Backgrounds to serviceability requirements

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Backgrounds to Serviceability Requirements

Considérations sur les conditions d'aptitude au service

Zuverlässigkeitsbedingungen für die Gebrauchstauglichkeit

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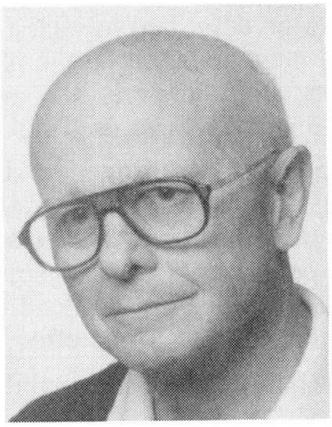

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SUMMARY

Physical, probability-based, and design-reliability requirements used in serviceability limit states design are discussed with emphasis on the constraint problem. Dependencies of constraints upon calculation models, importance of the building, and upon time are considered.

RESUME

On analyse les conditions de sécurité physiques et probabilistes et les conditions de dimensionnement utilisées dans les calculs aux états limites de l'aptitude au service avec une attention particulière pour les limites des variables considérées. La dépendance des limites en vue des modèles de calcul, de l'importance des ouvrages et du temps est considérée.

ZUSAMMENFASSUNG

Es werden die physikalischen, probabilistischen und Zuverlässigkeitsbedingungen betrachtet, die in der Bemessung nach dem Grenzzustand der Gebrauchstauglichkeit insbesondere unter Zwangsbeanspruchung benützt werden. Die Abhängigkeit der Bemessungswerte von dem Berechnungsmodell, der Wichtigkeit des Gebäudes und der Zeit werden untersucht.

1. RELIABILITY REQUIREMENTS AND CRITERIA

To understand correctly the backgrounds of the serviceability requirements applied in the design of buildings, it is necessary to get acquainted with the principal concepts of the "grammar" of the reliability-based design. Let us introduce here some basic concepts (for more detailed information see [3]).

Assume a *fully defined constructed facility* (for example, a building) that does not contain any uncertainties and indefiniteness; the properties of its three basic components, that is the *structure, load,* and *environment* are perfectly known. When this *reliability system* is to be assessed, the *relations* between the components have to be described in such a way we can decide whether the system is reliable or not. These relations must be based on the physical description of phenomena entering the particular system components, and, therefore, they are called *physical reliability requirements.* - In the following, the abbreviation *RelReq* is used for "physical requirement."

In general, scalar variables and vectors of distinctive kind form the physical RelReqs. The nature of these variables and vectors is denoted as *design criterion.* In the main, the serviceability design criteria are expressed in terms of *strain load-effects* (for example, the mid-span deflection, frame sway) and in terms of *vibration parameters* (for example, eigenfrequency, vibration velocity, acceleration). Criteria may also be quantities that are not load-effects; we may state RelReqs in terms of the depth of a beam cross-section referred to the effective span, etc.

In the serviceability design, scalar RelReqs are mainly used; two types of scalar RelReqs are encountered:

- open RelReq:

$$\forall t \in T_{ref}: \; A(a_1, a_2, \ldots, a_n) \le C \qquad (1)$$

- range RelReq:

$$\forall t \in T_{ref}: \; C_i \le A(a_1, a_2, \ldots, a_n) \le C_s \qquad (2)$$

where $A(.)$ = a quantity described by a physically defined function (or, *calculation model*), a_1 through a_n = elementary variables (called also *basic*), C = constraint, C_i, C_s = lower and upper bound of constraint, respectively; t = point in time, T_{ref} = reference period during which the particular RelReq must be satisfied (for example, life of the building, T_0).

RelReq (1) is typical for the majority of serviceability problems; RelReq (2) is used in design exercises where dynamic behavior of the structure is dealt with. We will not discuss the latter RelReq any more; all conclusions related to RelReqs of type (1) are valid also for type (2).

