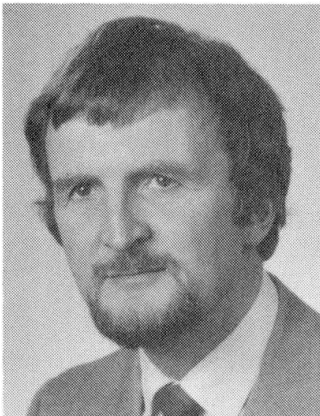# Watertight Concrete Structures

Etanchéité des structures en béton

Wasserundurchlässige Betonkonstruktionen

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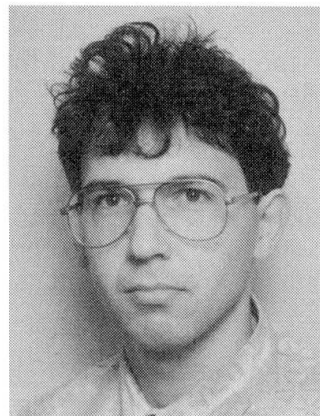Civil Eng.
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SUMMARY

For various projects like basements or subway-tunnels, which are built and remain permanently in the groundwater, watertight concrete structures are of increasing importance. The paper presents general design criteria for such constructions. It deals, in particular, with loading due to restraint under construction and final conditions, waterproof designs and their consideration in different design codes.

RÉSUMÉ

L'étanchéité est d'importance grandissante pour des projets variés, qui tels que fondations et tunnels, restant en permanence sous le niveau de la nappe phréatique. Cet article souligne les critères généraux de dimensionnement concernant ces types de constructions: l'accent est mis sur les contraintes en phase constructive et finale, la conception de l'étanchéité elle-même ainsi que sa prise en compte dans diverses normes de dimensionnement.

ZUSAMMENFASSUNG

Im Rahmen verschiedener Bauaufgaben wie Gründungen und U-Bahn-Tunnel, die in das Grundwasser einbinden, gewinnen wasserdurchlässige Betonkonstruktionen immer mehr an Bedeutung. Im folgenden sollten daher Entwurfskriterien für derartige Bauwerke vorgestellt werden. Insbesondere wird auf die in den verschiedenen Bau- und Endzuständen auftretenden Zwangsbeanspruchungen, auf die Nachweise der Dichtigkeit sowie deren Behandlung in den Normen eingegangen.

1. INTRODUCTION

The production of watertight concrete structures without additional waterproofing provisions is being practised successfully since many years [2], [4]. Projects which need watertight structures may be classified in three groups:

- As protection of structures against underground water penetration in cases in which the ground water level is located above the foundation slab (underground garages, cellars, subway tunnels).
- As protection of underground water against contaminating substances from purification plants, from manure dumps or from catch basins of chemical plants.
- Water reservoirs require a certain grade of impermeability (leakage rate) because of operating conditions, although their contents do not endanger the underground water.

The determination of the impermeability can result from two procedures, which differ on their practical evaluation:

- Limitation of the moisture content at the air side regarding the impermeability criteria:
  - complete dry - dry to a great extent - capillarily soaked -
- Limitation of the amount of moisture penetrated through the cross section (leakage rate).

The permeability or leakage of a buildung can by caused by its materials (because of porosity, that is the concrete texture) or by the construction (because of cracks, improperly performed construction joints or expansion joints, leakages within the range of perforations for installations).

The production of a concrete with enough tight texture is primarily a concrete technological problem. The causes of leakage dependent on the construction can be obviated by means of a corresponding clear construction, that harmonizes optimally with the building function (through states of stress due to loads and restraints which are statically easy to survey and through a practicable construction).
The following report deals mainly with the possible proof and examination of usefulness.

2. STATES OF STRESS

2.1 Causes of the states of stress

The states of stress acting on reinforced concrete structural parts may be classified according to the instant at which they occur and according to their causes. According to the instant of occurrence one may distinguish between:

- states of stress during the construction
- states of stress after the end of the construction

According to the causes one may distinguish between:

- states of stress due to loads
- states of stress due to restraints

Stress resultants due to loads (for example owing to dead load or to traffic load) can be easily calculated in most cases. The realistic calculation of stress resultants due to restraints, however, cause considerable difficulties. The dissipation of the heat of hydration [1], shrinkage, temperature and settlements can be regarded as the main reasons for the appearance of restraint stresses.

