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Safety concepts, with particular emphasis on reinforced and prestressed concrete

Concepts de sécurité dans le domaine du béton armé et du béton précontraint

Sicherheitsbetrachtungen mit besonderer Berücksichtigung des Stahl- und Spannbetons

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INTRODUCTION

The civil and structural engineering professions have always been concerned with the safety of the projects they were creating. Originally, the safety concept was embodied in the experience and intuition of the designer; this was a period in which experimental design was practised and, although many failures occurred, they led to an improved understanding of structural behaviour which, in turn, ensured an increased safety in subsequent projects. Following this period, and with the introduction of the theory of elasticity, the safety concept began to be formally expressed in the, so-called, factor of safety and the associated permissible stresses in materials. This period could, perhaps unkindly, be called the "little learning is a dangerous thing" period since a limited knowledge of material properties and loads was associated with an assumed improvement in the understanding of structural behaviour. It was certainly a productive and creative period and, apparently, gave a satisfactory degree of safety from the structural viewpoint; the only difficulty was that no one knew how much ! Whatever degree of safety was present then began to be reduced by increases in permissible stresses, these being justified by improvements in analysis, quality control and construction processes. At this stage, it began to be appreciated that the ultimate strength of members and structures could be utilized in a somewhat different concept of safety, namely that associated with load factors. This approach to safety was associated with the development of plastic methods of structural analysis and, while obviously a considerable improvement on previous treatments, the central problem of defining the safety concept and expressing it in a rational manner had still not been resolved.

This potted history of the treatment of safety concepts has been given simply as a background to a brief discussion of the activities of many individuals, committees and organizations over the past 15 - 20 years. Freudenthal(1), in his paper to the 8th Congress of the International Association for Bridge and Structural Engineering, has given a critical appraisal of safety criteria and has included an extensive bibliography; this covers the same period of time.

The first notable attempt by an organization to rationalise the treatment of safety concepts was that of the Institution of Structural Engineers in 1955; Professor Sir Alfred Pugsley chaired a committee which produced its report in 1955(2). This committee's approach was essentially the load factor approach in which the contributory factors had to be assessed by the designer in the light of his knowledge of the loading, control on site, accuracy of calculations, seriousness of failure and economic consequences. Only collapse was treated and the use of statistics in defining loads and material properties was advocated. Following this work, the Comité Européen du Béton (C.E.B.) formulated its proposals in 1963(3). The International Council for Building Research Studies and Documentation (C.I.B.) set up a committee in 1961 to study the loads assumed for the design of various types of building and the desirable safety margins and general design criteria; Thomas(4) published a paper giving the views of this committee in 1964. The Féderation Internationale de la Précontrainte (F.I.P.) set up a joint committee with the C.E.B. in 1962 which had the aim of treating prestressed concrete in a similar manner to that adopted for reinforced concrete. In 1964, the Construction Industry Research and Information Association (C.I.R.I.A.) set up a committee with Sir Alfred Pugsley as chairman to report on structural safety and the Convention Européen des Associations de la Construction Metallique (C.E.C.M.) also set up a committee in 1966 with the aim of unifying safety concepts. In addition to these, there is an International Standards Organization (.I.S.O.) Committee TC/98 which, obviously, is attempting to draft recommendations on this subject which will be accepted on an international basis. Another notable committee must be included in this catelogue; it is the committee of the American Society of Civil Engineers, under the chairmanship of A. M. Freudenthal which issued its final report in 1966(5).

In the past year, many of the above committees have been finalizing their work and preparing reports and, in addition, two important symposia have been held by the American Concrete Institute (6) and the American Society of Civil Engineers(7). In England, we have had two occurrences which are very relevant to any consideration of structural safety; the first was the collapse of the cooling towers at Ferrybridge(8) and the second the partial collapse of a block of flats(9). The latter has certainly resulted in a rather traumatic experience for the structural engineering profession, the repercussions of which are still with us. It is to be hoped that the whole episode will lend more weight to a rational consideration of structural safety rather than result in hasty measures and regulations serving as a palliative and not a remedy and divorced from any rational concepts of safety. We should bear in mind in this connection a statement made by Pugsley(10) in his book on "The Safety of Structures" namely "A profession that never has accidents is unlikely to be serving its country efficiently." !

The object of this paper is to restate the problems of structural safety, particularly with regard to reinforced and prestressed concrete, to indicate some of the suggested treatments of these, and to give views on the future activity and research in this field.

