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Performance-Based Engineering of Constructed Systems

The ASCE SEI Technical Committee:
"Performance-Based Design and Evaluation of Civil Engineering Facilities"
Performance of Structures Technical Activities Division
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Background

During the 1999 Structures Congress, the Executive Committee of the Technical Activities Division of the Structural Engineering Institute approved a new technical committee for defining the "performance of a civil engineering facility." This was considered a sufficiently important objective by the Technical Activities Division to justify forming a new technical committee.

The Committee's purpose (ASCE OR 2000, http://www.asce.org/or/) is: "facilitating the development and adoption of realistic, effective, comprehensive and reliable performance-based design and evaluation techniques and procedures for civil engineering facilities, helping to establish the foundations for specifications, model codes and commentaries for performance-based design and evaluation." The Committee has met four times during 2000-2003, and organized two technical sessions at 2003. Its membership comprised of about thirty, representing academe, government and the consulting industry, and included non-engineers. Formulating and articulating a clear, comprehensive and consistent consensus definition for the performance of a civil engineered facility was recognized as an important step and in fact a prerequisite for serving as an intellectual foundation before making a transition to a performance-based approach in civil engineering.

This paper offers a synthesis of specification-based versus performance-based civil engineering and articulates the committee's progress in framing and articulating: "what is performance-based civil engineering?", "how can we objectively define performance?" and, "what are the issues that should be recognized along our way to performance-based engineering and their possible resolutions?

As this draft report has been completed and is circulated within the committee and Performance of Structures TAC members, steps have been taken to merge the Performance-Based Design and Evaluation of Civil Engineering Facilities Committee with the Performance of Full-Scale Structures Committee. This merger took place during the 2004 Congress and a critical mass of academic and practicing members continue exploring how to innovate the art of civil engineering by taking advantage of the performance-based engineering paradigm.

The Paradigm of Performance-Based Engineering

To describe the distinction between "prescriptive versus performance based engineering" the following examples were offered by Harris (2002): "Performance based: An acceptable level of protection against structural failure under extreme load will be provided" and Prescriptive: 0.5 in. diameter bolts spaced no more than six feet on center shall anchor the wood sill of an exterior wall to the foundation." Hamburger (2002) described performance-based design as: "Design specifically intended to limit the consequences of one or more perils to defined acceptable levels". Harris referenced Hammurabi's code (based on a stiletto currently at the Louvre Museum, Paris) as the oldest known performance-based code.

Indeed, according to a translation of Hammurabi's (1795-1750 BC) Code by L.W. King at Yale Law School: (http://www.yale.edu/lawweb/avalon/medieval/hamframe.htm):

> *"228. If a builder build a house for some one and complete it, he shall give him a fee of two shekels in money for each sar of surface.*
> *229 If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.*
> *230. If it kill the son of the owner the son of that builder shall be put to death.*
> *231. If it kill a slave of the owner, then he shall pay slave for slave to the owner of the house.*
> *232. If it ruin goods, he shall make compensation for all that has been ruined, and inasmuch as he did not construct properly this house which he built and it fell, he shall re-erect the house from his own means.*
> *233. If a builder build a house for some one, even though he has not yet completed it; if then the walls seem toppling, the builder must make the walls solid from his own means."*

The standards, guidelines and recommendations that have shaped the current specifications used for design, construction and evaluation of common buildings and bridges have their origins in the first half of the 20th Century, formulated by the technical committees of ASCE, ACI, AISC, ASTM, AASHO (currently AASHTO) and others. For example, the first Joint Committee that issued the 1916 Report on Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete was made up by related committees of the American Concrete Institute, the American Institute of Architects, the American Railway Engineering Association, the American Society of Civil Engineers and the American Society for Testing Materials (Recommended Practice .., 1941). The first AISC Steel Construction Manual was published in 1926 (AISC, 1973), and the first earthquake provisions for design appeared in the 1927 Uniform Building Code (Recommended, 1975). The first Standard Specifications for Highway Bridges was issued by AASHO in 1931.

The rationale and the heuristic knowledge base that has shaped the "specification-based" prescriptive approach to civil engineering design and evaluation practice has served us reasonably well during the last Century. A prescriptive approach is easier to implement than a performance-based approach from a design standpoint. Prescriptive design also includes many factors of safety to account for unknowns in both the loading and resistance and to account for simplifications in the analytical techniques. Since their original formulations during the first three decades of the 20th Century, design recommendations, guidelines and model codes covering common structural materials and systems have offered a qualitative promise for performance in their commentaries or related committee reports. For example, the ACI code provisions seek to provide crack-width and deflection control at the serviceability limit states and a ductile failure mode at ultimate limit states. On the other hand, some long-standing prescriptive procedures may be unnecessarily conservative while others may not recognize the "blind-spots" that are created when empirical knowledge is stretched to cover newer and yet unproven materials, systems and processes.

Many ASCE members and especially seismic design professionals have been advocating the need for a more direct and explicit performance-based approach to civil engineering practice. It is generally accepted that prescriptive provisions do provide economical solutions for repetitive building and bridge structures with common, time-tested geometry, shape, form and materials. On the other hand, rapid changes in materials and especially new construction techniques that have emerged in the last decades are inevitably leading to a loss of rationale in prescriptive provisions. Moreover, maintenance, repair, rehabilitation and retrofit of existing facilities have now become as relevant a problem as design and construction of new facilities. Civil engineering of existing constructed facilities is an area that lacks a sufficient knowledge-base and has not yet been standardized or codified. In the performance-based approach, the fundamental reason for the creation or the sustenance or preservation of a constructed system is placed at forefront and innovation is permitted even encouraged (Harris, 2002). Large segments of civil engineering professionals now agree that an approach to design, construction, evaluation, and preservation of constructed facilities that has been based only on implicit or only qualitative descriptions of performance may fall short in the case of many contemporary civil engineering projects.

The specification-based approach is inevitably “process-oriented.” In contrast, a “product-oriented” approach is necessary where the desired performance characteristics of the constructed-facility are described in terms of rational and measurable quantitative indicators, and these become the actual deliverable instead of the brick and mortar of the facility. In a product-oriented engineering approach, the entire process that culminates in the commissioning and lifecycle performance of a facility is evaluated and identified as a system. All the sub-processes and parameters that may have an influence on the performance of the final product are established, and the entire process and parameters are optimized as a system to lead to the highest quality possible in the delivered product. Naturally, since constructed facilities are extremely complex and often unique, and they operate over decades to centuries, application of “Six Sigma” process quality control measures that have been proven successful for manufactured products requires a major effort for adaptation, and a major effort for problem-focused applied research and technology development are required. Until the small sampling problem inherent in building and bridge statistics is mitigated by widespread instrumentation and monitoring programs, it may not even be realistic to expect an adoption of systematic quality control measures.

