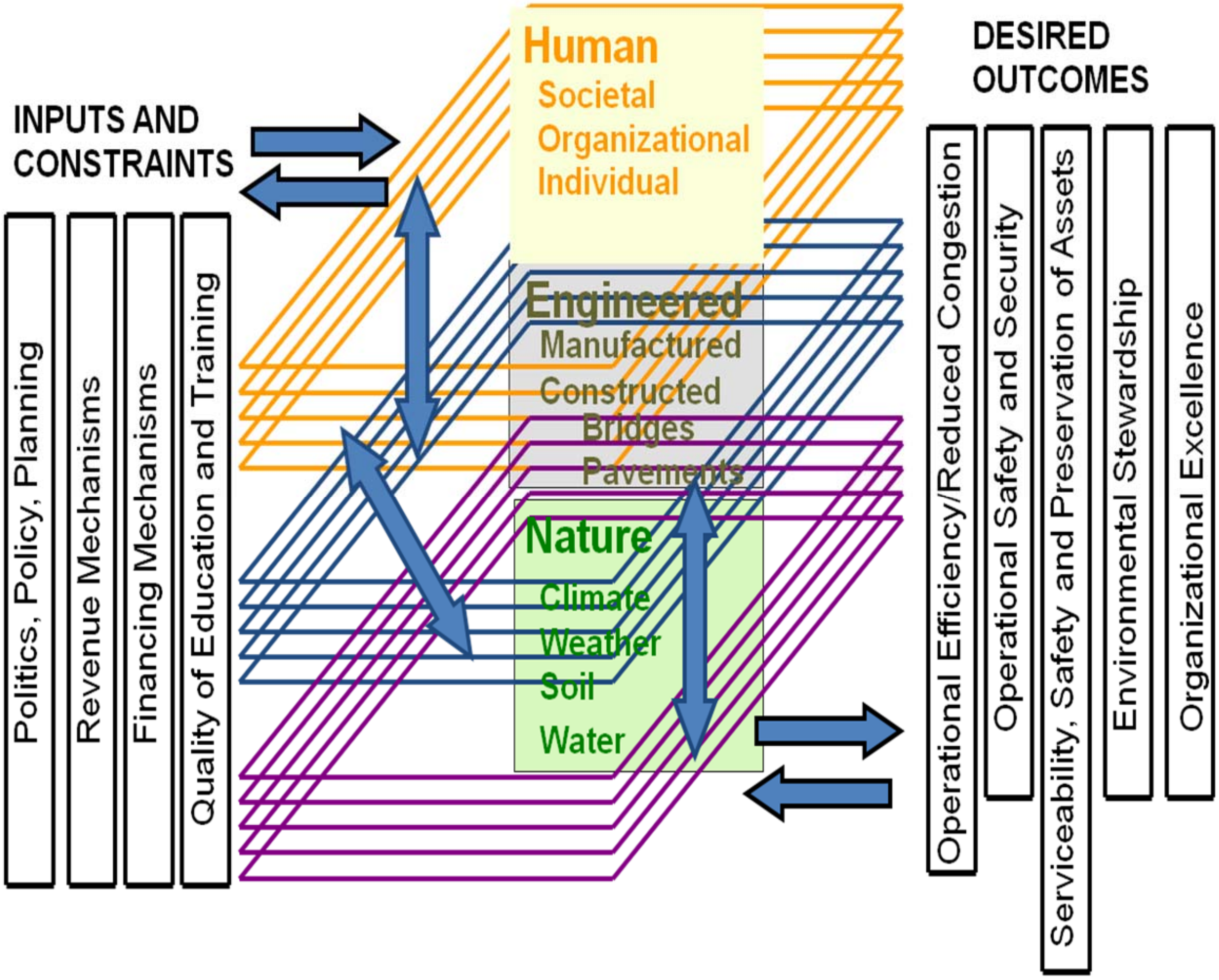

Figure 1: A Multi-Layered Representation of the Highway Transportation System

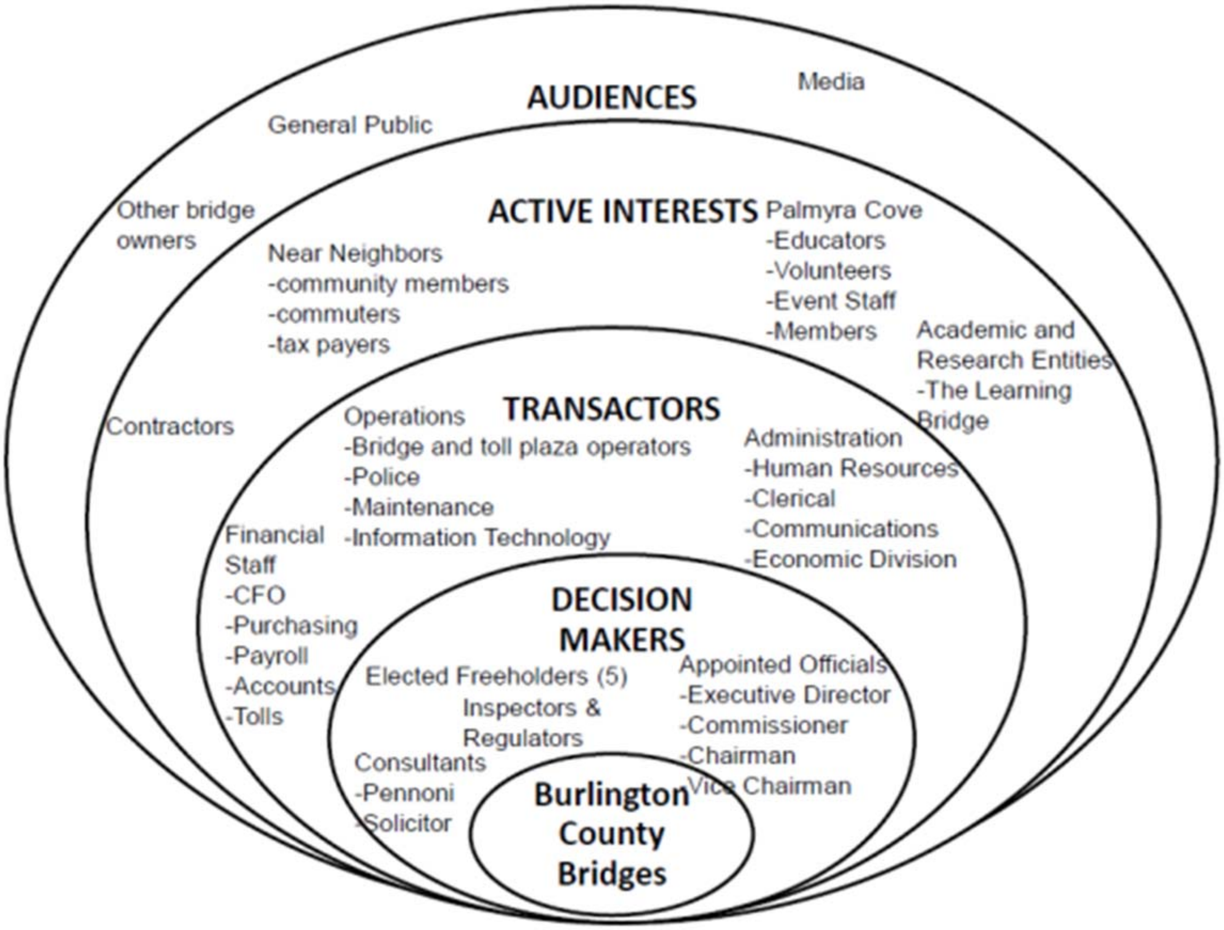

Figure 2: Schematic Representation of the Stakeholders of a Toll Bridge

LIST OF FIGURE CAPTIONS

Figure 1: A Multi-Layered Representation of the Highway Transportation System

Figure 2: Schematic Representation of the Stakeholders of a Toll Bridge

ASCE

COPYRIGHT TRANSFER AGREEMENT

Manuscript Number: STENG-1904

Type: FORUM PAPER

Publication Title: Structural Identification: Opportunities and Challenges

Manuscript Authors: AE Aktan and JMW Brownjohn

Corresponding Author Name and Address: Ahmet Emin Aktan, 50 Belmont Avenue Unit 1010
Bala Cynwyd, PA 19004

