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Contributions of the Reliability Method to Structural Safety

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Civil engineers have always been aware of the uncertainties (natural and man-made) that they must negotiate with in their practice of planning, design, analysis and construction. In particular, structural engineers have dealt with this problem by making allowances for them through safety factors. While the safety factor approach to structural engineering has worked remarkably well in practice, it is not entirely without problems. One of these problems stems from the fact that the process to specify key design parameters such as design loads and allowable stresses is based primarily on collective professional judgment of a subjective nature. Among other things, this makes it rather difficult to evaluate structural safety in quantitative terms. Obviously, the safety factor itself can be used for comparison purposes. Such a comparison, however, makes sense only in extremely simple situations.

In civil engineering, particularly in structural engineering, probabilistic concepts were first introduced in the 1940's in an attempt to develop a quantitative measure of structural safety. Over the last four decades or so, they gradually evolved into what is currently known as the structural reliability analysis method. More recently, some of the existing design codes were reexamined and modified on the basis of these probabilistic concepts, as exemplified by the introduction of reliability-based load and resistance factor design (LRFD) codes in various countries.

The emphasis of structural reliability analysis has been placed on the estimation of structural safety in terms of the probability that a structure subjected to loads and other adverse environments will perform its specified mission without failure. In the classical approach, this probability is defined as the structural reliability. It is classical in the sense that the reliability is estimated under the following assumptions: All possible failure mechanisms under the projected operational conditions and all the pertinent parameters involved are known and at the same time, the probabilistic characteristics of all these parameters are also known. Indeed, the theory of reliability analysis in this context is often referred to as the full-distribution theory. The full-distribution theory, however, is unrealistic not only because of its requirements for a substantial database, but also because of the enormous numerical chore that could entail. Nevertheless, it permits a sensitivity analysis with respect to the specific probability models assumed for design variables and therefore provides an analytical base for the engineering application of reliability concepts.

At an early stage of the development of reliability analysis methods, the necessity to examine the level of confidence of such a reliability estimate was recognized only implicitly; it was usually implied that the highest level of confidence could be obtained by taking advantage of all available data and by making use of state-of-the-art probabilistic and statistical techniques. More recently, the task of establishing such a confidence level in terms of a confidence interval became more of a routine, however crudely that might have been done. Reinforcing a reliability estimate with a confidence statement represents active recognition of uncertainties other than those arising from randomness. Reliability theories that recognize this are no longer classical.

In estimating the reliability and associated confidence level, we must keep in mind that the degree of analytical sophistication should be consistent not only with the quality and quantity of the pertinent information available but also with the current analytical and other capabilities of the profession in the following areas: (a) structural and stress analysis - linear, nonlinear, static and dynamic; (b) failure analysis for various modes of structural unserviceability and collapse; (c) environmental and load analysis; (d) durability analysis considering the effects of in-service inspections and repairs; and (e) quality assurance procedures covering the entire spectrum of planning, design, analysis, construction and maintenance. It is precisely in this context that we often recognize the results of first-order and second-moment analyses as as credible as those obtained by applying the full distribution theory.

Reliability analysis methodology has made and can further make genuine contributions toward enhancing the structural safety and integrity of constructed facilities. One might add that these contributions have so far been made primarily through such conferences as ICOSSAR and ICASP. Indeed, through these contributions, we have made it possible to (a) establish the correlation between structural safety and design parameters such as safety factors, stress allowables and inspection periods, (b) achieve balanced designs among structures with differing degrees of importance, (c) allocate the desired reliability performance to each component within an individual structure, (d) identify the additional information needed to upgrade the confidence of reliability estimates, and (e) develop a consistent and systematic procedure in which a safety analysis can be made logically. In accomplishing all these, the sensible and well-disciplined use of subjective engineering judgment in the Bayesian framework is considered beneficial in bringing about the compromise required and even desired for a reasonable blending between analytical rigor and availability of pertinent information.