In spite of the challenges that remain, the paradigm of performance-based engineering clearly promises to more definitively ensure the quality of a constructed system. In fact, performance-based engineering is expected to come with appropriate warranty for performance. This is a concept that is already being applied in many European Countries. However, in the US, although the warranty concept is common for manufactured products, it has not yet become a tradition for constructed systems. We note that a prerequisite for moving towards a warranted performance-based civil engineering is to take the measures for better integrating design, construction, operation and maintenance of constructed systems throughout their life-cycles. This pressing need is further illustrated in Fig. 1 and parallel issues that frame the problem of making a transition towards performance-based civil engineering are identified and discussed further in this report.

Drivers for Performance-Based Engineering

Many events in the last decade, including earthquakes, hurricanes, tornadoes, floods, terrorist attacks, power blackouts extending into several days and major traffic accidents leading to destruction of bridges, tunnels and highways as well as a large number of casualties increased our awareness of how our critical infrastructures such as transportation, water, power, fuel, communication, government, health-care, etc. impact our well-being. For example, wasted fuel and lost productivity resulting from traffic congestion cost the nation $69.5 billion (http://mobility.tamu.edu/ums/) and traffic accidents led to more than 42,000 casualties (http://www.bts.gov/publications/national_transportation_statistics/2003/index.html) in 2001, demonstrating how shortcomings in the day-today operational performance of infrastructures significantly affect productivity and well-being.

We now recognize that all infrastructures are complex interconnected systems made up of interacting ***engineered*** (further classified as constructed, e.g. buildings, bridges; fabricated, e.g. elevators, HVAC systems, or, manufactured e.g. autos), ***natural*** (soil, water, weather, climate, etc.) and ***human*** (users, organizations, agencies, industries, social, economical, political, etc.) sub-systems (Fig. 1). Civil engineers design, construct, operate, manage and maintain “civil-engineered facilities” or “constructed systems” that are commonly integrated with fabricated and/or manufactured mechanical and electrical systems and serve as elements of every one of the critical infrastructure systems (Aktan et al, 1994).

We recall an ASCE initiative following the 1981 Kansas City Hyatt Regency walkways collapse that led to 114 casualties. The collapse was attributed in part to disconnect between design and construction, and resulted in the publication of “Quality in the Constructed Project (Quality, 1987).”

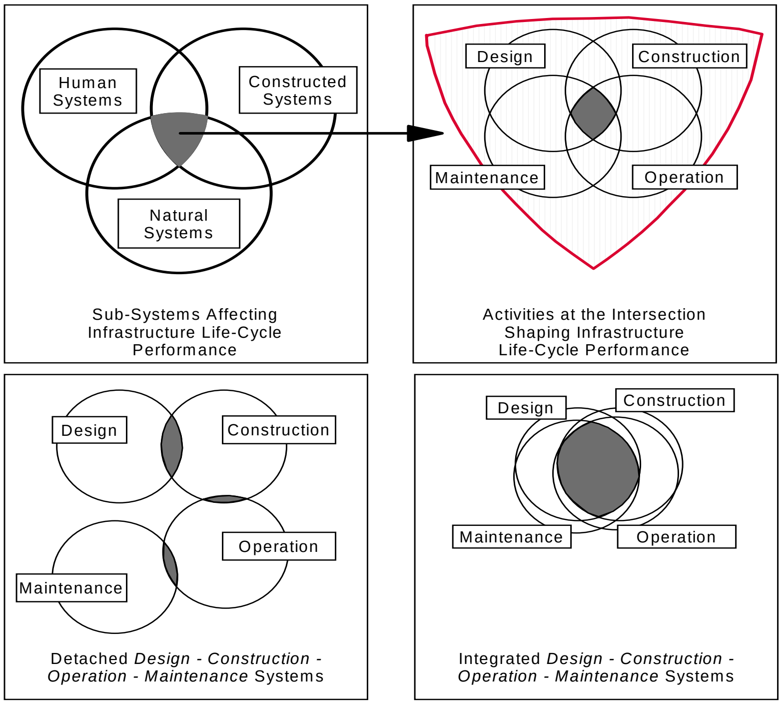


Fig. 1 Infrastructures, Constructed Systems and
Detached versus Integrated Civil Engineering (From Aktan et al, 1994)

Since then, many civil engineering professionals have asserted that the fragmented and often disconnected approach to the design, operation and maintenance of most civil engineered facilities is a fundamental concern. The least-price bid based contract delivery mechanism in the US has been recognized as a major barrier to a more integrated design-operation-maintenance process. Meanwhile, accountability in the construction industry is very different from other industries. In the US, common civil infrastructure facilities such as buildings, bridges and pavements are presently designed, constructed, operated, maintained and managed by a large number of fragmented sub-industries, and these facilities are regularly delivered with a minimal or no warranty of performance. It is in fact the fragmentation of the design and construction industry that is the principal impediment to the concept of requiring performance warranties for the final constructed system, in contrast to many other US industries. For example, even many used automobiles now come with warranties.

Many large civil-engineering infrastructure projects in Europe, the Far East and more recently North America are now being planned and contracted with innovative contract-delivery mechanisms such as design-build-warrant and design-build-operate. Such innovative approaches to planning and delivery of constructed systems in fact serve as drivers towards “performance-based” approaches in civil engineering practice. However, one should be able to define and measure the performance of a civil engineered facility in terms of objective indices. We need clear (as opposed to fuzzy) and quantitative definitions for critical design or evaluation limit-states, instead of loosely and broadly referring to serviceability, damageability, ultimate and failure limit-states and the subjective, qualitative descriptions of performance expected at each of these limit states.

Civil engineers are recognizing the need for describing performance in terms of objective, measurable indices. Concepts such as durability, life-cycle cost, integrated asset management, design-built-warrant and design-built-operate are recognized by policy-makers and many in the civil engineering community as innovative measures for mitigating a lack of infrastructure performance. In various parts of the world, engineers have started implementations of novel concepts such as health-monitoring, adaptive-systems, structural-control, intelligent materials, and intelligent systems. In Japan, the Building Standard Law has changed and is now permitting "Performance-Based Design" to take advantage of such novel technologies (Mita, 1999). These developments point to the need for objective, measurable descriptions and indicators of damage, condition, health and performance that would serve as a basis for future design and evaluations.

