LONG-TERM VISION FOR THE ASCE TECHNICAL COMMITTEE: STRUCTURAL IDENTIFICATION OF CONSTRUCTED SYSTEMS

A. Emin Aktan
Drexel University, USA

Franklin L. Moon
Drexel University, USA

F. Necati Catbas
University of Central Florida, USA

ASCE-SEI Performance of Structures Track established a technical committee on "Structural Identification (St-Id) of Constructed Systems," in 2005. The writers are currently serving as the control group. The near-term purpose and objectives of the Committee are as follows:

Committee Purpose
Foster advances and dialogue to enable the collection of data, its analysis and interpretation, and ultimately the assessment of constructed system performance beyond the anecdotal observations that currently form our bases for judging the merits of our designs.

Committee Objectives
Given that the actual mechanical characteristics and performance of constructed systems have been shown to be very different from those considered during a specification-based code design, a principal focus will be on defining metrics and establishing measurement standards for constructed systems, which represents a prerequisite for a meaningful transition to Performance Based Civil Engineering (Aktan et al, 2007). In addition, the Committee will aim to develop guidelines for reliable field-calibrated analytical modeling and characterization of existing constructed systems. Field-calibrated analytical modeling leverages objective measurements of geometry, soil and structural material characteristics, responses during controlled experiments, and, long-term monitoring for establishing the loading environments and performance at critical limit-states. To inform these two standards as well as the profession at large regarding the relevant issues and vast discrepancies between different applications of St-Id., the Committee will collect available data from existing tests, and interpret and archive case studies. In addition to preparing and publishing guidelines, conference sessions will be organized and papers will be published in proceedings.

Near-Term Deliverable
A state-of-the-art Report on St-Id will be compiled and edited before Dec 31, 2007 and published through ASCE. Dr. Catbas (who is the third writer) is leading the subcommittee that is working on this report.

COMMITTEE MEMBERSHIP

ASCE Roster (2007)
Alampalli, Aktan, Barr, Betti, Brownjohn, Catbas, DeRoeck, Fenves, Furuta, Grimmelsman, Halling, Kareem, Masri, Moon, Rutz, Sanayei, Shama, Smith, Sohn, Wu

New members (waiting to be added to the Roster)
Bell, Chen, Conte, DesRoches, Bruschi, Dyke, Gurian, Kehoe, Kijewski, Taciroglu, Wartman

Corresponding members-advisors
Akay, Ang, Arzoumanides, Beck, Chang, Chase, Doebling, Hjelmstadt, Dusenberry, Ghasemi, Ellingwood, Farrar, Foutch, Frangopol, Fujino, Helmicki, Inman, Liu, Mufti, Roesset, Sozen, Spencer, St. Pierre, Yegian, Yanev, Yao

THE PROPOSED LONG-TERM AGENDA OF THE COMMITTEE

Background and the Drivers Shaping the Agenda of the Committee
Structural identification (St-Id) is an adaptation of the system-identification concept which originated in electrical engineering in relation to circuit and control theory. St-Id has been defined as: "*the parametric correlation of structural response characteristics predicted by a mathematical model with analogous quantities derived from experimental measurements*" (Doebling et al. 2000). The St-Id paradigm was first introduced to engineering mechanics researchers by Hart and Yao (1977) and to civil-structural engineering researchers by Liu and Yao (1978). These seminal papers gradually inspired many researchers to investigate various aspects of St-Id, and nearly 30 years later St-Id remains an active research area in both engineering mechanics and civil-structural engineering. Recent advances in IT has rendered FE modeling of large structures for new design, or condition and vulnerability assessment, rehabilitation or retrofit commonplace. Civil engineering consultants are routinely using FE modeling and simulation for practical applications. However, it has been well established that due to the uniqueness and significant epistemic uncertainty associated with our constructed systems, reliable simulations, either by a 3D microscopic FE model or by much simpler and greatly idealized macroscopic models, require calibration and validation based on actual observations and measured experimental data. Meanwhile, the paradigm of making meaningful observations and taking reliable measurements from actual operating constructed systems in the field is still an emerging art. Using field observations and measurements for calibrating and validating a FE model is also a highly challenging problem. An ASCE Committee was therefore warranted to bring together researchers and practicing engineers with experience and knowledge in practical applications of FE models, fundamentals of various approaches to FE modeling, simulations and scenario analysis, field research, and their integration