2.2 Restraint stress resultants

2.2.1 Calculation

The restraint stresses of a thick structural member of concrete (Fig. 1) often have a non-linear development over the thickness of the structure. These non-linear restraint stresses can be divided into a constant part (shortening by restraint), a linear part (change of curvature by restraint) and a non-linear part (residual stresses). It is characteristic for the state of residual stresses, that these stresses do not create stress resultants.
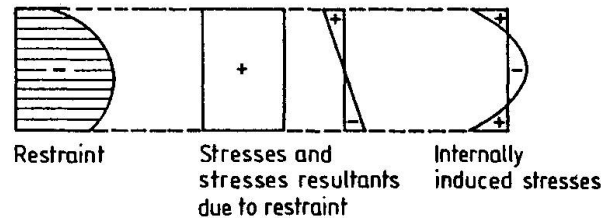

Restraint   Stresses and   Internally
                 stresses resultants   induced stresses
                 due to restraint

Fig. 1 Stress-strain of a thick concrete member due to non-linear restraint

The following denotations are valid for the calculation of the restraint stress resultants:

$$N_{zw} = \epsilon_r \cdot (EA_c)_{ef} \cdot \delta \cdot c_s \quad (1)$$

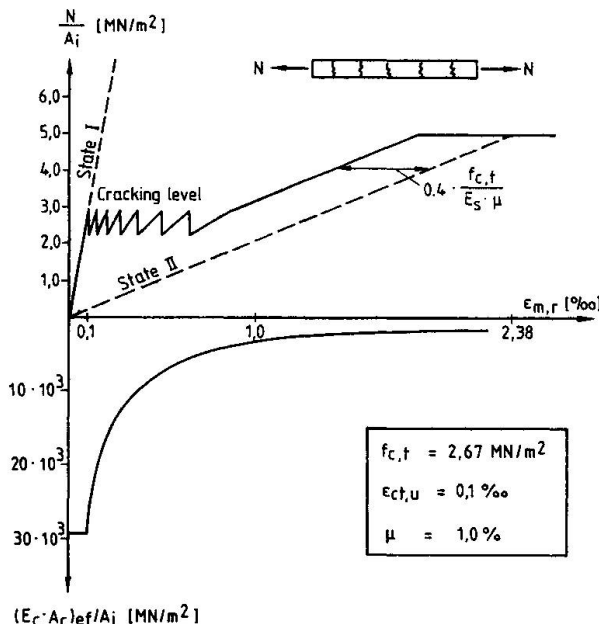$$M_{zw} = \chi_r \cdot (EI_c)_{ef} \cdot \delta \cdot c_s \quad (2)$$

$(EA_c)_{ef}$: effective longitudinal stiffness
$(EI_c)_{ef}$: effective bending stiffness
c_s : reduction of restraint by creep
δ : grade of impediment by the structural member

The effective stiffness used in equations (1) and (2) can be studied clearly by a centrically loaded member in Fig. 2.

Up to the load of the first crack ($\sigma_c = f_{c,t}$) the structural member remains in state I. After that a successive cracking starts. When the fully developed cracking pattern is reached, there is another ascent of the stress - strain - diagram, which is almost parallel to the plain state II, at a distance of $0,4 \cdot f_{c,t}/E_s \cdot \mu$ (tension-stiffening-effect)

f_{ct} : tensile strengh of concrete
ϵ_{ctu} : corresponding strain of concrete
E_s, E_c : modulus of elasticity of steel and of concrete
μ : percentage of reinforcement

Fig. 2 Stress-strain-relationship and effective stiffness of a concrete member under longitudinal force $(A_i = A_c \cdot (1+n \cdot \mu); \ n = E_s/E_c)$

At the final state the restraint effects (change of temperature, settlements) are of minor importance for the constructions, which are mostly box-shaped and bedded to the ground. During the construction however, the restraint effects, such as dissipation of the heat of hydration and shrinkage, are to be analysed more carefully. That is especially important for monolitically connected structures, which are cast however at different times. Regarding the dissipation of the heat of hydration, the calculation of the corresponding restraint stress resultants is very difficult because reliable informations about modulus of elasticity, reduction by creep and coefficient of thermal expansion for new (not matured) concrete are hardly available. An estimation of the restraint forces through shrinkage is possible in form of a difference value for shrinkage at structural components which are cast at different times (foundation slab/walls).

2.2.2 Evaluation of the limits of stress resultants for special structural components

- Regarding the load for first cracking

The upper limit of the restraint stress resultant at the instant of appearance of the first crack can bei determined through the sectional forces of the crack for state I.

$$N^I_{Crack} = A_c \cdot f_{ct,ef} \qquad (3)$$

$$M^I_{Crack} = W_c \cdot f_{ct,ef} \qquad (4)$$

- Regarding the interaction soil - building

For foundation slabs it is possible to get further limitations for the normal force due to restraint considering the effects of frictional forces. In this connection it has to be examined, whether slide of the foundation slab with respect to the soil results or whether a total bond exists. Fig. 3 shows the diagram of the forces at the contact surface with the soil and the forces at the foundation slab in the case of friction, bond and a combination of both effects.