Steps towards Performance-Based Design by the Civil Engineering Profession

Performance based engineering is not a new concept in civil engineering, and in fact it has been the actual practice in the automotive, aerospace, space and all other engineering fields where design is not code-driven. For building construction in the US, early efforts towards a performance based approach were initiated in the 1960's at NBS (currently NIST), described by Wright, et al (1972). An important feature of this effort was the incorporation of rational probability-based performance criteria (Performance, 1977, Ellingwood and Harris, 1977). An overview of the NIST efforts towards performance based engineering was provided by Ellingwood (1998, 2000).

Hamburger and Moehle (2000) chronicled performance based seismic design of buildings within the last ten years. "The *ATC-40* (ATC, 1996) and *FEMA-273* (ATC, 1997) reports provided engineering guidelines for more reliable attainment of performance-based seismic upgrade of existing buildings while the *Vision 2000* (SEAOC, 1995) report extended these concepts to new construction. The 1997 NEHRP Provisions (BSSC, 1998), which is the basis for seismic provisions in the International Building Code 2000 (ICC, 2000) adopted, within its commentary, the performance objectives from the *Vision 2000* report."

It follows that structural engineers have initiated discussions on performance-based design for earthquakes at least since the early 1970's, however these have generally remained qualitative. For example, building performance envisioned by the SEAOC Recommended Lateral Force Guidelines were articulated in the 1975 Edition of the Commentary of the Guide as "no damage during frequent-minor, some nonstructural damage during occasional-moderate, and reparable structural damage during a rare-major earthquake of the highest severity recorded," emphasizing that the SEAOC provisions are directed to life-safety and not to control of damage. However, precise and quantitative definitions for frequent-minor, occasional-moderate and rare-major are still not available. Following the Structural Engineers Association of California's Vision 2000 "A Framework for Performance Based Structural Engineering" for new buildings (SEAOC, 2000), FEMA issued FEMA 356 "Prestandard and Commentary for Seismic Rehabilitation of Buildings" (FEMA 2000), which is intended as a performance-based approach for the design of seismic rehabilitation of existing buildings. FEMA is currently sponsoring the development of ATC 58, which is intended to be a resource document for developing performance-based seismic design provisions." We also note that CALTRANS had issued performance-based design criteria for highway bridges for some years now (www.caltrans.gov) and MCEER is currently in the process of developing a "New Seismic Retrofitting Manual for Bridges and other Components" under contract to FHWA that will be performance-based.

In 1997, the producers of three of the widely adopted model building codes (Standard Building Code, Uniform Building Code and National Building Code) have joined together to form the International Code Council (ICC) producing the International Building Code (IBC). IBC is intended to replace the other three model building codes, and offer a unified design code for the entire country. In 2000 ICC issued IBC 2000 to serve as a starting point towards performance based standards for new buildings (http://www.iccsafe.org/). For example, ICC 2000 incorporates four performance groups ranging from "low hazard to humans," to "essential facilities." Given the size of an event raging from "small" to "very large," the code acknowledges that various performance groups designed in accordance to its provisions would be expected to experience between "mild" to "severe" levels of damage. The 2003 ANSI-Approved "Building Construction and Safety Code NFPA-5000" by the National Fire Protection Association also claims to incorporate a complete process for a performance-based design option to guide any work with non-traditional construction (http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=5000).

The above review indicates that civil engineers have been active for at least several decades in taking steps towards developing performance-based design guidelines, replacing or at least providing alternatives to the current specification (code) based practices. However, most of the discussions have been qualitative, without a clear road-map for how performance may be defined and assured in more quantitative terms. For example, Performance-based engineering (http://www.stanford.edu/group/strgeo/pbe.html) is considered a focal area by Stanford University's Civil Engineering Group, described as "a maturing concept and a target area in the design and construction of engineered facilities. It offers great professional opportunities for producing better new facilities faster and more cost effectively. It forms the foundation for strategies on which to base the revitalization of our decaying infrastructure. It also presents challenges for the utilization of emerging technologies to monitor the health of existing facilities through sensor technology and to control performance through the use of active control systems and smart materials."

It follows that before developing guidelines, there are great benefits if the civil engineering profession could reach consensus on the definition of performance and can establish quantitative, measurable indices that will permit the measurement of current or the projection of expected future performances. There is no questioning that many of our peers at the government, academe and practice have started commenting on the necessity of performance-based design guidelines in various forums. Unless we are able to take these conceptual and qualitative statements and move towards consensus quantitative metrics for performance, typical designers may understand the importance of such comments but may not be able to implement the concept in their practices. This should be considered by the leadership of ASCE as a significant objective.

Limit States Design versus Performance Based Design Approaches

Since a quantitative approach to performance-based design is a relatively new concept for most civil engineers, comprehensive basic research in this area is in its infancy. Performance-based design concept depends on many inter-connected issues including classification of constructed systems, definition of performance, tools for measuring performance, quantitative indices that may serve as assurance of performance, and especially, how to describe and measure performance especially under various levels of uncertainty. It is important to note that since all modern building and bridge design codes are now based on the Limit States, or, the Load and Resistance Factor Design (LRFD) concept; the future performance-based design guidelines should reflect the thinking behind this same concept.

The basic LRFD concept is based on satisfying various limit state functions with predetermined reliability levels. The limit state functions are expected to be different for different types of construction (buildings, bridges, tunnels, dams, nuclear facilities, etc.). They are also expected to be different for different types of loading or displacement actions. If seismic loading needs to be considered, it may have to involve different types of limit states depending on the expected return periods of minor, moderate and major earthquakes.

For example, the AISC Manual of Steel Construction (AISC, 2003) indicates that "*Two kinds of limit states apply for structures: limit states of strength which define safety against extreme loads during the intended life of the structure, and limit states of serviceability which define functional requirements. The LRFD Specification, like other structural codes, focuses on the limit states of strength because of overriding considerations of public safety for the life, limb and property of human beings. This does not mean that limit states of serviceability are not important to the designer, who must equally ensure functional performance and economy of design. However, these latter considerations permit more exercise of judgment on the part of designers. Minimum considerations of public safety, on the other hand, are not matters of individual judgment and, therefore, specifications dwell more on the limit states of strength than on the limit states of serviceability.*"

The probabilistic basis for LRFD has been described (Ravindra and Galambos, 1978, Ellingwood, MacGregor, Galambos and Cornell, 1982) based on assuming load effects and resistance factors to be statistically independent random variables. A reliability index β is defined in terms of the means and the coefficients of variations for the frequency distributions of the resistance and load effects. This index provides a comparative value of the measure of reliability of a structure or component. More recently, Ang (2004) described the distinctions between *aleatory* and *epistemic* uncertainties, and this implies a need for rethinking the reliability index by recognizing and incorporating the impacts of epistemic uncertainty.

