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Performance Requirements for Structural Concrete

Exigences concernant les performances du béton

Verhaltensanforderungen am Konstruktionsbeton

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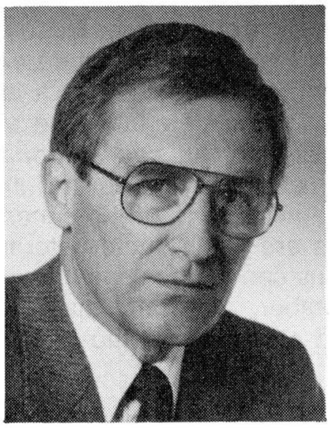

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SUMMARY

The performance requirements are recognized as boundary conditions applied to structural concrete by the associated systems. It is unimportant whether structural concrete is assigned to a system deliberately or unintentionally. Performance requirements are assigned to different areas. Using those applied to the relationships under service load conditions, measures which can be applied to fulfil the performance requirements will be explained. Here, it is shown that the construction material, structural concrete, can react very flexibly to a wide range of requirements.

RÉSUMÉ

Ce type d'exigences est reconnu en tant que condition marginale d'une structure en béton considérée comme un «système supérieur». Il n'est pas important de savoir si le béton est destiné à constituer un système supérieur par une manœuvre intentionelle ou aléatoire; en effet, la notion d'exigence sur la performance s'applique à divers domaines: dans ce cas, on s'efforcera d'aborder celle traitant des conditions régnant sous charges de service afin d'expliquer comment satisfaire pleinement ce type d'exigences. Ici, on montre particulièrement que le béton est un matériau de construction répondant de façon très flexible à une large catégorie d'exigences.

ZUSAMMENFASSUNG

Die Verhaltensanforderungen werden als die aus den übergeordneten Systemen auf den Konstruktionsbeton wirkenden Randbedingungen erkannt. Dabei ist es unerheblich, ob der Konstruktionsbeton planmässig oder ungewollt einem Obersystem zugeordnet ist. Die Verhaltensanforderungen werden verschiedenen Bereichen zugeordnet. Am Beispiel jener für die Verhältnisse unter Gebrauchslast werden die Massnahmen erläutert, die zur Erfüllung der Verhaltensanforderungen ergriffen werden können. Dabei zeigt sich, dass der Konstruktionsbeton sehr flexibel auf die unterschiedlichsten Anforderungen reagieren kann.

1. GENERAL REMARKS

The "performance requirements" establish conditions for structural concrete. These are, however, not the only terms which are made and which must be fulfilled. To serve the better understanding of their significance, one can apply the four different causality terms already formulated by Aristotle: the *causa finalis* (the final cause), the *causa formalis* (the formal cause), the *causa efficiens* (the effective cause) and the *causa materialis* (the material cause).

1.1 Causes and their Effects

Using the example of the construction of a house, these different causes become much clearer. The *causa finalis* is the intention of the builder to create a new residence for himself and his family. The reason for the house determines its function as a one-family dwelling. The house is constructed according to building plans. These determine the shape of the house and the application of structural materials, thus representing the *causa formalis* of the house. Financing is necessary for the realization of this construction project, so that the relevant activities, such as the engagement of an architect and the commissioning of the general contractor and additional specialists can take place. The financial means are the ultimate determinants of whether the construction project will be carried out or not, and thus can be labeled its *causa efficiens*. The completed house is made up of bricks, concrete, steel, timber, glass and many other materials which go into its construction. These materials, arranged according to the building plans, represent the structure's *causa materialis* (Fig. 1).

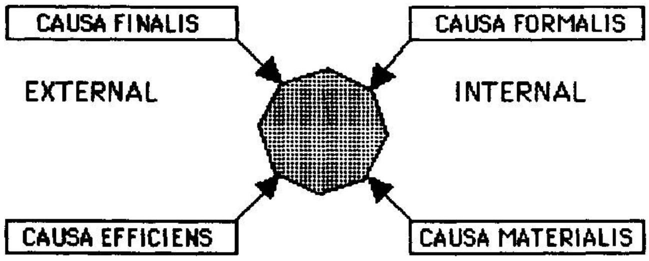

Fig. 1

1.2 System Structures

It is also possible to gain a perspective by thinking according to hierarchically arranged systems. The house is also part of a superordinate system, a city or village, along with other houses. It can simultaneously belong to additional superordinate systems, for example the environment or energy consumption systems. The system under observation, the house, is also made up of subordinate systems, the rooms. Just as it is possible to locate the house in diverse superordinate systems, it is conceivable that numerous subordinate systems can be applied as well. Another subdivision, for example, could be made up of the subsystems: brick, finishing work and housing technology (Fig. 2).