PHENOMENA TO BE CONSIDERED

The four basic phenomena which must be considered by the designer are :

(a) the loads to which the structure is subjected are variable; [11, 12, 13, 14]

(b) the properties of the materials used in construction are variable; [15, 16]

(c) the workmanship and control on site are variable;[15]

and (d) the relevance of the assumptions and the accuracy of design calculations are uncertain to a greater or lesser degree.

All these phenomena are being treated in other themes of this symposium; the references cited merely illustrate the nature and extent of the variability. As a result of these phenomena, it follows that, necessarily, all structural design must be based on a safety concept embodying the probability of failure. This has been stated in somewhat more astringent terms by Freudenthal as "The difference between safe and unsafe design is in the degree of risk considered acceptable, not in the delusion that such a risk can be completely eliminated." However, it must be accepted that the phenomena mentioned above are not necessarily random and hence that a complete probabilistic treatment of safety is not possible, either at the present time or in the immediate future, in the civil and structural fields.

AIMS OF DESIGN

It is becoming generally accepted that the aim of structural design is the achievement of an acceptable probability (which should be uniform for given structural types) that the structure being designed will not become unserviceable during some specified life. At the same time consideration must be given to the aesthetics and economics of the construction. The consideration of economy should ideally be related to the total cost by taking account of the costs of design, construction, normal maintenance, and insurance to cover risk of losses associated with accepted probability of unserviceability.[17, 18]

With our present design procedures, Freudenthal has quoted[1] the order of risks that exist as 10^{-4} to 10^{-6} for steel highway bridges or transmission towers and 10^{-3} to 10^{-5} for concrete structures. Hence it is clear, that the aims of structural design are not being attained, nor can they be, with the so-called treatment of safety which obtains at the present time.

A further point which needs to be emphasised here is that the concept of a useful life for any structure is one which is cardinal to the basic aims of design; not only is it essential for this reason but also because, in a rapidly changing sociological and technological environment, it is totally irrational to think in any other terms. Pugsley[10] has highlighted this aspect and categorised structures as:

(i) Monumental - life 200 - 500 years e.g. large churches, bridges and city halls;

(ii) Permanent - life 75 - 100 years e.g. blocks of flats, university buildings, ordinary road and rail bridges;

(iii) Temporary - life 25 - 50 years e.g. normal industrial buildings.

With the aim of design expressed in terms of probability of unserviceability the immediate question arises as to what constitutes an acceptable risk. Presumably the structures designed in various countries at the present time and in accordance with the existing national codes or regulations might be deemed to have an acceptable risk but, with the lack of uniformity in the probability of failure (as indicated earlier), we have no real basis for deciding what is the minimum acceptable. Hence this is one aspect that needs particular attention by research workers and the national committees, dealing with structural safety. It is pertinent, however, to suggest that, in defining the acceptable probabilities, due account be taken of other risks which the general public accepts, almost without notice. For example, in England the following probabilities were quoted in 1959 by Su[19] for travel by rail and car; 10^{-6} and 10^{-4} per annum for death respectively and, in the case of travel by car 58.4×10^{-4} per annum for injury or death. Other, perhaps more bizarre, examples may be gleaned from the statistics published by the Fire Research Station; such as assessed probability of death in home due to electric blankets 10^{-6} per annum !

TREATMENT OF SAFETY IN DESIGN PROCESS

From the foregoing discussion, it should be clear that the only rational basis for the treatment of safety is in terms of probability and that this basis is not required just for its rationality but because it is the only basis for progress now that our understanding of structural behaviour is improving so rapidly and when, with digital computers, we have tools commensurate with the needs of the required analysis. However, as Freudenthal[1] has pointed out, there are major problems to be resolved namely :

- the non-random phenomena having a bearing on design process and hence not capable of being included in a probabilistic approach;
- the considerable difficulty of obtaining the relevant data for the random phenomena;

and - the inclusion of probabilistic concepts in a simple form for use in design.

Of these, in my view, the last is the major problem and must condition the formulation of the safety concept. Let us now briefly consider the approaches which have been suggested.

1. Probabilistic Approach

The principal protagonist of this approach in recent years is undoubtedly Freudenthal[1, 5]. It would be presumptuous, and indeed totally unnecessary, for me to attempt to paraphrase the critical appraisal of safety criteria and the presentation of the probabilistic approach given in reference 1. However, I believe that this approach will only be used as a means of studying the probability of unserviceability as a function of the many parameters that affect it so that other, more suitable, design approaches can be formulated with a greater assurance of their complying with acceptable probability limits.

Ang[20] has proposed a modification to the classical probability approach which intorduces a factor of ignorance. This approach does offer certain advantages in deriving design procedures which are relatively simple and may therefore be a very useful tool in the codification of safety in design.