When, owing to *uncertainties and indefiniteness,* properties of the system investigated are not exactly known, this fact must be taken into account. Therefore, physical RelReqs must be either adjusted by parameters covering uncertainties and indefiniteness, or supplemented by further requirements. When the adjustments are based on experience, or also on theoretical considerations but without regard to the randomness of phenomena, the respective requirements are *deterministic.* If, however, the system uncertainties are treated as random, they can be expressed in terms of the *probability* *of occurrence of adverse realizations of the respective phenomena.* Then, *probability-based reliability requirements* can be formulated:

$$\forall t \in T_{ref}\text{: } \Pr(C - A \leq 0) \leq P_{ft} \tag{3}$$

where P_{ft} = the target value of the failure probability, P_f.

By synthesis of physical and probability-based RelReqs the *design requirements* are obtained. These are contained in the design codes, or, for particular cases, can be individually specified.

The general form of design requirements is

$$\forall t \in T_{ref}\text{: } A[F_d^{\text{SLS}}(t), R_d^{\text{SLS}}(t), G_{int}; \text{BC}; \text{EP}; t] \leq C \tag{4}$$

where F_d^{SLS} = design values of load considered in the SLS design, R_d^{SLS} = material characteristics (elastic moduli, strengths, creep factors, and others), G_{int} = intended dimensions of the structure; BC stands for boundary conditions, EP for environmental parameters (for example, temperature, humidity). Since RelReq (4) is currently used, we will not analyze it here in detail.

2. RELIABILITY AND DESIGN PARAMETERS

The quantities specifying the intended reliability level are called *reliability parameters.* RelReq (1) through (4) show that two principal reliability parameters must be considered:

- the *reference period,* T_{ref}, which is usually taken as the value of the life expectancy of the building, T_0,
- the *target failure probability,* P_{ft}, in its yearly form, $\dot{P}_{ft}$, or comprehensive form, $\bar{P}_{ft}$; the latter must be referred to a reference period $T_{ref} > 1$ year, for example, $T_{ref} = T_0$.

The values of T_0 and P_{ft} cannot be derived from the properties of the building or of the bearing structure. They have to be determined by *decisions* based on opinions and needs of individuals, groups, and social entities, supported by economic analyses, and, particularly, backed by experience gained with similar facilities. Decisions on T_0 and P_{ft} are not simple since many aspects have to be pondered. The principal aspect is, without any doubt, the *importance of the facility for individuals and the society.* Unfortunately, as far as the serviceability limits states, SLSs, are concerned, we are not yet clear on what values of P_{ft} should be considered. No special studies have been carried out, though for the ultimate limit states, ULSs, well formulated conceptual approaches already exist. Aspects governing P_{ft} for SLSs differ substantially from those related to ULSs. The main difference consists in the fact that according to general opinion, ULSs shall *never* be reached, while the attainment of SLSs can be *sometimes* tolerated.

3. LOADS AND MATERIAL PROPERTIES

Not too much attention has been paid to the design values of load that should be considered in the SLS design. As a rule, characteristic values, that is, 0.95-fractiles of the respective probability distributions, are used. In general, this is not correct, because at the SLS level the "average" loading conditions prevail. Thus the load values introduced should be defined by the mean, mode, or median of the *physical realizations* of load.

Analogous considerations can be made as far as material characteristics are concerned. It is amazing that great care has been paid to the definition of calculation models (for example, for bending stiffness and creep) but the problem of probability-based values to be included into these models is neglected.

4. CONSTRAINTS

In the majority of cases, constraints are specified by *fixed, decision-based values.* Constraint values that have been established in existing design codes have been derived in various ways. In the beginnings of codified design, most of C 's were based on traditions; nobody could give any scientific justification for the respective magnitudes. Now, the situation has been slowly changing, since statistical and probability concepts, the system of reliabilistic thinking, and, last but not least, practical needs have brought new ideas into the constraint issue. As for constraints, modern codes become open-minded, and allow or even encourage the designer to adjust values given in the respective code clauses whenever it is reasonable. Thus, occasions when designers themselves are compelled to specify a constraint value, are getting more and more recurrent. It then happens that the designer, having reached at the conclusion that some constraint is to be verified in the particular situation, founds the available design code unsatisfactory, as for the information given. Then, the designer has to answer *two questions:*

- What shall be the physical meaning of the constraint, C, or in other words, what criterion shall govern the RelReq?
- What shall be the magnitude of C?