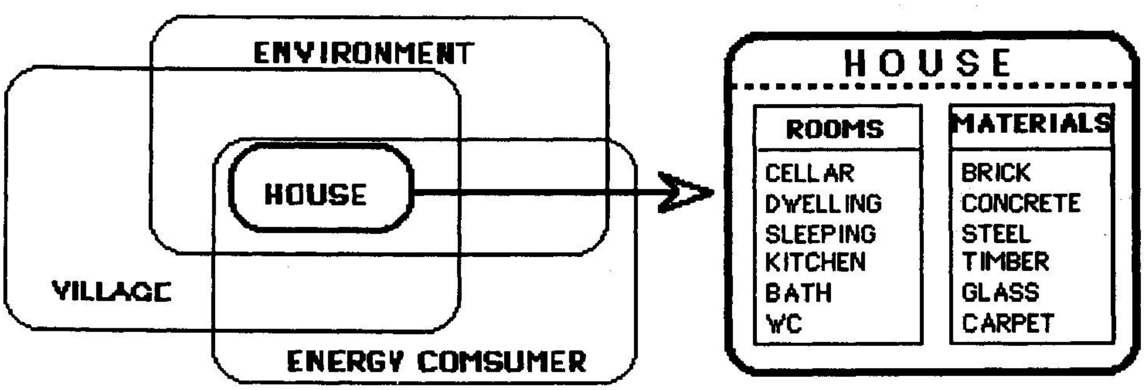

Fig. 2

Whether the system under observation is a sub- or superordinate system depends solely on the momentary perspective. Every system serves as a superordinate system for its subsystems, and simultaneously, a subordinate system for its supersystems.

1.3 Effects in a System Structure

One can also create a synopsis of both considerations discussed in 1.1 and 1.2 and combine them with one another. Here, the *causa finalis* and the *causa formalis* can be viewed as the influences of the supersystems on the subsystems, while the *causa efficiens* and the *causa materialis* function in the opposite manner, i.e. the subsystems affect the supersystems. Aristotle already deemed the *causa finalis* and the *causa efficiens* external causes, as opposed to the internal causes, *causa formalis* and *causa materialis*. Within a system structure comprised of super- and subsystems, it is therefore the internal causes which are particularly influential and clearly recognizable. In the example discussed above, the construction of a house, the building plans of the house establish the arrangement of the rooms, as well as the arrangement of the building materials, and thus act as the *causa formalis* with regard to the supersystem "house", on the subsystems of the individual rooms and construction materials. The latter, themselves to be viewed as subsystems, determine the supersystem, house, and thus represent the *causa materialis* of the house. The same holds true for the subsystems of the individual rooms. The dimensions and arrangement of the rooms, in turn, are determined by the superordinate system, "house".

The influences imposed by external causes cannot be followed to such an extent as those from internal causes. The decision to build a house to improve the living conditions of the family is ultimately the initiating factor - and thus the *causa finalis* - at the base of all further activities which are necessary for the realization of this decision. On the other hand, the decision has an external influence on the "room-house-city" system structure and is not founded in this itself. The same could be stated for the *causa efficiens*, which we can trace back to financial means in our economy-oriented world.

1.4 Evolution

The term "evolution" was originally introduced by Charles Darwin in the field of biology. According to its classic definition, which is adequate for our further considerations, evolution is the interplay of mutation and selection in the origin of species. This concept could also be applied with success in other fields, so that today, one recognizes chemical and physical evolution, social and cultural evolution, in addition to the original biological type of evolution, to only mention the most significant types. The field of engineering, and with it, structural engineering, are generally considered as belonging to cultural evolution. Evolution as a general process can be observed in any system built up in a hierarchical fashion, in that the diverse subsystems on one level compete with one another. In this case, the system develops its own dynamics, which we designate "evolution". Among competing systems, those which fulfill the demands of the superordinate system best will survive. These demands are, however, the *causa formalis*, which thus becomes the selective factor for competing subsystems.

