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State of the Art of Structural Engineering

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Abstract: The objective of this paper is to provide an overview of the developments in structural engineering that took place during the past century. This overview includes (1) some of the major structural accomplishments as selected by the writers, (2) the advances in mechanics as the basis of structural analysis, (3) the development of new materials, (4) new fields of research and practice, and (5) the changes in the way design projects are performed. In addition, the writers' personal predictions for future developments during the 21st century are also presented. One of the main features affecting the evolution of structural engineering over the last part of the 20th century has been the advent and rapid development of digital computers as engineering tools. Computers can be used to perform complex and cumbersome computations and to enhance worldwide communications, both with great speed and reliability. This has already had an important effect on the way we design structures and educate civil engineers, but the impact on structural analysis and design as well as on construction planning and management is still in progress. We believe that this impact will be fully felt in the 21st century. Computers will liberate engineers from tedious and routine computations, allowing them to concentrate on more creative and important endeavors. They will facilitate the design of constructed facilities as complete systems rather than by considering each subsystem (such as structure and foundation) separately. They will lead finally to the needed integration of the design and construction processes.

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Introduction

As we proceed into the 21st century and a new millennium it is worthwhile to reflect on what the 20th century brought us, on where we stand today and where we should be going in the future. As stated once by the late Charles L. Miller at Massachusetts Institute of Technology (MIT), rather than attempting to predict the future, it is more important to decide what the future should be and to try to influence change in that direction. Even this is a personal matter and what anybody sees as desirable features may be quite different from what others would select. The material presented here represents the writers' personal opinion, which is inevitably biased by their own backgrounds and education. This is even more so in selecting names of civil engineers that have made an impact on their profession. In attempting to select only a few, one has to be influenced again by personal feelings and background. No attempt was made to present a comprehensive or exhaustive list. The names mentioned are intended only as examples. Equally incomplete is the list of possible references dealing with structural engineering, structures, structural models, or the built environment, all terms used by Grigg et al. (2001) in their 264-page treatise entitled *Civil engineering practice in the twenty-first century*.

In this paper the writers attempt to look at some of the accomplishments of the 20th century in structural engineering and to put them in perspective with respect to earlier work. One can look then at some of the new developments that are likely to continue during the 21st century and some of the perceived needs. The main changes in structural engineering during the 20th century and in years to come are due to the developments in digital computers both as powerful tools to perform cumbersome computations and as new means of communication between members of design teams, professors and students, or any other persons. These changes affect both the practice of civil engineering and engineering education.

The computational capabilities provided by today's computers liberate the structural engineer from the laborious task of performing detailed stress analyses and allow the designer to concentrate on the more creative parts of the design process. This implies exploring alternatives, accounting for uncertainties, and integrating properly all the different components of the system (e.g., structure, foundation, and equipment) to be designed. In education they allow students to acquire experience in structural behavior by conducting simulations, looking at various alternatives, and observing visually the structure's response to different excitations.

The new ease in worldwide communications facilitates the concurrent work of many different teams in geographically dispersed regions of the world. This changes significantly the way the design of large projects is conducted. From the educational viewpoint, the new communication tools such as the Internet and e-mail complement the more traditional methods of teaching.

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J. Struct. Eng. 2002.128:965-975.

Combined with the computational capabilities, they allow the creation of virtual laboratories where students can carry out virtual experiments for those phenomena that are well known and thus can be simulated, as would be the case for most classroom demonstrations. Clearly, research work dealing with the discovery of new, as yet unknown, phenomena will still require physical experiments. The advantage of virtual experiments or computer simulations for educational purposes is that they can be repeated at will, at the convenience of each student, easily changing geometry and materials to observe immediately the effects of these changes, and learning by induction from direct and visual observation of the results.

The various structural engineering handbooks published during the 20th century, from the Kidder-Parker Architects' and Builders' Handbook (first published in 1884) (see Parker 1931), to Gaylord and Gaylord (1968, 1990) or Chen (1997), provide through the titles of their chapters and their contents an excellent and detailed history of the evolution of the field during that time. Although some topics are common, these handbooks have different chapters treating various subjects. It is thus necessary to read all of the recent ones in order to obtain a complete view of structural engineering in general. Equally instructive are the lists of courses offered, and their descriptions, in the catalogs of Civil Engineering Departments of the leading universities (particularly the most progressive ones that are willing to incorporate new subjects early on), as well as the lists of research projects in progress at these institutions at any given time. In this paper no attempt is made to present an exhaustive list of all the major developments that have taken place. The discussion is limited to those with which the writers are most familiar. Thus, their own education and background once again bias the selection.

Background

L'École Centrale des Ponts et Chaussees, the first Civil Engineering School in the world, was established in Paris, France, in 1747. In the late 18th century, John Smeaton in England coined the name of ''civil engineer'' as being distinct from the military engineer. The Smeatonian Society can be considered as the precursor of our civil engineering societies. While there were a number of prestigious engineers during this time (Vauban, Coulomb, Smeaton), in France and in Great Britain, civil engineering really took off as a technical profession during the 19th century, with most schools created in the early part of the century imitating the French model. Famous engineers like Castigliano, Cauchy, Navier, Rankine, or Saint-Venant were not only theoreticians but also practicing engineers who designed well-known and important structures. Other illustrious practicing structural designers included Gustave Eiffel, designer of many steel bridges (the Garabit viaduct, for instance) in addition to his famous tower in Paris; Thomas Telford, who designed an early iron chainlink suspension bridge (the Menai suspension bridge in 1826) in addition to many other bridges and aqueducts; and John Roebling, who is considered the father of modern suspension bridges and designed the Brooklyn Bridge. It can be said in fact that most of the structural concepts of the 20th century were a continuation of the accomplishments of the 19th century.