In the case of skidding friction the maximum normal force in the foundation slab results:

$$N_\mu = 1/2 \, \mu \, g \, l_\mu \qquad (5)$$
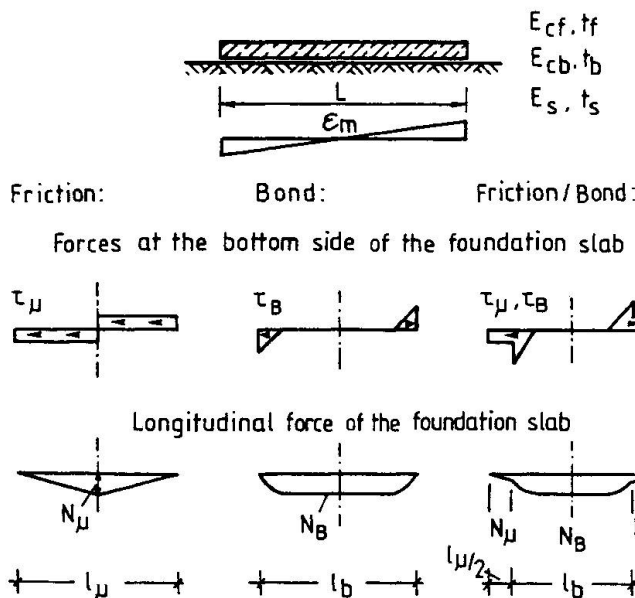
Assuming a total bond between foundation slab and soil the following value results:

$$N_B = \cfrac{\epsilon_m}{\cfrac{1}{E_{cf} \, t_f} + \cfrac{1}{(2 \, E_s \, t_s + E_{cb} \, t_b)}} \qquad (6)$$

Fig. 3 Longitudinal forces due to restraint of a foundation slab

3. PROOF OF WATER TIGHTNESS

3.1 Method of proof

The proof of watertightness is made for the limit state of serviceability. In additon to the demonstration of an available sufficient tight concrete texture, the leakage caused by construction is limited further through the following criteria.

- sufficient depth of the compression zone: $x > x_{nec}$
- limitation of the width of separating cracks: $w < w_{adm}$
- limitation of tensile stresses in concrete: $\sigma_{ct} < f_{ct}/\nu$

3.2 Proof of the depth of the compressive zone

The procedure is based upon the requirement that the resulting depth of the compression zone in working conditions must be greater than the depth of penetration of water in the watertight concrete, which is produced according to technological points of view. The determination of the depth of the compression zone in working conditions for bending with normal forces leads to a cubical equation if linear elastic behaviour is assumed for concrete and for steel.

Determinant parameters:
- the percentage of reinforcement ratio μ_1 / μ_2
- the relative edge distances $d_{1,2}/h$
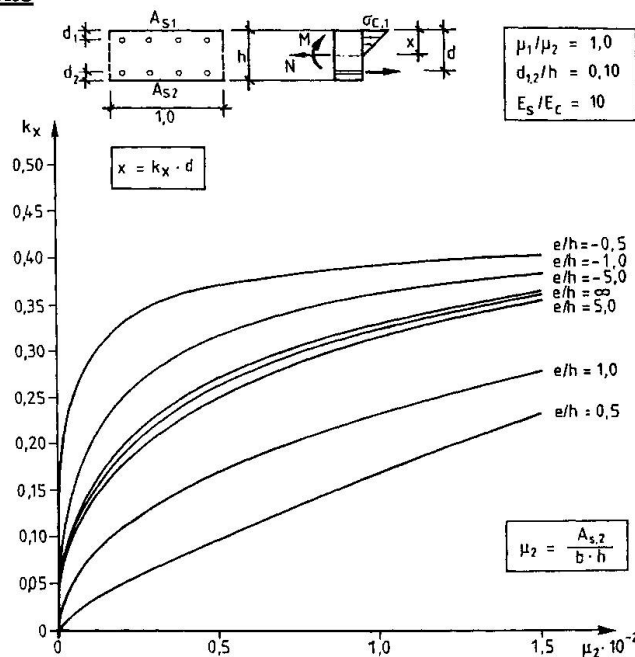- the E-moduli ratio $n = E_s/E_c$
- the relative eccentricity e/h

Fig. 4 Depth of compression zone under servie load

3.3 Proof of the width of crack

Separating cracks are critical with respect to the watertightness of a concrete structure. All national and international standards have renounced to fix an admissible width of crack w_{adm} in relation to watertightness (see paragraph 4). The determination of such a limit value needs the careful examination of the special function of the building and of environment conditions as for example the value of the water pressure acting on the examined structural members. In the references ([3], [4], [5], [7]) however, values for $w_{adm} = 0,1$ to $0,2$ mm are given. There are many theories which calculate the theoretical width of crack at the limit state of serviceability. The principles of equation (7) based on fig. 5 are common to all theories. Based upon this fundamental equation it is possible to control cracking through concrete technological provisions and through the adequate choice of reinforcement (steel stresses, diameters of bars) with minimum steel areas according to the restraint stress resultants given in paragraph 2.

