Kompetenz für die Wasserstraßen

BAWCode of Practice

Limiting crack openings for stress in massive hydraulic structures (MRZ)

2025 edition

EU Notification No XXX

Note:

Notified in accordance with Directive (EU) 2015/1535 of the European Parliament and of the Council of 9 September 2015 laying down a procedure for the provision of information in the field of technical regulations and of rules on Information Society services (OJ L 241, 17/9/2015, p. 1)

BAW Bundesanstalt für Wasserbau
Kompetenz für die Wasserstraßen

BAW leaflets, recommendations and guidelines

Publisher

Federal Waterways Engineering and Research Institute (BAW)
Kußmaulstraße 17
76187 Karlsruhe

Postfach 21 02 53
76152 Karlsruhe

Tel.: 0721 9726-0

info@baw.de
www.baw.de

Karlsruhe · May 2025 · ISSN 2192-5380

Table of contents Page

List of figures

List of tables

Note: The numbering of the recitals, figures and formulas follows the numbering of the document 'Explanatory notes on the BAW leaflet on the MRZ'. This results in jumps in the numbering of the recitals, figures and formulas in the aforementioned BAW leaflet on the MRZ, as the explanatory document contains additional content that is not required for compact application, and has therefore not been reproduced in this document.

Preliminary remark

The BAW leaflet 'Limiting crack openings limitation for stress in massive hydraulic structures (MRZ)' contains a compact summary of the measurement model for deformation-based limitation of the crack openings caused by strain for massive hydraulic structures.

The MRZ applies to hydraulic structures and structural components thereof made of reinforced concrete. For practical application, engineering simplifications have been made in the fundamentally mechanically-based calculation method, resulting in the scope of application being limited to the following:

- solid cross-sections with a minimum dimension ≥ 0.8 m
- arrangement of the minimum reinforcement close to the edge
- jointless structures with a L/H ratio ≥ 5

When used for thinner cross-sections with a minimum dimension of 0.8 m, the secondary crack formation used in the measurement cannot be assumed per se; therefore, an insufficient crack distribution with larger crack openings may occur. In principle, joint-containing structures with a smaller L/H ratio may come into application, whereby the additional reinforcement savings associated with a lower joint distance are not used here.

Detailed explanations can be found in the 'Explanatory notes to the BAW leaflet on limiting crack openings for strain in massive hydraulic structures' ('Explanatory notes to the MRZ'). The structure of both documents is identical to allow for easy orientation. The numbering of the figures, equations and tables is also taken from the explanatory notes to the MRZ.

This leaflet replaces the BMW leaflet 'Limiting crack openings for early strain in massive hydraulic structures' (MFZ (2011)).

When using the MRZ, the applicable ZTV-W LB 215 and other regulations introduced in the Technical Rules – Waterways (TR-W) must be taken into account.

1 General

In the measurement, a distinction must be made between the calculation value of the crack openings, the crack-opening criterion and the actual crack opening of the structure. This connection can be found in Erläuterungen zum MRZ, Chapter 1.1.

The deflection-compatible stress measurement determines the minimum reinforcement necessary to limit crack openings, taking into account the actual behaviour of the component, including the effective deformations. In contrast, the model in EC2 (DIN EN 1992-1-1:2011-01) is based on the fact that the coercive force cannot exceed the size of the crack span. Background on the nature of the deformation-compatible stress measurement and the difference with the concept in EC2 can be found in Erläuterungen zum MRZ, Chapters 1.2 and 1.3, and in Tue und Schlicke .

2 Construction recommendations

2.1 General recommendations

The deformation-compatible measurement approach generally enables single-layer crack-distributing reinforcement even with large cross-sections. Single-layer reinforcement is to be strived for in any case. Construction measures in the domain of concrete engineering can be availed of for this purpose. For wall sections, reducing the height of the concreting section is an appropriate measure. For base slabs, reducing the hydration heat is effective.

2.2 Concreting to counter lagging

The minimum reinforcement to limit the crack opening for wall sections when concreting against secant piles may be determined using the laying dimensions of the concrete cover on the air side, and may also use this method for the ground side. As regards diaphragm walls and sheet-pile walls, there are three options:

1) creating a tolerance compensation before concreting the wall, and determining of the minimum reinforcement to limit crack openings according to the MRZ;
2) designing the horizontal reinforcement in the target position as cross-reinforcement for the vertical reinforcement, and additionally installing the minimum reinforcement to limit crack openings according to the MRZ in the tolerance range;
3) in areas with very large concrete cover on the air side (¿$80\,mm$), , determining the minimum reinforcement to limit crack openings to exclude reinforcement flow when the crack force of the effective area of the reinforcement is absorbed, taking $h_{c,eff}$ into account the excessive concrete cover ($h_{c,eff} = min\{2.5 \cdot d_1 ; h/2\}$).