This rich history of civil engineering as a technical profession (without even accounting for all the magnificent civil works conducted by master builders from antiquity) is both a matter of pride and a reason for concern. Because so many of the basic theoretical developments in mechanics took place over a century ago (starting with Hooke's law in 1660), newer engineering professions tend to look at civil engineering as an established discipline without significantly new and revolutionary advances. Yet the 20th century saw not only new frontiers in the size of the structures built (bridge spans, heights of buildings and dams) but also the development of new analytical and numerical tools, new structural concepts, new materials, new construction techniques, and even new subdisciplines. The 25 longest span (suspension) bridges in the world, with spans exceeding 700 m, were all designed and built in the 20th century. So were all the steel cantilever truss bridges with spans exceeding 350 m, all steel arch bridges with spans longer than 300 m, and all concrete arch bridges with spans over 240 m. Prestressed concrete, high-strength concrete, composite construction, light-gauge steel construction, and, more recently and still in the incipient stages, composite and smart materials were all creations of the last century. So were cable-stayed bridges, shell roofs, double curvature arch dams, high-rise buildings with tube action, and offshore platforms. To the names of the famous engineers of the 19th century we can add in the 20th among many others those of Othmar Amman (George Washington and Verrazano Narrows Bridges), David Steinman (Mackinac Bridge), and Joseph Strauss (Golden Gate Bridge) in suspension bridges; Eugene Freyssinet (Plougastel Bridge), Robert Maillart (Salginatobel Bridge), and T. Y. Lin in prestressed and reinforced concrete structures; Fazlur Khan and Les Robertson in high-rise buildings; Eduardo Torroja, Pier Luigi Nervi, and Santiago Calatrava as designers of shell roofs and exciting new types of structures; Ray Clough, Hardy Cross, Fred (A. M.) Freudenthal, Wilhelm Flugge, Gaspar Kani, Eric Reissner, Stephen Timoshenko, and Olgierd Zienkewickz as analysts; and George Housner and Nathan Newmark as the fathers of earthquake engineering among other accomplishments.

Structural Accomplishments

General Comments

A number of excellent books such as those by Kirkham (1914, 1933), Sheiry (1938), Husband and Harby (1947), Goldberger (1981), Billington (1983), Collins (1983), Southworth and Southworth (1984), Westerbrook (1984), Nakamura (1988), Billington (1996), Jackson (1997), Berlow (1998), Stoller (2000), and Abramson (2001) provide detailed descriptions and photographs of various engineering landmarks of the 20th century. The reader is referred to these publications or similar ones for a more complete coverage of the topic and pictures of outstanding structures.

Tall Buildings

Tall buildings have always challenged the imagination of engineers and fascinated the general public. Even if the Ingalls Office Building in Cincinnati, completed in 1902, has been credited as the first skyscraper, tall buildings are emblematic of 20th century structural engineering achievement. Goldberger (1981) reviewed the history of skyscrapers and discussed several of them in some detail. As building height increased, a number of new problems, some requiring important research efforts, had to be faced. Traditional methods of analysis that ignored the axial deformation of the columns were no longer valid, for instance, to determine the lateral displacements due to wind loads. The economics of the project, associated with the amount of usable space per floor, dictated the need for structural solutions different from the standard moment-resisting frames. Wind vibrations became a poten-

J. Struct. Eng. 2002.128:965-975.

tial discomfort problem for the tallest structures, and methods to control these motions had to be devised (e.g., tuned mass dampers and viscous dampers). New types of foundations and new measures had to be conceived in some cases.

Each skyscraper is a unique project, incorporating new knowledge and experience. Skyscrapers like the Petronas Towers (445 m, 1997) and the Plaza Rakyat (376 m, 1998) in Kuala Lumpur, Malaysia, the Sears Tower (435 m, 1974) in Chicago, the Jin Mao Building (414 m, 1998) in Shanghai, China, or the World Trade Center Towers (410 m, 1973, destroyed during the attack on America of September 11, 2001) and the Empire State Building (375 m, 1931) in New York City have seen a significant evolution in their structural configurations and are not mere replicas of each other. On July 18, 2001, the Empire State Building was designated as a Civil Engineering Monument of the Millennium (ASCE 2001).

Long-Span Bridges

Long-span bridges have also attracted young people to the structural engineering profession. ENR (1999) listed the 1936 San Francisco–Oakland Bay Bridge, the 1937 Golden Gate Bridge, the 1957 Mackinac Bridge, the 1964 Chesapeake Bay Bridge-Tunnel, the 1966 Severn Bridge, the 1986 Sunshine Skyway Bridge, the 1995 Normandy Bridge, the 1998 Akashi Kaiko Bridge, and the 1999 Tatara Bridge as outstanding achievements of the 20th century. Cable-stayed bridges such as the Tatara Bridge in Japan, the Sunshine Skyway Bridge in Tampa Bay, Fla., or the El Alamillo Bridge in Sevilla, Spain, are also very aesthetic solutions developed during this last century. The Golden Gate Bridge was designated by ASCE as the Civil Engineering Monument of the Millennium in the long-span bridge category (ASCE 2001).

Dams

Although dams (either small diversion dams or larger dams for water storage) have been built since antiquity (e.g., Smith 1975), large dams are another kind of structure that fascinates the public. The Grand Coulee Dam and the Hoover Dam (Jackson 1997; ENR 1999) are two notable examples. The Hoover Dam was the tallest curved gravity dam upon completion in 1936, and continues to be a major tourism attraction up to today. Essentially all dams over 60 m high were designed and built during the last century, the only two exceptions being the 62 m high Goufre D'Enfer gravity dam built in France in 1866 and the 71 m high Puentes Dam built in Spain in 1884.

Shell Structures

Thin shell structures used for long-span roofs, dams, tanks, or cooling towers are creations of the 20th century. The Dorton Arena in Raleigh, N.C., the large domes of auditoria and arenas, the beautiful hyperbolic paraboloids of Felix Candela, the parabolic shells of the St. Louis Priory Chapel, are all innovative and impressive structures. So are the tension structures of Frei Otto or membrane roofs supported by air pressure such as the Pontiac Dome. While shell structures have unfortunately lost some of their appeal in civil engineering, many structural engineers have found challenging jobs in the aeronautics and aerospace industries where shell type structures are used and needed.

Offshore Platforms

Offshore platforms are another creation of the 20th century. The first platform for oil drilling out of the sight of land was installed in 1947 off the coast of Louisiana, in 6 m of water. The water depths at which platforms were installed increased steadily and at a fast pace. By 1955 they had reached 30 m, by 1965 67 m, by 1976 255 m (the Hondo platform, off the coast of California, which had to be fabricated in two pieces and then welded on site), by 1978 300 m (the Cognac platform, in the Gulf of Mexico, fabricated in three modules), and by 1988 405 m (the Bullwinkle platform in the Gulf of Mexico fabricated now in a single piece). Both Cognac and Bullwinkle won awards as the civil engineering achievements of the year. These were all steel jacket structures. In the North Sea the difficulties in accessing the platforms during severe and frequent storms required larger storage capabilities, which, coupled with the European preference for reinforced concrete, led to the design of gravity platforms. Neither of these solutions was feasible, however, as the oil industry was forced to venture into deeper and deeper waters in search of new reservoirs, because their natural periods would become too close to those of the design waves. It was thus necessary to conceive new structural types of much more flexible structures whose natural periods would be again far removed from those of the waves but on the other side of the spectrum.

