Part II

General Principles on Reliability for Structural Design

Principes généraux de la fiabilité structurale

Allgemeine Prinzipien der Sicherheit von Tragwerken

PREAMBLE

Within the ECE an ad hoc meeting of government officials and experts concerned with regulations on structural safety and loads was held in Vyskov in Chechoslovakia from 9 to 13 May 1977. One of the resolutions of this meeting was to recommend to the Working Party on the Building Industry that the Joint Committee on Structural Safety (JCSS) be asked to produce a suitably flexible internationally harmonized code based on the Level 1 approach. The paper presented here is a result of the work in the JCSS on this project. It was later circulated to the member countries of ECE and some comments were obtained. However, these are not included in this paper which is the original JCSS paper.

This paper is intended for code committees of different countries or groups of countries. It is not intended for direct use by designers and thus it is not to be regarded as some kind of a functional model code. It describes the possibilities for the harmonization of regulations concerning structural reliability.

PREAMBULE

Dans le cadre de la Commission Economique pour l'Europe une réunion ad hoc de fonctionnaires et experts gouvernementaux concernés par la réglementation de la sécurité structurale et des charges eut lieu à Vyskov (Tchécoslovaquie) du 9 au 13 Mai 1977. Une des résolutions adoptées fut de recommander au Groupe de travail de l'Industrie du bâtiment de demander au Comité Mixte de la Sécurité Structurale (JCSS) de produire un code d'harmonisation internationale basé sur l'approche de niveau 1 et ayant un caractère suffisamment flexible. Le document présenté ici est le résultat du travail accompli au JCSS dans ce but. Il a entre-temps été distribué aux pays membres de la CEE et a donné lieu à certaines réponses. Ces réponses ne sont pas incluses ni considérées dans ce qui suit, qui est la reproduction du document original du JCSS.

Ce document est destiné à des commissions de codification de différents pays ou de groupes de pays. Il n'est pas destiné à un usage direct par les projeteurs et n'est donc pas à considérer comme un code modèle. Il décrit les bases possibles de règlements harmonisés traitant de la fiabilité structurale.

VORBEMERKUNG

Im Rahmen der Wirtschaftskommission für Europa ECE fand vom 9. bis 13. Mai 1977 in Vyskov, Tschechoslowakei, ein ad hoc Treffen von Regierungsvertretern und Experten zum Thema Tragwerksicherheit und Lasten statt. Einer der Beschlüsse dieser Zusammenkunft war die Empfehlung an die Arbeitskommission Bauindustrie, das „Joint Committee on Structural Safety (JCSS)" zu veranlassen, eine international vereinheitlichte Tragwerk-Norm ausreichend flexiblen Charakters auf anwendungsorientiertem Niveau (level 1) zu schaffen. Das hier folgende Dokument ist das Ergebnis dieser Arbeit im JCSS. Es wurde den Mitgliedländern der ECE vorgelegt, und gab Anlass zu einigen Stellungnahmen. Diese wurden jedoch im vorliegenden Text – welcher der ursprünglichen Fassung des JCSS entspricht – nicht eingearbeitet.

Das Dokument richtet sich an Normen-Kommissionen von Ländern oder Gruppen von Ländern. Es ist nicht für eine direkte Anwendung durch den praktisch tätigen Ingenieur gedacht und erhebt deshalb auch nicht den Anspruch, gebrauchsbereit zu sein. Es zeigt die Möglichkeiten auf, die sich für eine Harmonisierung von Normen bieten, welche sich mit der Zuverlässigkeit von Tragwerken befassen.

1. OBJECTIVES AND GENERAL RECOMMENDATIONS

Structures or structural elements should be designed such that, with appropriate degrees of reliability, they

- sustain actions liable to occur during construction and use
- perform adequately in normal use
- maintain sufficient structural integrity during and after accidents (such as fire, explosions and local failure).

These requirements should apply throughout the anticipated life of each structure (including the period of construction), which means that structures should be designed and maintained so that they

- have adequate durability (for example, against biological, chemical and other influences).

The choice of the various degrees of reliability should take into account the possible consequences of failure in terms of risk to human life or injury, the number of human lives endangered in the case of failure, economic losses and the degree of social inconvenience resulting from failure. It should also take into account the amount of expense and effort required to reduce the risk of failure.

> Thus, as an example, the consequences of failure may be classified according to the following:
>
> - risk to life negligible and economic consequences small or negligible;
> - risk to life exists and/or economic consequences considerable;
> - risk to life great and/or economic consequences very great.

The objects of a national code are presumed to be the achivement of structures which are optimal with regard to the state of economy and development and the general values of the nation.