2. Limit State Approach (Semi-probabilistic)

This is the approach adopted initially in Russia and then by the C.E.B. and which is now generally accepted by the F.I.P., C.I.B. C.E.C.M., and by I.S.O. The C.E.B. has finalized its revised recommendations on the approach (these are to be formally approved at a plenary session in September) and a summary of them has been given by the author[21]. These have now been endorsed by the other organizations mentioned above and hence could well be recognised internationally. Before giving a brief resume of them it is necessary to state that the C.E.B. was aware of the fundamental need to draft recommendations that could readily be applied in practice and hence departed from the strict probabilistic approach.

The aim, or object, of design is as defined earlier in the paper. In defining unfitness for use, the concept of limit states is introduced; a limit state is defined as being reached when the structure, or part of the structure, ceases to fulfil the function for which it was designed. The limit states are placed in two categories :

(a) Ultimate limit states, which correspond to the maximum load carrying capacity associated with collapse or inelastic deformations of an unacceptable magnitude;

(b) Serviceability limit states, which are related to criteria governing normal use with regard to unacceptable deformations, displacements, vibrations, stresses or other undesirable damage.

It is envisaged that the criteria referred to in (b) will be defined by the various national committees drafting the relevant codes of practice. It is worth noting that the effects of blast loading, explosive pressure, fire and vehicle impact, although not treated as specific limit states, since the above cover them, are referred to as being relevant in the consideration of the structural concept or as being catered for by other appropriate measures.

In the design calculations, it is required that each of the relevant limit states for the structure being considered should be treated and adequate safety, appropriate to the degree of seriousness of the particular limit state, should be provided. Hence the effects of loading, of all types, should be assessed on the basis of a particular limit state for the structure as a whole and the sections designed accordingly.

Since the factors which govern the attainment of a limit state in any structure are in themselves variable, whether random or otherwise, attempts must be made to take account of the variation by the application of probability theory. The main factors to be treated in this way are:

(i) the actual strengths of the construction material in the structure and the actual dimensions and tolerances in the geometry of the structure;

(ii) the actual loadings, arising from any cause, to which the structure may be subjected during its life;

(iii) the degree of approximation adopted in the calculations.

Since all the data necessary for a rigorous probability approach to the treatment of safety are not available, it is convenient at this stage to utilize "characteristic values" of the strength defining the mechanical properties of the materials, and of the loads, which are based upon a fixed probability that the actual values will be either less or greater than the values selected, and to cover the remaining uncertain factors by transforming these "characteristic values" into "design values" by the introduction of certain coefficients, the values of which depend on the limit state being considered, the behaviour of the construction material and the structure itself and the probability of combinations of load occurring. Thus, the material strengths, as given by appropriate tests, are used to define the characteristic strength; for a normal distribution the characteristic strength, σ_k, is given by

$$\sigma_k = \sigma_m - ks \quad (1)$$

where σ_m = arithmetic mean of different test results;

s = standard deviation;

k = coefficient depending on probability, accepted a priori, of obtaining results less than σ_k.

A similar treatment of the characteristic loads, S_k, is suggested which is essentially the same as that proposed in the earlier Recommendations(3).

In deriving design values the following equations are used.

The design strengths of materials, σ^*, are given by

$$\sigma^* = \frac{\sigma_k}{\gamma_m} \quad (2)$$

The design loads, S^*, are given by

$$S^* = \gamma_s S_k \quad (3)$$

The strength reduction coefficient, γ_m, is regarded as the product of two coefficients γ_{m1} and γ_{m2} which take account of the reduction in strength, as compared with the control test specimen, in the structure as a whole and the possible local reductions in stren th due to other causes respectively. The breakdown of the coefficient γ_m in this way is simply to facilitate the derivation of appropriate numerical values for γ_m.

Similarly the coefficient γ_s is regarded as being composed of three coefficients γ_{s_1}, γ_{s_2} and γ_{s_3} ; thus

γ_{s_1} allows for abnormal or unforeseen loads other than catered for in the characteristic loads;

γ_{s_2} is intended to cover adverse modifications in the assessed effects of loading i.e. inaccuracies in design assumptions, constructional errors such as dimensions of cross section, position of steel and eccentricities of loading on members;

and γ_{s_3} allows for the reduced probability of combinations of load all at characteristic value.

Again this subdivision of γ_s is simply to facilitate the derivation of appropriate values for γ_s. It is recognised that this approach is not consistent with a probabilistic treatment of safety since the individual factors cannot be treated separately; however for practical purposes, this is the most convenient approach at the present time and, obviously, can be modified as our knowledge improves.

In the approach so far outlined, certain aspects of safety have not been covered specifically and therefore a further coefficient, γ_c, is introduced which is used to modify the design values in appropriate cases.