In general case, several design RelReqs (4), formulated for *various deformation criteria,* have to be checked. Only in very simple cases, such as floor beams, floor slabs, etc., a single deflection check is sufficient. During the evaluation we must not forget that deformations should be verified also for *several stages of the construction process,* not only for the stage of current use. Further, we must keep in mind the *time-dependencies* involved: first, those related to loads, then those related to material (including soil), and finally also the time-dependence of constraints themselves. The latter is usually underestimated; it will be discussed below.

It is now acknowledged that constraints are, in general, random variables, or more exactly, that they can be established by statistical analysis of aspects which determine their values.

■ **Example 1.** A lecture hall is regularly visited by a group of N individuals. Owing to time-dependent properties of the bearing structure the deformation of the floor grows with time. Let us take the mid-span deflection, f, as deformation criterion. At a certain value of f one of the regular visitors becomes disturbed and begins to be suspicious about the *safety* (not serviceability!) of the structure. Obviously, the respective value of f is the *personal constraint,* f_{lim}, of the visitor. When the deformation continues to grow, the number of alarmed visitors, n, increases. At each lecture, additional Δn visitors will observe the dangerous deflection (let us assume that sensitive visitors' worries are not transferrable). The alarm process is discrete, though the growth of the deformation is continuous; however, the periods when lectures are given are intermittent. The probability that a randomly selected visitor will get annoyed by $f \leq f_{lim}$ is given by

$$P = \frac{n}{N} \tag{a}$$

and the probability that a randomly selected visitor will get annoyed just when f_{lim} has been achieved is

$$p = \frac{\Delta n}{N} \qquad \text{(b)}$$

Obviously, each individual has a *personal threshold,* whose exceedance arouses discomfort. As psychological and emotional properties of humans are random, the personal limit deflection, f_{lim}, is also a random variable. Considering a very large population of individuals, Equations (a) and (b) can be written as

$$P = \Phi(f_{lim})$$

$$p = \varphi\,(f_{lim})$$

where, T_{ref} $\bar{P}_f$ $\Phi(.)$ and $\varphi(.)$ = cumulative distribution function and probability density function, respectively, of the random variable f_{lim}. Consequently, were the probability distribution of f_{lim} known, the value of admissible deflection, f_{adm}, could be find for an intended probability P_{lim} from

$$\Pr(f_{lim} \le f_{adm}) = P_{lim} \qquad ■$$

Unfortunately, experimental information on random behavior of constraints is still very scarce, or nil. This fact compels us to establish values of constraints, often called "admissible deflections," "admissible crack width," etc., on empirical considerations. Methods, based on the *fuzzy set theory,* are now available that can raise the empiricism to theoretical level [2].

When no guidance on constraints is found in codes and other documents, the designer should ask qualified persons, acquainted with the problem area, for advice. *For example,* we can get

- from *civil and structural engineers:* admissible displacements and deformations with regard to bearing and non-bearing structures that are adjacent to the building designed;
- from *mechanical engineers:* admissible displacements of elevators, piping, etc., that will not impair safe function of the equipment;
- from *agricultural engineers:* admissible deflections and vibrations that do not fright animals stalled. Etc.

However, data supplied shall be always checked for consistency, and the background of such data should be known. It happens that we are offered data on admissible deformations and displacements that are either exaggerated, or, on the contrary, understated.

As for vibration parameters, not only engineers are the source of decisions on constraints. In case of buildings, admissible vibration parameters are, as a rule, specified by *health regulations.* Many designers are unhappy with the prevailing rules, which are often based on concepts different from those built-up in the structural reliability area. Mutual understanding of engineers and hygienists is needed.