The measures that can be taken to achieve the required degrees of structural reliability include not only the relevant design calculations and the choice of associated safety elements but also the choice of general arrangement of the structure (and in particular the degree of redundancy and robustness), the degree of quality assurance, the degree to which actions are controlled and the standard of maintenance.

The assignment of a structure to a particular reliability classification requires the selection of the relevant safety requirements and the selection of appropriate standards of control and maintenance.

In order to control the effects of human error and negligence, higher control levels should generally be required for higher safety classes (corresponding to a greater risk to life).

2. PRINCIPLES OF LIMIT STATE DESIGN

2.1 Limit states

The structural performance of a whole structure or part of it should be described with reference to a limited set of limit states beyond which the structure no longer satisfies the design requirements.

Limit states can be regarded as a discretisation of a more general and often continuous loss function.

The limit states are classified into the following two categories, which in turn may be subclassified:

a) the ultimate limit states, which are those corresponding to the maximum load carrying capacity or where exceedande results in complete unserviceability.
b) the serviceability limit states, which are those related to the criteria governing normal use.

Ultimate limit states may for example correspond to:
- loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body (overturning).
- rupture of critical sections of the structure due to exceedance of the material strength (in some cases reduced by repeated loading) or by deformations.
- transformation of the structure into a mechanism (collapse).
- loss of stability (buckling etc).
- qualitative change in the configuration of the system.
- states which prevent the full use of the structure until a damaged part has been repaired. Such states may occur by plastic deformation of the material, creep or excessive cracking.

Serviceability limit states may for example correspond to:

- deformations which affect the efficient use of a structure or the appearance of structural or non-structural elements.
- excessive vibrations producing discomfort or affecting non structural elements or equipment (especially if resonance occurs).
- local damage (including cracking) which reduces the durability of a structure or affects the efficiency or appearance of structural or non-structural elements.

2.2 Design

2.2.1 General

All relevant limit states should be considered in design. A calculation model should be established for each specific limit state; this model should incorporate appropriate variables allowing for the uncertainties with respect to actions, the response of the structure as a whole and the behaviour of individual elements and materials of the structure.

The method of partial coefficients is described in chapter 5 and can generally be used for the verification of reliability.

> It may also be possible to verify reliability according to a probabilistic method[1]. Its level of sophistication should be governed by the amount of knowledge concerning the nature and magnitude of the uncertainties. Furthermore, a probabilistic method is theoretically indispensable in determining partial coefficients.

2.2.2 Design situations

For any structure it is generally necessary to consider several distinct design situations. Corresponding to each of these design situations there may be different structural systems, different reliability requirements, different design values, different environmental conditions, etc. Separate reliability checking

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[1] See for example: CEB-FIP Model Code for Concrete Structures, COMITE EURO--INTERNATIONAL DU BETON (CEB), Volume I, Appendix 1, Paris, May 1978.

is required for each design situation.

The design situations may be classified as

- persistent situations having a duration of the same order as the life of the structure
- transient situations, having a shorter duration and a high probability of occurrence
- accidental situations (during or after an accident), generally having a short duration and a low probability of occurrence.

For example accidental situations may be associated with:
- fire
- impact
- important local damage.

Temporary situations may be used as a concept that includes transient situations and accidental situations.

2.2.3 Design requirements

For persistent and transient situations, all parts of a structure and the structure as a whole should be designed for relevant ultimate limit states and relevant serviceability limit states.

In general for accidental situations, the main structure alone should be designed only for relevant ultimate limit states.

2.2.4 Robustness requirements

The main structure should normally be designed in such a way that it should not subsequently be damaged to an extent disproportionate to the extent of the original incident. This requirement may be achieved by:

a) designing the structure in such a way that if any single load bearing member becomes incapable of carrying load this will not cause collapse of the whole structure or any significant part of it

or

b) where necessary, ensuring (by design or by protective measures) that no essential load bearing member can be made ineffective as a result of an accident.

3. BASIC VARIABLES

3.1 General

The calculation model expressing each limit state considered should contain a specified set of basic variables. In general the basic variables should correspond to measurable physical quantities. Normally basic variables are parameters characterising:

- actions
- properties of materials
- structural and environmental geometry
- uncertainties of calculation models (see 5.1).

Basic variables are considered as being random variables.

3.2 Actions

3.2.1 Definitions

An action is

an assembly of concentrated or distributed forces acting on the structure (direct actions)
or

the cause of imposed or constrained deformations in the structure (indirect actions).

Actions and their random variations should be established on the basis of reliable observations, tests, decisions, or from data supplied by producers of material, equipment, etc.