The structures that have been and are being designed for water depths of the order of 1,000 m and more consist basically of a large floating body tied to the sea bottom by vertical tethers, prestressed by the hull's buoyancy, or mooring lines (catenary or taut moorings). The possible solutions are tension leg platforms (TLPs), spars, floating production systems (FPSs or semisubmersibles), and tanker based floating production, storage, and offloading systems (FPSOs). The Auger platform, a TLP, was installed in the Gulf of Mexico in 1994 in 858 m of water and again won the civil engineering achievement of the year award. It was followed by Mars (887 m in 1995), Ram Powell (900 m in 1997), and Ursa (1,140 m in 1998), all TLPs, as well as the Neptune Spar (570 m in 1997) and the Genesis Spar (840 m in 1998). The industry is looking now at water depths of the order of 3,000 m. The uncertainties in the loads, the need to deal with the interaction between the structure, the surrounding sea, and the bottom soil, and the difficulties of working in such extreme water depths have made offshore structures the new exciting challenge for structural engineers over the last quarter of the century.

Concluding Remarks

We have attempted in the previous sections to provide an overview of some of the developments in different types of structures during the 20th century since the subject of this paper was structural engineering. We must realize, however, that no civil structure can survive without an adequate foundation and that designs become meaningful only when constructed. One cannot ignore entirely therefore the progress made in soil mechanics and in construction methods.

Although Coulomb, Rankine, and others had already been involved with important problems related to soils, the field of soil mechanics as a separate discipline emerged in the 20th century and expanded rapidly due to the contributions of Karl Terzaghi and a large number of outstanding followers worldwide. The progress in our understanding of soil behavior under different conditions and in our ability to numerically predict their behavior has been considerable. It has led to the safer and more reliable design of a number of different types of foundations, the design and construction of a large number of earth dams, and the understanding of how soils affect the characteristics of earthquake motions and the dynamic response of structures. Unfortunately, the needed integration between the design of a structure and its foundation is still lacking. The expansion of the field of soil mechanics with a change in name to geotechnical engineering, the creation of a number of subdisciplines or areas (e.g., geotechnical earthquake engineering or geoenvironmental engineering), and the widening gap at the professional level (ASCE, for instance) between structural and geotechnical engineers are aggravating the situation. It is necessary to consider a structure and its foundation as a single system and to do so it may be necessary for structural engineers to learn more about soils and to design their own foundations.

The 20th century has seen also substantial advances and innovation in construction methods and techniques, which once again influence the designs. Different forms of formwork, precast construction, and segmental construction of bridges are but a few examples. As construction and project management have evolved and become separate programs within civil engineering departments at universities, the gap between structural and construction engineers has increased. We consider this gap a deplorable situation. An effort must be made to integrate design and construction as well as the design of the various subsystems (e.g., structure and foundation).

Structural Analysis

General Comments

Girvin (1948) gave a historical appraisal of mechanics beginning with the first logical proof of Archimedes' principle in approximately 300 B.C., following with the early Greek developments, the medieval period (500–1500 A.D.), the Moorish culture in Spain, the contributions of Roger and Francis Bacon, the Renaissance (1400–1600 A.D.), and the modern period when the principles of statics, dynamics, strength of materials, and theory of elasticity were established.

The bases for structural analysis were set by Hooke and Mariotte in the 17th, by Coulomb, Euler, and Lagrange in the 18th, and by Airy, Betti, Boussinesq, Castigliano, Cauchy, Green, Kirchhoff, Lamb, Muller-Breslau, Navier, Poisson, Rankine, Ritter, Saint Venant, Stokes, Voigt, and Young among others in the 19th century. In the first half of the 20th century Hardy Cross in the United States and Gaspar Kani in Europe developed schemes based on the mathematical solution of simultaneous equations by iteration or relaxation that enabled the computation with a slide rule of the bending moments in large frames with negligible axial deformations. These developments had a major impact in structural analysis and the method of moment distribution (or the method of Cross) in particular was adopted worldwide. The first half of the century saw also the development of the elastic theory of shells with the work of such pioneers as Dischinger, Krauss, Flugge, Mushtari, Novozhilov, Pfluger, Reissner, and Vlasov.

Computer Methods

The main changes and innovations in structural analysis occurred in the second half of the century and were due to the advent of the digital computer. The formulation of matrix structural analysis of assemblies of linear members (plane and space trusses and frames as well as plane grids) was followed by the development and implementation in general purpose computer programs of the finite element and the boundary element (or boundary integral equation) methods for two- and three-dimensional continua. This allowed solving complex structures such as plates and shells of arbitrary shapes with their actual boundary conditions. Previously it was necessary in many cases to introduce approximations and/or to simplify the support conditions in order to find analytical, closed form, solutions. This represented also an important change in emphasis from continuous to discrete mathematical models, and made the routine structural analyst obsolete. Yet continuous solutions, where they exist, remain valuable as a check on the accuracy of the discrete formulations and on the validity of the model or discretization selected. Although analog computation was popular in the 1960s, the fast development of digital computers has dominated the field. Recently, because of the experimental usage of biomaterials in computers, hybrid computers again appear promising.

The advantages and potential pitfalls of excessive dependence on computers is a topic that deserves serious discussion but it falls beyond the scope of this paper.

Nonlinear Analysis

Our understanding of the effect of changes in geometry, due to the deformation and displacements caused by loads, on the stiffness and stability of structures has seen significant progress in the 20th century, beyond the simple concepts of Euler buckling. The work of Timoshenko and Bleich provided designers with the tools to estimate the buckling loads for structural members subjected to a variety of loading conditions, plates, shells, and pipes. This work was extended by a large number of researchers, with more rigorous mathematical formulations, with experimental work, and with simplified procedures at the more practical level. The distinction between bifurcation and limit point buckling and the possibility of predicting both from a single formulation were clarified. The ability to predict the buckling load of a complete assembly of members instead of considering each column as a separate entity with a different buckling load represented another important improvement. Much progress was achieved in the study of shell buckling and nonlinear instability. Yet many of the simplified models and analogies used in practice have at times confused practicing engineers, making them think of stability as a strength rather than a stiffness consideration and leading to improper estimates of buckling effects under dynamic loads.

