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General principles for the verification of the safety of structures

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FOREWORD

ISO (the International Organization for Standardization) is a worldwide federation of national standards institutes (ISO Member Bodies). The work of developing International Standards is carried out through ISO Technical Committees. Every Member Body interested in a subject for which a Technical Committee has been set up has the right to be represented on that Committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work.

Draft International Standards adopted by the Technical Committees are circulated to the Member Bodies for approval before their acceptance as International Standards by the ISO Council.

International Standard ISO 2394 was drawn up by Technical Committee ISO/TC 98, *Basis for design of structures.*

It was approved in February 1972 by the Member Bodies of the following countries :

Australia	Hungary	South Africa, Rep. of
Belgium	Ireland	Spain
Czechoslovakia	Israel	Sweden
Denmark	Netherlands	Thailand
Egypt, Arab Rep. of	New Zealand	United Kingdom
France	Norway	U.S.S.R.
Germany	Romania	

No Member Body expressed disapproval of the document.

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The development of new concepts of structural safety and the related extensive international cooperation on the scientific and economic aspects has led to the need to unify the principles governing the design calculations of constructions.

This International Standard aims to give the principles and the methods which at the present stage of knowledge are adopted as a first step to the unification of different kinds of structural calculations, with a view to ensuring the safety of structures, taking account of all the essential factors governing safety and serviceability in their use.

The drafting of this International Standard was carried out in cooperation with the following specialist international organizations :

the European Concrete Committee (CEB);

the International Council for Building Research Studies and Documentation (CIB);

the European Convention of Associations for Steel Construction (CEACM);

the International Federation for Prestressing (FIP);

the International Association for Bridge and Structural Engineering (AIPC);

the International Union of Research and Testing Laboratories for Materials and Structures (RILEM);

the International Association for Shell Structures (IASS).

These organizations are represented by the Liaison Committee of the International Technical Associations.

The successive drafts of this International Standard have been established from documents prepared by these organizations and with the active participation of their competent representatives.

This International Standard does not contain details on materials or constructions relevant to the particular needs of the specialist organizations since it was considered that the specification of safety considerations should be as general as possible to allow its application to all types of construction.

NOTE — Throughout this document, explanatory notes and comments are printed in a smaller type face than the general principles themselves.

General principles for the verification of the safety of structures

0 INTRODUCTION

This International Standard forms a common basis for defining rules for the design calculation relevant to the construction and use of all civil engineering works whatever the nature or combination of the materials used (concrete, steel, wood, brick, etc.). However, their application to each type of material will require a particular adaptation to ensure a uniform degree of safety.

This International Standard is intended to serve as a basis for those committees having the task of preparing national standards or codes of practice in accordance with the conditions, both technical and economic, in the country considered, and taking account of the nature and type of structure, and the properties of the materials during a defined life with defined conditions of use.

Design methods may be distinguished in the following ways :

1) according to the way the coefficients related to safety are introduced :

a) the permissible stresses method, where the stresses occurring under the expected maximum loads are compared with some fraction of the resistance of the materials;

b) the limit state method, where factored loading effects are compared with the relevant resistance of the structure (ultimate limit states) or the effects of the service loads are compared with the specified values (serviceability limit states).

2) according to the type of safety conditions :

a) deterministic design methods, where basic parameters are treated as non-random;

b) probabilistic design methods, where basic parameters are treated as random.

The design method selected is a combination of 1) b) and 2) b) above. It is therefore a semi-probabilistic limit state method.

However, certain phenomena, such as fatigue and resonance, cannot be treated rigorously by this method and other appropriate verification procedures should be used.

1 SCOPE AND FIELD OF APPLICATION

This International Standard specifies the general principles for the verification of safety which define a procedure for the calculation of the behaviour and strength of structures subjected to known or foreseen actions to ensure an appropriate degree of safety. The safety is considered in relation to the strength of the structure, the maintenance of the requirements for the normal use of the structure and the qualities, properties or characteristics associated with the durability of the structure.

