Probability-Based Load Criteria for Structural Design

Structural codes and standards provide the foundation of good engineering practice and a framework for addressing safety and serviceability issues in structural design. They identify natural and man-made forces that must be considered, define magnitudes of these forces for design, and prescribe methods for determining structural resistance to these forces. The framers of these documents on which the structural engineer places so much reliance must address the question: "How safe is safe enough?" on behalf of society as a whole. Code development is a grave responsibility and, for the most part, has clearly been done well since failures of constructed facilities are rare. On the other hand, such failures, when they do occur, are highly visible and their consequences are severe in human and economic terms for all involved. This publication, *Development of a Probability-based Load Criterion for American National Standard A58* [1], marked a major advance in the approach to formulating such codes.

At the root of the structural safety problem is the uncertain nature of the man-made and environmental forces that act on structures, of material strengths, and of structural analysis procedures that, even in this computer age, are no more than models of reality. The natural consequence of uncertainty is risk. Structural engineering, as applied to civil construction and in contrast to other engineering fields, relies heavily on analysis and computation rather than on testing because of the scale and uniqueness of typical civil projects in both public and private sectors. Structural codes are linked to computational methods of safety assessment, and their primary purpose is to manage risk and maintain safety of buildings, bridges and other facilities at socially acceptable levels.

Until the 1960s, the safety criteria in structural codes were based on allowable stress principles. The structural system being designed was analyzed under the assumption that it behaved elastically (the fact that structures seldom behave elastically to failure was disregarded). Uncertainties were addressed by requiring that the computed stresses did not exceed a limiting stress (at yielding, rupture, instability) divided by a factor of safety. These factors of safety were selected subjectively; one might, for example, identify the load acting on a structure and then design the structure so that the elastic stresses due to that load remain below 60 % of the stress at yield (implying a factor of safety of 5/3). Of course, no one knew what the risk of failure was for such a structure. The factor of safety of 5/3 simply represented a value judgment on the part of the standard-writers, based on past experience. During the past century, with the advent of formal structural calculations, the trend in the factor of safety generally has been downward.

This judgmental approach to safety works well as long as the technology being dealt with is stable or evolves slowly and there is opportunity to learn from experience in the standard development process. Occasionally, of course, engineers become overconfident, ignorance catches up, or construction practice overreaches the state of the art; then failures occur. More than in most other engineering disciplines, the profession of structural engineering seems to have progressed by learning from its mistakes. To the discomfort of many structural engineers, this learning process usually takes place in the public arena.

During the late 1960s and 1970s, a number of natural disasters occurred worldwide that caused extensive loss of life and property damage and focused the attention of the structural engineering community and the public on the need to advance building practices for disaster mitigation. Professional staff from the Structures Division in the Center for Building Technology (CBT) of the National Bureau of Standards were involved in a number of the damage surveys and failure investigations that followed these disasters. Among the more notable of these were the structural failure investigations that followed the San Fernando, California, Earthquake of 1971, the Managua, Nicaragua, Earthquake of 1972, and the Miyagi-ken-oki Earthquake of 1978; the investigation of snow and rain load conditions prior to the collapse of the Hartford Civic Arena roof in 1978; and the evaluations of wind loads, wind load effects, and building performance following Hurricane Camille on the Gulf Coast (1969) and Cyclone Tracy in Darwin, Australia (1974). These and other investigations of building performance revealed a number of deficiencies in the provisions for structural safety appearing in the codes of practice of the time, and emphasized the need for improvements in design for natural hazards.

Fig. 1. Collapse of the Psychiatric Unit of the Olive View Medical Hospital (San Fernando Earthquake of February 9, 1971).

Fig. 2. Collapse of the Hartford Civic Arena roof following a winter storm with snow and freezing rain (January 18, 1978).

Fig. 3. Damage to buildings due to hurricane winds (Hurricane Camille, August 17, 1969).

The late 1960s also witnessed the beginnings of the move toward a new philosophy of structural design in the United States, Canada, and Western Europe. The shortcomings of allowable stress design were recognized in many quarters, and a search was underway for more rational approaches to distinguish between various conditions (termed limit states) that affect building performance, to ensure safety under rare but high-hazard conditions, and to maintain function under day-to-day conditions. Concurrently, the new field of structural reliability was developing around the notion that many of the uncertainties in loads and strengths could be modeled probabilistically. Advances were being made in first-order reliability analysis, stochastic load modeling and supporting statistical databases. Several probabilistic code formats were suggested [2], including an early version of Load and Resistance Factor Design (LRFD) for steel buildings [5]. However, these early proposals were relatively narrow in scope and dealt with single construction technologies in isolation from one another. With this lack of coordination, there was a risk that as different standard-writing groups moved toward probability-based limit states design, each would develop load requirements independently, and that these load requirements would be mutually incompatible in structural engineering practice, where construction technologies usually are mixed. Leaders of the profession agreed that structural load requirements must be independent of construction technology to facilitate design with different construction materials.