Figure 1 illustrates the St-Id paradigm in terms of an integrative application of Six Steps. Integration may be accomplished by linear progression, or across, or in various combinations until convergence. Although each step of the paradigm has been researched to some extend, many challenges do remain. For example, the integration of the Steps and how we may describe and accomplish convergence remain open questions. However, the profession has already begun to apply the paradigm. For example, recent projects on many of the major suspension bridges in NY City, including the Brooklyn Bridge, an operating historic monument, incorporated some level and form of St-Id. Unless we establish standards and guidelines for proper, meaningful and reliable applications of this paradigm, it will be very difficult, if at all possible, to leverage and advance the application of IT tools by the civil engineering profession.

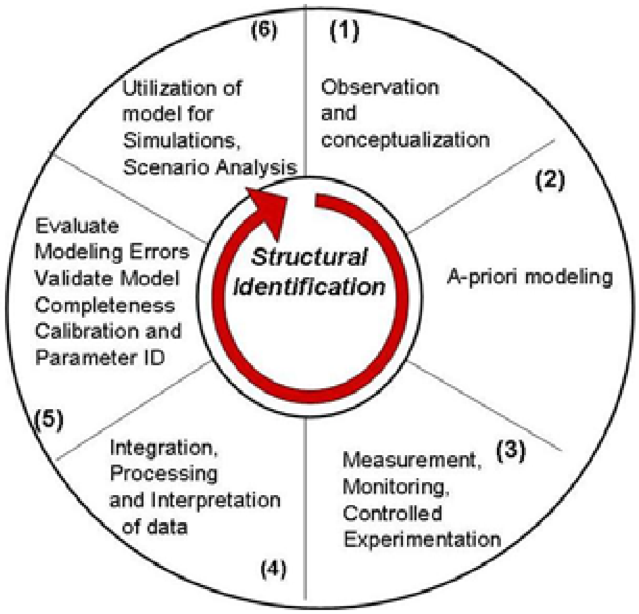

Figure 1. The Six Steps of St-Id

St-Id Application Scenarios

There are several scenarios which may justify the construction and identification, based on the results of field experiments, of an analytical model for simulating an actual constructed system. Examples include:

1. Design verification and construction planning in case of challenging and/or ground-breaking new designs,
2. A means of measurement-based delivery of a design-build contract in a performance-based approach,
3. Documentation of as-is structural characteristics to serve as a baseline for assessing any future changes due to aging and deterioration, following hazards, etc.
4. Load-capacity rating for inventory, operations or special permits,
5. Evaluation of possible causes and mitigation of deterioration, damage and/or other types of performance deficiencies (e.g. vibrations, cracking, settlement, etc.),
6. Evaluation of reliability and vulnerability (changes in live-load demands, threats, hazards, increased performance requirements),
7. Structural modification, retrofit or hardening due to changes in use-modes, codes, aging, and/or for increasing system-reliability to more desirable levels,
8. Health and performance monitoring for operational and maintenance management,
9. Asset management (based on lifecycle benefit/cost).