This form *must** be returned *with* your final manuscript to: American Society of Civil Engineers, *Journals Production Services Dept*., 1801 Alexander Bell Drive, Reston, VA 20191-4400.

The author(s) warrant(s) that the above cited manuscript is the original work of the author(s) and has never been published in its present form.

The undersigned, with the consent of all authors, hereby transfers, to the extent that there is copyright to be transferred, the exclusive copyright interest in the above-cited manuscript (subsequently called the "work"), in this and all subsequent editions of this work, and in derivatives, translations, or ancillaries, in English and in foreign translations, in all formats and media of expression now known or later developed, including electronic, to the American Society of Civil Engineers subject to the following.

- The undersigned author and all coauthors retain the right to revise, adapt, prepare derivative works, present orally, or distribute the work provided that all such use is for the personal noncommercial benefit of the author(s) and is consistent with any prior contractual agreement between the undersigned and/or coauthors and their employer(s).

- In all instances where the work is prepared as a "work made for hire" for an employer, the employer(s) of the author(s) retain(s) the right to revise, adapt, prepare derivative works, publish, reprint, reproduce, and distribute the work provided that such use is for the promotion of its business enterprise and does not imply the endorsement of ASCE.

- No proprietary right other than copyright is claimed by ASCE.

- An author who is a U.S. Government employee and prepared the above-cited work does not own copyright in it. If at least one of the authors is not in this category, that author should sign below. If all the authors are in this category, check here ☐ and sign here: ________________________. Please return this form by mail.

SIGN HERE FOR COPYRIGHT TRANSFER [Individual Author or Employer's Authorized Agent (work made for hire)]

Print Author's Name: Ahmet Emin Aktan
Signature of Author (in ink): AEAktan

Print Agent's Name and Title:
Signature of Agency Rep (in ink):

Date: 17 August 2012

Note: If the manuscript is not accepted by ASCE or is withdrawn prior to acceptance by ASCE, this transfer will be null and void and the form will be returned to the author.

*Failure to return this form *will* result in the manuscript's not being published.

To: Editorial Board of Journal of Structural Engineering

Manuscript Submission- Structural Identification: Opportunities and Challenges

Dear Editors,

The referenced manuscript was submitted to the Journal, and following its review, revisions were suggested. We are grateful for these suggestions and implemented them.

Here we would like to submit the captioned ***revised*** manuscript as a FORUM PAPER to the Special Issue of the Journal of Structural Engineering on Structural Identification for your consideration. The first author of the manuscript is Dr. A. Emin Aktan and the Co-author is Dr. James Brownjohn. The corresponding author is Dr. Aktan and the contact information is below for your reference.

Discussion of the SIX STEPS has been reduced - however, the remaining discussion is not thought to be repeated in the other reports. The discussion is based on the personal experiences of two highly experienced "senior citizens" that are not necessarily shared by the younger generation.

This paper exceeds the 5,000 word limit. However, The FORUM Paper was invited by the Guest Editors to offer an overview of the concept from its origins to current state of art. The concept of St-Id holds so much promise for enhancing the performance of constructed systems and for reforming civil engineering education that we submit that there is value to increase the word limit.

Address: Drexel University
CAEE Department
3141 Chestnut Street
Philadelphia, PA, 19104

Tel: 215-895-6135
Fax: 215-895-6131
E-mail: aaktan@drexel.edu

Best Regards,
A.Emin Aktan
Roebling Professor of Infrastructure Studies
Department of Civil, Architectural and Environmental Engineering
Drexel University
Philadelphia, PA 19104