Plastic analysis was also developed during the 20th century as a means to estimate ultimate loads and failure conditions with relatively simple models, predicting in some cases upper or lower bounds. So were fatigue analysis and fracture mechanics. Once again the finite element method changed drastically the way nonlinear behavior due either to nonlinear material properties or to changes in geometry (stability considerations) was studied. Instead of being able to predict only the ultimate load and failure mechanism for relatively simple assemblies of members or to estimate buckling loads under a number of simplifying assumptions, one can now follow the behavior of a complex structure as the loads increase and it undergoes inelastic deformations, until a limiting condition is reached. This is a very important capability, particularly when considering extreme loads, such as the maximum credible earthquake, for which it might be too expensive to maintain the structure in the linear elastic range, or when considering nonlinear instability or progressive buckling of pipelines. It is an area in which much work remains to be done, to gain confidence in the existing nonlinear constitutive models for various materials, to incorporate three-dimensional effects, and to account for nonstructural components when dealing with actual buildings (rather than idealized bare plane frames).

Structural Dynamics

Structural dynamics is another area that has seen a substantial development in the 20th century, dealing with the problems of impacts and moving loads, wind effects on very flexible structures, design of machine foundations, and earthquake and offshore engineering. These last areas have brought with them the need to account for the interaction between different media, such as the structure and the underlying (or in some cases surrounding) soil, the structure and the surrounding water, or the combination of water, structure, and soil as a single system. Soil-structure, fluid-structure, and fluid-soil-structure interactions have become important areas of research. During the 20th century, many significant advances have been made in these fields.

Concluding Remarks

Mechanics are the basis for structural analysis and should be taught to all engineering students (Roësset and Yao 1988). Unfortunately, many practicing structural engineers do not appreciate their education in mechanics or the many credit hours devoted to mechanics courses that they took. Educators need to examine how mechanics can be taught in universities so that future engineers will appreciate its role and importance and be able to see its practical usefulness.

Materials

General Comments

We tend to think of iron first, and steel next, as the materials of the 19th century, and attribute to the 20th century reinforced concrete. We should remember, however, that reinforced concrete, first used for flowerpots in 1857, was already extensively used for structures in Europe by the 1880s and that Mörsch's book on the design of reinforced concrete structures was published in 1902. The last century, however, has seen important changes in the types and properties of these two materials. We have seen new alloys for steel, higher-strength steel, and high-performance steels. Meanwhile, additives for concrete were developed along with a greatly enhanced understanding of their chemical and physical characteristics. Dams and pavements have seen the use of roller compacted concrete. The combined use of concrete and steel members in composite construction has proven to be a popular and interesting solution for buildings. The strength of both materials has increased continuously with the major changes in concrete and during the last quarter of the century. It is possible to have today concretes with compressive strengths of the same order of magnitude as those of steel and with similar tensile strength, as well as flowable and self-compacting concrete.

New Materials

The second half of the 20th century has seen the development of materials science as a separate discipline. Plastics, fiberglass, and more recently composite materials consisting of a resin (thermoplastic or thermoset) base with glass or graphite fibers (or a combination of both) have found their way in a number of important applications in the automotive, aerospace, and naval industries. It is possible today to design materials, just as one designs a structure, so as to obtain any desired combination of strength, stiffness, toughness, and ductility. It is also possible to design ''smart'' materials whose properties change following a desired pattern depending on various conditions (e.g., states of stress or strain, temperature, humidity, and electric current). Unfortunately, civil engineers have not played a major role in this effort because of the high costs of these newer materials.

To date, composite materials (fiber-reinforced polymers) have found application in traditional civil engineering structures for seismic strengthening and retrofit, structural repair, and new forms of bridge decks. Different types of fibers have also been used as reinforcement in reinforced or prestressed concrete structures.

In the offshore field, weight is an important factor, making the use of composites very attractive. It has been reported that (1) a pound saved in the weight of floating structures such as tension leg platforms can represent a saving of about $4 if it is properly accounted for in the design, and (2) the use of phenolic compounds for the grate floors and stairs of the Mars platform resulted in total savings of some $25 million. Even so, the civil engineering applications have not yet reached the volume of these in the aeronautical, naval, and automotive industries. In some cases more research is necessary to understand the long-term behavior of these materials in potentially aggressive environments under different states of stress. Whether the use of these new materials in civil structures will expand will depend primarily on their unit cost and their availability in large quantities with a reliable supply.

Nondestructive Evaluation

At the same time that new materials are being developed, techniques to test these materials (as well as the conventional ones) in place (in situ) and in a nondestructive way have been established. This is essential for quality control, particularly for new materials, and to assess the condition of existing structures, particularly old ones, to evaluate their load resistance capacity and to identify potential damage in these existing structures. The use of nondestructive evaluation (NDE) techniques to determine material properties or structural behavior requires, for a proper interpretation of the data, the use of system identification and damage assessment methodologies that are also the result of research conducted primarily during the last quarter of the century.

Dealing with Uncertainties

General Comments

The desire to account in a more rational way for the uncertainties that exist in the prediction of the loads acting on a structure, in the properties of the materials used, and in the accuracy of the methods of analysis, led engineers in Europe to modify the form of their codes and to make use of probabilistic concepts by the middle of the 20th century. The interest in applying the theory of probabilities to real civil engineering problems started shortly after in the United States, at the academic level, in institutions such as Columbia University, MIT, Stanford, and the University of Illinois, among others. Earthquake engineering, particularly when dealing with the design of important facilities such as nuclear power plants, and offshore engineering, among other

J. Struct. Eng. 2002.128:965-975.

fields, are fertile grounds for the application of probabilistic methods. Risk analyses have started to become standard requirements in these fields. Yet the introduction in practice of probability concepts has been slow. Even when the probability-based load and resistance factor design (LRFD) specifications were introduced in design codes, they were used without explicit mention of probabilities. The load and resistance factors were selected through calibration, in order to obtain results similar to those of the working stress design and past experience, rather than on the basis of the existing uncertainties.

Uncertainty Analysis

Almost all civil engineering curricula have now a basic introductory course on statistics/probabilities. In some instances this is purely a mathematical treatment. In others the course emphasizes applications to real civil engineering problems. Unfortunately, this course usually is not followed by other courses. Unless the material is applied again in following design and analysis courses so that the student can see its practical importance, it will be only an additional requirement that can be forgotten once the course is over. Much remains to be done to make probabilities and reliability an integral part of civil engineering education and practice. Yet one must remember that this is just a way to account rationally for uncertainties in predicting the performance of a structure during its life. The uncertainties can only be reduced through a better understanding of the actual physical processes involved. The existence of uncertainties should not be construed as an excuse to introduce systematic errors through the use of either inadequate models or methods of analysis.