2. STRUCTURAL CONCRETE

The following is an attempt to describe how the system "structural concrete" is integrated into the appropriate supersystem, as well as what subsystems are involved. Moreover, competitive construction materials will also be taken into consideration in this discussion.

2.1 Supersystems and their Requirements

Structural concrete is used for the construction of structures, which in turn comprise construction works. The individual construction works do not stand alone; they, too, are components of super-ordinate systems. In our example, the house was a component of the systems "city" and "environment." Similarly, a bridge is a component of the superordinate systems "transport route" and "environment", a pressure pipeline, a component of the systems "power plant" and "environment", and finally, a television tower, a component of the systems "environment", "city", and "information transmission". Innumerable similar examples could be found, but these should be sufficient in providing a good idea of what is meant here. The supersystem directly above structural concrete is always the structures itself. This is a component of a construction work and assumes a load-carrying function. The structure itself belongs to several superordinate systems, of which one is always the environment.

We have recognized the influences of closely interrelated supersystems as the *causa formalis*. The supersystem directly above structural concrete, the structure, has the greatest influence. The requirements which arise from the loads-carrying function are basically similar for various types of structures. We can therefore expect to find very similar requirements, ones which bear great significance. Such requirements would be high resistance to fracture, ductility and economy. In fulfilling these requirements, however, structural concrete must compete with other construction materials such as steel, timber, masonry, composite structures, etc., whereby the requirements mentioned above are also criteria for the selection of these materials.

The supersystems of the structure, the construction work, the environment, etc., may also make additional demands on the structure and could make themselves known as far down as the construction material level. An example here would be a water tank, which requires not only that the walls and floor slab support the load, but also that these be waterproof. This also means that additional require-ments must be fulfilled by the structural concrete, such as "uncracked state" or "limitation of crack width". In general, it can be stated that the requirements established as a result of the supersystems can be extremely varied. Nevertheless, it is possible that the same requirements be imposed on different structures when the superordinate system is the same, as is commonly the case with the super-system, "environment".

The influences imposed on structural concrete by the supersystems described above, which we have recognized as the *causa formalis*, represent the performance requirements for structural concrete mentioned in the title. In addition, these provide the selection criteria for the construction materials. The performance requirements, therefore, also play a significant role in the evolution of construction materials, and thus in the types of construction.

2.2 The Subsystems

The simplest way to determine which subsystems are involved is by asking which components comprise a system. When this question is posed about structural concrete, the answer would be: concrete, reinforcing steel, bond behavior, tendons and grout (Fig. 3).

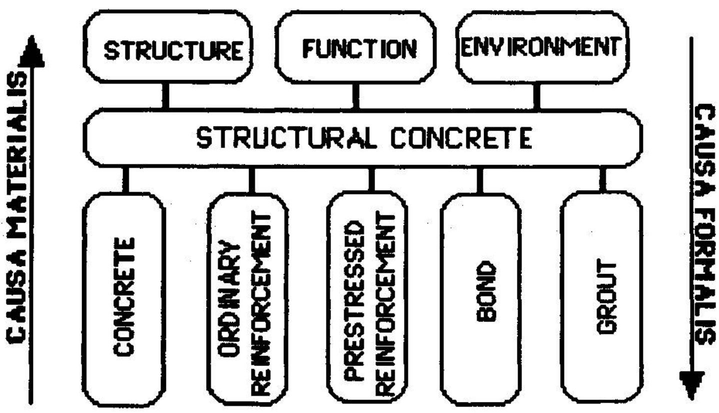

Fig. 3

It is not necessary that all components be represented, however, since we also want to include reinforced concrete and plain concrete, as well as unbonded tendons, in the term structural concrete. By combining the mentioned components appropriately, it is possible to make a very wide range of construction materials, for example: plain concrete, lightly reinforced concrete, reinforced concrete and prestressed concrete with partial, limited or full prestressing and with unbonded tendons, or with pre- or posttensioned tendons (Fig. 4).