Cracks are a phenomenon encountered in all materials. However, only concrete and masonry structures and also structures made of other brittle materials are subjected to serviceability RelReqs based on the occurrence and width of cracks. Considering the crack width as a constraint, we have to take into account that cracks in building structures, for example, may

- be a starting factor in *material corrosion;*
- deteriorate the *sound-proofing* and also *odor-proofing* of partition walls;
- cause *annoyance of the users* of the building.
- impair the *fireproofing* of the building.

Similarly as in the case of deflections, a sensitivity threshold can be found both for structures and for people involved. This threshold can be expressed simply in terms of a limit crack width, w_{lim}, which again is a random variable. Its admissible value, w_{adm}, can be found in the same manner as that of the admissible deflection, f_{lim}; see Example 1.

We should mention here that the *crack width* need not always be the actual governing quantity. Individuals never evaluate the crack width in terms of a physical distance of the opposite faces of a cracked body; their attitude to a cracked structure depends on many factors: *length, shape,* and *density of cracks.* It happens, that a crack of considerable width, say 3 mm, escapes any attention of users and even inspection engineers. When aesthetic reasons affect the admissible crack width, this is only a simplified criterion. A more suitable criterion would be, say, the area of visible cracks per 1 m^2.

We always must keep in mind that cracks are an *unavoidable phenomenon.* Therefore, when a 100%-proof protection against sound, odors, and fire is to be assured, sealing of cracks before the building is put in use must be provided. Then, in the design, delayed movements in cracks due to temperature changes, shrinkage, and other time-dependent effects should be verified taking into account properties of the sealant applied. The same refers to joints that can open because of deformations (for example, joints between partition walls and supporting floors). To facilitate repairs, it is a good practice to assure access to all places sealed.

5. DEPENDENCIES

Various physical and statistical dependencies can be identified in the calculation models for A; for example, the dependence between the elastic modulus and creep factor of concrete. These dependencies are sufficiently known and do not induce any difficulties; they are, in the main, neglected.

However, there is a substantial dependence between the calculation model, $A(.)$, and the constraint, C, though it is not acknowledged in codes. When mandatory values of C are specified by a code, they must be considered valid only for the calculation model given. It happens that a change in calculation model can substantially affect the results of design. Members that were acceptable according to old calculation models, become suddenly unreliable when verified by the new model. In general, this holds also for ULS calculation models, which, fortunately, are not so sensitive as the SLS models.

The above "meta-dependence" between A and C can be source of legal problems whenever neither calculation model nor constraint are specified. Contract documents should always be clear on acceptable deflections, which should be preferably specified on the performance basis, not on calculation model basis.

6. IMPORTANCE

When considering the background of RelReqs, the importance problem should not be ignored. In fact, importance of buildings is not directly expressed in the codified SLS design. No *importance factors* for SLSs are used because the importance and purpose of the building or its part is *embedded in values of constraints specified.* Higher importance is expressed not only by more conservative constraint values than the usual ones but also in the *number of RelReqs assessed.* Performance demands on floors under gymnasiums, dancing halls, assembly halls, and others are much more rigorous than on floors under and over apartments. The difference in importance can be easily considered in the probability-based design.

■ **Example 2.** Consider a hypothetical building with 1000 rooms. The building is used by 1000 persons, each person being allocated to one room at random. Assume that one of the persons is sensitive to any crack in the ceiling, while no cracks are ever registered by any of the remaining persons. Obviously, an event $E_1 \equiv$ Ev(**sensitive person in a room**) is considered. Assume further that also $E_2 \equiv$ Ev(**occurrence of cracks in a particular ceiling**) is random. The floor slabs have been designed exactly so that the target probability of crack occurrence in a slab during the life of the building is P_{rt} = 1.0E-3. Obviously,

$$\bar{P}_{rt} = \mathrm{Prob}(E_2)$$

Now, the probability that the crack-sensitive person will become a user of a particular room is

$$\bar{P}_{sp} \equiv \mathrm{Prob}(E_1) = \frac{1}{1000} \equiv 1.0\mathrm{E}{-3}$$