Given the foundation provided by the LRFD design concept, it appears logical for the performance based design to build on this foundation. First, we should broaden the way we look at the critical design limit-states and provide a better coupling between functionality, serviceability, safety and economy during the course of the design to facilitate the integration of planning, design, construction, operation and maintenance. Second, we should properly synthesize the experiences brought upon by the terrorist attacks on September 11, 2001, and expand the concept of reliability to risk as a basis for strength design under extremely rare events.

For example, we should not expect two structures to be designed for exactly the same performance at two different locations of the country if the expected return periods of similarly destructive events are respectively 250 and 2500 years at these locations. Current LRFD that is based on structural reliability would not differentiate between the performances we would expect from these two structures. If, on the other hand, we were to base performance on ***risk***, which is a function of the ***probability of an extreme event*** and its ***consequences*** in addition to ***structural reliability***, then we would justify differentiating between the performances of these hypothetical structures and design them differently. At least, incorporating risk together with performance in design will offer a greater flexibility as long as we are able to measure and assure performance as would be the case if we were able to demand a warranty.

Limit-States and Limit-Events for Performance Based Design

It has now been introduced that in the case of constructed systems that have decades-to-centuries long life-cycles, references for design and code commentaries have conventionally described performance in conjunction with various limit-states such as serviceability and safety (Ellingwood, et al, 1982, Galambos et al, 1982). Each limit-state would be associated with a distinct and broad category of demands. Limit-events within each limit-state further specify in detail various demand categories that need to be considered in the design or evaluation of constructed systems.

The "***limit-states design***" or "***load-and- resistance factor design***" aims to assure that the designed constructed system will have sufficient capacity to satisfy the demands associated with each limit-event with an acceptable probability of failure or with a desired level of structural reliability. In a performance based design, we would not limit our consideration to only the "***probability of failure***" but consider the "***risk of failure***," that would explicitly incorporate the return period of the loading or hazards that prevail at a site and the consequences of failure in addition to the probability of failure. In this context, failure refers to a failure to meet the intended performance objective and not strictly the loss of structural strength or stability leading to a life-safety peril.

Table 1 lists the limit-states, limit-events, and expected performance goals that are being recommended by the ASCE Committee on Performance Based Design and Evaluation of Constructed Facilities ***to serve as a starting point for discussions within our profession***. We note that a consensus in the description of limit-states, the corresponding limit events and the corresponding performance goals is a most important step before we may start standardizing performance-based civil engineering. An issue is whether the same set of limit states and events may govern all types of constructed systems. If we consider two of the largest populations of constructed systems in the US, typical buildings and highway bridges with short-to-moderate span lengths, respectively, we realize that their design and construction have been traditionally governed by

Table 1: Limit States, Limit Events and Performance Goals

Limit States	**Utility and Functionality**	**Serviceability and Durability**	**Life Safety and Stability of Failure**	**Substantial Safety at Conditional Limit States**
Limit- events	▪ Environmental impacts ▪ Social impacts ▪ Sustainability of functionality throughout lifecycle ▪ Financing: Initial cost and life-cycle costs ▪ Operational: capacity, safety, efficiency, flexibility, security ▪ Feasibility of: construction, protection, preservation ▪ Aesthetics	▪ Excessive: Displacements, Deformations, Drifts ▪ Deterioration ▪ Local damage ▪ Vibrations **Lack of Durability:** Special limit-state that should govern aspects of global design, detailing, materials and construction	▪ Excessive movements, settlements, geometry changes ▪ Material failure ▪ Fatigue ▪ Local, Member Stability failure **Stability of Failure:** ▪ Incomplete premature collapse mechanism(s) without adequate deformability and hardening ▪ Undesirable sudden-brittle failure mode(s)	Lack of: Multiple escape routes in buildings Lack of: Post-failure resiliency leading to Progressive collapse of buildings Cascading Failures of Interconnected Infrastructure Systems Failures of Infrastructure Elements Critical for Emergency Response: Medical, Communication, Water, Energy, Transportation, Logistics, Command and Control
Goals	▪ ***Multi-objective performance function for integrated asset-management:*** Functions Relating to Operations and Security	▪ ***Multi-objective performance function for integrated asset-management:*** Functions Relating to Inspection, Maintenance and Lifecycle	▪ ***Multi-hazards risk management:*** Assurance of Life-safety and quick recovery of operations following an event (Days-months)	▪ ***Disaster Response Planning:*** Emergency management, protection of escape routes, evacuation, search and rescue needs, minimize casualties. ▪ Economic Recovery (within Years)

different specialty groups with different traditions and codes as discussed earlier. However, the broader fundamentals of performance-based engineering for either type of construction should not be different. Hence the limit-states recommended in Table 1 are intended to apply to both buildings and bridges.

