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General principles on reliability for structures

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Foreword

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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. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

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This second edition cancels and replaces the first edition (ISO 2394-1973), of which it constitutes a revision.

Users should note that all International Standards undergo revision from time to time and that any reference made herein to any other International Standard implies its latest edition, unless otherwise stated.

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0 Introduction

This International Standard constitutes a common basis for defining rules for design relevant to the construction and use of all building and civil engineering works whatever the nature or combination of the materials used, for example, concrete, steel, wood, brick, etc. However, their application to each type of material will require specific adaptation to ensure a level of reliability which, as far as possible, is consistent with the objectives of the code drafting committees for each material.

NOTE — This International Standard is intended to serve as a basis for those committees responsible for the task of preparing national standards or codes of practice in accordance with the conditions, both technical and economic, in each particular country and which take into account the nature and type of structure, the properties of the materials during the intended life, with defined conditions of use. It will also provide a common basis for other International Standards dealing with loadbearing structures.

However, to allow continuing development of practice in different countries, the national standards or codes of practice may be simplified or more detailed by comparison with this International Standard.

It is important to recognise that structural safety is an overall concept comprising models for describing actions, design rules, safety elements, workmanship, quality control procedures and national requirements all of which are mutually dependent.

The modification of one factor in isolation could therefore disturb the balance of safety inherent in the overall concept.

In making progress towards harmonization, it is important that the modification of any one factor should be accompanied by a study of the implications involved in relation to the overall concept of safety.

1 Scope and field of application

This International Standard specifies general principles for the verification of reliability of structures subjected to known or foreseeable types of actions.[1] Reliability is considered in relation to the performance of the structure throughout its intended life.

The general principles are applicable to the design of complete structures (buildings, bridges, industrial structures, etc.), the structural elements making up the structure and the foundations.

This International Standard is applicable also to the successive stages in construction, namely the fabrication of structural elements, the transport and handling of the structural elements, their erection and all work on site, and the use of the structure during its intended life.

Generally, the principles are also applicable to the redesign of existing structures when they are in the course of being repaired or reconstructed.

2 General requirements and conditions

2.1 Fundamental requirements

Structures and structural elements should be designed and constructed so that they are suited to their intended use. The structures should normally be designed so that they are not subsequently damaged disproportionately to the original cause, which implies a certain degree of robustness. In particular they should, with appropriate degrees of reliability, fulfil the following performance requirements:

a) They should withstand all normal actions imposed upon them during their construction and anticipated use.

b) They should, in general, retain sufficient integrity to withstand local failures and specified accidental events such as explosions, fire and vehicular impact.

c) Structures and structural elements should perform adequately under normal use.

These requirements should be fulfilled during the intended life of the structures.

NOTE — This means that the durability of the structures in their working environment should be such that the deterioration of material properties will not lead to an unacceptable probability of failure. Thus length of intended life should be attained with an acceptable level of maintenance.

1) The term "load" may be used instead of "action". See note to 4.1.

A further requirement is that design solutions should be economical in their utilization of materials, energy, financial resources, manpower, space and time.

NOTES

1 The term "failure" as used in this document refers to either inadequate safety or serviceability of the structure.

2 The first two requirements refer to the safety of structures whilst the third requirement refers to their serviceability.

3 In the narrow sense implied by this document, the term "reliability" is used to describe by probabilities that neither inadequate safety nor inadequate serviceability will be encountered during the intended service life. In a general sense, the reliability of a structure is its ability to fulfil its design purpose for some specified time under the environmental conditions encountered.

Safety, serviceability throughout the intended service life, and durability are not simply functions of the design calculations but are also dependent on the quality control exercised in manufacture, the supervision on site and the manner in which the structure is used and maintained.

The choice of the various levels of reliability should take into account the possible consequences of failure in terms of risk to human life or injury, the potential economic losses and the degree of social inconvenience. It should also take into account the amount of expense and effort required to reduce the risk of failure and should depend on the cause of failure.

NOTE — Thus, as an example, structures or structural parts may be classified according to the consequences of failure as follows:

a) risk to life negligible and economic and/or social consequences small or negligible;

b) risk to life exists, economic and/or social consequences considerable;

c) risk to life great, economic and/or social consequences very great.

As a result of such a classification structures or structural parts could be assigned to different safety classes for which the extent of the measures taken to ensure safety, and possibly serviceability, differs.

The consequences of a failure generally depend on the mode of failure, especially in those cases when the risk to human life or injury exists. Thus a structure which fails suddenly without warning should be designed for a higher level of reliability than one in which the failure is ductile (see 3.2.3).