In addition to the above, many civil engineers are interested in advancing our knowledge regarding how actual structural systems are loaded (during construction and after commissioning), how they deform, i.e. their kinematics at supports, joints, connections, and how they transfer their forces through the members to foundations and to soil. There is sufficient evidence that our current knowledge base on the loading, behavior and performance of constructed systems is greatly incomplete, especially when new construction materials and systems are considered. The significant epistemic uncertainty prevailing in the actual loading mechanisms, intrinsic force distributions, kinematics, failure modes and capacities of existing constructed systems, especially after aging may lead to discrepancies between predicted responses and capacities that are different by more than an order of magnitude, and not always in a conservative way. Many members, joints and connections may be loaded less than assumed while many others may be loaded with demands that are far greater than anticipated. Some of the mechanisms that may control the distribution of demands and the corresponding capacity at the critical regions of constructed systems are often very difficult to discover and quantify even with measurements unless a rigorous St-Id is carried out by experts.

Observations in the field, followed by properly designed, executed and interpreted experiments are the only definitive approach for reducing epistemic uncertainty that clouds constructed system behavior. Further, it is not possible to reliably design, execute and interpret field experiments without first studying, observing, conceptualizing, and modeling a constructed system, so that sensing and loading can be designed effectively and data can be interpreted. These are some of the reasons that make advancing St-Id and conducting applications important and in fact necessary for civil engineers if we are to respond to the needs of the society regarding improving the lifecycle performance and sustainability of our constructed systems.

Systems-Identification of Infrastructure Systems

An application scenario that is especially compelling is regarding the engineering and management of infrastructures. Critical infrastructures that are considered vital to national defense, economic security, public health and safety and national morale include telecommunications and information networks, energy, banking and finance, transportation, water, emergency services and government, health services, national defense, foreign intelligence, law enforcement, foreign affairs, nuclear facilities and power plants, food/agriculture, manufacturing, chemical, defense industry, postal/shipping, and, national monuments and icons (Congressional Research Service, 2003). Every one of these infrastructures rely on constructed systems (buildings, bridges, towers, industrial plants, pipelines, etc) and some like the highway transportation and water infrastructures are virtually exclusively in the civil engineering domain. Recently, the importance of a systems level identification of these infrastructures, inclusive of their engineered, natural and human elements, their intersections and interactions has been articulated by many researchers. For example Hansman et al (2006) stated that "*our infrastructure is a system of systems involving different technical manifestations and social organizations. The implication is that we need a fundamental reconsideration of how we look at system design, away from traditional disciplinary considerations and toward a multi-domain, multi-disciplinary effort.*"

Table 1. Mathematical Modeling Forms

Physics-Based Models	Non-Physics-Based Models
Mathematical Physics Models • F=MA • $E=MC^2$ *Continua Models* • Theory of Elasticity • Field and Wave Eqns • Idealized Diff. Eqns (Bernoulli, Vlasov, etc.) *Discrete Geometric Models* • Network Models • Smeared-Macro or Element Level Models • FEM-for Solids and Field Problems • Modal Models: - Modal Parameters - Ritz Vectors *Numerical Models* • K,M,C Coefficients	*Semantic Models* • Ontologies • Semiotic Models *Meta Models* • Input-Output Models • Rule-based Meta Models • Mathematical (Ramberg-Osgood, etc.) *Numerical Models* • Probabilistic Models - Histogram-Based Frequency Distributions - Standard Probability Distributions - Independent events - Event-based (Bayesian) - Time-based - Symptom-based • Agent Models • Statistical (Data-Based) Models - ARMA, ANN, others - Signal/Pattern Analysis, Wavelet, EMD, others

A number of approaches have been developed for modeling different infrastructure systems at different resolutions, and the authors see great potential for integrating these models into a comprehensive, multi-resolution meta-model of a regional infrastructure system, followed by validating and calibrating this through a systems-identification (Sys-Id) process similar to validating and calibrating an FE model for a constructed system. Some of the mathematical modeling approaches that have been investigated and may be integrated for such a purpose are listed in Table 1. Given that critical planning and financing policy decisions are currently taken without the benefit of system-wide modeling and scenario analyses, many decisions may lead to unintended and undesirable consequences. A Sys-Id based field-calibrated modeling of infrastructure systems would offer excellent opportunities for reliable scenario analyses. Extending Sys-Id from constructed systems to the simulation of entire infrastructures may therefore offer a new frontier for civil engineering.