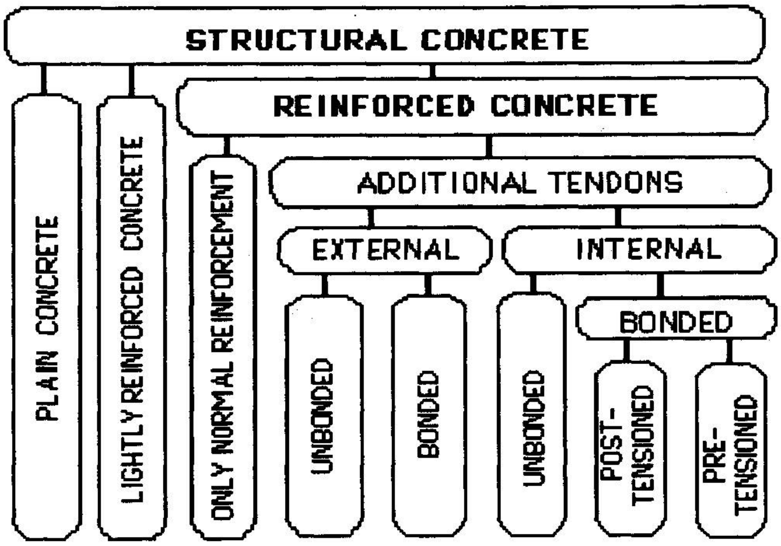

Fig. 4

By applying the criteria for selection, it is possible to choose the most applicable construction material for a specified task. As mentioned above, the selection cannot be made only in the area of structural concrete, but must also include other construction materials such as steel, timber, masonry, etc.

The range of choices expands even further when one regards each of the five components mentioned above as a system as well, and divides each into its subsystems. For example, concrete is comprised of aggregate, cement, admixtures, and water. There is a wide range of each of the first three components available. Furthermore, the relationships with which these components can be combined can influence the properties of the concrete. Thus, the construction material structural concrete offers a broad range of mutants. By applying the selection requirements (performance requirements), it is possible to choose the ideal type and combination needed for an actual task. To enable determining the fittest material from the numerous mutants, sometimes with fluid boundaries between, an exact formulation of the relevant performance requirements is necessary.

3. PERFORMANCE REQUIREMENTS

In Section 2.1, we presented a detailed discussion explaining that performance requirements are the conditions imposed on structural concrete by its supersystems. A supersystem is any system to which structural concrete would belong, regardless of whether membership to the superordinate system is planned or whether it happens as necessity. For example, a bridge pier belongs to the planned supersystems "bridge" and "roadway", while at the same time, is an element of the "river" and "environment" systems. It is essential to remember that performance requirements are determined by **all** supersystems.

As shown at the beginning, the intention to build a structure comes ultimately from the builder, who expects the structure to satisfy a particular need. Therefore, the builder is primarily interested in the function of the structure. Since he usually is not an expert, he is only able to present his ideas in a very general fashion, i.e. with such formulations as:

> The structure should enable the intended use, whereby the construction costs as well as maintenance expenses for the required life of the structure should be reasonable.

Deriving concrete information about the demands on the structure's design and construction materials requires the assistance of an engineer. This remains true in for the compilation of generally applicable rules, such as those found in technical handbooks, as well as determining the detailed requirements for an actual construction project. Since structural concrete is always used in structures, many of the demands placed on it can be directly derived from the requirements applicable to the entire structure itself. In addition, other superordinate systems impose further requirements. Because of the dominant position of the supporting function, the danger exists that these other requirements might be overseen, a reason to pay them increased attention.

3.1 Requirements made by the Supporting Function

It is advantageous to separate the requirements made by the supporting function into those for the ultimate limit state and those for the serviceability limit state. When applying the ultimate limit state, it is helpful to consider an extremely improbable but nevertheless possible condition. With the serviceability limit state, on the other hand, the daily situations which can occur in the supporting structure are considered. With this information, it is possible to determine the performance requirements:

For the ultimate limit state: sufficient strength, ductility, clear fracture warnings, ductile fracture, possibility of redristribution, etc., and

for the serviceability limit state: sufficient rigidity, controlled crack formation, controlled long-term deformation, etc.