2.2 Use and environmental conditions

The influences arising from the intended use of the structure and the environmental conditions can be described as the design situations associated with normal use of the structure.

NOTE — These influences and conditions can, for example, include actions due to specified normal use combined with all foreseeable environmental conditions which occur at the same time.

These influences and conditions form a basis for the design of the structure in the serviceability limit state and possibly in the ultimate limit state. They should be used *inter alia* as parameters for defining design situations (see 3.2.2).

2.3 Hazards

It is necessary to take into account hazardous circumstances which alone or in combination with normal conditions could cause the serviceability or ultimate limit state to be attained.

The hazards may occur due to

— consequence of an error such as lack of information, omission, misunderstanding, etc.;

— effects of extreme loading arising from the environment (climatic influences, geotechnical conditions, etc.).

The measures taken to counter such hazards would basically consist of

— avoiding the structural effects of the hazards by either eliminating the source or by bypassing and overcoming them;

— designing for hazards [see 3.2.3b)];

— accepting the risk of failure due to the hazards and trying to minimize the consequences [see 3.2.3a)].

If a specific hazard has to be considered it should be used to define a design situation (see 3.2.2). This design situation will normally be dominated by one hazardous occurrence which could be combined with other normal conditions.

2.4 Design considerations

In order that the properties of the completed structure should be consistent with the assumptions made during design, a number of conditions should be fulfilled.

2.4.1 Initial choice of structural system, material, detailing and method of construction

With regard to safety, the choice of the structural system should be made so that important parts of it are able to maintain sufficient structural integrity during and after accidents. Material, detailing and method of construction may also influence the structural integrity.

2.4.2 Responsibilities

For every foreseeable activity during the building process, as well as for the interfaces between them, the responsibility should clearly be defined. It is important that the meaning and scope of their responsibility and task is known by all concerned. This also refers to the transfer of information and documents.

NOTE — Many causes of structural failures can be traced back to those situations where such responsibilities are not clearly defined.

2.4.3 Measures against human mistake

The effects of human mistake should be eliminated to a reasonable extent by taking such measures as:

a) improving conditions to the point that the occurrence of human mistakes may be reduced or avoided. This means, for example, selection of qualified staff, improved communications, precautionary measures against human mistake, such as an adequate checking system:

b) improving working procedures. Particularly the places of work and their approach should be appropriately organized. These conditions are also necessary for separation and conservation.

NOTE — Experience indicates that structural failures are often due to human mistake arising from the incorrect selection of a structural system, choice of a material, design and construction.

2.4.4 Quality control

All steps in planning, design, construction and use of a structure should be controlled to an extent which depends on the possible consequences of error and unfavourable deviations and cost-effectiveness of control.

NOTE — Many cases of structural failures are caused by errors which slip through undetected by those engaged in the building process.

Control should also include the introduction, execution and supervision of measures required in cases where the results obtained do not agree with the original requirements.

NOTE — Control is treated in more detail in clause 7.

2.4.5 Maintenance and repair

Structures should be maintained in such a way that they can be used during their intended life for the purpose for which they were designed. When a structure has been damaged or has deteriorated to such an extent that its use would entail an unacceptable risk, then repairs should be undertaken.

NOTE — Under certain circumstances, demolition could be a better solution than repair.

Damage or deterioration may be discovered through inspection, which should be undertaken at regular intervals. The effort to be undertaken in the maintenance should be specified with regard to the importance and type of the actual structural part, the conditions of use, knowledge of the durability of the material, environmental conditions, the protection against external actions and the cost of investigations.

Structural elements which are essential to the stability of a structure should, as far as possible, be made accessible for inspection without the need for difficult or extensive dismantling of the structure.

3 Principles of limit state design

3.1 Limit states

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

NOTE — Limit states can be regarded as a discrete representation of a more general and often continuous loss function.

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

a) the ultimate limit states which generally correspond to the maximum load carrying capacity (safety related);

b) the serviceability limit states which correspond to the criteria governing function related normal use.

3.1.2 Ultimate limit states correspond to, for example

— loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body (e.g. overturning),

— rupture of critical sections of the structure caused by exceeding the ultimate strength (in some cases reduced by repeated loading) or the ultimate deformation of the material,

— transformation of the structure into a mechanism (collapse),

— loss of stability (buckling, etc.).

3.1.3 Serviceability limit states correspond to, for example

— deformations which affect the efficient use or 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.

3.1.4 To control serviceability limit states by design, it is often necessary to use one or more constraints (C) which describe acceptable deformations, accelerations, crack widths, etc.

NOTE — These constraints may be determined by statistical methods but are normally introduced into codes with deterministic values.

