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Safety, Economy and Rationality in Structural Design

Sécurité, économie et rationalité dans l'étude des ouvrages

Sicherheit, Wirtschaftlichkeit und Aufwand in der Tragwerksberechnung

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1. Introduction

Present methods of structural design seem to provide adequate service to society. The techniques of producing safe designs have evolved gradually; once acceptable levels of safety have been reached, further moderate progress has occasionally been made in economy. In the accretion of new data, however, it often happens that new information evidently contradicts previous assumptions, and there arises from time to time considerable confusion about the rationality of design procedures.

Such conflicts, and the realization that the design goals of maximum safety and minimum cost in themselves are contradictory, have led several investigators, notably JOHNSON [1] and FREUDENTHAL [2] to examine the problem of formulating the design process so that known allowances may be made for risk and uncertainty in design. These studies are preliminary in nature; TURKSTRA [3] has demonstrated the impossibility of formulating a statistical approach to structural design on an empirical basis without including engineering judgment, because of the nature of the assumptions underlying statistics and the limited extent of the factual information available as a basis for design. (In this paper "design" is used in the narrow sense, as meaning the proportioning and dimensioning of members.) Although TURKSTRA [3] developed a more realistic design model, his study has not provided an improved practical system of design. It is the purpose of this paper to suggest practical means for the improvement of design in the form of natural extensions of the present codes. The proposals provide for a planned, continuous search for design loads that would reconcile the requirements of safety and economy.

2. Current Design Practice

The irrationality of the traditional design method using allowable stresses has been studied by many writers [1, 2, 3, 4]. The extent of the inconsistencies in the present-day design may be judged from Table I: comparable erratic

Table I. Live Loads for Different Uses in Various Codes (psf)

Code Authority	Church Fixed Seats	Private Office Upper Floor	Private Dwelling	School Classroom
Australia [5]	40	50	30	60
Britain [6]	60	50	30	60
Canada [7]	60	50	40	60
France [8]	103	41	36	72
India [9]	80	50	40	80
Netherlands [10]	82.5	51.5	31	41
New Zealand [11]	80	60	30	60
U.S.A. [12]	60	80	40	40

variations may be seen in tabulations of wind pressure coefficients, coefficients for moments in continuous beams and in other arbitrarily determined design parameters. From such data the annual economic loss incurred by society may be estimated: for Canada alone, magnitudes of the order of \$ 10^5 to \$ 10^7 per annum have been suggested. It may be concluded that although the problem of rational structural design is one of considerable economic importance, it may not be sufficiently important to warrant the complete collection of data necessary to obtain a scientific solution. It seems reasonable to suggest, however, that in the long run codes may be "improved" through the realization of reductions in design-loads from present levels of the order of 10 to 50 per cent.

Criticism of conventional design techniques stems from the realization that there is little factual basis for the design loads assumed; and that the maximum stresses and maximum deflections under the hypothetical design loads are, at best, very coarse criteria for "loss behaviour" of a structure. The methods are based on an extensive physical idealization; computed stresses bear no resemblance to the stresses actually occurring in a structure [13]. Similarly, the allowable deflection is rarely a functional requirement but is only a coarse idealization of a psycho-physiological measure.

3. Statistical Design

The direct statistical approach seeks the minimization of total cost including expected cost of failure, or in a more generalized form, maximization of an unspecified utility function. Not only is this approach severely limited by a lack of information [2, 14, 15], but there is also reason for some concern over its logical foundations [3, 16, 17].

Some writers [18] have set themselves the more modest goal, by means of the probability of failure concept, to improve the design process by modification within the bounds of the design load, safety factor, allowable response scheme. It is not difficult to demonstrate the inadequacy of such approaches by suitable examples.

A comprehensive design theory holds two elements that as yet have no rational solution, namely that of interpersonal utility and that of decision making under uncertainty [19]. Also, structural design does not result in populations [16] to which a probability can be attached in the relative frequency sense, but the potency of this concept is nevertheless required if the design method is to be termed rational in the sense of VON NEUMANN [19].

This latter objection unfortunately also applies to the development of a compromise theory in which the design criterion is a limiting value of the probability of failure or unserviceability [2, 14, 20, 21]. By circumventing the problem of utility these analyses centering around the probability of failure appear to have approached a more practical stage of development. But they are also restricted by an almost complete lack of information regarding load and resistance distributions, without which no true probability of failure can be obtained.