2.3 Recesses in massive hydraulic structures

In the transitional area of cross-sectional joints, a modified required minimum reinforcement to limit crack openings $A_{s,min,mod}$ must be determined using the modified number of secondary crack pairs

$n_{mod} = 2 \cdot n$. This is independent of the length of the recess and the expected crack formation. Furthermore, care must be taken to ensure that the remaining wall thickness is ≥ 0.8 m. In addition, a sufficient anchorage length l_{bd} must be provided for the reinforcement. This may be simplified for the conditions of use by using equation (2 .1). The reinforcement must be carried out on the side of the wall that does not have a recess.

$$l_{bd} = \frac{100 \cdot d_s}{f_{ctm}} \tag{2.1}$$

l_{bd}	Anchorage length for conditions of use, in mm
d_s	Reinforcement diameter in mm
f_{ctm}	Mean centric tensile strength of the concrete in N/mm²

2.4 Vertical construction joints in base slabs

In the local area of vertical construction joints in base slabs, parallel to the construction joint, the reinforcement on the underside must be increased to the reinforcement amount on the upper side. The reinforcement need only be increased a distance of ≥ $0.75\,m$ from the vertical construction joint; the length of the local area is determined by:

$$l_{local} = min\left\{2 \cdot h_{Pl}; 0{,}2 \cdot b_{Pl}\right\} \tag{2.2}$$

l_{local}	Length of the local area for vertical construction joints
h_{Pl}	Cross-section height of the base slab
b_{Pl}	Section width of the base slab parallel to the construction joint

2.5 Surface reinforcement in areas without minimum reinforcement

If it results from a measurement that no minimum reinforcement is required to comply with the deformation compatibility if the crack-opening criterion is adhered to, a surface reinforcement must be arranged. In accordance with DIN 19702:2013-02, areas that have free end faces after the construction of the structure also require a surface reinforcement as a minimum structural reinforcement.

$$a_{s,erf} = \rho \cdot A_c \leq a_{s,max}\ \mathrm{cm}^2/\mathrm{m} \tag{2.3}$$

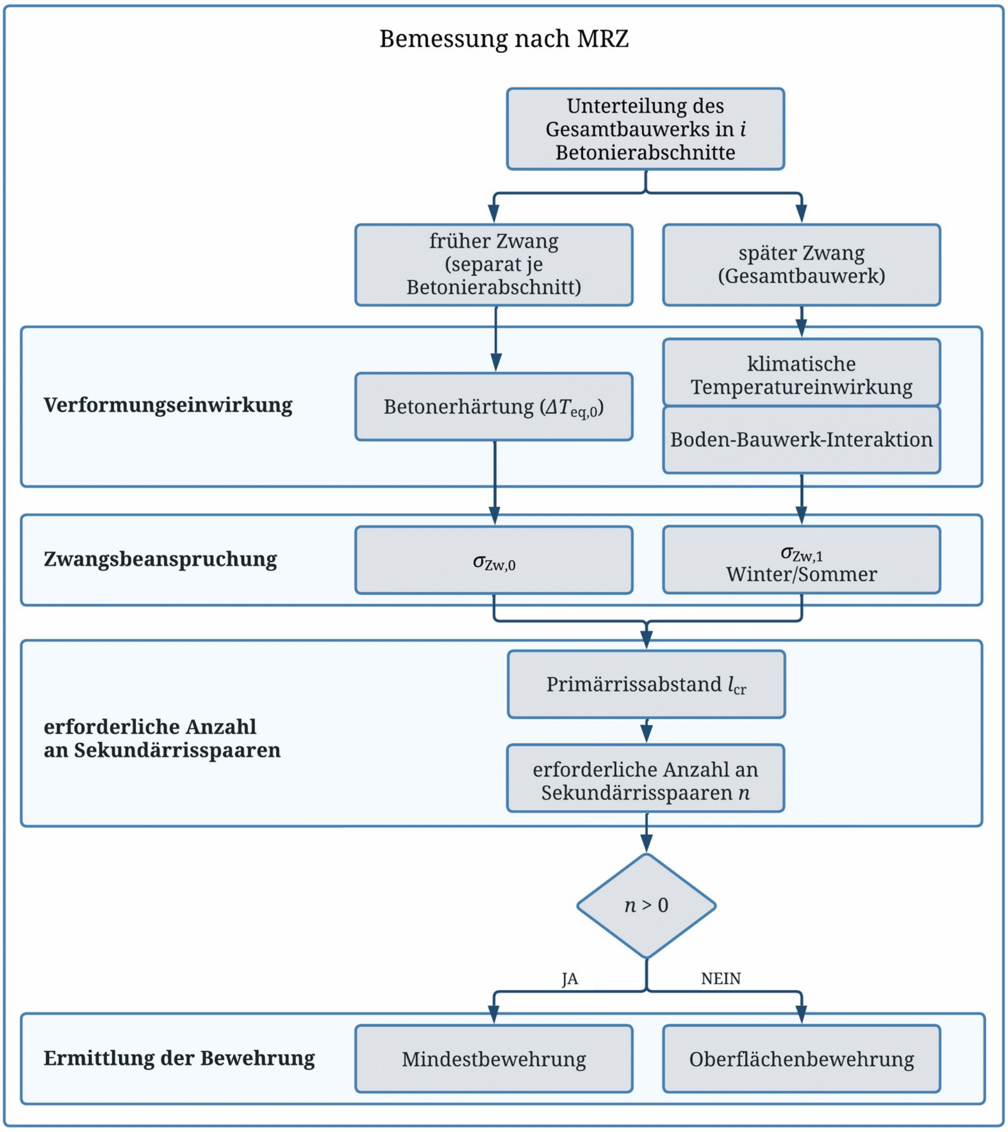
$a_{s,erf}$	minimum reinforcement required per m
A_c	Cross-sectional area of concrete per m
ρ	Calculation value of reinforcement rate For components with a watertightness requirement $\rho = 0.1\,\%$ for components without a watertightness requirement $\rho = 0.06\,\%$
$a_{s,max}$	Maximum value of minimum structural reinforcement, in accordance with DIN 19702:2013-02 With watertightness requirement $a_{s,max} = 25\ \mathrm{cm}^2/\mathrm{m}$ Without watertightness requirement $a_{s,max} = 15\ \mathrm{cm}^2/\mathrm{m}$