Each of these verbally designated requirements must first be quantitatively determined to justify its functioning as a selection criterion. In the very recent past, much research has been conducted regarding this matter, though a much more in-depth consideration of this question would be desirable. The verbal requirements are as old as the reinforced concrete itself: to provide an example, however, it has only been with the quantification of ductility requirements and their relationship to the rotation capacity on the narrow sector of bending moments, which has first been dealt with very recently in connection with discussions about the MC 90, that progress has been made.

3.2 Additional Requirements made by Function

The planned function could place further requirements on the behavior under service load. In particular, liquid or gas impermeability could be named, when structural concrete must provide a sealing function in addition to its supporting function. Using the example of water impermeability, it becomes especially clear that the performance requirements need to be precisely defined to ensure that the desired behavior is obtained. Financial requirements differ significantly, depending on whether the requirement states that the structure must be "completely dry" or "mostly dry" or whether occasional damp spots will not cause complaint.

3.3 Durability

Here, the basic requirement made is that within the estimated life time, no destructive events occur which could interfere with the planned use of the structure. For example, concrete cover dimensions can be derived for the anti-corrosives needed for the reinforcement under normal environmental conditions. When harmful chemical substances such as the chloride ions of road salt are involved, it has not yet been possible to provide a reliable and final statement; the allowable crack width is still under discussion.

The requirements with regard to other harmful chemical substances also require additional quantitative clarification and which go beyond today's very general considerations. This also applies to planned attacks by harmful substances, such as those in the chemical industry, as well as to unintentional attacks by the ever increasing amounts of harmful agents in air, water and soil. In the field of storage and treatment of wastes, including special wastes, better data are urgently required.

3.4 Environmental Tolerability

This carries over o the field of active environmental protection. Structural concrete must meet the requirements of not introducing any harmful substances into the environment. This must hold true for the structure's planned functions as well as under exceptional conditions, such as fire. Even though structural concrete possesses comparably significant advantages, involvement with this aspect must be increased, particularly in view of the sensitivity to environmental awareness on the part of the public.

One could also include the aesthetic suitability of the structure into its surroundings as a part of environmental tolerability. This aspect, however, is more applicable to the structure and construction work, and less to the construction material structural concrete. It must not be overlooked that at least in German-speaking countries, severe animosities are expressed with regard to concrete and cement. There is therefore a tremendous need for informational and educational efforts.

3.5 Economy

It is also important that the economic side of these requirements not be ignored, since it provides the regulatory factor which helps bring requirements which have gotten out of hand, back down to reality. Economic requirements can lead to new production procedures, combinations and the use of new components in the construction material, structural concrete.

4. MEASURES TO MEET THE PERFORMANCE REQUIREMENTS OF SERVICEABILITY LIMIT STATE

The requirements imposed by structural safety are for the most part independent of the construction material used. The requirements imposed by environmental acceptance, durability and economy provide very diverse measures for the construction materials structural concrete, structural steel, timber and masonry. The same holds true for requirements arising out of utility, with the addendum that a structure's function can produce additional differentiation of requirements.

The utilization requirements are decisive in establishing which measures are necessary to ensure serviceability. They play a role in determining how structural concrete will be applied - as plain or lightly reinforced concrete, or as reinforced concrete with or without prestressing. In the latter case, a decision must be reached as to whether the tendons are to be bonded or not, and whether they are better placed inside or outside the cross-section. There are numerous and diverse requirements imposed by utility, which certainly cannot be listed without overlooking one or the other. An attempt is therefore made to compare the advantages and disadvantages of the different types of structural concrete with regard to the essential and repetative performance requirements.

4.1 Deformations

The determining deformations could be deflection, inclination a bearings and in some cases, curvatures, which are associated with one another through the differential equation of the bending line.

In plain and lightly reinforced concrete, deformations do not generally play a decisive role since dimensions are usually very massive, which means that the rigidity is very high.

In reinforced concrete, bends are essentially influenced by the slenderness ratio (l/h) or by the prestressing tendons. Other measures, such as increasing the ordinary reinforcement or raising the strength class of the concrete, have theoretical influence, which in fact is subordinate and usually covered by the diversity of the construction material characteristics. A reduction of the slenderness ratio by enlarging the depth of a member will in part be compensated by the associated higher selfweight. On the other hand, even a small percentage of prestressed reinforcement produces a significant reduction in deflection. Furthermore, the confidence value of the predicting calculation is increased, since the affect of the dispersion of the tensile strengths of the concrete is reduced.