An action should be considered to be <u>one</u> single action if it can be assumed stochastically independent, in time and space, of any other action acting on the structure.

> However, actions often occur simultaneously and they may be stochastically dependent to some extent. For the purposes of calculation it is more convenient to treat them as single actions. The problem of stochastic dependence may be treated as a special case.

To facilitate the calculation of the action effects, it may be convenient to regroup several elementary analogous actions into one composite action or to resolve certain actions into a sum or difference of several components.

3.2.2 Classification of actions according to their occurrence in time and to the variation of their magnitude with time.

In order to define the type of treatment in reliability checking and to determine their rules of combination, actions should be classified according to their variations in time taking into account the reference period chosen for the given type of structure and for the particular design situation.

One can distinguish:

- permanent actions, which are likely to act throughout a given design situation and for which variations in magnitude with time are negligible in relation to the mean value; or those for which the variation is in one sense and the action attains some limiting value.
- variable actions, which are unlikely to act throughout a given design situation or for which variations in magnitude with time are not negligible in relation to the mean value.
- accidental actions, the occurrence of which, in any given structure and with a significant value, is unlikely during the reference period, but the magnitude of which could be important.

  Temporary actions may be used as a concept to include variable actions and accidental actions.

3.2.3 Classification of actions according to their variation in space.

According to their variation in space, actions should generally be divided into two groups:

- fixed actions, which have a fixed spatial distribution over the structure, so that the magnitude of the action is unambiguously determined for the whole structure if it is given for one point.
- free actions, which may have arbitrary spatial distribution over the structure within given limits.

Actions which cannot be defined as belonging to either of these two groups may be considered to consist of a fixed part and a free part.

The treatment of free actions needs the consideration of different load cases. A load case is determined by fixing the configuration of each of the free actions.

3.2.4 Classification of actions according to structural response.

According to the way in which the structure responds to an action, one can distinguish:

- static actions, which are applied to the structure without causing any significant acceleration of the structure or structural member;
- dynamic actions, which may cause significant acceleration of the structure.

Whether or not an action is to be considered as a dynamic one is thus dependent on the structure.

Often dynamic actions may be treated as static actions by taking into account the dynamic effects by an appropriate increase in the magnitude of the static actions.

3.3 Properties of materials and soils

The properties of materials including soil are described by quantities, time-dependent functions, etc.

The properties of materials and their random variations should be determined by tests on appropriate standard test specimens. These properties relating to standard test specimens should be converted to the relevant properties of the actual material in the structure by the use of conversion factors or functions. The uncertainty of the properties of the material in the structure should be derived from the uncertainties of the standard test results and of the conversion factor or function. Thereby allowance should also be made for different standards of workmanship and control.

3.4 Geometrical parameters

Geometrical parameters describe the shape, size and overall arrangement of structures, elements and cross sections. When the deviation of any of the geometrical parameters from their sprescibed values may have a significant effect on the structural behaviour and the resistance of the structure, these parameters should be considered as basic variables. The parameters describing their variability should be determined by taking into account prescribed tolerance limits (see 5.4).

In most cases, however, the random variability of the geometrical parameters may be considered to be small in comparison with the variability of the actions and of material properties, or dealt with as included in these variabilities. Hence, in general, the geometrical parameters may be assumed to be non-random and as specified in the design.

4. ANALYSIS

Calculation models and basic assumptions for the calculation should express the structural response according to the limit state under consideration.

For the ultimate limit states,linear, non-linear and plastic theories may be applied depending on the response of the material and the structure to the actions.

For the serviceability limit states linear methods of analysis will usually be appropriate because the material normally remains within the linear elastic range.

For the purpose of analysis, a structure can generally be idealized by reducing it to one dimensional elements (beams and columns), two dimensional elements (slabs and shells) and three dimensional elements.

The influence of the working and environmental conditions on the behaviour of materials, elements and structures should be taken into account by the specific codes for each special material and each special type of structure. If this influence is of a systematic nature it should be expressed directly in the analysis. Sometimes it is possible to express this influence by some working condition factor (see 5.3.2).

The working conditions may, for example, include the effects on strength of temperature (also in case of fire), environmental humidity, duration of a given action, etc and also the influence of any technological peculiarities of construction.

The uncertainties of a calculation model can be included in the model itself e.g. by use of additional parameters (see 3.1 and 5.1). The nature and magnitude of these uncertainties should be estimated by a comparison between calculated results and results observed during relevant tests. These uncertainties can be treated in a similar way to the uncertainties associated with the other basic variables.

5. THE METHOD OF PARTIAL COEFFICIENTS

5.1 Principles

The recommended method of partial coefficients requires the introduction of design values for each basic variable.