The underlying input variable is the cross-sectional area of concrete A_c. In this case, the cross-sectional area of the concrete in the component in question should be used to determine the reinforcement on end faces. The reinforcement quantity determined according to equation (2 .3) must be arranged for each side and direction of laying. The boundary surfaces of disc- and plate-like components must be cross-reinforced.

3 Measurement

3.1 General instructions for measurement in accordance with the MRZ

The deformation-compatible stress measurement aims to mathematically limit crack openings. The measurement concept presented is designed for homogeneous cross-sections. Discontinuity points such as built-in parts, cross-sectional jumps and other inhomogeneities are not explicitly included here and must be taken into account separately. Recommendations in this regard are provided in Chapter 2. The measurement according to the MRZ is subject to a certain system. In order to better illustrate the deformation-compatible stress measurement, Figure 3 .1 contains a flow diagram for the measurement procedure according to the MRZ.



Bemessung nach MRZ	Measurement according to the MRZ
Unterteilung des Gesamtbauwerks in i Betonierabschnitte	Subdivision of the entire structure into i concreting sections
Früher Zwang (separat je Betonierabschnitt, später (Gesamtbauwerk)	Early stress (separate for each concreting section, Later stress (entire structure)

Verformungseinwirkung, Betonierhärtung (ΔTeq0), klimatische Temparatureinwirkung, Boden-Bauwerk-Interaktion	Deformation effect, Concrete hardening (ΔTeq0), Climatic temperature effect, Soil-structure interaction
Zwangsbeanspruchung, *Ozw*0, *Ozw*1 Winter/Sommer	Stress load, *Ozw*0, *Ozw*1 winter/summer
Erforderliche Anzahl an Sekundärrisspaaren, Primärrissabstand *l*cr, erforderliche Anzahl an Sekundärrisspaaren *n*	Required number of secondary crack pairs, primary crack spacing *l*cr, Required number of secondary crack pairs *n*
n > 0, Ja, Nein	*n* > 0, Yes, No
Ermittlung der Bewerhung, Mindestbewehrung, Oberflächenbewehrung	Determination of the reinforcement, Minimum reinforcement, Surface reinforcement

Figure 3.1: Flow diagram for the measurement procedure in accordance with the MRZ

3.2 Material input variables

The material input variables specified in Table 3 .1 are relevant for the measurement.

Table 3.1: Material input variables for the measurement

Abbreviated term	Material input variable
$\Delta T_{adiab,7d}$	Adiabatic temperature increase in the concrete after 7 days (unless otherwise specified, the upper limit according to ZTV-W LB 215 must be used)
α_T	Thermal expansion coefficient of the concrete (may be obtained without more precise knowledge by using $10 \cdot 10^{-6} K^{-1}$)
f_{ctm}	Mean centric tensile strength of the concrete according to DIN EN 1992-1-1, depending on the planned concrete strength class
E_{cm}	Mean modulus of elasticity of the concrete (expressed as E_G, E_{Gl}, E_{Pl} or E_W, depending on the component) according to DIN EN 1992-1-1, depending on the planned concrete strength class

3.3 Stress due to concrete hardening (early stress)

3.3.1 Base slab

3.3.1.1 Deformation effect

The equivalent temperature effect for the base slab $\Delta T_{Mz,eq,0}$ differs depending on the component-typical stress history between bend stress on the upper side and on the underside.