Structural Reliability

Structural reliability has been traditionally defined as the probability of the useful life of a given structure exceeding a certain time period. This is a good measure of the level of safety of a structure but it is more meaningful to base reliability of existing structures on symptoms that can be related to structural damage. Cempel (1991) in Poland introduced the concept of symptom-based reliability first, in connection with testing of diesel engines based on their noise level. The same principle could be applied to civil engineering structures. Natke and Cempel (1997) and Wong and Yao (2001) attempted to apply it to civil infrastructure systems. However, the symptoms indicative of structural damage in these structures (damage states, the variables that characterize them, and the values of these variables corresponding to each state) are yet to be defined.

Fuzzy Logic

While academic researchers apply structural reliability principles and develop new methodologies assuming that the required probability distributions (including the tails of these distributions that characterize the rare, extreme events) are perfectly known, engineers in practice find that in many cases it is nearly impossible to select with accuracy a probability distribution or its parameters. The best that can be done in many cases is to define vaguely the probability of an event occurring as low, medium, or high. This has led to the theory of fuzzy sets. Zadeh (1965) published the first paper on fuzzy sets. Basically, the theory of fuzzy sets deals with those events that are meaningful but not well defined. For example, a damaged structure might be classified as collapsed, severely damaged, lightly damaged, and not damaged. With the exception of the category of ‘‘collapsed,’’ the other classifications are meaningful but not clearly defined and thus they are fuzzy events. Although civil engineers were among the first to apply the theory of fuzzy sets (e.g., Wong et al. 1999), there have been very few practical applications to date. Yet in structural reliability studies, there are many situations where fuzzy logic (e.g., Yen and Langari 1999) is potentially applicable.

Earthquake and Wind Engineering

General Comments

Earthquake engineering started as a technical discipline after the 1906 San Francisco earthquake. Thanks to the considerable amount of research that has been conducted in this field over the last 100 years, we have made tremendous progress in our understanding of the nature of earthquakes and earthquake mechanisms. For example, we now understand better the effects of magnitude, distance, geology, topography, and local soil properties on the characteristics (amplitude and frequency content) of the seismic motions that are expected at a specific site, and the behavior of soils and structures when subjected to seismic excitations. Earthquake related research still represents a major fraction of the funds allocated by the National Science Foundation to structural or geotechnical engineering, in addition to the funds provided by this and other government agencies for seismological work. This funding led first to the creation of a National Earthquake Engineering Center at the State University of New York in Buffalo, to the creation later of three national centers, and more recently to the investment of a very large amount of funds to upgrade and create new experimental capabilities, to connect them, and to create a national network of laboratories (NEES).

Earthquake Engineering Research

Structural research in earthquake engineering has dealt with (1) the development of improved dynamic analysis techniques, and (2) many experiments on isolated members, joints, and small assemblies of elements or scaled models of frames, to better understand various failure modes, to fit curves to the measured data in order to obtain design formulas, or to improve structural detailing. As a result of this work, buildings can be designed today, using present codes, to resist earthquakes much more safely than 50 years ago. Although the increase in safety may be attributed in large part to improvements in the supervision of the construction process, the numerous changes particularly in reinforcement of concrete members to provide continuity and ductility, and in the details of the connections, have also played a key role in adding to the safety. The lack of quality control of materials and the construction process are still, however, major causes of catastrophic failures in some countries.

A major shift in seismic research as applied to structures occurred in the last quarter of the century, when the emphasis moved from the design of new buildings to the retrofitting and strengthening of existing structures and the repair of structures damaged during earthquakes. Given the large inventory all over the world of buildings that were designed without appropriate seismic considerations (early building codes or codes in certain regions without any seismic provisions) this represented a logical move. It is ironic, however, that in a highly publicized case of repair and retrofitting, a 10-story building was reduced to seven stories because of lack of information on the condition or capacity

J. Struct. Eng. 2002.128:965-975.

of its foundation. This illustrates the importance of damage identification through nondestructive damage evaluation techniques, a field that has been developing over the last quarter of the century, as well as the limitations of looking at only one component of a building (the structure) instead of following the systems approach and integrating it with its foundation and underlying soils supporting it.

Research on the more creative, conceptual, phase of the design process, exploring alternative structural configurations which may be better suited to resist the loading resulting from earthquake excitation, as well as new mechanisms of energy dissipation, base isolation or, in general active and passive control systems, is only relatively recent in spite of the pioneering efforts of Frank Lloyd Wright in the design of the Imperial Palace Hotel in Tokyo. It is to be hoped that research in the 21st century will look more at these topics rather than just continuing forever to test standard configurations. It is also hoped that the earthquake engineering community will look at the overall problem as one involving many important factors instead of trying to look at each component in isolation as a one-dimensional problem. At present, we try to characterize each earthquake by a single value, soil effects by a single descriptive or numerical parameter, and damage to a building by a single measure of ductility.

The National Center for Earthquake Engineering Research at Buffalo also started a coordinated research program involving social scientists and engineers. They looked not only at technical issues but also at the social and economic implications of earthquakes. This was important pioneering work. The cooperation of social scientists and earthquake engineers has been continued by the three succeeding centers: the Pacific Earthquake Engineering Research (PEER) Center on the West Coast, the Mid-America Earthquake (MAE) Center in the Midwest, and the Multidisciplinary Earthquake Engineering Research (MCEER) Center in the East.

Seismic Design Codes

It is fair to say that regular buildings can be designed at present to perform satisfactorily under the potential earthquakes to which they may be subjected during their lifetime. According to the code's philosophy, some nonstructural or even structural damage may occur depending on the severity of the motions but collapse and loss of life should be avoided. Particularly important is the evolution of the codes from working stress design based on linear elastic analyses that are meaningless when substantial inelastic deformations are accepted in the structure. These design codes have now changed to load/resistance factor design based on ultimate conditions, and the profession is expected to finally adopt performance-based design. In a performance-based design code, one would design for an expected or desired level of damage in the case of extreme loads, accounting for the uncertainties present in the process, assuming that one could in fact predict the expected damage accurately. This represents a major improvement in the code philosophy. The main limitation of the approach is in the last assumption. Present analysis procedures cannot predict yet with accuracy the amount of damage that would occur in a complete building, including all its components, under a given earthquake.

The main source of uncertainty remains still the characterization of the design earthquake, due to lack of sufficient historical data on real earthquakes. Starting with the famous 1940 El Centro earthquake record, there are only slightly more than 60 years of real earthquake records. In the long history of the earth, 60 years of data collection is simply not sufficient. Thus the need to take into account the uncertainty of the excitation in earthquake engineering is continuing.