Recently, reliability analysis has become an integral part of the risk assessment and management procedures for a wide variety of structures including such risk-sensitive structural systems as nuclear power plants. This demonstrates an added dimension of the usefulness of reliability concepts beyond their applicability to traditional engineering structures. Since the perception of risk stems from the recognition of the possible occurrence of undesirable events with grave consequences, a risk assessment and management procedure is usually built around a reliability methodology with one more analytical component, i.e., consequence analysis, integrated into it. Parenthetically, one might add this is precisely where the cost-effectiveness issue should be addressed. The acceptable level of risk is correlated to acceptable reliability levels of the components of the system for which the risk is to be evaluated and managed. In this sense, the difficulty in arriving at a consensus on the acceptable level of risk, translates into the same difficulty in determining acceptable reliability levels, although the latter can be somewhat lessened by means of calibration at least for traditional civil engineering structures.

Having made these observations, it is appropriate to point out a number of major issues that have not really been resolved in the structural reliability analysis methodology. First, it is by no means easy to obtain a consensus on the target levels of reliability even for traditional civil engineering structures. For example, when we attempt to develop the Load and Resistance Factor Design approach, a question still remains as to how we can specify target reliability levels for various load combinations. This specific issue is the main theme of this author's preliminary report for this symposium. Second, the reliability analysis methodology developed so far presumes that we can somehow formulate everything in terms of probability. Obviously, not everything is always probabilistic. In this respect, fuzzy set concepts are advocated by some to provide an alternative interpretation of uncertainty. Third, even if we somehow agree that we can interpret everything as probabilistic, the casual fashion in which the source of the variability is often divided into that arising from "randomness" and that from "uncertainty" could give the false impression that such a division is easy, while it certainly is not. Fourth, we often get carried away in constructing the simplest possible analytical model out of a structure for the sake of wider applicability of reliability analysis methodology. The case in point is severely nonlinear structural behavior that must be dealt with for the analysis of structural integrity against collapse, say, under earthquake acceleration. A reliability analysis using too simplistic models in such a situation will not only produce a grossly wrong answer but also cost us credibility in such a way that even those credible structural reliability analysis results we endeavored to derive on the basis of carefully constructed models will be placed under suspicion.

Two more items should be added to this list. Fifth, the confidence interval we evaluate for the reliability estimate is often too wide to be useful. Sixth, so far the reliability methodology has been unable to properly incorporate human factors, managerial as well as technical. This is particularly important in view of such unfortunate recent events as the Three Mile Island accident, the Chernobyl accident, the Challenger explosion and the Japan Airlines' crash last year. At least for these accidents, managerial factors, rather than technical factors, appear to be more crucially responsible. In many cases like these, however, engineers are also guilty at least to the extent that they have not asserted themselves strongly enough to change managerial decisions or improve managerial procedures, on the basis of their technical knowledge.

In the remainder of this paper, the author wishes to comment on the issue of quality assurance, since it is part of the theme of this symposium. The issue is particularly important to the medical and civil engineering profession, and, to a lesser extent, for that of architects, although the implied commonology may appear farfetched. The medical profession deals primarily with the physical nature of human bodies, whereas the civil engineering profession with mother nature itself. In either case, nature challenges the profession with its unpredictability. Also common to these professions is the fact (well known even before the current craze for often frivolous liability suits lodged against them particularly in the United States) that they are both highly vulnerable to poor judgment, incompetence and mismanagement. In spite of such a similarity, we tend to accept the following statement which suggests the different ways in which each profession handles its affairs under distress. "Doctors bury their mistakes, architects cover them with ivy, engineers write long reports that never see the light of day, and contractors call their lawyers and notify their insurance carriers." Even though doctors nowadays find themselves in a liability bind more often than before, the statement requires a modification which is even worse for engineers. It now reads: "Doctors bury their mistakes, architects pass the buck to engineers, contractors declare bankruptcy, and engineers write long report that will be used against them in courts of law."

The issue of quality assurance has always been at the heart of civil engineering, particularly of structural engineering. However, the recent concern for potential liability problems has made the profession even more acutely aware of the importance of quality assurance. These days, quite extensive efforts are probably needed to assure the delivery of high-quality products. This is particularly so because the profession must currently operate in an environment where excessive competition, tighter fiscal maneuverability, inferior workmanship, and a less productive labor force are likely to prevail. Moreover, the profession at large appears to command less prestige and fewer financial rewards than other professional groups, and as a consequence, suffer from a decline in the quality of the human resources it must depend on. These contemporary non-technical issues certainly influence the quality of the overall performance of the profession, of which the technical quality assurance issue is possibly a small part. Therefore, the profession, and in particular, its leadership are well advised to address themselves to these non-technical issues and map out strategies for improving the environment in which they must survive and prosper.