3.2 Design

3.2.1 General design requirements

All relevant limit states should be considered in design. A calculation model should be established for each specific limit state; this model should incorporate all appropriate variables and also allow for the uncertainties with respect to actions; the response of the structure as a whole, the behaviour of individual elements and materials of the structure and the conditions of the environment. Appropriate measures should be taken to avoid any mistakes in the design interpretation. However, the design procedure should not be refined beyond a point that is compatible with the standard of workmanship likely to be achieved.

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

To verify the reliability of the structural design, the format of partial coefficients, described in clause 6, is generally recommended. However, for certain design problems, e.g. in the case of dynamic analysis, direct reference to the respective design values may be more convenient.

NOTE — Not all limit states can be verified exclusively by calculation. This applies, for example, to limit states specified with regard to chemical or biological attack or to the prevention of brittle failure.

3.2.2 Design situations

For any structure it is generally necessary to consider several distinct design situations (see 2.2). 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 is required for each design situation with due regard to different consequences of failure.

The design situations may be classified as:

a) persistent situations, having a duration of the same order as the life of the structures,

NOTE — A structure of a residential building which, for example, is subjected to loads from the weight of furniture and a normal number of persons.

b) transient situations, having a shorter duration and a high probability of occurrence,

NOTE — Where a structure is, for example, subjected to loads caused by storage of material during construction or repair.

c) accidental situations (during or after an accident) normally of short duration and low probability of occurrence.

NOTE — Where a structure is, for example, subjected to actions due to fire, explosions, impact or considerable local damage.

3.2.3 Structural integrity

Where appropriate, all parts of a structure and the structure as a whole should be designed for relevant ultimate limit states and relevant serviceability limit states. However, for accidental situations, generally, only the principal load-bearing system need be designed for relevant ultimate limit states.

NOTE — This does not preclude that verification of additional limit states may be required for certain accidental situations, e.g. thermal insulations and integrity to fire penetration, which may not only refer to members of the principal load bearing system.

The principal load bearing system should be designed for accidental situations when certain hazards occur in such a way that the probability of damage disproportionate to the original incident is sufficiently small (see 2.3).

NOTE — This requirement may, for example, be achieved by

a) designing the structure in such a way as to ensure that, should a single member fail, then neither the whole nor a significant part would collapse immediately, thus allowing the necessary emergency measures — for example, evacuation of the building — to take place;

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

In addition, the structure should have adequate resistance to lateral forces. Thus, if the true horizontal forces are unknown or are of insufficient magnitude to provide a robust structure, then the structure should sustain a horizontal force of magnitude equivalent to a specified proportion of the total vertical action.

4 Basic variables

4.1 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 characterize:

— actions,[1]

— properties of materials and soils,

— geometrical parameters.

Basic variables are often considered as being random variables.

The basic variables are often affected by the environmental conditions. This influence should be taken into account by the specific codes for each special material and each special type of structure.

4.2 Actions

4.2.1 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).

1) The term "load" (which is prevalent in some countries) may be used with essentially the same meaning as "action". In the past, it has often been used to describe direct actions only.

The term "action" was introduced to cover also the effects due to imposed deformation.

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

NOTE — In reality, actions which are introduced simultaneously are often stochastically dependent to a certain extent. To simplify calculations, those which, where they are present, depend closely on each other and attain their upper values at the same time, are considered together as a single action. Actions where the dependence is small (low correlation) can be considered as independent.

In case of ambiguity, actions should be considered such that they result in the most unfavourable action effect resulting from the combination rule of concern.

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

4.2.2 Classification of actions according to the variation of their magnitude with time

Actions are divided — according to their variation in time — into:

a) permanent actions (G) 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 actions attain some limiting values;

b) variable actions (Q) which are unlikely to act throughout a given design situation or for which variations in magnitude with time are not monotonic and not negligible in relation to the mean value;

c) accidental actions (A or F_a), the occurrence of which, with a significant value, is unlikely on a given structure over the period of time under consideration and also in most cases is of short duration. The occurrence of an accidental action could in many cases be expected to cause severe consequences unless special measures are taken.

NOTE — Examples of permanent, variable and accidental actions are given in annex A.

4.2.3 *Classification of actions according to their variation in space*

Actions are divided — according to their variation in space — into two groups:

a) fixed actions are those which have a spatial distribution over the entire structure, such that the magnitude and orientation of the action is unambiguously determined for the entire structure if they are given at a single point of the structure;

b) 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 requires the consideration of different load arrangements. A load case is determined by fixing the configuration of each of the free actions.