γ_c is the product of γ_{c_1} and γ_{c_2} where:

γ_{c_1} takes account of the nature of the structure and its behaviour e.g. structures or parts of structures in which partial or complete collapse can occur without warning or where failure of an element can lead to overall collapse;

γ_{c_2} takes account of the seriousness of attaining a limit state from other points of view e.g. economic consequences, danger to community, etc.

Thus the treatment of the safety aspect in structural design is in the definition of three so-called partial factors of safety γ_m, γ_s, and γ_c which are introduced into the design calculations in the treatment of the various limit states. By the assignment of appropriate values to these partial factors of safety for each limit state, it is possible to provide a reasonable and adequate safety against the structure becoming unfit for use during its design life.

It is of interest to note that certain papers[22, 23] presented at the ACI Fall Convention, Memphis, 1968, also discuss rather similar approaches to the formulation of codes on a probabilistic or semi-probabilistic basis. In England, the limit state approach has been used in the drafting of the Unified Code for Structural Concrete. It has also been endorsed by the C.I.R.I.A. committee.[24]

3. Deterministic Approaches

These have long been used as the basis for design but, I believe, have always been regarded with a healthy suspicion by designers. Now it appears they can no longer serve any useful purpose and hence should be discarded.

FUTURE ACTIVITIES IN THE FIELD OF STRUCTURAL SAFETY

As I have indicated, the general principles of the treatment of safety concepts, by way of limit state methods, have now been propounded such that they may be assimilated readily and incorporated in relatively simple design procedures. In addition, the framework provided enables advances in the analytical treatment of safety to be incorporated as well as improved knowledge of loads, materials and structural behaviour. Furthermore, I believe that this framework will give a considerable incentive to designers and contractors since, in the future, by appropriate treatment of the partial safety factors, the more realistic analytical procedures and improved quality control on site can be recognised.

Perhaps of more interest however is the fact that this treatment of safety highlights those areas of ignorance and ensures that the significance of new knowledge on the design process can be assessed. In this respect the major problems now requiring attention are :

(i) the definition of characteristic loads for all types of structure for specific useful lives;

(ii) the significance of combinations of load and the frequency of their occurrence;

(iii) the definition of acceptable probabilities for different limit states;

and (iv) the refinement of the partial safety factors in the light of (i) - (iii).

There is very considerable scope in (iv) for the use of computers in applying probability theory to specific structural forms; Ferry Borges(25) has already indicated the possibilities in this field. The acceptable probability levels in (iii) are being considered by the C.I.B. and it is very appropriate that this body should extend its work in this field; C.I.B. is also attempting to define the loading as mentioned in (i).

Finally, I should like to stress the very considerable improvement in our treatment of structural safety which would be possible with an improved understanding of the variability of the strength of structures as built. This will entail considerable research effort to define the variability of the material properties and then analytical work to assess the significance of this variability.

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SUMMARY

A brief history of the treatment of structural safety is given followed by a statement of the phenomena relevant to the design process and a definition of the aims of design. The treatment of the phenomena to comply with the aims of design is then discussed in terms of the probabilistic, semi-probabilistic (limit state) and deterministic approaches. The limit state approach is amplified and finally the future work necessary to improve this treatment of structural safety is discussed.

RESUME

L'exposé part de l'historique du traitement des problèmes de sécurité des constructions; il définit ensuite les phénomènes à prendre en considération dans l'établissement des projets ainsi que les objectifs propres à ce processus. L'exposé se poursuit par l'étude du traitement des phénomènes requis en vue d'obtenir une conformité aux objectifs propres de l'établissement de projets, étude des points de vue probabiliste, semi-probabiliste (état limite) et déterministe. On développe la théorie des états-limites, et l'on discute les modifications futures qui seront nécessaire pour améliorer cette théorie de la sécurité des constructions.

ZUSAMMENFASSUNG

Es wird eine kurze Geschichte der Behandlung des Sicherheitsproblems von Tragwerken und eine Aufzählung aller Faktoren, die für den Entwurf wichtig sind, gegeben. Weiterhin wird eine Festlegung der Entwurfsziele getroffen und diesen Faktoren gegenübergestellt, sowie die Behandlung der Faktoren im Hinblick auf Wahrscheinlichkeitsverfahren, exakte und gemischte (Traglastverfahren) Lösungsverfahren diskutiert. Das Traglastverfahren wird ausführlich behandelt, gefolgt von einer abschliessenden Erörterung der notwendigen Forschung, um dieses Verfahren zur Sicherheit von Tragwerken zu verbessern.

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