The method of calculation is based on experimental data (including tests on scale models and prototype structures) and scientific theory interpreted, as far as possible, in a statistical manner.

The general principles are applicable not only to complete structures (buildings, bridges, industrial structures, dams, etc.) but also to the structural elements comprising the structure and to the foundations.

The principles are applicable to the use of the structure during its specified life and also to the successive stages in construction, namely the fabrication of the structural elements, the transport and handling of the structural elements, their erection and all work on site.

The present principles assume that the projects are carried out by personnel having the qualifications, the required skill and experience, and that the required supervision is always available on the site.

They also assume that the actual conditions of use of the structure during its life do not depart significantly from those specified during the design stage.

It is not generally required that structures should be able to sustain certain actions[1] of an exceptional character such as those arising in wars. In the case of certain other actions, such as earthquakes, explosive pressure, vehicle impacts, etc., when their frequency or intensity is ill defined, the designer should ensure that, either in the construction or in the concept of the structure, the risks associated with these effects are limited, and should refer in every country to any special specifications relating to these actions.

Any attempt aiming at the treatment of this kind of action in terms of probabilistic concepts of risk, even by rough estimation, will be considered as concordant with the intention of this International Standard.

Finally, a structure may be subjected to other effects such as fire and corrosion which are not considered in the present International Standard. The treatment of these problems lies essentially in the general concept, in the detailing of the structure and in any preventive measures of protection.

1) The term "action" designates those influences (permanent loads, variable imposed loads and imposed deformations) which, either singly or together, are capable of inducing stresses or deformations in a structure.

2 BASIC PRINCIPLES OF DESIGN

2.1 Object of design

All structures or structural elements must be designed with an appropriate safety to sustain all loads and deformations liable to occur during construction and in use and should have adequate durability during the life of the structure. The design method aims at guaranteeing adequate safety against the structure or structural element being rendered unfit for use.

An adequate safety against the structure or structural element being rendered unfit for use is provided when the probability of the structure attaining any particular state, associated with unfitness for use, is sufficiently small.

The integrity of the structure, or structural element, must be assured during the life of the structure; the durability must be adequate as well as the strength.

The application of the principles of the probability theories is also a means of attaining the optimum cost for the construction while providing the appropriate degree of safety.

This optimum cost of construction should ideally take account of :

- the initial cost of construction;
- the maintenance cost, capitalized over the life of the construction;
- the cost of losses, both material and human, arising from the eventual unserviceability, as defined by the limit states, during construction and use;
- the general social inconveniences resulting from failure;
- the moral considerations (with respect to human life) and psychological considerations (such as, for example, the possible reactions from public opinion following an accident).

2.2 Definition of limit states

A structure, or a part of a structure, is rendered unfit for use when it reaches a particular state, called a "limit state", in which it ceases to fulfil the function, or to satisfy the conditions, for which it was designed.

The limit states can be placed in two categories :

a) the ultimate limit states, which are those corresponding to the maximum load-carrying capacity;

b) the serviceability limit states, which are related to the criteria governing normal use or durability.

Examples of the causes leading to the attainment of the limit states are as follows :

a) Ultimate limit states :

- loss of equilibrium of a part or the whole of the structure when considered as a rigid body;
- rupture of critical sections of the structure;
- transformation of the structure into a mechanism;
- instability by deformation;
- deterioration due to fatigue;
- elastic, plastic or creep deformation, or cracking leading to a change of geometry which necessitates replacing the structure.

The ultimate limit state may equally be caused by the sensitivity of the structure to the effects of a repetition of the loads, fire, explosive pressure, etc. It is then necessary to consider such effects in the structural concept.

b) Serviceability limit states :

- excessive deformations with respect to normal use of structure;
- premature or excessive cracking;
- undesirable damage (corrosion);
- excessive displacement without loss of equilibrium;
- excessive vibrations;

etc.