At that time, the Secretariat for American National Standard Committee A58 on Minimum Design Loads for Buildings and Other Structures was administered in the Structures Division of the Center for Building Technology. The antecedents at NBS for this standard dated back to 1924, when the Building and Materials Division published a report under the auspices of the Department of Commerce Building Code Committee on Minimum Live Loads. Research on probabilistic methods in structural codes was a central thrust in the CBT throughout the 1970s, with the work of Bruce Ellingwood in probabilistic analysis of live and snow loads [3,7] and load combinations for reinforced concrete design [4], and of Simiu and Marshall in wind loads [6]. This work stood at the intersection of research and practice, and its products were internationally recognized in both research and professional communities. Various standard-writing groups in the United States agreed that the A58 Standard was the logical place for material-independent load criteria to appear.

In 1978, Ellingwood accepted the challenge of leading the development of a set of common probability-based load requirements for limit states design that would be compatible with all common construction technologies. He arranged for three other leaders in reliability-based structural codes, T. V. Galambos, J. G. MacGregor, and C. A. Cornell, to join him at NBS during the summer of 1979 to develop a set of load requirements using advanced structural reliability analysis methods and statistical databases. The objectives of this joint effort were to: (1) recommend a set of load factors and load combinations for inclusion in the A58 Standard that would be appropriate for all types of building construction (e.g., structural steel, reinforced and prestressed concrete, engineered wood, masonry, cold-formed steel and aluminum); and (2) provide a methodology for various material specification groups to select resistance criteria consistent with the A58 load requirements and their own specific performance objectives.

The product of this collaboration is NBS Special Publication 577, *Development of a Probability-based Load Criterion for American National Standard A58* [1], which was published in June 1980. Subsequent developmental work on probability-based codes in the United States in such diverse applications as buildings, bridges, offshore structures, navigation facilities, and nuclear power plants in the intervening two decades can all be traced back to this one seminal document.

The basic notions underlying the probability-based load requirements and resistance criteria contained in NBS Special Publication 577 are relatively simple. Structural failure occurs if the resistance, R, is less than the structural action, Q, due to the applied loads. If R and Q are modeled as random variables, the limit state (or failure) probability can be computed as the probability that R is less than Q [1]. Much of the early history of structural reliability revolved around difficulties in performing this computation. If a desired or target limit state probability for design can be established (by assessing historically acceptable designs, professional consensus, or legislative or regulatory fiat), then structural design should strive to achieve solutions yielding limit state probabilities close to that target value. Design solutions with higher limit state probabilities are unacceptable from a safety point of view; designs with lower probabilities are needlessly expensive.

In probability-based limit states design, the structural reliability formulation is presented in such a way as to make it practical for design by engineers who may not be familiar with reliability concepts or have access to the necessary statistical data. Structural safety requires that

$$\text{Required strength} < \text{Design strength} \qquad (1)$$

where the required strength is determined from structural analysis utilizing the specified design loads, and the design strength is calculated from principles of structural mechanics with specified material strengths and structural element dimensions. With the performance requirement that the member reliability should exceed a target reliability, Eq. (1) can be restated for practical design purposes as

$$\Sigma \gamma_i Q_i < \phi R_n \qquad (2)$$

In this equation, R_n is the nominal strength corresponding to the limit state of interest and Q_i is the nominal load. These strengths and loads traditionally have been provided in codes and standards, and most engineers are familiar with them. The factors ϕ and γ_i are resistance and load factors that reflect (1) uncertainty in strength and load, and (2) consequence of failure, reflected in the target reliability measure. The right hand side of Eq. (2) is the purview of each material specification (steel, concrete, engineered wood, etc.). The left-hand side is defined for all construction materials by American National Standard A58, Building Code Requirements for Minimum Design Loads for Buildings and Other Structures [8], the national load standard referenced by the Model Codes and other regulatory documents in the United States.