$$w_m = s_{rm} \cdot \epsilon_{sm} \quad (7)$$

w_m : average width of crack
s_{rm} : average distance between cracks
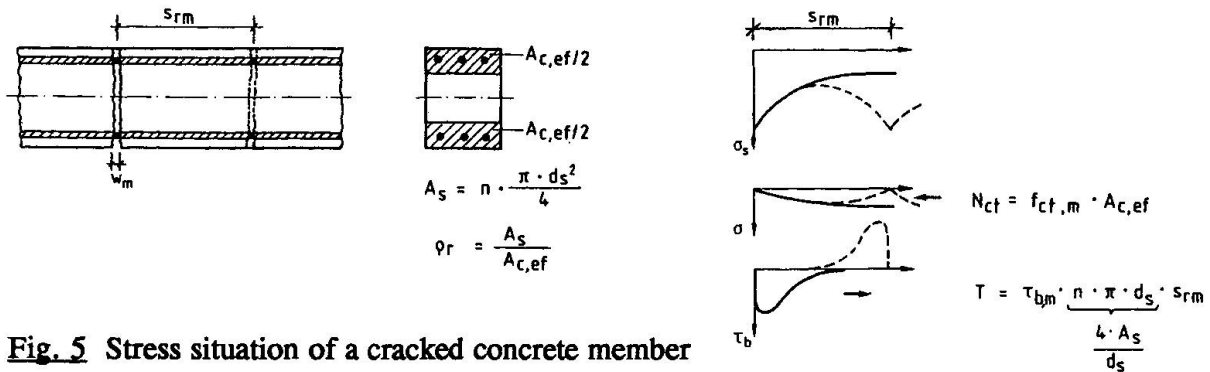ϵ_{sm} : average strain of steel

$$A_s = n \cdot \frac{\pi \cdot d_s^2}{4}$$

$$\varrho_r = \frac{A_s}{A_{c,ef}}$$

$$N_{cf} = f_{cf,m} \cdot A_{c,ef}$$

$$T = \tau_{bm} \cdot \underbrace{\frac{n \cdot \pi \cdot d_s}{4 \cdot A_s}}_{\frac{4 \cdot A_s}{d_s}} \cdot s_{rm}$$

Fig. 5 Stress situation of a cracked concrete member

3.4 Limitation of the concrete tensile stresses in state I

On the one hand this criterium leads to relativ thick strctural members, which are sensible to states of stress due to restraint, and on the other hand the accurate knowledge of the tensile strength of concrete is necessary, although the values show the well known large statistical dispersion. For that reason the proof based on the latter criterium should be given up.

4. COMPARISON OF NATIONAL AND INTERNATIONAL STANDARDS

Whereas in many standards the production of a concrete with tight texture is mentioned, as Tab. 1 shows, nearly all standards which have been studied have renounced to define requirements for a numerical proof of the watertightness. The corresponding proof of limitation of crack width from most standards serves therefore only to insure the durability.

Code/Country/ Year	Water-tightness	Permeability of Concrete	Minimum reinforcement	Crackwidth-Control	Tensile stresses of Concrete
MC - 90/ - / 1990	No	Yes	Yes	Yes	No
EC - 2 / - / 1989	No	Yes	Yes	Yes	No
DIN 1045/D / 1988	No	Yes	Yes	Yes	No
SIA 162/CH/ 1989	Yes	Yes	Yes	Yes	No
CP-110/GB / 1972	No	Yes	Yes	Yes	Yes
B 4200 / A / 1979	No	Yes	No	No	No
ACI 318/USA/1983	No	Yes	Yes	Yes	No

Tab. 1 Comparison of standards

REFERENCES

1. SPRINGENSCHMIDT R., BREITENBÜCHER R:, Investigation of a thermal cracking frame. Material and Structures, No. 23/1990.
2. KRAUS D., Wasserundurchlässiger Beton. VBI-Kolloquium, March 1990.
3. DAFSTB, Erläuterungen zu DIN 1045 - Beton und Stahlbeton, Bemessung und Ausführung, Ausgabe Juli 1988. DAfStb-Heft 400, Januar 1989.
4. DBV, DBV-Merkblatt: Wasserundurchlässige Baukörper aus Beton, Fassung August 1989
5. TROST H., CORDES H., Zur Wasserundurchlässigkeit von Stahlbetonbauteilen mit Trennrissen. Beton- und Stahlbetonbau 84/1989, Heft 3, Seite 60-63.
6. DBV, DBV-Merkblatt: Begrenzung der Rißbildung im Stahlbeton- und Spannbetonbau, Fassung April 1986.
7. WICKE M., Performance Requirements, IABSE-Colloquium "Structural Concrete", April 1990.