2.3 Actions to be considered in the determination of the loading effects[1]

The actions to be considered in determining the loading effects, *S*, on the structure for the different limit states are :

a) direct actions (loads) :

- permanent loads (self weight and other constant loads), variable imposed loads and inertial loads;

b) indirect actions (imposed deformations) :

- thermal and hygroscopic effects, shrinkage, prestressing effects, differential settlement of supports, etc.

The stress condition associated with imposed deformations (state of co-action) arises from the occurrence of complementary deformations, which must be such that the total deformation (imposed plus complementary) is compatible with the internal and external members of the system acting as a continuous geometric whole. The state of co-action may equally well exist within the members of the structure and in its external connections, depending on whether internal compatibility or compatibility with the external conditions is considered.

Permanent deformations arising out of creep or plasticity of materials, as well as those corresponding to the opening of cracks, are normally considered as being part of the response of the structure to the system of imposed stresses.

Under this method, it can be seen that the effect of imposed deformations is generally important only in the elastic phase, where the materials have a low deformability which accentuates the stresses produced by the complementary deformations. On the contrary, this effect is lower when there are large inelastic deformations : cracking or plastic deformation before the ultimate limit state is reached. In other cases it is an advantage to include in these imposed deformations all those which do not correspond to the elastic effects of the applied forces.

1) The term "loading effects" designates the stress resultants (normal force, shear force, bending moment, etc.) calculated taking into account the actions or combination of actions on one or more sections of elements of the structure.

3 APPLICATION OF PROBABILITY THEORIES

In a structure, a limit state may be reached as the result of a number of random factors affecting the safety factors which combine and originate

– in the uncertainty of the values taken into account by the engineer for the strengths of the materials used, bearing in mind the conditions in the structure which affect the particular limit state (these values being necessarily selected from among values more or less dispersed);

– in the uncertainty of the realization of the assumed geometry of the structure and sections;

– in the uncertainty of actions : permanent loads or variable imposed loads, or imposed deformations impossible to foresee accurately for the entire intended life of the structure;

– in the departure of the actual loading effects from the calculated values.

The object of the calculations or prototype testing is to keep the probability of a limit state being reached below a certain value previously established for the type of structure in question.

The ideal method of calculation would include at the same time the statistical determination of

– the loading effects on the basis of a limit state for the structure as a whole;

– the behaviour of the various elements for this limit state.

4 DETERMINATION OF SAFETY

A complete probability analysis requires a knowledge of the statistical nature of the permanent loads (dead loads), the variable imposed loads, and the imposed deformations (see 2.3) acting on the construction, and also of the loading effects produced by these actions, and of the variability of the mechanical properties of the material and the geometry of the individual sections and the construction as a whole.

A complete study of this type being practically very difficult and all the necessary data not being available, it appears convenient, to avoid excessively complicated calculations,

1) to take into account characteristic values both of the strength defining the mechanical properties of the materials and of the actions; each value being determined in advance by fixing the probability that the actual values would be effectively less than or greater than the values selected;

2) to cover the other uncertain factors by transforming the characteristic values into design values by multiplying by certain coefficients.

The design strengths of the materials are obtained by multiplying the characteristic strengths by the coefficients $1/\gamma_m$, γ_m being greater than or equal to unity.

The design actions are obtained by multiplying the characteristic actions by appropriate coefficients γ_s, which may be greater than or less than unity.

The values adopted for the different coefficients depend on the seriousness of the limit state considered, the behaviour of the material and the structure, and the probability of combinations of loading occurring;

3) to verify that the calculated loading effects are less than those that can be sustained by the structure for the limit state considered.

In the method proposed, safety will be ensured by the selection of various coefficients, dependent on the limit state considered and the degree of danger that it presents.