Upper side of base slab

$$\Delta T_{Mz,eq,0} = 0.6 \cdot \left(k_0 \cdot \Delta T_{adiab,7d} + \Delta T_{nom} \right) \tag{3.2}$$

$\Delta T_{Mz,eq,0}$ Linear equivalent temperature effect as a result of concrete hardening

k_0 Base factor for determining the equivalent temperature effect

$k_0 = 0.14 + 0.2 \cdot h_{Pl} \leq 0.74$

$\Delta T_{adiab,7d}$... Adiabatic temperature increase in the concrete after seven days

ΔT_{nom} Tolerance; generally $\Delta T_{nom} = 5$K, unless specific measures are taken to modify the temperature of the concrete when fresh. In the case of fresh concrete cooling in summer, ΔT_{nom} may be reduced by the cooling capacity, in which case the following applies: $\Delta T_{nom} = 5\,K + min\left\{0; \left(T_{FB} - T_0\right) \cdot k_{FB}\right\}$.

k_{FB} Component thickness factor to take into account the difference in temperature between fresh concrete and the ambient temperature

$k_{FB} = 0.1 + 0.25 \cdot \ln\left(h_{Pl}\right)$

T_{FB} Temperature of the fresh concrete at the installation site

T_0 Mean ambient temperature at the installation site on the installation date

h_{Pl} Cross-section height of the base slab in m

Underside of the base slab

$$\Delta T_{Mz,eq,0} = -0.8 \cdot \left(k_0 \cdot \Delta T_{adiab,7d} + 0{,}25 \cdot \Delta T_{nom}\right) \quad (3.3)$$

$\Delta T_{Mz,eq,0}$ Linear equivalent temperature effect as a result of concrete hardening

k_0 Base factor for determining the equivalent temperature effect

$k_0 = 0.20$

$\Delta T_{adiab,7d}$...Adiabatic temperature increase in the concrete after seven days

ΔT_{nom} Tolerance; $\Delta T_{nom} = 5\text{K}$

3.3.1.2 Stress forces

The following applies to the stress forces and the degree of obstruction during the hardening period:

$$\sigma_{Zw,0} = \pm \frac{\alpha_T \cdot \Delta T_{Mz,eq,0} \cdot E_{Pl}}{2} \cdot a_{M,0} \quad (3.4)$$

$$\text{where: } a_{M,0} = \frac{3}{2} \cdot \frac{\gamma_c \cdot l_{BA,eff}^2}{\alpha_T \cdot \left|\Delta T_{Mz,eq,0}\right| \cdot E_{Pl} \cdot h_{Pl}} \le 1 \quad (3.5)$$

$\sigma_{Zw,0}$ Stress forces in the concrete in condition I as a result of concrete hardening

α_T Thermal expansion coefficient of the concrete

$\Delta T_{Mz,eq,0}$ Linear equivalent temperature effect as a result of concrete hardening

E_{Pl} Mean modulus of elasticity of the concrete in the base slab

$a_{M,0}$ General degree of obstruction in the event of bend stress during the hardening period

γ_c Unit weight of the concrete

$l_{BA,eff}$ Effective concreting section length of the base slab in the viewing direction

$l_{BA,eff} = l_{BA,Pl}$ ... for free-standing concreting sections

$l_{BA,eff} = 2 \cdot l_{BA,Pl}$ ... for front-head concreting

$l_{BA,Pl}$ Concreting section length of the base slab in the viewing direction

h_{Pl} Cross-section height of the base slab

3.3.2 Wall sections

The sizes of the stress section of wall are only influenced by one part of the base slab. The maximum activatable cross-section width of the base slab $b_{Pl,eff}$ indicates this sub-area and is determined by:

$$b_{Pl,eff} = b_W + \sum b_{eff,i} \text{ where } b_{eff,i} = min\left(b_{vorh,i}; 1.2 \cdot h_{BA,W}/2\right) \quad (3.6)$$

$b_{Pl,eff}$ Maximum active cross-section width of the base slab (the maximum active cross-section width of the base slab is calculated for the first wall section and retained for all other wall sections)

b_W Cross-section width of the wall

$b_{eff,i}$ Activatable cross-section width of the laterally protruding base plate per side

$b_{vorh,i}$ Existing cross-section width of the laterally protruding base plate per side

$h_{BA,W}$ Concreting section height of the wall or the wall section

3.3.2.1 Deformation effect

The deformation effect due to concrete hardening may be used for wall sections using equation (3.7).

$$\Delta T_{N,eq,0} = -0.7 \cdot (k_0 \cdot \Delta T_{adiab,7d} + \Delta T_{nom}) \quad (3.7)$$

$\Delta T_{N,eq,0}$ Constant equivalent temperature effect due to concrete hardening

k_0 Base factor for determining the equivalent temperature effect

$k_0 = 0.7 - 0.2 / b_W^{0.3}$

$\Delta T_{adiab,7d}$...Adiabatic temperature increase in the concrete after seven days

ΔT_{nom} Tolerance; generally $\Delta T_{nom} = 5$K, unless specific measures are taken to modify the temperature of the concrete when fresh. In the case of fresh concrete cooling in summer, ΔT_{nom} may be reduced by the cooling capacity, in which case the following applies: $\Delta T_{nom} = 5\,K + min\{0\,K; (T_{FB} - T_0) \cdot k_{FB}\}$. In the case of hot concrete in winter, the following applies: If the difference between the fresh concrete and the ambient temperature is > 10 K,the following applies: $\Delta T_{nom} = 5\,K + max\{0\,K; (T_{FB} - T_0 - 10\,K) \cdot k_{FB}\}$.

k_{FB} Component thickness factor to take into account the difference in temperature between fresh concrete and the ambient temperature