Table 2: Typical Design Demands for Buildings and Their Frequency

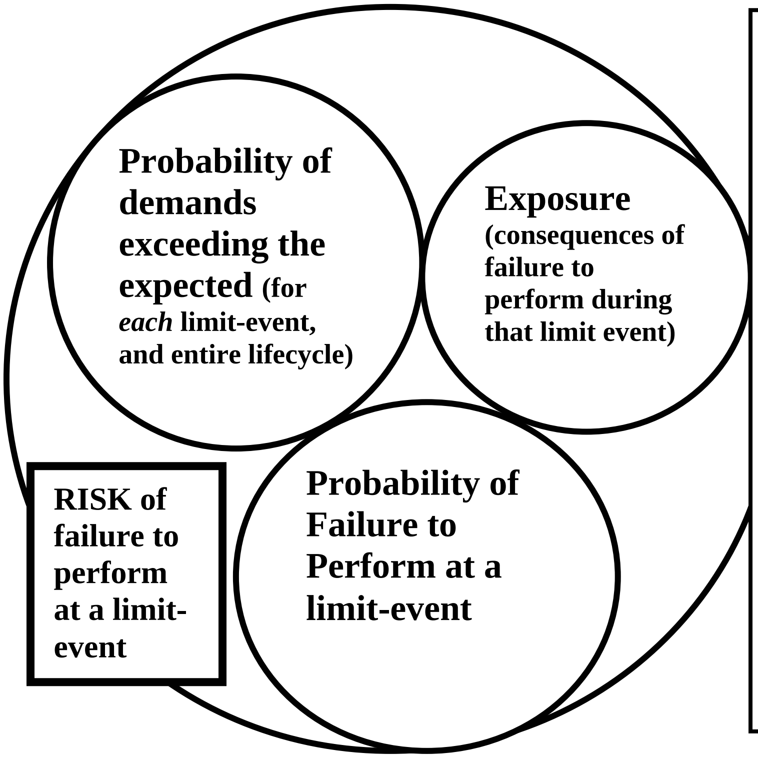
	Frequency (Return Period in Years)			
Demands:	**Normal (0)**	**Occasional (5-25)**	**Rare (250-500)**	**Extreme (2500-5000)**
Dead load	Sustained, as designed	Sustained, with remodeling		
Live load	Typical occupancy	Live load = design live load	Live load exceeds design	
Wind load	Typical wind	Strong windstorm	Hurricane, Tornado	
Earthquake load		50% exceedence in 50 years	10% exceedence in 50 years	2 % exceedence in 50 years
Temperature	Average heat and cold cycles	Above normal heat or cold cycles	Extreme cold or Fire	Sustained fire
Flood		100 year	500 year	
Extremely Rare Loads				War, Terrorism

Table 3. Mean Return Periods in Years for Environmental Loads Taken as a Basis for Design

Event Size	**Flood**	**Wind**	**Snow**	**Ice**	**Earth-quake**
Small	20	50	25	25	25
Medium	50	75	30	50	72
Large	100	100	50	100	475
V. Large	500	125	100	200	2475

Two related Tables are also introduced to serve as a basis for discussions. **Table 2** lists the typical design demands for buildings and their frequency of occurrence (return period) whereas **Table 3** lists the Mean return Periods for Environmental Loads that have been taken as a basis for design for various event sizes as envisioned in ICC 2000 (Harris, 2004).

The four performance limit-states of "utility and functionality," serviceability and durability," "safety and stability of failure," and, "safety at conditional limit-states" in Table 1 were adopted by modifying the recommendations of a CEB-fip inter-association joint committee on structural safety that developed an "International System of Unified Standard Codes of Practice for Structures (1976) for the European Community" and leading to the current European Design Code (1994). Each limit state incorporates the set of limit-events that are listed in the Table to govern the design or evaluation of a constructed system for that limit-state. The Committee carried out extensive discussion on the importance of and distinctions between these limit-states and especially their scope, as there are differences between those in Table 1 and many reference books or code commentaries as discussed earlier in relation to the AISC's Manual (2003).



Performance-Based Design Based on Uncertainty/Risk:
Establish the resistance envelope to meet the demands ***at each limit-event*** based on an acceptable risk of failure to perform at that event i.e.:

P (Φ Capacity <=γ Demand)

Establish **P *for each limit-event*** and select **Demand, actions**, Φ and γ based on an ***acceptable risk of failure to perform at that limit-event.*** Define and guarantee performance by process quality control and management of the integrated system of design, construction, operation and maintenance. The performance of the constructed system should be based on a set of objective and measurable indices.

Figure 2. Performance-Based Design and Evaluation Under Uncertainty and Risk

An additional example is found at the Commentary of AASHTO's LRFD Code (1995) which lumps the "Safety and Stability and Failure", and, "Safety at Conditional Limit States" into a single "EXTREME EVENT LIMIT STATES," defined as "the structural survival of a bridge during a major earthquake or flood, or when collided by a vessel, vehicle or ice flow possibly under scoured conditions." Meanwhile (Table 2) the same bridge would be designed for extreme events with return periods ranging between 50-475 year that are all expected to drive a bridge to a state of damage and loss of function.

Table 1, however, differentiates between performance expectations at events that have very different return periods, such as earthquakes that may govern the design of a bridge at a highly seismic region in the Western

US as opposed to earthquakes that are anticipated in the Central and Eastern US that are associated with much greater return periods and possible consequences. Also, Table 1 provides a comprehensive and integrated view of all of the performance limit-states including utility and functionality. A design approach that incorporates the risk of a constructed structure not achieving its expected performance at each limit-state and limit-event would offer a far greater flexibility for optimizing how the financial resources available for any given project are allocated to various features of the system. This is illustrated in Fig. 2 which presents an overview of the performance based design and evaluation approach that incorporates risk as envisioned by the Committee.

We note that the limit-states, limit-events and performance goals described in Table 1 are presently quite conceptual in nature. Our heuristic knowledge regarding limit-events within the serviceability and safety realms are good only for certain limited construction with conventional materials and systems. The changing economics of construction in conjunction with the advent of a variety of “high-performance” materials and a wide spectrum of innovative systems render most of our earlier research and our heuristic knowledge questionable. Fundamental research is needed to arrive at a mix of subjective as well as objective and quantitative measures that would altogether determine the attainment of a limit-event within a limit-state, based on the attributes of a constructed facility. We note that most limit-events governing the “Utility and Functionality”, and “Serviceability and Durability” limit-states are typically triggered by defects in design, materials or construction whereas those governing “Safety and Stability of Failure” and “Safety at Conditional Limit States” are usually triggered by various loading events associated with some probabilistic model in conjunction with defects in design, construction or maintenance.