The calculations should take account of all the factors which influence the probability of attaining a given limit state during the construction and useful life of any structure, including :

a) the degree of approximation in calculation (in particular the basic assumptions), which should be related to the nature of the structure and its different elements, its total cost and the nature of the method of construction;

b) the mechanical properties of the materials in the structure, which depend on a number of factors including : the choice of construction methods and the quality of workmanship in general; the quality control procedures adopted; the deterioration of the structure during its useful life;

c) the values assigned to the most unfavourable loadings;

d) the simultaneous occurrence of loadings due to different causes.

However, all the relevant statistical data necessary for this approach are not available; further, certain factors are not amenable to statistical analysis. Therefore, the systematic application and generalization of the probability theories present serious difficulties. It is necessary to utilize the existing statistical data in the most suitable manner and to assess, as accurately as possible, the ranges for which few valid data exist at the moment, the necessary corrections being made later as knowledge improves.

The simplified procedure, defined above, includes the adoption of coefficients which may be greater or less than unity, applied to the characteristic values; these are intended to take account of those aspects not yet amenable to statistical treatment.

5 CHARACTERISTIC VALUES

5.1 Characteristic strength of materials

For the materials, the characteristic strengths are, by definition, those which have a probability, accepted *a priori*, of not being attained. To determine the characteristic strength, a statistical distribution of appropriate type is assumed; generally, a normal distribution will be taken.

The characteristic strengths, R_k, are then defined by :

$$R_k = R_m - ks$$

where

R_m is the arithmetic mean of the different test results;

s is the standard deviation;

k is a coefficient depending on the probability, accepted *a priori*, of obtaining test results less than R_k.

When statistical data are not available, the nominal values given in standards, codes of practice or other regulations, may be taken as the characteristic values, provided that they offer an equivalent guarantee.

5.2 Characteristic actions

5.2.1 Where statistical data are available :

1) For loadings that may be considered random, a characteristic value Q_k may be defined – if not in contradiction with the distribution curve – by the relation

$$Q_k = Q_m (1 + k\delta)$$

where

Q_m is the value of the most unfavourable loading, with a 50 % probability of its being exceeded, up to abnormally high values, once in the expected life of the structure;

δ is the relative mean quadratic deviation of the distribution of the maximum loading;

k is a coefficient depending on the probability, accepted *a priori*, of maximum loadings being greater than Q_k.

The value of the average loading Q_m is derived from the statistical analysis of a number of structures of the same type as that under consideration and with similar durability.

2) On the other hand, when it is a question that the reduction of a load may endanger the stability of the structure, the characteristic value Q_k' will be defined by the relation

$$Q_k' = Q_m' (1 - k'\delta')$$

where

Q_m' denotes the value of the most unfavourable loading with a 50 % probability of it dropping toward abnormally low values once only in the expected life of the structure;

δ' is the relative mean quadratic deviation of the distribution of minimum loads;

k' is a coefficient depending on the probability, accepted *a priori*, of minimum loads being less than Q_k'.

5.2.2 When it is not possible to use a statistical distribution, the characteristic loads must be chosen as a function of the use for which the construction is intended.

These chosen loads are called "nominal loads" and are given in standards, codes of practice or other regulations. These "nominal loads" should be introduced into the calculations as "characteristic loads" Q_k'.

5.2.3 For the direct actions (forces or loads), the characteristic values, Q_k, are, by definition, those which have a probability, accepted *a priori*, of not being changed (toward more unfavourable values) during the envisaged life of the structure. In cases where the effect of a reduction in load is more dangerous for the stability of the structure, the minimum values should be taken as the more unfavourable.

5.2.4 For the imposed deformations, the characteristic values should ideally be those which have a probability, accepted *a priori*, of not being exceeded (toward more unfavourable values) during the envisaged life of the structure.

In general, the characteristic imposed deformations are more difficult to define than the characteristic loads, and in most cases they will be taken as the nominal values specified in particular standards, codes of practice or other regulations.

For certain imposed deformations, such as the effect of prestressing, in the calculations the imposed deformation may be considered as the effect of an external force.