Concluding Remarks

The economic losses due to earthquakes are very large and seem to increase continuously. Thus the large amount of funding that has been made available for research in earthquake engineering, particularly after a large and damaging earthquake, is justified. The losses due to wind (hurricanes or tornadoes) are also very significant but the funding for wind related research has always been considerably smaller. Wind engineering is, however, another very important area in need of research. In addition to the study of the damage caused by hurricanes or tornadoes and the development of design measures to reduce this damage, there are important problems associated with wind induced vibrations. In tall and flexible buildings wind loads tend to control the design, even in seismic areas, and can result in serious discomfort problems. In suspension and cable-stayed bridges wind can result in vibrations of the cables, as well as serious aerodynamic instabilities. While the failure of the Tacoma Bridge is well known and documented, other types of damage caused by wind are less well understood.

Maintenance, Repair, and Retrofit

General Comments

The need to assess the condition of existing structures, to repair them if they are damaged, or to strengthen them if they do not meet the requirements of modern codes is not just limited to earthquake engineering. It is much more general and related to the upkeep of our vast civil infrastructure. The decision of whether to demolish large amounts of structures once they reach their design lives in order to replace them or whether to maintain and repair them needs to be made. Meanwhile major landmarks throughout the world that had withstood the passage of time for many centuries (some times with periodic repairs) are beginning to suffer more serious, accelerated, deterioration, due to age and environmental conditions aggravated by atmospheric pollution. Conservation of these historic monuments has become a theme of major interest at the international scale and the subject of an increasing number of conferences.

Note that the question is not just how to strengthen existing structures but also how to assess their condition and the need for strengthening. This involves the use of nondestructive testing techniques and the application of new methodologies for damage assessment and identification. Academic programs on evaluation and rehabilitation of buildings have already been created at a number of universities, ranging from the introduction of one or two courses within an existing curriculum, to the development of a set of courses leading to a diploma, and more recently the creation of a complete degree granting program.

Forensic Engineering

Structural engineers have been involved for many years in the rating of bridges and old buildings on the basis primarily of visual inspection, following sets of established procedures. The occurrence of major collapses has led in general to the creation of blue ribbon panels of experts charged with the investigation and determination of the causes of the failure. Forensic engineering was developed as a specialty within structural engineering dealing with these two issues as well as quality control in construction. The new emphasis on maintenance, repair, and retrofit can thus be considered to some extent as a broadening of its scope.

Structural Control

It is equally important to consider how new structures can be designed and built to facilitate their future maintenance as they age, the continuous monitoring of their condition, the early detection of potential problems, and the identification of damage after an extreme loading event such as an earthquake. One could thus talk about design for maintainability and repairability, as well as design for durability. Research in other fields such as electronics, with the development of a large variety of new sensors, health monitoring, fiber optics, ''smart'' materials, and control mechanisms should play a key role in this effort (e.g., see Housner et al. 1997).

Structural Design

General Comments

The objective of a civil engineer involved in the design of a specific structure is to obtain a system that satisfies a given set of functional requirements both aesthetically and economically. In addition, this system must perform its intended use safely under all the potential loads and environmental actions to which it may be subjected during its lifetime. The complexity of the computations and the effort required to perform structural analyses, to determine the stresses in the members due to a specified set of loads, and to compare them to allowable values provided by the codes, exaggerated for many years the importance of this phase of the design, at the expense of other considerations. In many cases the dimensioning process, where member sizes are selected on the basis of the computed stresses (or strength) and the code requirements, has been considered synonymous with design (particularly in so-called design courses in typical civil engineering curricula), whereas it is in fact just the last step of the analysis. Codes required initially that the computed stresses remain in the linear elastic range of the materials and applied a factor of safety with respect to the onset of yielding to account for potential variations in the loads or material properties. This approach (working stress design) made sense when dealing with performance under normal service loads but did not provide a reliable indication of the margin of safety with respect to collapse. The use of different factors for the loads and the material strength to account for uncertainties and the consideration of the limiting or collapse condition led to the load and resistance factor design codes. When dealing with extreme loads (such as earthquakes) and accepting the possibility of nonlinear behavior, it is no longer sufficient to know the safety or reliability index with respect to collapse. One must be able to predict the amount of expected damage (and the economic losses) for different load levels. This has led finally to performance-based design codes as already discussed in relation to earthquake engineering.

Economy and Computer Applications

It seems that in some cases designers might also have forgotten the fact that their structures had to be built and at a reasonable cost in order to achieve the goal of economy (clear exceptions were offshore structures where the fabrication, transportation, and installation procedures controlled the design). This was probably a logical consequence of separating the design and construction planning processes instead of integrating them. As a result it was necessary in the last quarter of the century to create a new word and to talk about ''constructability'' as an attribute of the design. Equally important is the need to look not only at the original cost of the structure but also at the costs of maintenance and repairs during its intended lifetime. One could thus add as mentioned above two new words and attributes to the structural design: ''maintainability'' and ''repairability,'' both closely associated with the possibility of using instrumentation to monitor the performance of the structure on a continuous basis, and to obtain early diagnoses of potential troubles or malfunctions. And all this must be performed within a probabilistic framework.

The reduction in time and cost of the structural analyses brought by the availability of verified software packages allows the designer to concentrate on other issues, such as a better estimation of the potential loads, the investigation of alternatives looking for an optimum solution, the integration of the design of the different components of the system, and the coordination of the design and construction. In the second half of the 20th century there were a number of research efforts on structural optimization. Unfortunately, the application of mathematical optimization techniques to structural design required the selection of an objective function. Total weight seemed a logical choice and the simplest one. Yet weight, which is very important for aeronautical or aerospace applications, as well as for some types of offshore structures, is not a significant contributor to the cost of buildings or most civil engineering structures. New and promising methodologies to perform structural optimization in a much more practical sense were beginning to be developed at the end of the century.

Analysis-Design Integration: Computer Applications

In the late 1950s, a young civil engineer named Charles L. Miller pointed out that the computer should not be just a research instrument in the departments of mathematics or electrical engineering of universities but an everyday tool for practicing engineers. This was the time when we were still laboring with IBM 1620s and experts had predicted that a handful of IBM 7040s would saturate the computation market until the year 2000. He also indicated that to achieve this goal it would be necessary to facilitate the communication between man and machine and proposed the creation of problem oriented languages to replace the cumbersome fixed format data input forms and make the computer more user friendly. This extraordinary vision resulted in his becoming head of the Civil Engineering Department at MIT while in his early 30s. In this capacity he oversaw the development of the first major structural analysis package, the *STRESS* program, and he conceived next the creation of an integrated civil engineering system (ICES) with problem oriented verbal input, dynamic memory allocation, and a common data base, which could be used by structural, geotechnical, construction, mechanical, and electrical engineers to integrate the complete design of a building.