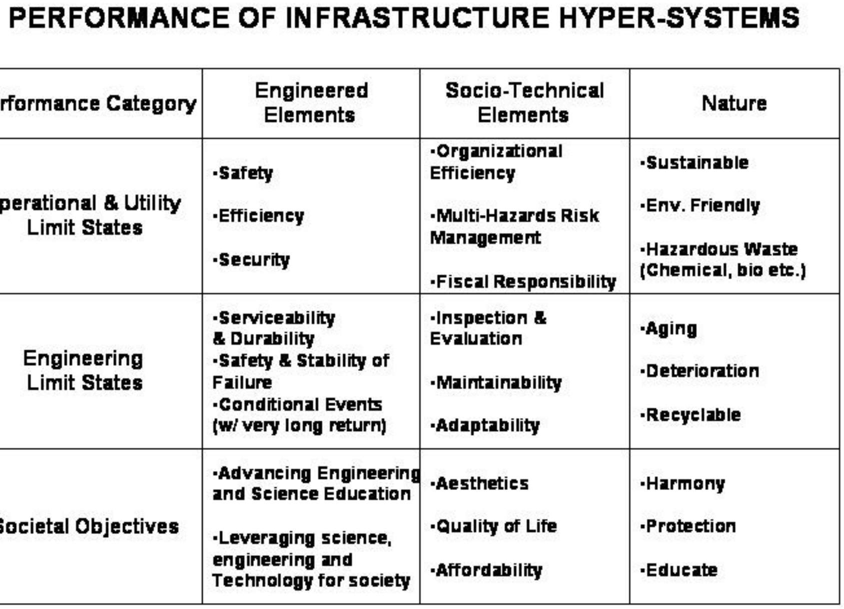
Two limit-states justify further discussion. The “durability” limit-state that is included within “serviceability” is only now widely recognized as concern justifying its distinct limit-state that deserves special attention in design and in evaluation. ***Durability brings a different dimension and may justify a different approach to the selection of materials, proportioning, detailing, construction, maintenance, etc. than a design based only on serviceability and safety***. For example, we have to recognize that special cover and detailing of reinforcement for crack control in a reinforced concrete element may justify more attention to it than the attention we spend in detailing for capacity. In many cases durability may be assured only if a designer is in full command of all the mechanisms that influence deterioration. To assure the durability of a design may require extensive “scientific” research in the field on real constructed facilities, integrated with laboratory and analytical studies in order to reveal the actual mechanisms that cause deterioration and how they may be effectively mitigated. This would have to be coupled with an in-depth knowledge of material behavior at the microscopic level.

In the case of “safety at conditional limit-states,” additional remarks may be offered. Introducing this limit-state makes it possible to rationalize designing for hazards that may have an order of magnitude difference in their return periods and consequences with a “comparable risk-based” approach. For example, “large” destructive earthquakes at highly-seismic regions in California have been characterized with return periods of 475 years while those in the Midwest and Eastern US have been characterized with return periods of 2475 years. Presently, there is little distinction in how we design and evaluate constructed systems for earthquake given the significant difference in the return periods of destructive earthquakes at these regions as well as the differences in the consequences of failure of constructed systems with various functions and at various locations during such earthquakes. For example, a recent New York Times opinion-editorial (Stein and Tomasello, NY Times, January 10, 2004) indicates that FEMA has strengthened design standards in the New Madrid seismic zone to levels to comparable to California’s while the actual earthquake risk in the New Madrid zone is one-tenth of corresponding risk in California. A performance based approach incorporating risk as opposed to just structural reliability would permit evaluating the fragility of various lifeline systems under different extreme event scenarios and investing greater resources into those constructed systems that have a greater impact on the fragility of a lifeline or critical infrastructure.

An important characteristic of each limit-event is therefore the return period of the associated demands or loading events within each limit-state. The risk due to failure of a constructed system to perform is defined as the product of three factors: (a) The probability of a demand exceeding an expected value, (b) the probability of the system not performing as desired, and, (c) the consequences of this failure to perform. It follows that the return period (which in turn defines the expected probability of occurrence of a limit-event during the lifecycle of a facility), is a critical factor in defining the risk that should be controlled during design or evaluation. Further, the envelope of actions and resistances to be considered in design or evaluation should be based on an acceptable risk associated with each of the limit-events. For example, the acceptable risk associated with the "incomplete and premature collapse mechanism(s) without adequate deformability and hardening" limit-event within the "safety and stability of failure" for a building system may be as high as 0.0001 and as low as 0.0000001 given the importance and functions, the infrastructure system that is served by the building, location, occupancy, architecture, site and structural attributes of the building. The risk and reliability basis of performance-based design is illustrated in Fig. 2 and discussed further in the following.

Definitions for Performance and Health

Following a description of the limit-states for performance-based design or evaluation of a constructed system (Table 1), we may offer definitions for the "performance" of a constructed system and the related concept of its "health". Since virtually any constructed system will function as an engineered element of a "parent" infrastructure system (Fig. 1), it is obvious that a definition for its performance will have to recognize the interactions between engineered, natural and human systems that are components of the same infrastructure system. Therefore, we should adopt a multi-dimensional approach to defining performance of infrastructures as illustrated in Figure 3 to pave the way for defining the performance of a constructed system.



PERFORMANCE OF INFRASTRUCTURE HYPER-SYSTEMS

Performance Category	Engineered Elements	Socio-Technical Elements	Nature
Operational & Utility Limit States	·Safety ·Efficiency ·Security	·Organizational Efficiency ·Multi-Hazards Risk Management ·Fiscal Responsibility	·Sustainable ·Env. Friendly ·Hazardous Waste (Chemical, bio etc.)
Engineering Limit States	·Serviceability & Durability ·Safety & Stability of Failure ·Conditional Events (w/ very long return)	·Inspection & Evaluation ·Maintainability ·Adaptability	·Aging ·Deterioration ·Recyclable
Societal Objectives	·Advancing Engineering and Science Education ·Leveraging science, engineering and Technology for society	·Aesthetics ·Quality of Life ·Affordability	·Harmony ·Protection ·Educate

Figure 3. A Multi-Dimensional Performance Matrix for Infrastructures

Given the complex multi-dimensional nature of performance of an infrastructure system that includes the performance of constructed as well as natural and human systems that constitute its sub-systems and elements, we need to start from general definitions. The dictionary definition of performance is "the fulfillment of a promise. An associated parallel concept is health, and the dictionary definition of health is "the condition of being sound in body, mind and soul." ***Health provides the ability to a system to perform as promised***, and we should therefore focus on health of a system as a means to proactively evaluate and assure its future performance. Hence the importance of the health monitoring paradigm as an enabler for performance based civil engineering.

Structural engineers have traditionally used various indices for defining the health of a structure depending on purpose, such as safety factor, condition rating, load-capacity rating, sufficiency index, capacity-demand ratio, redundancy, etc. Although it is pragmatic to continue using such deterministic indices that are mainly related to "structural safety" most engineers now recognize the need for a broader definition that relates to performance and health in relation to the entirety of Table 1. Such a definition, in fact can be made by generalizing the structural reliability concept (Ang and Tang, 1975):

We define the health of a constructed system as the probability that it possesses adequate capacity against all probable demands that may be imposed on it in conjunction with the limit-states and limit-events listed in Table 1. Here we emphasize that system reliability should cover the entire spectrum of limit states and limit-events in Table 1 and not just "structural safety". Further, according to Ellingwood (2004), the distinction between health and reliability is that health is a desirable state and reliability is a measurement of it.