6 DESIGN VALUES

The following breakdown of the partial safety factors is relevant to normal calculation. Where experimental verification is used, the data should be assessed having regard to the scope of each factor.

6.1 Design strengths of materials

The design strengths, R^*, are defined by :

$$R^* = \frac{R_k}{\gamma_m}$$

The reduction coefficient, γ_m, is in principle a function of two coefficients γ_{m1} and γ_{m2}.

γ_{m1} is intended to cover the possible reductions in the strength of the materials in the structure as a whole as compared with the characteristic value deduced from the control test specimen;

γ_{m2} is intended to cover possible weakness of the structure arising from any cause other than the reduction in the strength of the materials allowed for γ_{m1}, including manufacturing tolerances.

In general, for calculation purposes, a single coefficient will be used; thus

$$\gamma_m = \text{function } (\gamma_{m1}, \gamma_{m2})$$

6.2 Design loads and loading effects

The design loading effects, S^*, are determined from the characteristic actions, Q_k, by taking account of a coefficient γ_s, in the following relation :

$$S^* = \text{effects of } (\gamma_s . Q_k)$$

(increase of the characteristic actions and assessment of their effects using non-linear theory).

For particular cases where there is proportionality between the actions and the resulting loading effects, the following relation may be used :

$$S^* = \gamma_s \text{ (effects of } Q_k)$$

To allow the values of γ_s to be derived, the following treatment may be accepted. The coefficient γ_s is assumed to be a function of partial coefficients γ_{s1}, γ_{s2} and γ_{s3}.

where

γ_{s1} takes account of the possibility of unfavourable deviation of the loads from the characteristic external loads, thus allowing for abnormal or unforeseen actions;

γ_{s2} takes account of the reduced probability that various loadings acting together will all be simultaneously at their characteristic value;

γ_{s3} is intended to allow for possible adverse modification of the loading effects due to incorrect design assumptions (introduction of simplified support conditions, hinges, neglect of thermal and other effects which are difficult to assess), constructional discrepancies such as dimensions of cross-section, deviation of columns from vertical, and accidental eccentricities.

In general, for calculation purposes, a single coefficient will be used; thus

$$\gamma_s = \text{function } (\gamma_{s1}, \gamma_{s2}, \gamma_{s3})$$

Thus

a) The design actions, Q^*, may be determined by using coefficients γ_{s1}, γ_{s2} which may be greater or less than unity, applied to the characteristic value, Q_k :

$$Q^* = \text{function } (\gamma_{s1}, \gamma_{s2})\, Q_k$$

b) The design loading effects, S^*, may be determined by introducing a coefficient γ_{s3}, which may be greater or less than unity, on the loading effects resulting from the application of the design external loads, Q^*.

Thus

$$S^* = \gamma_{s3} \text{ (effects of } Q^*)$$

The above subdivision of γ_s, like that of γ_m in 6.1, is not consistent with a probabilistic treatment of safety, because the individual causes cannot be treated separately. However, the suggested treatment highlights the separate effects and enables a single coefficient γ_s to be derived more easily for use in practice.

6.3 Possible modifications to the design values

The design values, previously defined in 6.1 for the materials and alternatively in 6.2 for the design loading effects, may be adjusted by multiplication by a further coefficient γ_c, which is a function of two coefficients, γ_{c1} and γ_{c2} :

γ_{c1} is intended to take account of the nature of the structure and its behaviour, for example structures or parts of structures in which partial or complete collapse can occur without warning, where redistribution of internal forces is not possible, or where failure of a single element can lead to everall collapse;

γ_{c2} is intended to take account of the seriousness of attaining a limit state from other points of view, for example economic consequences, danger to community, etc.

The coefficient γ_c is, in general, already implicitly covered by appropriate adjustment to γ_m and γ_s. In certain cases, however, γ_m and γ_s will be corrected by a third coefficient γ_c.

7 VERIFICATION OF SAFETY

For a satisfactory design the following relation has to be satisfied :

$$R^* \geqslant S^*$$