The probability-based load criteria in NBS Special Publication 577 [1] were first implemented through the voluntary consensus process in the 1982 edition of American National Standard A58. They have appeared in all editions of that Standard (the standard has been published as American Society of Civil Engineers (ASCE) Standard 7 since 1985) since then, most recently ASCE Standard 7-98, and have remained essentially unchanged since 1982. They have been adopted by reference in all standards and specifications for limit states design in the United States, including the American Institute of Steel Construction's LRFD Specification for Steel Structures (1986, 1994 and 2000 editions), ASCE Standard 16-95 on LRFD for Engineered Wood Construction, and American Concrete Institute Standard 318-96 (Appendix B). They also have been adopted in the International Building Code 2000, the new single model code in the United States. In retrospect, the move toward probability-based limit states design may seem like a small step, but in fact it was not. It required a thorough re-examination of the philosophical and technical underpinnings of the current bases for structural design, as well as the development of supporting statistical databases. Much of this supporting research is still utilized in code development and improvement activities worldwide. It has become the basis for structural design as it is now practiced by professional engineers in the United States.

It is unlikely that these probability-based load criteria efforts would have been completed and implemented in professional practice successfully had they been managed by any other than CBT/NBS.

CBT was viewed as representing the structural engineering community at large rather than any one special interest group. The load criteria were completed successfully because they were developed by engineering researchers who were familiar, first of all, with the structural engineering issues involved, as well as with the reliability tools necessary for analyzing uncertainty and safety.

In a more general sense, the load criteria that were developed in this study and reported in NBS Special Publication 577 have had a profound influence on structural codes used worldwide in design of buildings and other structures. The approach taken—developing supporting statistical databases, calibrating to existing practice, and calculating load and resistance factors to achieve desired reliability levels—was followed in a subsequent National Cooperative Highway Research Program study to develop limit states design procedures for highway bridges, now published as an American Association of State Highway and Transportation Officials standard. The National Building Code of Canada will adopt a similar approach to combining loads in its 2000 edition. Standard development organizations in other countries, including Australia, New Zealand, South Africa, Japan, and Western Europe (through the Eurocodes) have adopted similar load combination requirements for structural design. The NBS Special Publication 577 load combinations have been recognized internationally as the first developed using modern probability-based load combination analysis techniques. They have stood the test of time, and only minor changes have been required as a result of additional research and advances in other areas of structural load modeling during the past two decades.

The probabilistic approach to structural safety embodied in this groundbreaking activity continues to resonate in the structural engineering community. The aftermath of natural and man-made disasters during the past two decades, rapid evolution of design and construction methods, introduction of new technologies, and heightened expectations on the part of the public, all have made judgmental approaches to ensuring safety of the built environment increasingly difficult to defend. The traditional practice of setting safety factors and revising codes based solely on experience does not work in this environment, where such trial and error approaches to managing uncertainty and safety may have unacceptable consequences. In an era in which standards for public safety are set in an increasingly public forum, more systematic and quantitative approaches to engineering for public safety are essential. The probabilistic approach addresses this need, and in the past two decades has been widely accepted worldwide as a new paradigm, for design of new structures and evaluation of existing facilities. NBS Special Publication 577 was the path-breaking study in this area.

Bruce Ellingwood held the position of Research Structural Engineer in the Structures Division of the Center for Building Technology, NBS, at the time this work was conducted. Ellingwood was responsible for administering the Secretariat of the A58 Committee, and provided the technical leadership for the load combination development. He left NBS in 1986 to accept an academic appointment at Johns Hopkins University, where he chaired the Department of Civil Engineering from 1990 to 1997. He currently holds the Willard and Lillian Hackerman Chair in Civil Engineering, and continues to be actively involved in a number of standard-writing activities. Theodore V. Galambos was Professor at Washington University, and widely recognized as the father of LRFD for steel structures. He accepted a position at the University of Minnesota in 1981, from which he retired in 1997. He maintains an active schedule, particularly with the American Institute of Steel Construction. Professor James G. MacGregor recently retired from the University of Alberta, Canada. He has been a leading figure in both the American Concrete Institute and the Canadian Standards Association for three decades and continues his involvement with concrete standards activities in Canada and the United States. C. Allin Cornell was Professor at MIT, and had proposed one of the early probability-based structural codes in the late 1960s. In recent years as Professor at Stanford University, his research and consulting activities have involved risk analysis of offshore structures and other critical facilities and earthquake-resistant design of building structures.

A number of archival publications were prepared from the NBS study. Most notably, references [9] and [10] were awarded the American Society of Civil Engineers' Norman Medal in 1983. The Norman Medal is the oldest and most prestigious of ASCE's prizes, and is awarded annually to the paper(s) that the ASCE Awards Committee and the Board of Directors judge most significant and meritorious for the advancement of the civil engineering profession. Reference [11] was an invited contribution to the inaugural issue of the *Journal of Structural Safety,* which in the intervening period has become the leading international journal in the field of structural reliability and integrated risk assessment.

Prepared by Bruce R. Ellingwood.

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