4. Structural Design as a Social System

While these studies have illuminated the complexity of the problem of formulating the design process for optimization it is now quite apparent that they, unfortunately, will not soon be of much direct use in practical design. One must look in other directions for improvement over present design procedures.

Improvement may be expected to arise from a broadening of perspective in which design is exposed as one only of the devices whereby the goals of modern society are pursued. Present-day design is primarily an individual process in which engineers "play it safe" and design according to codes to satisfy the designer's own immediate interests but not necessarily the interests of the owner, or of society as a whole. For example, the immediate problem is that of designing a particular structure to serve a given function. The risk involved in this problem is associated with variables for which statistics are available, for instance snow loads in a location where snow loads already have been extensively studied. The uncertainty involved in this problem is associated with variables to which an empirical probability cannot be assigned, for instance the maximum wind suction in an area where a tornado has never occurred but is still thought to be a likely possibility. The designer may reasonably be expected to choose amongst the variables he can control to produce a design that will stand as being of the best value to the client.

In recognition of the uncertainties involved the engineer therefore faces a secondary design problem: should the client's money be spent on research to reduce the uncertainty or should the design be made according to a code, through which payment in extra material is a penalty for ignorance? The structural engineer usually has no choice now but to design by the existing code, although the designer may himself recognize that his design is unnecessarily conservative. Thus we have the schizophrenic and costly result that it is optimal to overdesign. Structural design is in fact a realization of a system for which optimization of the whole is far from achieved through sub-system optimization [1]).

Although the structural designer is ostensibly a responsible competent professional the decision problem is effectively relegated to the code writing authorities. The necessary decisions must be made as choices between various design loads, allowable stresses, etc. The simplicity of the engineer's problem, namely that of maximizing the client's utility, has thus become complicated: a code clearly should be optimal in the interests in society as a whole. The decision problem has now reached a political level in which the common goals of society must be assessed through answers to questions such as: is too much money being spent on structural safety as compared to fire safety?; would it be more reasonable to expend available funds towards increasing the traffic safety of a highway system by reducing the structural safety of the bridges in that highway system?

Although a problem of political proportions the goals of structural design are not a matter of public concern. The reasons for this must be sought in the fact that the public sees structural safety as a matter of course, and that the well-being of an individual depends on the safety of a large number of structures whereas his profits or losses depend only upon a few structural designs. The resolution of the problem lies with the code writing authorities. In view of the fact that most structural failures are attributed to bad workmanship or other human error, which presumably would occur regardless of the level of design loads, there is no ground for countering the postulate that present design loads are at least 25 per cent too high overall. No design load can be said to be verified as optimum until it is so low that the failures associated with it are on the verge of becoming a public concern. Present design load levels are so high that the problem has been concealed from the public.

Associated with this circumstance is a drain of public funds into unnecessary structural safety of such proportions that the code writing bodies cannot claim as responsible professional engineers to act in the interests of the society which employs them. The problem becomes more complicated because public values themselves change. The quality of workmanship which was considered essential in an earlier age when the individual's rate of acquisition was low is

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[1]) Social systems in which the aggregate of the actions of a number of individuals is undesirable for the interests of the whole are by no means uncommon [19]. Suitable coercive powers are usually established, often in the form of government control, to alter such systems (civil and criminal law). Other solutions are possible (the "soil bank"), or are still being sought (multilateral disarmament).

nowadays a useless luxury. Thus, longevity in automotive parts is associated with undesirable and unnecessary expense in their production in a society where, for other reasons, automobiles have a useful service life of less than a decade. Modern building structures, especially in North America, reflect the understanding that a building is likely to have outlived its usefulness in less than fifty years, and is then ready for demolition as a nuisance and deterrent to further progress.

As a result of the considerations outlined above, although certainly not often reflecting a conscious view of the social aspects of design, code writing authorities have on the whole tended to reduce the safety margin over the past several decades. Now and then a partial increase in the safety margin has been introduced as a result of unforeseen failures. Usually the goals of the code writing authority do not coincide with those of society and the codes often remain unnecessarily conservative until other forces, such as sharpening competition between competitive materials of construction, lead to reductions in the safety margin.