$k_{FB} = 1$

T_{FB} Temperature of the fresh concrete at the installation site

T_0 Mean ambient temperature at the installation site on the installation date

b_W Cross-section width of the wall in m

3.3.2.2 Stress forces

$$\sigma_{Zw,0} = -\alpha_T \cdot \Delta T_{N,eq,0} \cdot E_W \cdot a_{N,0} \quad (3.8)$$

$$\text{where: } a_{N,0} = \frac{1}{1 + \frac{E_W \cdot A_W}{\Sigma E_{F,i} A_{F,i}}} \leq 1 \quad (3.9)$$

$\sigma_{Zw,0}$ Stress forces in the concrete in condition I as a result of concrete hardening

α_T Thermal expansion coefficient of the concrete

$\Delta T_{N,eq,0}$ Constant equivalent temperature effect due to concrete hardening

E_W Mean modulus of elasticity of the concrete in the wall section

$a_{N,0}$ General degree of obstruction in the event of centric stress during the hardening period

$\Sigma E_{F,i} A_{F,i}$..Rigidity of the obstructing components i (taking into account the maximum activatable cross-section width of the base slab $b_{Pl,eff}$)

$E_W \cdot A_W$ Rigidity of the wall section

If the obstructing components are to be classified in different concrete compressive strength classes, the modulus of elasticity of the component with the higher strength class may also be used in a simplified manner for the rigidity of the obstructing components.

3.3.3 Base cover

For base covers, the same behaviour as for wall sections is assumed for temperature development and distribution. However, with regard to the obstruction situation, however, complete restraint is assumed.

3.3.3.1 Deformation effect

$$\Delta T_{N,eq,0} = -0.7 \cdot (k_0 \cdot \Delta T_{adiab,7d} + \Delta T_{nom}) \tag{3.10}$$

$\Delta T_{N,eq,0}$ Constant equivalent temperature effect due to concrete hardening
k_0 Base factor for determining the equivalent temperature effect
$k_0 = 0.7 - 0.2 / h_{Gl}^{0.3}$
$\Delta T_{adiab,7d}$...Adiabatic temperature increase in the concrete after seven days
ΔT_{nom} Tolerance; $\Delta T_{nom} = 5\text{K}$
h_{Gl} Cross section height of the base cover in m

3.3.3.2 Stress forces

$$\sigma_{Zw,0} = -\alpha_T \cdot \Delta T_{N,eq,0} \cdot E_{Gl} \cdot a_{N,0} \tag{3.11}$$

$$\text{where: } a_{N,0} = 1 \tag{3.12}$$

$\sigma_{Zw,0}$ Stress forces in the concrete in condition I as a result of concrete hardening
α_T Thermal expansion coefficient of the concrete
$\Delta T_{N,eq,0}$ Constant equivalent temperature effect due to concrete hardening
E_{Gl} Mean modulus of elasticity of the concrete in the base cover
$a_{N,0}$ General degree of obstruction in the event of centric stress during the hardening period

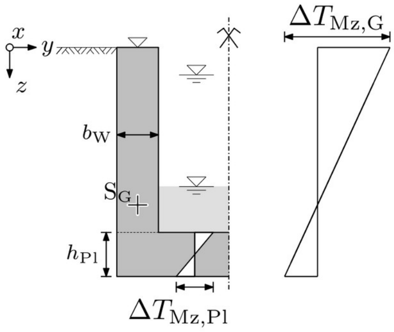
3.4 Stress during the period of use (later stress)

Stress during the period of use is always considered with regard to the entire structure and the entire cross-section.

3.4.1 Deformation effect

3.4.1.1 Climatic effects

Based on the investigations in Turner (2017), the following temperature approaches are recommended:



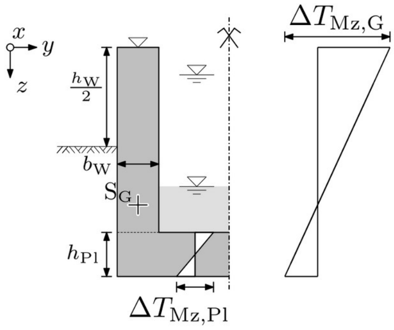
$$\Delta T_{Mz,G} = 5\,K$$ (winter, colder at the top than at the bottom)

$$\Delta T_{Mz,G} = -10\,K$$ (summer, warmer at the top than at the bottom)

$$\Delta T_{Mz,Pl} = min\{3 \cdot h_{Pl}[m]; 12\}\,K$$ (winter)

$$\Delta T_{Mz,Pl} = -min\{3 \cdot h_{Pl}[m]; 12\}\,K$$ (summer)

Figure 3.9: Seasonal temperature effects for water tanks with 0.8 m ≤ b_W, h_{Pl} ≤ 10 m according to Turner (2017)



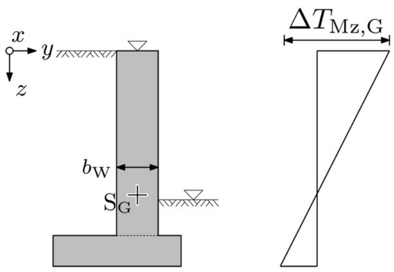
$$\Delta T_{Mz,G} = 10\,K$$ (winter)

$$\Delta T_{Mz,G} = -12\,K$$ (summer)

$$\Delta T_{Mz,Pl} = min\{3 \cdot h_{Pl}[m]; 12\}\,K$$ (winter)

$$\Delta T_{Mz,Pl} = -min\{3 \cdot h_{Pl}[m]; 12\}\,K$$ (summer)