As discussed earlier, we may take advantage of the "Reliability Index: β" as a measure of health or reliability as this relates in concept to the deterministic "Safety Factor" or "Load Rating" most engineers use in practice (Ellingwood, et al, 1982). For example if Capacity and Demand are independent and normal random variables, $\beta = 0$ corresponds to a reliability or ($1-P_f$) of 0.5, $\beta = 3$ corresponds to a reliability of 0.999, and $\beta = 4.75$ corresponds to a reliability of 0.99999. The latter corresponds to one in a million chance of inadequate capacity to perform.

Engineers often lack sufficient data, especially on peak demands corresponding to most limit-events at the safety and conditional limit-states that would be needed to quantify the reliability of a constructed system. Further, different measures of reliability may be appropriate for different systems and for demands at different limit states and events. For example, a β of 3 may be considered quite acceptable for the safety against collapse of smaller bridges on secondary roads, but a more stringent β of 5 may be necessary for the collapse safety of a major, long-span bridge. Similarly, different β values would be admissible when evaluating traffic flow capacity, operational safety due to wind and ice, serviceability due to deflection or vibrations, chemical intrusion into a concrete deck, fatigue cracking at a critical weld, safety against element failure, structural system safety, etc. What is important is that all stakeholders should aspire to collect data so that we may quantify health in terms of reliability indices and start using these as the basis for management (Chase, 1999). For example, the Long-Term Bridge Performance Program that is envisioned by FHWA (Chase, 2004) is being designed to collect scientific quality quantitative data on the performance and health of thousands of bridges for decades. There is merit for initiating similar programs on various building types by NIST and FEMA.

Fundamental Issues Related to Performance-Based Civil Engineering

Basic Steps of Performance-Based Design:

Twelve basic steps describing a process for the performance-based design of a constructed facility are tentatively listed as follows:

1. Stakeholders and needs in terms of social/societal impacts: Related policy and legal issues, financing, environmental impact studies, lifecycle considerations
2. Conceptual design and construction planning, construction, inspection and maintenance feasibility and impact studies, study contract-delivery options
3. Regional and site-specific studies, geo-investigations, demands analysis

4. Establish qualitative performance criteria with stakeholders; Given applicable Guides/Standards/Specifications and past experience, transform these to quantitative criteria, in conjunction with verification methods and warranties
5. Preliminary designs of the facility in conjunction with an objective-function for optimizing its performance at all critical limit-states
6. Feasibility, performance and reliability assessment of preliminary designs, alternatives analysis
7. Final detail design, construction process design and finalize contract delivery method
8. Design Verification: Heuristics, analytical, experimental, warranty-based, combination
9. Fabrication/erection/construction and the integration of mechanical, electrical and communication systems
10. Documentation and archival, structural-identification and health-monitoring
11. Integrated operational and maintenance management
12. Rehabilitate, retrofit, renew, preserve or decommission, salvaging and recycling considerations

We note that for different classes constructed facilities such as buildings, bridges, towers, pipelines, etc. the detailed processes and deliverables within each of the twelve steps would vary. However, the common elements that are underlined should be common, and these describe the distinction between specification-based versus performance-based design approaches.

Basic Steps in a Performance-Based Evaluation:

The steps for performance-based evaluation of a constructed facility ***that has been constructed by a specification-based approach*** are tentatively listed as follows:

1. Review: Stakeholders and needs in terms of social/societal impacts: Related policy and legal issues, financing, environmental impact studies, lifecycle considerations
2. Review: Conceptual design, feasibility and impact studies
3. Review: Regional and site-specific studies, geo-investigations, demands analysis
4. Review: Final design and available documentation on construction and maintenance
5. Inspection and condition/health and performance evaluation by structural-identification and health-monitoring for a reasonable period (months)
6. Interpretation of data and observations, simulations for prognosis of performance and health for the remainder of the lifecycle
7. Based on the insight gained from (5)and (6), develop a multi-objective performance function in conjunction with the resources and expectations of stakeholders (owners)
7. Finalize quantitative performance criteria and indicators for measurement of health
8. Design any rehabilitation, retrofit, renewal or just maintenance as needed based on (7)
9. Integrated Management of Operations and Maintenance

The terms structural-identification, health-monitoring and integrated management may deserve further description. Although these terms have become well-established in research, many practicing engineers may not be very familiar with these terms. Considerable work exists in these areas and referenced in this report.

Urgent Research Needs

As the profession makes the transition to performance-based civil engineering, civil engineers will serve society in increasingly more responsible roles related to infrastructures. This will have to occur at several stages as we do not have all the necessary data, information and knowledge for a transition to a completely performance-based practice. For example, field measurements and structural identification of a variety of constructed facilities in US, Europe, and Asia indicate that the reality of actual loading environments, long-term intrinsic responses and the corresponding behavior and lifecycle performance of even typical, recurring structures such as short-span bridges and mid-rise buildings may have very little correlation with the code prescriptions that implicitly aim to ensure performance (Aktan and Yao, 1996, Aktan et al, 1997). The predicted values of stresses, displacements, drifts and other indices specified by codes for design, and their actual values following construction can be quite different. Furthermore, many other mechanisms, which are not properly recognized in design and construction, may have greater correlation to performance than do the indices for which limits are specified in the code for assuring performance.

It follows that just an analytical simulation for validating the performance that is expected from a design cannot be accepted as sufficient for assuring the performance of an actual constructed system, especially if the system has been designed and constructed by recent technology, such as by utilizing high-performance materials, or by the erection of prefabricated elements by using post-tensioning as only two of many ongoing “innovations”. A related issue is to establish those properties or responses of constructed facilities that are feasible to measure reliably, and understanding the temporal and spatial variability in such measurements before correlating measured indices or properties to various measures of performance. We recognize that a large number of measurements should be made with a sufficiently fine spatial resolution to permit detecting local deterioration and/or damage within large facilities, and, conducted over longer than the return periods for a full climate cycle, and the return periods of occasional events that lead to damage, before we can establish quantitative, objective measures of performance for a constructed facility.

To develop objective, quantitative performance indices, it will make sense to turn our attention to the past to identify the performance measures that are explicit or implicit in common design/evaluation guidelines/specifications, and others formulated by experienced practicing engineers (some related issues: Formulating crisp definitions for service-life, durability, system-redundancy, damage and ultimate (failure) limit-state performance during various natural disasters). We expect great benefits in a re-review and synthesis of the implications of performance from documented post-earthquake investigations, experiences following other disasters, and, from the efforts for life-cycle management of typical construction, such as highway bridges.

