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Structural Identification: Opportunities and Challenges

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ABSTRACT

The Intertwined Nature of Civil Engineering Systems in 2024 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, "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, 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).

INTRODUCTION

Overview

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 . 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.

REVIEW OF LITERATURE

A Perspective on Infrastructure Performance in 2023

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 (Table 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 US76

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).

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. Gaffer'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 etal. 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 (Brown john 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 Throngs' 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; Brown john 2002; Brown john et al. 2011), (b) forced excitation testing (Brown john 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.

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).

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.

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 6348 should certainly include the owners and managers of the system.

2. OPERATIONAL MONITORING AND CONTROLLED EXPERIMENTATION.

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.

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.

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.

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