CHALLENGES

Whenever we question status-quo and would like to promote a paradigm that forces civil engineers to become performance-oriented as opposed to their current process-based practice, we should expect considerable social, organizational and individual resistance. This represents a more critical challenge than any technical one. Overcoming such a “soft” challenge requires bringing together a critical mass of champions from academe, government and industry, and coordinating their time and effort for educating the profession and new civil engineers. Meanwhile, to better understand the technical challenges, we need to recognize the distinctions between St-Id applications to manufactured-mechanical and constructed-civil systems. In the case of manufactured systems, the concept of St-Id has matured over the past three decades and has been widely and reliably applied to various automotive and aerospace systems. In contrast, while hundreds of investigations focused on the St-Id of constructed systems have been performed (Moon and Aktan, 2006), the use of St-Id for constructed systems remains in its infancy and has enjoyed only sparse implementation in practice. While several researchers have argued this is primarily due to a lack of practical sensing and networking technology, recent advances in these areas have not been accompanied by widespread implementation of St-Id. Rather, it is becoming increasingly clear that the lack of implementation and the skepticism towards St-Id held by many owners/stewards of constructed systems also stems from an inability to reliably interpret measurements to influence management decisions. This is compounded by the reality that in many cases irrelevant and unreliable data, especially erroneous identification of deterioration or damage, become a liability for managers.

The writers believe that this difficulty principally results from a lack of appreciation for the inherent distinctions between constructed systems and their manufactured counterparts. Overcoming this challenge requires that the recent advances in St-Id, control and monitoring of manufactured systems be adapted to explicitly recognize and address the unique attributes of constructed systems. An example of this type of development is the recent progress associated with operational (or output-only) modal analysis, which recognizes the cost and difficulty of performing forced vibration tests on large constructed systems (Brownjohn et al. 1992, Fujino et al. 1999, Wenzel and Pichler 2005, among others). In addition, several researchers have developed St-Id approaches that explicitly address aleatory uncertainty (due to natural randomness), which can be significant for constructed systems (Bucher et al. 2003, Yuen and Katafygiotis 2002, Beck and Katafygiotis (1998), Beck 1990). However, while these advances are highly relevant, the distinctions they address are far from exhaustive, and do not include epistemic uncertainty. Thus a wider, sustained effort, especially recognizing the challenges associated with epistemic uncertainty (due to our inability to correctly understand, model or predict the behavior of constructed systems) have to be recognized and addressed. As a first step, civil-structural engineers must identify and communicate the principal distinctions that lead to the unique challenges associated with the St-Id of constructed systems to the wider community from engineering mechanics.