We should further re-evaluate the roots and justifications for the specifications that have been used in standard codes/guidelines that aim to ensure performance at envisioned design limit-states. Which ones are still valid or invalid given the major changes in materials, systems, construction practices and societal expectations in the last decade? Postulate explicit and measurable definitions of performance that will indeed guarantee the minimum implicitly expected performance from facilities that are being constructed with newer materials such as fiber reinforced polymers, high-performance concrete and newer steels, elements and surfaces with complex geometries, construction techniques using segmental, post-tensioned elements with cast-in-place regions, staged, launched, composite and hybrid construction, tension structures, and especially those systems that take advantage of advanced technologies such as structural-control, instrumented health monitoring, supervisory control and data acquisition (SCADA) systems, intelligent transportation systems, etc.

An increasing number of constructed facilities in Japan, Europe and the US are taking advantage of advanced technologies such as operational and/or structural control based on intelligent-systems concepts. Such facilities equipped with health monitoring systems permit the measurements and observations that are necessary for quantifying performance if we had established the proper indices. At the same time, it is not possible to operate innovative and/or intelligent systems unless we have quantitative measures of performance. We further note that the measurements and indicators required for quality control and evaluation of future performance as a facility is constructed may have to be considerably different from those measurements and indicators for a quantitative evaluation of performance of an existing aged facility that may show signs of damage.

Conclusions and Recommendations

1. We anticipate that in the future, constructed facility performance will be described in terms of a matrix, containing sets of both subjective and objective parameters. We note two examples of performance descriptions for products that pose somewhat similar challenges: automobile performance by instruments such as Road and Track, Consumers Report, etc., and for PhD programs in Engineering by instruments such as the National Academy of Engineering, and, US and World Report, etc. In both of these examples, a mix of subjective and objective indicators have been described and have been used consistently to reach global ranking of complex products. In the case of constructed facilities, we expect many additional challenges but the feasibility of a similar approach.

The development of performance metrics for constructed facilities offers major societal implications. It is also is a prerequisite in order to transition from the current process-oriented approach to a product-oriented, performance-based design and evaluation approach for infrastructure. The dynamic set of societal and technology parameters that govern the built environment demand such a transition. Qualitative performance descriptions are too nebulous and incomplete for the industry to step away from the domain of practice that has relied on our heuristic knowledge base for its success.

2. In the last several decades, the civil engineering community has progressively ventured outside of traditional boundaries in terms of materials, sizes and configurations for structural systems, fabrication and construction processes and functional challenges. Meanwhile, societal expectations for the performance of constructed facilities have increased in parallel with the advent of technology and globalization. For example, the impact of the 1999 Taiwan Earthquake was felt worldwide by the computer industry. Beginning in the 1980's, a large number of facilities in Japan and the US have been equipped with special active, hybrid and passive devices to control earthquake damage. The Japanese building standards have been recently modified to permit performance-based design, especially for "intelligent or smart-structure" applications, and US engineers are interested in adopting a similar approach to infrastructure design and evaluation.

Furthermore, in the US, there are major government and industry initiatives on the use of new and/or improved materials for construction, such as geo-synthetics, high-performance concretes and steels, structural steel-reinforced concrete and fiber-reinforced polymer composites. Extensive use of aluminum, stainless steel, cable, glass, fabrics and plastics in cladding and architectural systems are being integrated with structural systems. Segmental post-tensioned construction and piecewise launching of elements and systems are becoming common construction practice for bridges. Recently, the AASHTO and the National Steel Bridge Alliance initiated a collaboration to enhance steel bridges by using advanced steels and innovative structural systems (Medlock and Shirole, 2000). Formulating performance metrics will enable and encourage implementation of similar innovations.

A related and compelling need for performance metrics is in the case of facilities that are designed, constructed and operated incorporating newer "intelligent" technologies such as active, hybrid and passive damping and energy dissipation devices for earthquake damage control. The Japanese Standards have been modified to permit performance-based design especially for such "intelligent or smart-structure" applications (Mita, 1999, MEDAT 1, 2000). In the US, similar applications of emerging technologies are increasing in number not only for new construction but also for retrofits of existing structures. Relevant examples include efforts in California to retrofit thousands of bridge pier-columns using several materials, and the increasing use of externally bonded carbon-fiber reinforcement for concrete retrofits in Europe (Proceedings, U.S.-Canada-Europe Workshop on Bridge Engineering, 1997), and Japan (Otani and Kaminosono, 1999). Some of these applications are accompanied by instrumented monitoring systems to confirm and track their performance. However, without any metrics to describe required performance during design, it is not possible to adapt uniform standards for the acceptance and standardization of innovative retrofit or damage-control devices.

3. A further compelling need for establishing rational performance metrics relates to the management of existing civil infrastructure systems. The lack of desirable performance of civil infrastructure systems has been articulated by many agencies in the last few decades (Matalucci, 1997). The two fundamental strategies that have been adopted by the executive and legislative branches of the federal government to address this problem are: (a) to leverage technology for innovating infrastructure preservation, and, (b) to adopt asset-management principles for infrastructure. Highway bridges are an especially vital component of the national land transportation infrastructure, and they serve as a good example of the need for performance metrics to enable more cost-effective and reliable management (Chase, 1999).

Federal bridge funds are presently allocated to each State according to a "sufficiency index" that is based on many features of a bridge. However, all of the data incorporated in the "sufficiency index" relating to the structural condition of a bridge is based on standardized yet subjective visual inspections. In order to formulate a more effective bridge management process, complete and accurate data on the actual load carrying capacity of a bridge is required (Das, 1998). It follows that if the US wishes to adopt an asset-management approach for existing and future constructed facilities and infrastructure systems, performance metrics including accurate measures of structural capacity becomes a critical requirement. Re-qualification of the nation's stock of aged constructed facilities and infrastructure systems with objective performance metrics therefore stands as a major challenge before the country can embark on meaningful implementations of asset-management principles.

4. We recommend the formation of an ASCE Task Committee for coordinating the execution of examples for performance-based designs of constructed facilities, including both buildings and bridges. The execution of these example designs may be supported by and carried out under the auspices of federal agencies such as FHWA and NIST. Such a Task Committee should include experts from academe, government and industry, including designers and contractors who are interested in demonstrations of projects through the design-build paradigm.

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Membership (2003) of the ASCE Committee on Performance-Based Engineering of Constructed Systems :
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