NOTE — In some cases it is necessary to distinguish between fixed actions and actions which are movable or act in a probabilistic way at certain parts of structures. In such cases and in the absence of a more detailed study, it is generally agreed to separate such actions into different elementary actions such as those applied to points or parts which are recognized as the most unfavourable and those applied to other parts.

4.2.4 Classification of actions according to the structural response

Actions are divided — according to the way in which the structure responds to an action — into:

a) actions which may produce static action-effects without causing significant acceleration of the structure or structural member, so-called static action;

b) dynamic actions which may produce dynamic action-effects in the structure.

NOTE — Whether or not the action is regarded as dynamic is dependent on the structure.

For simplicity, dynamic actions may often be treated as static actions in which the dynamic effects which depend on the behaviour of the structure are taken into account by an appropriate increase in the magnitude of the action.

4.3 Properties of materials and soils

The values describing the properties of materials and their random variations should be based on either specific tests, results of previous tests, or *in situ* observations in conjunction with other sources of information. Properties relating to special test specimens should be converted to the relevant properties of the actual material in the structure by the use of conversion factors or functions, which should take account of any scale effects and any dependence on time and temperature. The uncertainty in the properties of the material in the structure or of the soil should be derived from the uncertainties of the standard test results and of the conversion factor or function. Allowance should also be made for different standards of workmanship and control.

4.4 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 prescribed values may have a significant effect on the structural behaviour and the resistance of the structure, these parameters should be considered as random variables. The magnitudes and their variability should be determined by taking into account prescribed tolerance limits (see 6.4).

NOTE — In many 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. In such cases the geometrical parameters may be assumed to be non-random and as specified in the design. Some examples of random geometrical parameters are unintentional eccentricities, inclinations and curvature affecting columns and walls.

5 Analyses, calculations and testing

5.1 General

In many cases the design procedure consists of

- structural analysis which gives the action-effects (forces and moments) in the cross-sections, and
- analysis of cross-sections, joints etc. which gives their resistance and more generally their behaviour.

However, in some cases it is not possible to make this distinction. An example of such a case would be when the stability of an entire structure is studied.

The analysis of a structure can be made with the aid of calculation, model testing or prototype testing. In some cases a combination of these methods is useful.

It is important to recognize clearly the principal load-bearing system by which forces are safely transmitted to the foundations, and to identify those features (including the layout) of the structure which have a critical influence on its overall stability and integrity. Those features should then be consistently examined and maintained throughout all stages of the design and construction.

5.2 Calculation

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

For the purpose of analysis, a structure can generally be described by a model consisting of one-dimensional elements (beams, columns, cables and arches), two-dimensional elements (slabs and shells) and three-dimensional elements.

For the serviceability limit states, linear elastic methods of analysis will usually be appropriate. However, sometimes non-linear methods have to be used.

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

In treating free actions, it is necessary to define simplified spatial models for each action and to use them in order to define different load arrangements. For a given structure, it is necessary to select the load arrangement which is the most unfavourable. However, it will sometimes be justified, from statistical considerations, not to consider certain load arrangements with low probability of occurrence.

If the influence of the environmental conditions on the behaviour of materials, elements and structures is of a systematic nature it can be expressed directly in the analysis.

Examples of influence of environmental conditions which can be expressed directly in the analysis are:

- the influence of environmental humidity conditions on the strength of wood or on the shrinkage and creep deformations of concrete,
- the influence of high temperature during a fire on the strain distribution and the yield strength of steel.

The uncertainties in a calculation model can be included in the model itself, for example by use of one or more parameters, which may be treated as an additional basic variable with its own mean and variance. These may be determined by comparing predicted and observed data in relevant tests.

5.3 Model testing

A structure or part of it may be designed on the basis of results from appropriate model testing coupled with the use of model analysis to predict the behaviour of the actual structure.

NOTE — In most cases, model testing is used for structural analysis to verify calculations or as a substitute for them. Conversion of model test results to be compatible for use in the actual structures should be ensured.

5.4 Prototype testing

A structure or part of it may also be designed on the basis of results from testing prototype units relevant to the particular design under consideration.

NOTE — This type of testing is sometimes used as a substitute for calculation to verify the resistance of small units or details. It is important, therefore, that the prototype testing is conducted as nearly as possible under the same conditions and assumptions as for the actual structure regarding strength, dimensions, loading and environmental conditions. If only a few prototype test results are available, statistical uncertainties should be indicated.

6 Design format of partial coefficients

6.1 Principles

The partial coefficient format separates the influence of uncertainties and variabilities originating from different causes by means of partial coefficients assigned to basic variables.

The principles of the method are given in this clause. However in practical application slight modifications are sometimes necessary or convenient. (See 6.2.2 and 6.3.2.)