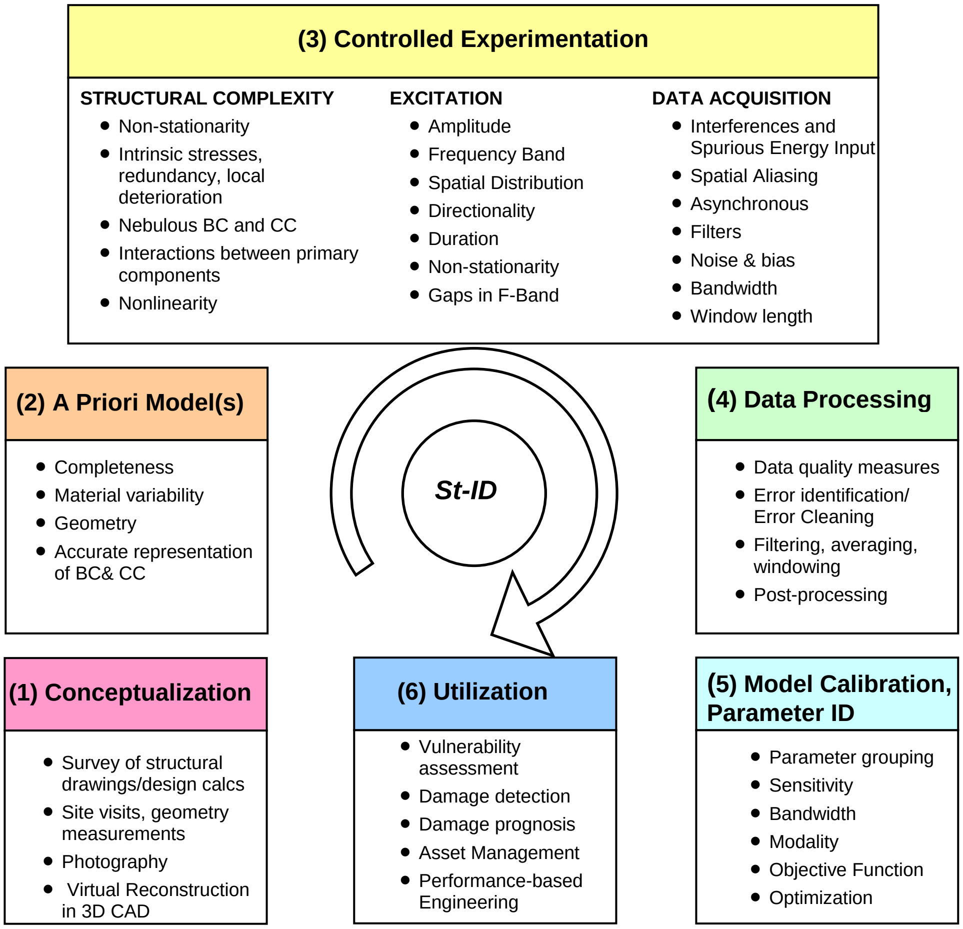

Figure 2. Uncertainties associated with the St-ID of constructed systems

Fig. 2 illustrates how the Six Steps of St-Id may be affected by both aleatory and epistemic uncertainty, by a partial listing of the known mechanisms that are affected by uncertainty. Step 2 – Modeling; and Step 3 – Experimenting, are governed by especially challenging epistemic uncertainty due to size, complexity and a lack of observability at soil-foundation boundaries as well as sub-and-super-structure interfaces, and the magnitude and nonstationarity of intrinsic forces of constructed systems. Although a clear understanding of such mechanisms may appear 'academic' to some, this is a most critical and pervasive challenge facing civil engineering today. Consider that civil engineering remains as the only engineering discipline without a clear understanding of the products it constructs. In the last decade we have seen awe-inspiring scientific achievements, while both the education and practice of civil engineering remains within the quasi-reality of many disconnected processes without a clear understanding of the final product.

There is sufficient evidence in relation to infrastructure performance that the society cannot afford to allow civil engineers to live in a process-based quasi-reality any longer. Without an ability to properly observe and measure, and extract reliable and meaningful data and information that will permit us to develop generic knowledge from existing constructed systems, we will not be able to advance civil engineering to serve the societal needs related to infrastructures.

Finally, we do need to embrace and guide the large number of research projects conducted on analytical and numerical modeling and computation, as well as the theoretical aspects of "health-monitoring," by bright researchers mainly with an engineering mechanics background. Researchers engaged in such studies often use simulated data or take advantage of data collected by others on actual constructed systems. However, all of the limitations that obstruct extracting generic knowledge from commonly conducted tests on constructed systems will naturally also apply to such theoretical research unless grounded on an integrated systems approach that fully leverages real-life constructed systems. Similarly, we should be grounding the efforts towards technology-push. For example, research dedicated to sensing and communication that intends to produce innovative sensors and sensor networks, should be formulated and developed in conjunction with experts in the design and execution of field research on actual constructed systems.