In this method:

- actions are expressed by design values F_d according to 5.2.
- strength of materials are expressed by design values f_d according to 5.3. Other relevant properties are treated in a similar way.
- geometrical parameters are expressed by design values a_d according to 5.4.

If the general conditions for the actual limit state not being exceeded is written as

$$\theta\ (F,\ f,\ a,\ \mu,\ C) \geq 0 \qquad (1)$$

the design criterion will be

$$\theta\ (F_d,\ f_d,\ a_d,\ \mu_d,\ C) \geq 0 \qquad (2)$$

where F represents actions
f represents material properties
a represents geometrical parameters
μ are quantities covering the uncertainties of the calculation model
C are constants including preselected design constrainst
and $\theta\ (\cdot) = 0$ represents the limit state function.

In many cases the condition for the actual limit state not beeing exceeded can also be represented by

$$\mu_R\ R\ (f,\ a,\ C) - \mu_S\ S\ (F,\ a,\ C) \geq 0 \quad (3)$$

and

$$\frac{1}{\gamma_R}\ \mu_{Rd}\ R\ (f_d,\ a_d,\ C) - \gamma_S\ \mu_{Sd}\ S\ (F_d,\ a_d,\ C) \geq 0 \quad (4)$$

where R represents a resistance function
S represents an action effect function
μ_R and μ_S are quantities covering the uncertainties of the calculation models
γ_R and γ_S are safety elements.

In many cases μ_{Rd}, μ_{Sd}, γ_R and γ_S may not appear explicitly and are compensated for by appropriate modifications of other factors.

If the design criterion is written according to inequality (4) the form of the expressions for R and S must be completely specified.

> If the form of the expressions are, to some extent, allowed to be arbitrarily chosen, there is a risk that the resulting reliability of the structure may depend on the individual choice.

5.2 Actions and their combinations

5.2.1 Representative values

Actions are introduced into the calculations by representative values. The main representative values are the characteristic values.

For a permanent action, when the action consists of the self weight of the structure (or in other similar cases), the characteristic value G_k should be obtained from the intended values of the geometrical parameters (in general taken from the drawings) and the mean unit weight of the material. I cases where the uncertainties in the permanent actions are important, the characteristic values may be determined so that the probability of their exceedance is sufficiently small. In such cases it may be necessary to define both upper and lower characteristic values.

For a variable action the characteristic value Q_k is defined as that value which has a prescribed probability of not being exceeded within the reference time and thus has a given return period (under certain conditions of stationarity). When characteristic values for variable actions cannot be determined from statistical data, as for example for actions from special equipment, the corresponding values may be estimated on the basis of available information.

For variable actions reduced representative values may also be used. The reduction can be made by factors ψ_i which may be different depending on the cause of the reduction.

Thus a factor ψ_0 may be used to take account of the reduced probability of simultaneously exceeding the design values of several actions as compared with the probability of the design value of a single action being exceeded;

Other factors ψ_1, ψ_2 etc may be used to determine reduced values of variable actions which are assumed to occur frequently or are used to evaluate long-time effects etc. This reduction is especially relevant for serviceability limit states.

For an accidental action the characteristic value F_{ak} corresponds to some event with a pre-selected occurrence rate and magnitude. In general this value is chosen so that it can be used directly as a design value.

5.2.2 Design values

The design values should be obtained from the representative values by multiplication with a partial coefficient γ_f.

$G_d = \gamma_f \, G_k$

$$Q_d = \gamma_f \, Q_k \quad \text{or} \quad Q_d = \gamma_f \, \psi_i \, Q_k \tag{5}$$

γ_f takes account of:

- the possibility of unfavourable deviations of the actions from their representative values. In most cases an increase in the magnitude of the action is unfavourable but in some cases a decrease in the magnitude is unfavourable.
- uncertainty in the loading model.
- possible inaccurate assessment of the action effect (if not included in μ_{Sd} or γ_S), insofar as it is independent of the structural material.

The total partial coefficient may be decomposed into several different factors, each of them taking account of one or more of the uncertainties mentioned above.

For particular actions additive elements may be used to transform characteristic values into design values, when appropriate, as in the case of geometrical parameters (see 5.4.2).

For accidental actions design values should be taken as equal to their characteristic values.

5.2.3 Combinations of actions

In the ultimate limit states the following two types of combinations may be applied:

- ordinary combinations - combinations of permanent actions and variable actions. In most cases a combination should not involve more than one variable action having short duration and unreduced characteristic value.
- accidental combinations - combinations of one accidental action with permanent actions and variable actions with reduced values.