One of the first components of this system was the *STRUDL* package representing an extension of *STRESS* with more sophisticated analysis capabilities and a design orientation. Unfortunately the success of *STRESS* and *STRUDL* led other universities to develop faster, more efficient, and more sophisticated analysis programs, forgetting about the user friendly features or any design considerations. As a result, what was an important advance in computational analysis capabilities represented a significant step backward on the communications, design, and integration fronts. It is interesting to notice that the present analysis packages that take advantage of more user friendly input-output capabilities (with computer-aided design, graphical displays, etc.) have not been developed in academia but by industry. Programs that perform real design, rather than simply checking stresses with code formulas, or integrate the design of the structure and its foundation or the design and the construction phases are scarce and mostly of a proprietary nature. To a large extent the dream of Charles Miller remains yet to be fulfilled. Reinschmidt (1991) discussed this topic in more detail.

Education

General Comments

In the 1950s engineering education in the United States experienced a major shift in emphasis from a very pragmatic know-how and can-do approach to a much more rigorous theoretical treatment of basic and engineering sciences. While the strengthening of the scientific basis was desirable, unfortunately, it was done at the expense of the more practical engineering subjects. At the same time, there has been an increased emphasis on more basic research, not only as an important component of the educational process (particularly for graduate students), but also as an end by itself (and eventually as a main source of funding). Up to that time most engineering professors had a substantial amount of practical experience and maintained themselves in touch with the practice of engineering as did the great engineers of the 19th century. At that time, research was often motivated by real problems encountered in practice, rather than being dictated by funding agencies with the assistance of government panels, often consisting of other academic researchers.

Civil Engineering Education

The composition and background of engineering faculties has changed substantially. At present most faculty members in the United States are hired upon completion of their PhDs without any exposure to practice. After five (or fewer) years of service faculty members will undergo a tenure review that will require their having (1) generated a certain amount of research funding, and (2) published a substantial number of papers. Exposure to practice usually will not count for promotion/tenure considerations and therefore cannot be a serious consideration for a young person trying to make it in the present academic environment. As a result, a situation is reached where many universities have trouble finding faculty members who can teach realistic design courses that are required for accreditation. It seems that many faculty members at research universities are trying to recreate themselves, producing more researchers and faculty members rather than competent, top level professional engineers. This is a dangerous situation in need of remedy.

Some enlightened institutions foresaw the problem and started many years ago hiring practicing engineers as adjunct professors to teach design courses. A better solution is to have prominent engineers retire early and join full time university faculties, participating in the teaching and research efforts in combination and close collaboration with the other faculty members, coordinating and integrating their contributions so as to incorporate realistic examples in all the courses. The time has come for the case study approach, commonly used in other disciplines, to become more widely used in civil engineering education.

Reinstating education, and education of professional engineers in particular, as a major goal of universities will require major changes in their philosophy (Roësset and Yao 2000). It will require also a new type of closer industry-university cooperation. Final decisions on curriculum content should rest with the faculty but industry should receive clear and well-defined benefits from this cooperation. Persons involved in planning civil engineering curricula would do well to read carefully the little jewel by Cross (1952), *Engineers and ivory towers*.

Predictions

On the basis of their own knowledge and of their perceived needs and hopes, reluctantly the writers are willing to make the following predictions.

- There will be taller buildings, deeper platforms in the ocean, and longer bridges built. There will also be new structures built in space and perhaps on other planets, as well as structures under water for an increased number of applications. It is interesting to notice that while Jules Verne's futuristic predictions for space have been greatly exceeded by reality, his vision of submarine life remains to be fulfilled, perhaps because the sky exerts a stronger appeal on human beings than the ocean bed. Yet the importance of the ocean and its resources for human life will continue to increase.
- There will continue to be important progress in our analysis capabilities, allowing us to predict better the behavior of structures under static and dynamic loads, particularly on two fronts: (1) the three-dimensional analysis of complete structures, including nonstructural as well as structural components, considering both the structure and its foundation; (2) the nonlinear analysis of structures with realistic constitutive models and the ability to predict the location and extent of damage that they might suffer. As the methods of analysis advance so will our knowledge and understanding of the physical processes that cause the loads on the structures, such as wind, earthquakes, or sea states, allowing us to better model the excitation. To achieve this, we must continue to collect data on these loads.
- There will be an increased use of uncertainty and risk analyses in structural engineering. Although there have been reliability-based design codes and much progress has been achieved already in structural reliability, most people working in these fields are analysts. Experiments must be performed in order to make further progress. In addition to probabilistic methods, uncertainty analyses will include fuzzy sets if they are to be applied in practice to cases where the probabilities can only be estimated in vague terms. Soft computation including fuzzy logic, genetic algorithms, and neural networks will be applied to more practical problems in structural engineering. Hybrid computers combining the respective advantages of analog and digital computations may enable structural engineers to deal with more practical problems.
- One can foresee buildings and bridges that are instrumented so as to be able to monitor their performance and diagnose potential troubles easily, and structures conceived so that they can be easily maintained, repaired, or replaced. One can foresee also increased use of passive and active control systems as means to respond more effectively to different types of external excitations. There will be increased practical applications of symptom-based reliability and health monitoring of existing structures. Symptom-based reliability will become more useful

once we are able to define variables characterizing the different damage states that can be obtained from field measurements and nonlinear analyses, as well as their limiting values. This will require more experimental and analytical research. Future developments in damage assessment and measurement technologies (especially nondestructive evaluation and in situ testing techniques) will also help to increase its practical applications.