In the verification procedure the values assigned to the basic variables are called design values.

The design values for actions, F_d (see 6.2.2) are given by the equation

$$F_d = \gamma_f F_r$$

Strengths of materials are expressed by their design values f_d (see 6.3) by the equation

$$f_d = f_k / \gamma_m$$

Other relevant properties may be treated in a similar way or by introducing additive elements.

Geometrical parameters are expressed by their design values a_d (see 6.4.2) by the equation

$$a_d = a_k \pm \Delta a$$

where

F_r are the representative values of actions;

f_k are characteristic values of material properties, for example strength;

a_k are characteristic values of geometrical parameters;

γ_f are partial action coefficients. Their values reflect the uncertainties of the actions (see 6.2.2);

γ_m are partial material coefficients. Their values reflect the uncertainties of the material properties (see 6.3.2);

Δa are additive partial geometrical quantities. Their values reflect the uncertainties of the geometrical parameters (see 6.4.2).

The condition for a limit state not to be exceeded can be written as follows:

$$\theta(F_d, f_d, a_d, C, \gamma_n, \gamma_d) \geqslant 0 \qquad \dots (1)$$

where

C are constraints, for example according to 3.1;

γ_n is a coefficient by which the importance of the structure and the consequences of failure, including the significance of the type of failure, are taken into account. The value of γ_n could be made dependent on the safety class (see 2.1) of the actual structure or structural part;

γ_d are coefficients related to model uncertainties or other circumstances which are not taken into account by the other γ-values;

F_d, f_d and a_d are the same as above.

The coefficients γ_d will take on different values depending on the degree of confidence in the design model as an accurate representation of the real structure or structural element. They may also cover the effect of the sensitivity of the structural system (underproportional or overproportional behaviour).

NOTE — Many sources of variability have been identified in design and construction, such as poor mathematical modelling, standards of construction, the difference between test and *in situ* material properties, human error and workmanship. The common feature of these uncertainties is that, while it is possible to identify them qualitatively, it is not always possible to quantify them.

In general, the limit state function is time-dependent. In many practical applications the effects are accounted for by assigning appropriate numerical values to the basic variables.

For practical applications the design condition can often be separated into one action effect function S and one resistance function R so that for ultimate states it can be expressed by

$$\gamma_n S(F_d, a_d, \gamma_{Sd}) \leqslant R(f_d, a_d, C, \gamma_{Rd}) \qquad \dots (2a)$$

In many cases this equation can be changed to

$$\gamma_n \gamma_{Sd} S(F_d, a_d) \leqslant \frac{1}{\gamma_{Rd}} R(f_d, a_d, C) \qquad \dots (2b)$$

γ_d has been split into one load effect part γ_{Sd} and one resistance part γ_{Rd}. Splitting of γ_d is not however a prerequisite for the form of equations (2a) or (2b).

In practical application the coefficient γ_n could be introduced on either side of the equation and also directly to the design values.

For the serviceability limit states the design condition can often be represented by an expression of the type

$$S(F_d, f_d, a_d, \gamma_n, \gamma_{Sd}) \leqslant \frac{C}{\gamma_{Rd}} \qquad \dots (3a)$$

or

$$\gamma_n \gamma_{Sd} S(F_d, f_d, a_d) \leqslant \frac{C}{\gamma_{Rd}} \qquad \dots (3b)$$

where C is a serviceability constraint (see 3.1).

Equations (1), (2) and (3) should be regarded only as a schematic description of the principles. Each symbol F, f, a and C may represent several variables. Thus in the equations used for a calculation, F may represent a set of actions entering into a combination. Furthermore, for example regarding a reinforced concrete construction, f may represent both the strength of concrete and the strength of steel.

Each of the equations (1), (2) and (3) could represent several equations which are valid simultaneously as a design condition. The equations could also be vectorial.

The problem of static equilibrium can be described by equation (2) where R is equal to zero.

NOTE — In some cases the character of the problem requires the design condition to be written according to equation (1). This could be the case if the problem involves a thorough study of the stability of a frame system.

If the actual problem is non-linear, special care is necessary. The non-linearity could, for example, imply that some action-effect varies with material properties.

For fatigue problems it may be necessary to make some adjustments to equations (1) or (2).

Equation (3) for the serviceability limit states could be used for most of the ordinary problems of deformations, cracking, etc. However for some types of problems, such as vibrations and fatigue, the equations may not be applicable.

6.2 Actions and their combinations

6.2.1 Representative values

For different purposes different values may be assigned to each action. These values are called representative values. They are given in codes or in other documents.