Recommended Agenda

If the ASCE Committee on St-Id of Constructed Systems was only interested in documenting the state-of-the-art, this would not have been a great challenge. The Committee membership includes many of the major contributors to this field. However, the Committee is interested in advancing the field and promoting meaningful applications of St-Id to various classes of structures. By accumulating reliable and comprehensive data, information and knowledge about the actual, as opposed to assumed, loading, behavior and performance of constructed systems and entire infrastructures we expect to have a true impact on advancing the practice, training and education of civil engineers. Given this ambition and importance of success, the Agenda follows:

Recruiting Champion Experts

The first step is to bring together as many of the champions and experts as possible from academe, industry and government who have been advocates in changing the way we teach and practice civil engineering. Such experts would be the first to recognize the importance of St-Id as a paradigm offering an effective path to integration and discovering the reality of constructed systems and infrastructures. Civil engineers knew of this reality before the 20th Century through intuition and heuristics. After losing this to a proliferation of university programs and prescriptive codes; and to the shift to applied science in the 1950's without distinguishing the differences between constructed and mechanical systems, we now have a chance to rediscover reality. The most important long-term goal for the Committee would be to establish reality of civil engineered systems in a factual and quantitative manner, as accurately and completely as possible, comparing the assumed-predicted and true reality, and to disseminate this information. In this manner we may contribute to changing the way we teach and practice by basing it on ground truth which we can discover through St-Id of existing systems. The Committee has been formed and the membership has been endowed with the best possible global expertise. The Committee will be meeting at least once a year, and the membership will be interacting through e-mail and other means more frequently. Paper sessions at conferences will spread the word by illustrating meaningful applications of St-Id to the profession and students.

Establishing the State-of-the-Art

The first deliverable identified by the Committee is a state-of-the-art report that is complete and that recognizes the distinctions between constructed and mechanical systems. This report is being prepared by a subcommittee led by the third writer. There is another paper in the Session, written by the second and third authors that will describe the report.

Organizing/Coordinating Research on Lab Benchmarks

Well-designed physical laboratory models are invaluable benchmarks for exploring and demonstrating each of the Six Steps that make up the St-Id process (Fig. 1), and the many possible products that may come out of the process. Such models also serve as excellent case-study based learning opportunities for students and practicing engineers interested in continuing education. Recognizing that there is no unique characterization for a constructed system, but a ground truth that we can approach only as close as uncertainty permits, the art of St-Id becomes how we deal with the challenges of managing uncertainty. The age-old strategy in civil engineering analysis has been investing only as much into modeling and computation that is commensurate with what the uncertainty will permit us to predict within some confidence. The issue is in how we may reduce the uncertainty by virtue of having a physical model that does NOT have many of the uncertainties we face in the field, and one that may be tested as many times, by as many persons, and, in as many different ways as needed. The Committee has organized TWO laboratory benchmarks, at the home institutions of the first two and the third writers, respectively. The benchmark at Florida is a more basic one, and has been designed mainly for a systematic exploration of how we may apply and integrate Steps 1-6 of Fig. 1, whereas the benchmark at Philadelphia has been designed to more systematically explore the impacts of various types and forms of uncertainty, some of which have been listed in Fig. 2. These benchmarks will be described further in a separate paper by the second and third writers. These writers have initiated partnerships and have started using the two benchmarks for purposes that they describe in a separate paper in the same Session.

Organizing/Coordinating Demonstrations on Real Systems

A long-term goal is to leverage the expertise of the Committee in St-Id demonstration projects on real bridges and buildings. Such an effort may be initiated in NIST's leadership for buildings and FHWA's leadership for bridges, with ASCE and other agencies such as NSF's participation and support.

ACKNOWLEDGEMENTS

This Committee was established by ASCE Performance of Structures TAC following the activities and final Report of the Committee on Performance-Based Design and Evaluation of Constructed Systems (Aktan, Ellingwood and Kehoe, 2007). This Report described that a prerequisite for performance-based engineering, a paradigm subscribed to by all other engineering disciplines for ensuring the quality of their products, is a complete and detailed knowledge of the product and the process with which it is created. This has not yet been the case in civil engineering due to the fragmented manner in which our products are created and a lack of measurements as they are commissioned.