- It is believed that the liberating aspects of computers on the demands on structural designers will see their full impact in this century. The time should come to see finally a fully integrated design process in which the engineer can look at the complete system and the interactions of its different components, while technicians carry out on computers the analysis of the various subsystems. The designer will be able to devote more time to seeking optimum solutions (materials and topology) in relation to the functional use of the structure and its overall cost (including initial cost of materials and construction, cost of money, and cost of maintenance and repairs). Life-cycle costs will be considered at the beginning of each project, and visualization will be more commonly used.
- The writers see a more intensive use in civil engineering of the design tools that have been developed in the automobile and aeronautics industries, with three-dimensional graphical models of the structures in the computer that can be updated as the design progresses and modifications are introduced by different teams in concurrent design, or as the simulated or actual construction process goes on. There will also be increased use of simulation and consideration of the construction process during the design in order to guarantee the constructability of the project. More research is necessary, however, to guarantee that concurrent interactive design will proceed smoothly.
- Designers will have a tremendous variety of materials to choose from, but whether ultrahigh-strength and ductile concrete or composite materials consisting of a resin matrix with glass or carbon fibers will see extended use in civil construction, as compared to aerospace or automobile applications, will depend on their cost and commercial availability in large quantities.
- Performance-based design codes will be further developed. More methods of analyses will be acceptable and used in analysis and design. As long as the structure will perform according to the specified usage, engineers will have more freedom in their designs.
- There should be a much larger concern of the structural engineer for issues that are not directly related to the resistance of the structure or the distribution of forces in the members, but which are essential for the functional, economic, or aesthetic viability of the work, or for the acceptance of the project by the owners or the public at large. This will necessitate important changes in the way we educate structural engineers (or civil engineers in general).
- There will be significant changes in engineering education affecting both form (the way in which we teach) and substance (the content of the curriculum). The new multimedia and simulation capabilities available will complement and enhance the effectiveness of the more traditional forms of teaching without replacing them, for education is not merely making information available. There will be as a result an increase in visual and inductive learning. Curricula will pay more attention to sociopolitical and economic issues affecting civil engineering projects and to imparting communication and team working skills to the students. Whether one can teach leadership (in contrast to management or bureaucratic skills) is not clear to the writers, but leadership skills can be further enhanced.
- There will be an increase of virtual congresses and conferences starting with the CE World, the 2002–2003 ASCE virtual congress celebrating the 150th anniversary of ASCE.

Concluding Remarks

The role of design engineers and the practice of structural engineering will change substantially due to the impact of computers in our society. There should not be any reason for concern since these changes will make design work much more interesting and exciting. We may not need as many engineers practicing at a professional level as we are producing today, but hopefully they will have better jobs.

The writers hope also that the 21st century will see a return to valuing substance over appearance. They realize that the best project has no value unless it is sold to the stakeholders and they believe in the importance of communication skills in engineers. Marketing ability is indeed very important. Yet a book should not be judged only by its cover, and, contrary to what was written on the wall of a particular building at a university, marketing is not everything.

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References

Abramson, D. M. (2001). *Skyscraper rivals*, Princeton Architectural Press, New York.

ASCE. (2001). ''ASCE designates Empire State Building as a Civil Engineering Monument of the Millennium.'' *ASCE News.*, 26(8), 1.

Berlow, L. H. (1998). *The reference guide to famous landmarks of the world*, Oryx Press, Phoenix.

Billington, D. P. (1983). *The tower and the bridge*, Basic Books, New York.

Billington, D. P. (1996). *The innovators*, Wiley, New York.

Cempel, C. (1991). *Vibroacoustical condition monitoring*, Ellis Horwood, Chichester, England.

Chen, W. F., ed. (1997). *Handbook of structural engineering*, CRC Press, Boca Raton, Fla.

Collins, A. R., ed. (1983). *Structural engineering: Two centuries of British achievements*, Institution of Structural Engineers Anniversary Publication, London.

Cross, H. (1952). *Engineers and ivory towers*, McGraw-Hill, New York.

ENR. (1999). ''125 top projects,'' *ENR*, 〈http://www.enr.com/new/125topproj2.asp〉.

Gaylord, E. H., and Gaylord, C. N., eds. (1968). *Structural engineering handbook*, McGraw-Hill, New York.

Gaylord, E. H., and Gaylord, C. N., eds. (1990). *Structural engineering handbook*, 3rd Ed., McGraw-Hill, New York.

Girvin, H. F. (1948). *A historical appraisal of mechanics*, International Textbook Company, Scranton, Pa.

Goldberger, P. (1981). *The skyscraper*, Alfred A. Knopf, New York.

Grigg, N. S., Criswell, M. E., Fontane, D. G., and Siller, T. J. (2001). *Civil engineering practice in the twenty-first century: Knowledge and skills for design and management*, ASCE, New York.

Housner, G. W. et al. (1997). ''Structural control: Past, present, and future,'' special issue, *J. Eng. Mech.*, 123(9), 897–971.

Husband, J., and Harby, W. (1947). *Structural engineering*, 5th Ed., Longman's, New York.

Jackson, D. C., ed. (1997). *Dams*, *studies in the history of civil engineering*, Vol. 4, Ashgate Vriorium, Brookfield, Mass.

Kirkham, J. E. (1914). *Structural engineering*, Myron C. Clark Publishing Company, Chicago.

Kirkham, J. E. (1933). *Structural engineering*, McGraw-Hill, New York.

Nakamura, T., ed. (1988). *American high-rise buildings*, Japan Architect Company, Tokyo.

Natke, H. G., and Cempel, C. (1997). *Model-aided diagnosis of mechanical systems—fundamentals, detection, localization, and assessment*, Springer, New York.

Parker, H. E., ed. in chief. (1931). *Kidder-Parker architects' and builders' handbook*, 18th Ed. (1st Ed. 1884), Wiley, New York.

Reinschmidt, K. F. (1991). ''Integration of engineering design and construction.'' *J. Constr. Eng. Manage.*, 117(4), 756–772.

Roësset, J. M., and Yao, J. T. P. (1988). ''Civil engineering needs in the 21st century,'' *J. Prof. Issues Eng.*, 114(3), 248–255.

Roësset, J. M., and Yao, J. T. P. (2000). ''Roles of civil engineering faculty,'' *J. Prof. Issues Eng. Educ. Pract.*, 126(1), 8–15.

Sheiry, E. S. (1938). *Elements of structural engineering*, International Textbook Company, Scranton, Pa.

Smith, N. (1975). *Man and water*, Peter Davies, London.

Southworth, M., and Southworth, S. (1984). *A.I.A. guide to Boston*, Boston Society of Architects, Boston.

Stoller, E. (2000). *The John Hancock Center*, Princeton Architectural Press, New York.

Westerbrook, R. (1984). *Structural engineering design in practice*, Construction, New York.

Wong, F. S., Chou, K. C., and Yao, J. T. P. (1999). ''Chapter 6: Civil engineering including earthquake engineering.'' *Practical applications of fuzzy technologies*, H.-J. Zimmermann, ed., Kluwer Academic, Boston, 207–245.

Wong, F. S., and Yao, J. T. P. (2001). ''Health monitoring and structural reliability as a value chain.'' *Comput.-Aided Civ. Infrastruct. Eng.* 16, 71–78.

Yen, J., and Langari, R. (1999). *Fuzzy logic*, Prentice-Hall, Upper Saddle River, N.J.

Zadeh, L. A. (1965). ''Fuzzy sets.'' *Information Control*, 8, 338–353.

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