Perhaps the most important characteristic of a profession is the commitment to make significant decisions. The introduction of codes of design clearly represents an attempt at reducing engineering design in many important respects to a routine procedure to be carried out by persons of limited competence and experience. A fundamental engineering decision, namely that of determining the margin of safety appropriate to a given structure is put in the hands of a few remote individuals — the code-writing authority. The result is an often absurd commitment to over-design imposed upon experienced engineers. It would seem to be of paramount importance for the economic welfare of society as a whole that a design system be established which allows ample freedom to the competent designer while providing at the same time guidance for the less experienced designer.

5. A Proposal for Code Improvement

The proposal consists in the establishment of systematic reductions in design loads coupled with an improved system of monitoring structural performance. While it is clear that present design loads are unduly conservative, reductions must be made cautiously because of the complex nature of the existing design process, in which individual components may have significances that are not superficially evident.

Before suitable final levels of safety would be reached, each cycle of review would generate a new code from the previous one. If the time rate of reduction is too large, the sequence of codes may not converge aperiodically. On the other hand if the rate is too low, the result is a loss of economy. No optimal decrement may be calculated, since the magnitude of the decrement depends upon much the same factors as determine the load distributions. While any reasonable decrements would necessarily contribute to the improvement desired, decrements may be based upon studies of past experiences in reducing design loads. Otherwise, an annual relative reduction in live load of a tenth of the standard deviation might be reasonable.

This proposed system for the evolution of design codes could be implemented in either of two alternative fashions. It would of course be a simple matter arbitrarily to reduce design live loads as suggested from time to time in the various codes. It would be more attractive, however, to establish dual-level design loads in the codes representing the values currently established through the proposed process, and the values, say, of five years before. The larger values would be clearly conservative, and the lower values could be opted for by the designer depending upon his interpretation of the client's utility. It is seen that such a dual level code would return to the designer some important discretionary power.

While, at first sight, the proposal made here may seem very radical, it may fairly be held to represent the best pattern for progress in view of the total problem. With the adoption of such a system for code improvement, it clearly would be appropriate to accelerate the already recognizable trend in codes to encourage designs in which the presence of ductility would tend to avoid catastrophic failure [22]. The monitoring of experience under a regime such as that proposed could be carried out effectively in any country at modest cost by such national agencies as building research organizations. Such a monitoring process would enable appropriate code authotities to halt the reduction of design loads before "failure" rates reached a level sufficient to alarm the public.

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Summary

The role of the safety concept in structural design is analysed from the viewpoint of rational design as a decision problem under uncertainty and risk. Fundamental systematic weaknesses are indicated in both classical and probabilistic design. A new approach is suggested which will generate an iterative solution to the problem of rational design. A design process, in which the requirements of safety and economy are consistently reconciled, can be developed through continuous modification of design loads and strength parameters in current codes.

Résumé

Les auteurs analysent le rôle de la notion de sécurité dans l'étude des ouvrages en la considérant, du point de vue d'un principe de calcul rationnel, comme un problème de décision à prendre dans l'incertitude et le risque. Ils signalent les faiblesses fondamentales systématiques tant dans la conception

classique que dans la conception probabiliste. Ils proposent de prendre une nouvelle attitude, dynamique, en ce qui concerne le problème de l'étude rationnelle. Il est possible d'établir un principe de calcul, conciliant harmonieusement les exigences de la sécurité et de l'économie, en prévoyant une modification permanente des hypothèses de charge et des paramètres de résistance définis par les normes en vigueur.

Zusammenfassung

Der Sicherheitsbegriff in der Tragwerksberechnung wird, vom Standpunkt einer vernünftigen Bemessung aus, als Entschlußproblem zwischen Ungewißheit und Risiko gedeutet. Hiebei werden, sowohl in der klassischen als auch in der statistischen Betrachtungsweise, grundsätzliche Schwächen aufgedeckt. Die Verfasser unterbreiten einen neuen Vorschlag, welcher zu einer schrittweisen Annäherung an eine wirklichkeitsgetreuere Bemessung führt. Dieses Bemessungsverfahren will die Bedürfnisse der Sicherheit und Wirtschaftlichkeit durch eine laufende Anpassung der normenmäßigen Belastungs- und Festigkeitswerte befriedigen.