Recognizing the importance of this concern, ASCE-SEI has re-established the St-Id of Constructed Facilities Committee. We note that from 1997-2002 the current Chair founded and co-chaired an earlier committee with the same name together with the pioneer who introduced the concept to the civil engineering community, Dr. J.T.P. Yao. This past committee developed a draft state-of-the-art report but it became inactive in 2002. The new Committee will review, update and complete this report, including the lessons learned from actual St-Id applications since 2002.

Writers deeply acknowledge the leadership of Dr. J.T.P. Yao, and the contributions of the members of the former ASCE Committee on St-Id of Constructed Facilities. Special thanks are overdue to Drs. Doebling and Helmicki who have made major contributions to the draft report.

REFERENCES

1. Aktan, A.E., Ellingwood, Bruce, and Kehoe, Brian, "Performance-Based Engineering of Constructed Systems, Forum Paper, *Journal of Structural Engineering*, 311-323, March 2007.
2. Beck, J.L. and L.S. Katafygiotis (1998) "Updating Models and Their Uncertainties: Bayesian Statistical Framework," Journal of Engineering Mechanics, 124, No. 4, 455-461
3. Beck, J.L. (1990) "Statistical System Identification of Structures," Structural Safety and Reliability, 1395–1402, ASCE, New York
4. Brownjohn, J. M. W., Severn, R. T. and Dumanoglu, A. A. (1992). "Full-scale dynamic testing of the second Bosporus Suspension Bridge." Proc. Of the 10th World Conference on Earthquake Engineering, A. A. Balkema, Rotterdam, Vol.5, 2695-2700.
5. Bucher, C., O. Huth, and M. Macke (2003) "Accuracy of system identification in the presence of random fields," Proceedings of ICASP'9
6. Congressional Research Service: Moteff, J., Claudia Copeland, and John Fischer, "Critical Infrastructures: What Makes an Infrastructure Critical?", Library of Congress, 2003
7. Doebling, S.W., C.R. Farrar, A.E. Aktan, J. Beck, P. Cornwell, A. Helmicki, E. Safak, and J. Yao (2000) "The State of the Art in Structural Identification of Constructed Facilities," A Draft Report by the ASCE Committee on Structural Identification of Constructed Facilities
8. Fujino, Yozo; Nakamura, Shun-Ichi; Shibuya, Hajime; Sato, Masashi; Yanagihara, Masato; Sakamoto, Yoshifumi (1999) "Forced and ambient vibration tests of Hakucho Suspension Bridge," Structures Congress - Proceedings, 1999, p 328-331
9. Hansman, J.R., C. Magee, R. De Neufville, R. Robins, and D. Roos (2006) "Research agenda for an integrated approach to infrastructure planning, design and management," International Journal of Critical Infrastructures, Inderscience, Vol. 2, No. 2-3, pp. 146-159
10. Hart, G. C. and Yao, J. T. P. (1977) "System Identification in Structural Dynamics." ASCE Journal of the Engineering Mechanics Division, 103(EM6), 1089-1104

11. Liu, S.C. and Yao, J.T.P. (1978) "Structural Identification Concept" J. Structural Division, ASCE, 104(ST12), 1845-1858
12. Moon*, F.L. and A.E. Aktan (2006) "Impacts of epistemic uncertainty on structural identification of constructed systems", *The Shock and Vibration Digest*, Vol. 38, No. 5
13. Wenzel, H. and D. Pichler (2005) "Ambient Vibration Monitoring," John Wiley & Sons, Inc
14. Yuen, K-V and L.S. Katafygiotis (2002) "Bayesian modal updating using complete input and incomplete response noisy measurements," Journal of Engineering Mechanics, v 128, n 3, p 340-350