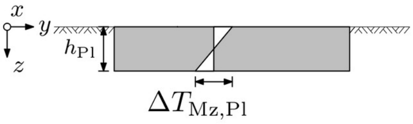
Figure 3.10: Seasonal temperature effects for saving basins with 0.8 m ≤ b_W, h_{Pl} ≤ 10 m according to Turner (2017)



$$\Delta T_{Mz,G} = 10\,K$$ (winter)

$$\Delta T_{Mz,G} = -12\,K$$ (summer)

Figure 3.11: Seasonal temperature effects for retaining walls with 0.8 m ≤ b_W ≤ 10 m according to Turner (2017)



$$\Delta T_{Mz,Pl} = min\{3 \cdot h_{Pl}[m] + 2; 14\}\,K$$ (winter)

$$\Delta T_{Mz,Pl} = -min\{3 \cdot h_{Pl}[m] + 5; 17\}\,K$$ (summer)

Figure 3.12: Seasonal temperature effects for base slabs with 0.8 m ≤ h_{Pl} ≤ 10 m according to Turner (2017)

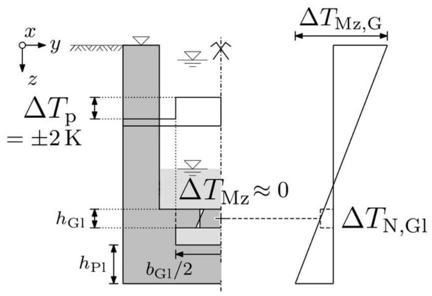


Figure 3.13: Seasonal temperature effects for the base cover

The vertical temperature difference in base covers is small during the hardening period and the period of use. During the period of use, due to the lower mass and thermal inertia of the component, a temperature difference of ΔT_p = ± 2 K from adjacent components should be taken into account. In addition, a constant temperature effect $\Delta T_{N,Gl}$ arises from the linearly variable temperature effect on the entire structure $\Delta T_{Mz,G}$.

The temperature effects for dams can be taken from the temperature effects for water tanks and saving basins. End abutments are deposited on one side, whereby the temperature effect of water tanks is assumed (Figure 3.9). River bridge pillars are surrounded by water on both sides, thereby setting the temperature approaches of a saving basin (Figure 3.10).

In addition to the vertical temperature differences, horizontal temperature differences can be expected in the wall areas. In the context of this leaflet, the horizontal temperature differences should not be taken into account in the calculation.

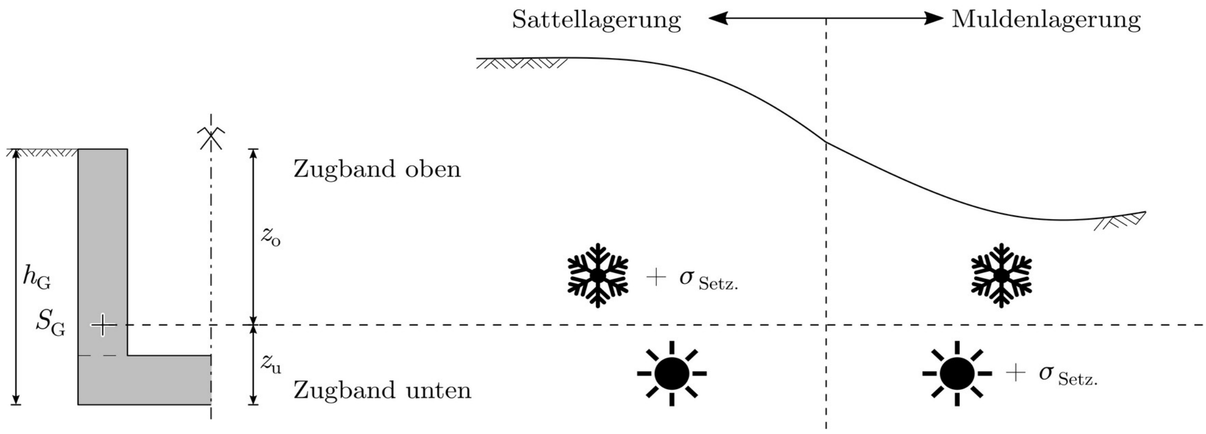
3.4.1.2 Soil-structure interaction

The soil-structure interaction results in additional deformation effects. Sites should be determined in close consultation with the geotechnical engineer. For the verification procedure, the final site trough is imposed on the entire structure. The calculation of the site trough and the resulting stress forces must be carried out at the limit condition of suitability for use.

3.4.2 Stress forces

The climatic influences and the soil-structure interaction lead to bend stress on the entire cross-section during the period of use. For normal longitudinal dimensions of hydraulic structures, the degree of obstruction is a_1 always set at 1 during the period of use.