Since in this P_f case E_1 and E_2 are independent and discrete, the *serviceability failure probability* is

$$\bar{P}_{f1} \equiv \mathrm{Prob}(E_1) \cdot \mathrm{Prob}(E_2) \equiv \bar{P}_{sp} \cdot \bar{P}_{rt} = 1.0\mathrm{E}{-6}$$

Consider now the entrance to the building. The reinforced concrete frame is visible and it has been designed for the same cracking probability, 1.0E-3. All 1000 users of the building, including the sensitive one, pass daily through this entrance. If a crack in the frame occurs, it is surely noticed by the sensitive person, and so P_{sp} = 1. Thus, the failure probability is

$$\bar{P}_{f2} = 1.0\mathrm{E}{-3} \times 1 \equiv 1.0\mathrm{E}{-3}$$

The discomfort of the public is substantially different in both cases; in the rooms only a single user will feel uneasy because of the crack appearance, whereas almost all users will become aroused by the crack in the entrance hall (the sensitive person will tell the colleagues about it) with a probability 1.0E-3. Consequently, if for the two facilities the same level of reliability should be achieved, the concrete frame should be designed for P_{rt} = 1.0E-6. ■

At buildings used by public the possible discomfort of people is always greater, and so higher levels of reliability have to be used than for buildings used by individuals or small groups.

7. TIME

The time affects the serviceability RelReqs in three ways. First, variables entering the calculation model are time-dependent, each to a certain degree; as a rule, time-dependence of elastic modulus of steel, of structural dimensions, and others is not considered in the calculation models.

Second, some RelReq can govern the design in only the initial periods of the existence of the building and can be entirely ignored later. Therefore, the RelReqs and also the design criteria can differ during the construction and use periods. This is typical for assembled systems where in the erection phase demands on stiffness can vary from operation to operation. Thus, the number and criteria of RelReqs change with time.

Finally, also the constraints can be time-dependent; this fact has not been considered in codes yet. For example, the older the building, the less sensitive the user is to deflections. The deformation of timber frames accumulated in 50 years of service would be unacceptable if it would occur in the first day of service. A client buying an old farm house to spend holidays and vacation there is little sensitive to large deflection of floor beams, considering it unavoidable. The same effects can be observed as far as cracks are concerned. When the deflection and crack width grow slowly and steadily, the owners and users do not become suspicious about safety of the building even when their magnitude is high.

8. CONTEXT

The subjective assessment of existing deflections, crack width, and other serviceability criteria is always a part of the *risk assessment.* The actual risk is evaluated along a large scale of values, starting with simple repeated costs necessary for current maintenance and ending with costs involved with the evacuation of the building.

In the main, the risk assessment is carried out by users (for example, tenants living in a residential building) in the first plane, than also by owners (landlords, farmers), and *in extremis* by reliability experts. The users' assessment is virtually subconscious, but later it becomes more and more specific. The owner's assessment is based on economic thinking, and the reliability experts make benefit of their theoretical knowledge and experience. The nature of the assessment is successively psychologic, economic, and scientific. It is felt that some general *risk units* should be introduced; in the absence of such, monetary units can serve the purpose.

Observe that people are the principal component of the assessment process. Thus, the assessment is exposed to subjective attitudes the complex of which is called the *context* (see Elms in [1]). The results of assessment and the ensuing actions taken depend upon the context substantially. At the same situation, different decisions will be made by users, owners, and experts. The evaluation of deflections, cracks, vibrations, and further serviceability phenomena will be different with men and women, users and owners, old people and young people, etc.

> The foregoing paragraphs have shown the variety of problems encountered with serviceability reliability requirements. These problems are manifold; we can maintain that they are more diversified than those associated with ultimate reliability requirements.

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