In general the combinations of actions can be expressed by

$$C\,(\gamma_{f1}\, G_{k1},\ \ldots .\ \gamma_{fm}\, G_{km},\ \gamma_{f\ m+1}\, \psi_{i1}\, Q_{k1},\ \ldots .\ \gamma_{f\ m+n}\, \psi_{in}\, Q_{kn},\ F_{ak}) \tag{6}$$

where C is a symbol of combination
m is the number of permanent actions
n is the number of variable actions
i is a variable intex (0, 1, 2, ...)
and the other notation is in accordance with 5.2.1 and 5.2.2.

In the serviceability limit states the combinations of actions should be chosen with regard to the purpose of the actual calculation.

5.3 Properties of materials and soils

5.3.1 Characteristic values

In general the characteristic value of material properties can be presented as that value which has a prescribed probability of not being attained in a hypothetical unlimited test series (corresponding to a fractile in the distribution of the resistance parameter).

The method of quality control including the acceptance rules should be chosen so that the actual characteristic value is assured.

In cases where environmental conditions may cause deviations in the material properties, the characteristic values used for the design should be modified to take into account such deviations.

5.3.2 Design values

The design value f_d of the strength of materials (or other material properties) are obtained from the characteristic value f_k by division with a partial coefficient γ_m.

$$f_d = \frac{f_k}{\gamma_m} \qquad (7)$$

γ_m takes account of:

- the possibility of unfavourable deviations of the strength of material, interpreted as a random variable, from the characteristic value,
- possible inaccurate assessment of the resistance of sections or load carrying

capacity of parts of the structure (if not included in μ_{Rd} or γ_R).
- uncertainties in geometrical parameters, if they are not taken into account according to 5.4.2.
- uncertainties in the relation between the material properties in the structure and those measured by tests on control specimens, i.e. uncertainties in the conversion factor or function according to 3.3.

The total partial coefficient γ_m may be decomposed into several different factors each one of them taking account of one or more or the uncertainties mentioned above.

For particular material properties additive elements may be used to transform characteristic values into design values, when appropriate, as in the case of geometrical parameters (see 5.4.2).

Further factors (or additive elements) may be introduced to take occount of working conditions. They may be used in the same way as the partial coefficients although they are not safety elements.

5.4 Geometrical parameters

5.4.1 Characteristic values

For geometrical parameters the characteristic values a_k usually correspond to the nominal values specified in the design.

5.4.2 Design values

The design values a_d of geometrical parameters should be obtained from the characteristic (nominal) values a_k and an additive element

$$a_d = a_k \pm \Delta_a \tag{8}$$

Δ_a takes account of

- the importance of variations i a
- the given tolerance limits for a.

In the cases where deviations of the geometrical parameters have less significant effects and where the effects are accounted for by γ_m, Δ_a should be set equal to zero.

For geometrical parameters, additive elements (Δ_a) are generally more suitable than factors (γ).

5.5 Choice of values for the partial coefficients

The values of the partial coefficients should be chosen with regard to the actual limit state and may depend on the methods used for assessing of the action effects, resistance, etc.

The influence of the consequences of failure, including the significance of the type of failure, may be taken into account by a modifying, γ_n, introduced to adjust the values of the partial coefficients.

The values of the partial coefficients may be chosen on the basis of:

- decisions taking into account the available amount of knowledge and experience,
- a semi-probabilistic approach in which each design value considered separately has a prescribed probability of being exceeded in the unfavourable sense,
- an approach in which the target reliability index, or target operational failure probability is established from a study of the values implicit in existing acceptable designs. Deviations from target indices for a proposed design criterion should be examined over the domain of application of the criterion,
- other appropriate probabilistic analyses including optimization studies.

APPENDIX

GLOSSARY

Reliability: In the most general sense, the reliability of a structure is its ability to fulfil its design purpose for some specified time. In a narrow sense (implied by this document) it is the probability that the structure will not attain each specified limit state (ultimate or serviceability) during the reference period.

Failure has been used in this document with reference to both the ultimate limit states and the serviceability limit states to express that a structure does not fulfil the requirements.

Reference period is a time interval that must be specified if the definitions of variable actions and the degrees of reliability are to be unambiguous. The reference period relates to the particular design situation under consideration.

Characteristic values are those values which serve as a basis for determination of all values of actions, material properties and geometrical parameters used in the design calculation.

Nominal values for measurements and dimensions are for example values given on drawings, in tables of prefabricated products, etc.

Safety element is a general term including partial coefficients (partial safety factors) and additive elements. The magnitude of the safety element takes into account the probability of exceedance of the characteristic or nominal value.