The stress forces from the period of use are determined for the entire structure and taken into account using a tension rod at the bottom and the top. The climatic stress force resulting from the summer and/or winter cases are applied over the entire length of the structure. The stresses from the soil-structure interaction are adversely superimposed in the relevant areas. Figure 3.15 shows the superimposition of climatic effects and soil-structure interaction. The stress forces resulting from the soil-structure interaction are calculated conservatively to be on the safe side.



Sattellagerung, Muldenlagerung	Anticline stratification, trough stratification
Zugband oben	Top of tension rod
Zugband unten	Bottom of tension rod

Figure 3.15: Superimposition of climatic effects and soil-structure interaction (Ober et al.)

The superimpositions for the stress forces from climatic effects and soil-structure interaction shown schematically in Figure 3.15 are summarised separately below for the bottom of the tension rod and the top of the tension rod.

3.4.2.1 Bottom of the tension rod

The stress forces for the bottom of the tension rod are calculated as follows:

$$\sigma_{Zw,1} = \frac{-\alpha_T \cdot \Delta T_{Mz,G} \cdot E_{Pl}}{h_G} \cdot z_u - \frac{\alpha_T \cdot \Delta T_{Mz,Pl} \cdot E_{Pl}}{2} \cdot a_{M,1} + \sigma_{site} \quad (3.13)$$

$\sigma_{Zw,1}$	Stress forces in the concrete in condition I during the period of use
α_T	Thermal expansion coefficient of the concrete
$\Delta T_{Mz,G}$	Linearly variable temperature effect on the entire structure during the summer period of use
$\Delta T_{Mz,Pl}$	Linearly variable temperature effect on the base slab during the summer period of use
E_{Pl}	Mean modulus of elasticity of the concrete in the base slab
z_u	Distance from the centre of gravity of the entire structure to the lower edge
h_G	Height of the entire structure
$a_{M,1}$	General degree of obstruction in the event of bend stress; $a_{M,1}=1$
σ_{site}	Stress forces below from the site trough in the event of trough stratification ($\sigma_{site} \geq 0$)

3.4.2.2 Top of the tension rod

The stress forces for the top of the tension rod are calculated as follows:

$$\sigma_{Zw,1} = \frac{-\alpha_T \cdot \Delta T_{Mz,G} \cdot E_W}{h_G} \cdot z_o + \sigma_{site} \tag{3.14}$$

$\sigma_{Zw,1}$	Stress forces in the concrete in condition I during the period of use
α_T	Thermal expansion coefficient of the concrete
$\Delta T_{Mz,G}$	Linearly variable temperature effect on the entire structure during the winter period of use
E_W	Mean modulus of elasticity of the concrete in the uppermost wall section
z_o	Distance from the centre of gravity of the entire structure to the upper edge
h_G	Height of the entire structure
σ_{site}	Stress forces below from the site trough in the event of anticline stratification ($\sigma_{site} \geq 0$)

3.5 Required number of secondary crack pairs

3.5.1 Primary crack spacing

3.5.1.1 Base slab

For the upper side and underside of the base slab, the maximum primary crack spacing is determined by an engineer using:

$$l_{cr,Pl} = min\{5.5 \cdot \sqrt{h_{Pl}}; l_{BA,eff}/2\} \tag{3.15}$$

$l_{cr,Pl}$ Geometrically determined primary crack spacing of the base slab in m
h_{Pl} Cross-section height of the base slab in m
$l_{BA,eff}$ Effective concreting section length of the base slab in the viewing direction in m
$l_{BA,eff} = l_{BA,Pl}$ ... for free-standing concreting sections and base-slab sections between two completed sections in the pilgering process
$l_{BA,eff} = 2 \cdot l_{BA,Pl}$ ... for front-head concreting
$l_{BA,Pl}$ Concreting section length of the base slab in the viewing direction in m

3.5.1.2 Wall sections

The primary crack spacing for wall sections must be determined as follows, regardless of the concreting section length:

$$l_{cr,W} = min\{1.2 \cdot h_{BA,W}; l_{BA,W}/2\} \tag{3.16}$$

$l_{cr,W}$ Geometrically determined primary crack spacing of the wall or the wall section
$h_{BA,W}$ Concreting section height of the wall or the wall section
$l_{BA,W}$ Concreting section length of the wall or the wall section

3.5.1.3 Base cover

The spacing of primary cracks in base cover may be determined depending on the cross-section width of the base cover using equation (3.17).

$$l_{cr,Gl} = 0.6 \cdot b_{Gl} \tag{3.17}$$

$l_{cr,Gl}$ Geometrically determined primary crack spacing of the base cover in the longitudinal direction
b_{Gl} Cross-section width of the base cover