The cracking situation of the structural concrete has a significant influence on the extent of deformation. Deformation in cracked state can be a multiple of that in uncracked state. The ratio between the deformations in these two states are reduced, however, under long-term loading, since the influence of creep is less in a cracked section that in an uncracked one. In the performance requirements for structural concrete, it must be determined whether these are to apply to short-term or long-term loads. It could also be reasonable to limit the increase in deflection from a specified point in time on. As an example, the long-term deflection from the time of construction is decisive in the occurrence of cracks in partitions. The question of relevant load combinations is also to be considered in individual cases and used as a basis for the performance requirements.

4.2 Crack Control

Crack control means the avoidance of cracks as well as the limitation of crack widths. The original demand that prestressed concrete be crack-free can no longer be maintained in this form. Therefore, controlling crack widths plays a significant role in all types of structural concrete. Here, emphasis is placed on ordinary reinforcement, which should, for this purpose, possess high bond quality. Prestressed reinforcement only has a subordinate significance; it can contribute absolutely nothing when unbonded tendons are used, while its influence is minor with pretensioning or post-tensioning, since its bond strength is low in comparison to that of normal reinforcement.

The measures to be applied are also influenced by the purpose of crack control. Crack control can be applied for reasons of appearance, corrosion protection or tightness with regard to gas or liquid permeability. For appearance and corrosion control, only crack width at the surface are of importance. When discussing impermeability, a distinction must be made between cracks caused by bending and those from separation. Flexion cracks which do not extend over the entire section are tight, as long as the ccompression zone has an adequate thickness of about 20 cm. When dealing with separation cracks, it is also necessary to determine tolerated leakage rates. This is best accomplished by defining such requirements as *completely dry* or *damp spots* or *small puddles tolerated* . Fulfilling such requirements is, on the one hand, dependent on such nominal dimensions as water pressure, wall thickness and crack width, and on the other, by the evaporation rate on the exposed side. To fulfill highest demands, the structure is to be forseen with joints or prestressing tendons, whereby limitation of crack width may also be taken into account for tolerated water penetration.

Separation cracks are often caused by imposed or hindered deformations which are induced by cooling of hydration heat alone, or in conjunction with subsequent shrinkage. Tension forces, however, only occur when shortening caused by the affects mentioned above are partially or totally hindered. For example, in a slab located on the foundation, tension forces can only occur to such an extent as can be introduced by friction along the base. This condition makes it possible to derive the necessary joint distances required to avoid separation cracks. Separation cracks can also occur as flexion cracks when the bending moments change their signs, which means that cracks originating at both surfaces grow together. This occurs, for example, on the inner walls of silos placed in groups. Should separation cracks be hindered by pretensioning, care must be taken to determine the tensile stresses resulting from all influences, regardless of whether these are induced by loads or imposed or hindered deformations.

4.3 Vibrations

Vibrations can have numerous detrimental effects on the serviceability of structures. Their causes are in a close relationship with the function of the structure, and can be induced, for example, by the following variable actions:

Jumping and dancing
Machines
Waves due to wind and water
Rail or road traffic
Construction work such as the driving in of piles
Blasting work

The vibrational behavior or structures can be influenced by the following measures:

Changing the dynamic actions
Changing the natural frequencies by changing the structure's stiffness or the vibrating mass
Increasing the damping

A comparison between the frequency of the action (excitation frequency) and the structure's natural frequencies can be used to assess the situation. It should be taken into consideration that when periodic vibrations are involved, a substantial amount of dynamic stress can be induced when a natural freqency of the structure (the fundamental or a higher frequency), is an integral multiple or an integral fraction of the freqency of the action.

5. SUMMARIZING COMMENTARY

The construction material, structural concrete, covers a broad range - from plain and lightly reinforced concrete to reinforced concrete with and without tendons. The great wealth of variations allows this construction material to be adapted to the relevant performance requirements as no other. To be able to do fulfill these possibilities, it is necessary that the performance requirements be exactly defined. It is hoped that the new attitude toward structural concrete will accelerate the evolution of this construction material.