3.5.2 Number of secondary crack pairs required

The number of secondary crack pairs required n to achieve deformation compatibility is determined depending on the deformation effect, the primary crack spacing and the crack width criterion. According to Turner (2017), the following generally applies:

$$n = 1.1 \cdot \left(\left(\frac{\sigma_{Zw,0}}{a_0^{0.6}} + \sigma_{Zw,1} \right) \frac{l_{cr}}{E_{cm} \cdot w_k} \cdot k_{BD} - 1 \right) \tag{3.19}$$

where: $k_{BD} = \begin{cases} 0.75 ; \sigma_{Zw} < 2 \cdot f_{ctm} \\ 0.85 ; \sigma_{Zw} \geq 2 \cdot f_{ctm} \end{cases}$

n	Number of secondary crack pairs
$\sigma_{Zw,0}$	Stress forces in the concrete in condition I as a result of concrete hardening
$\sigma_{Zw,1}$	Stress forces in the concrete in condition I during the period of use
l_{cr}	Geometrically determined primary crack spacing
E_{cm}	Mean modulus of elasticity of the concrete
w_k	Crack width criterion
k_{BD}	Coefficient for taking into account the elastic strain of the concrete between the cracks
a_0	General degree of obstruction during the hardening period
f_{ctm}	Mean centric tensile strength of the concrete

The stress forces in the concrete in condition I are determined separately for early and late stress. For the areas of the tension rods on the upper side and underside of the overall structure, the stress forces from early and late stress must be superimposed. In all other areas (wall sections and upper side of the base slab), only early stress must be taken into account.

3.6 Determining the minimum reinforcement required to limit crack width

The minimum reinforcement required to limit crack width is determined in accordance with the scientific findings from the works of Bödefeld (2010) and Turner (2017) using equation (3.20).

$$a_{s,erf} = \sqrt{\frac{d_s \cdot d_1^2 \cdot b^2 \cdot f_{ctm}}{w_k \cdot E_s} \cdot (0.5 + 0.34 \cdot n)} \tag{3.20}$$

$a_{s,erf}$	Minimum reinforcement required
d_s	Reinforcement diameter
d_1	Distance of the centre of gravity of the reinforcement to the edge of the component
b	Cross-sectional width of the cross-section, usually per linear metre
f_{ctm}	Mean centric tensile strength of the concrete
w_k	Crack width criterion
E_s	Modulus of elasticity of the reinforcement steel
n	Number of secondary crack pairs

4 Example: Minimum reinforcement required for a seamless river or canal lock

A detailed example of how to determine the minimum reinforcement required to limit crack width for a seamless river or canal lock is provided in the Erläuterungen zum MRZ in Chapter 4.

Literature

Bödefeld, Jörg (2010): Rissmechanik in dicken Stahlbetonbauteilen bei abfließender Hydratationswärme. Karlsruhe: Bundesanstalt für Wasserbau (Mitteilungsblatt der Bundesanstalt für Wasserbau, 92).

DIN 19702:2013-02: Massivbauwerke im Wasserbau - Tragfähigkeit, Gebrauchstauglichkeit und Dauerhaftigkeit.

DIN EN 1992-1-1: Eurocode 2: Bemessung und Konstruktion von Stahlbeton-und Spannbetontragwerken -Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau.

DIN EN 1992-1-1:2011-01: Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken - Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau; Deutsche Fassung EN 1992-1-1:2004 + AC:2010.

Erläuterungen zum MRZ: Bundesanstalt für Wasserbau (Hrsg.): Erläuterungen zum BAW Merkblatt - Rissbreitenbegrenzung für Zwang in massiven Wasserbauwerken (MRZ). Karlsruhe: Bundesanstalt für Wasserbau (BAW-Merkblätter, -Empfehlungen und -Richtlinien).

MFZ (2011): Bundesanstalt für Wasserbau (BAW) (Hrsg.): BAWMerkblatt Rissbreitenbegrenzung für frühen Zwang (MFZ). Karlsruhe: Bundesanstalt für Wasserbau (BAW) (BAW-Merkblätter, -Empfehlungen und -Richtlinien).

Ober, Julia; Krenn, Christina; Schlicke, Dirk: Bestimmung der Mindestbewehrung mittels verformungskompatiblen Ansatzes unter expliziter Berücksichtigung der Zwangspannungen aus der Boden-Bauwerk-Interaktion bei massiven Wasserbauwerken. In: Schlicke, Krüger et al. (Hrsg.) 2024 – 6. Grazer Betonkolloquium, S. 267–273.

Tue, Nguyen Viet; Schlicke, Dirk: Zwangbeanspruchung und Rissbreitenbeschränkung in Stahlbetonbauteilen auf Grundlage der Verformungskompatibilität. In: Bergmeister, Fingerloos et al. (Hrsg.) 2020 – Beton Kalender 2020, S. 831–887.

Turner, Katrin (2017): Ganzheitliche Betrachtung zur Ermittlung der Mindestbewehrung für fugenlose Wasserbauwerke. Dissertation. Technische Universität Graz, Graz. Institut für Betonbau.

ZTV-W LB 215: Bundesministerium für Digitales und Verkehr (Hrsg.): Zusätzliche Technische Vertragsbedingungen Wasserbau, Wasserbauwerke aus Beton und Stahlbeton - Leistungsbereich 215. Bonn/Berlin: Bundesministerium für Digitales und Verkehr (Zusätzliche Technische Vertragsbedingungen - Wasserbau).