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German Guideline for the Assumption of the Effective Concrete Tensile Strength for Crack Control Due to Early Cracking According to Eurocode 2-2 (DIN EN 1992-2/NA)

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Abstract: Recently, an adjustment of the German national annex of Eurocode 2-1-1 (general rules for design and buildings) has been published, which concerns, amongst others, the assumption of the effective concrete tensile strength for design of the minimum reinforcement for crack control due to early cracking. Cause for this adjustment has been a change in cement composition, in order to reduce CO_2 emissions. The calculation of the minimum reinforcement for crack control has been controversial in Germany since the 1980s and is subject of research and development ever since. Especially, in the particular case of thick and restrained structural members, which frequently occur in traffic infrastructure or hydraulic-related constructions, very large reinforcement quantities result. These large reinforcement quantities endanger the cost-effectiveness of the construction design and the installation feasibility of the reinforcement on the construction site. In addition, these dimensioning results frequently do not correspond to experience of the construction involved persons. The following article gives background information on the topic of design for crack control due to early cracking and explains the reasons for this adjustment. Furthermore, main differences concerning crack control between the general design of buildings and bridge design are being outlined in order to explain why the adjustment of the national annex has not been made for bridge design (Eurocode 2-2).

Keywords: Design of Concrete Structures, Early Restraint, Hydration Heat, Crack Control, Effective Concrete Tensile Strength

1. Introduction

As a result of hydration induced early restraint forces, cracks can occur, particularly in thick structural members such as for example abutment walls (Figure 1). These cracks are frequently observed as an impairment to the appearance or as possible weak points concerning the durability.

Within the manufacture of abutments, the base slabs or the pile caps are usually manufactured first. Several days or weeks later, the abutment walls are concreted as following members. Due to the exothermic process of the cement hydration, heating occurs in the young concrete of the abutment wall, which leads to a temperature difference between the two-member section. In this case, the temperature expansion, leads to only small compressive stresses due to the still low modulus of elasticity of the young concrete at the beginning and its large creep properties, (Figure 2). Since the modulus of elasticity increases quickly with time, corresponding large forced stresses arise as tensile stresses during cooling of the concrete, which lead to crack formation in case of exceeding the tensile strength.

In addition to the restraint forces, non-uniform self-equilibrating stresses occur over the cross-section.

At first, the fresh concrete temperature constant over the cross-section. The heat quantity released during hydration of the cement warms up the core of the concrete member in the initial phase and leads to a corresponding strong temperature rise within the core. Since the temperature of the concrete edge zones adjusts somewhat to ambient temperature, a temperature difference, with a time-dependent, non-linear progress over the cross-section, arises between the concrete core and the concrete edge zones. Simultaneously, the concrete continuously hardens. Due to the higher temperatures, the concrete wants to expand into the core more than into the outer zones, which would lead to different changes in length. Because of their restraint due to the cross-sections remaining plain, internal compression stresses arise with the member heating in the core and in the cooler outer zones internal tensile stress arises. Cracks resulting from this do not affect the whole cross-section, they only occur in the outer zones in the area of the large internal tensile stresses. They are only a few cm deep and are therefore called surface cracks. They close again when the core, cools down and internal compression stress arises in the outer zones. However, if the forced stresses reach the existing tensile strength due to increasing cooling of the abutment wall on the old concrete of the base slab, these surface cracks can be starting points for separating cracks. With regard to particularly larger temperature differences between core and outer zone, two points of times are to be considered concerning the hazard of crack formation:

1. the first few days during heating, when the member is located in the formwork
2. later, when the formwork is removed early at cold air temperatures and if the outer sides are cooled down suddenly.

If the member is left in the formwork for a sufficiently long time, only the first few days are critical. The critical temperature difference between core and outer zone is approx. 15°C in case of thick structural members [1].

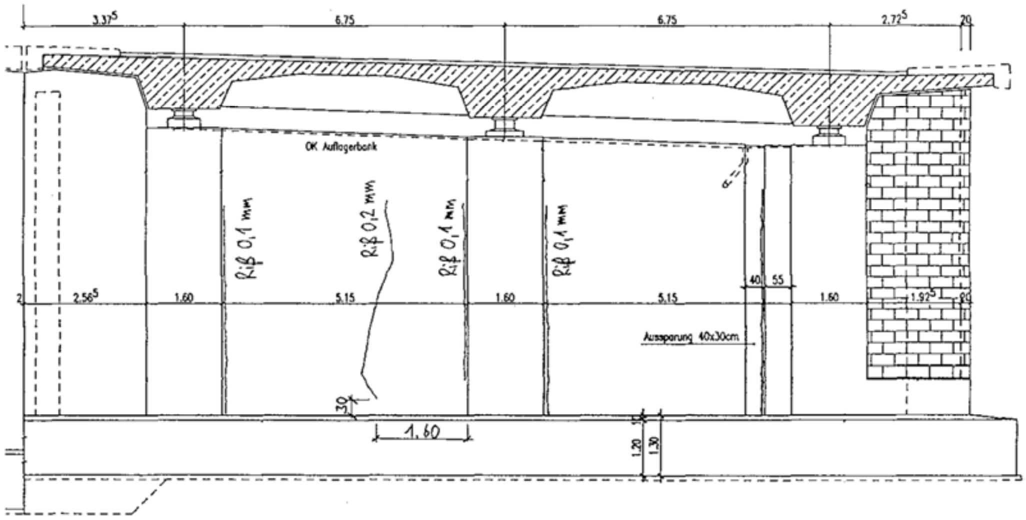


Figure 1. *Typical crack pattern of a restrained abutment wall due to the decrease of temperature induced by hydration heat.*

In addition, the concrete tensile strength in the member is subject to scattering (Figure 2). A crack formation in this early phase can be avoided if the developing tensile strength outpaces the tensile stresses. Similar crack formation takes place in numerous other structural members subjected to stress, such as retaining walls, trough constructions, reservoirs, tunnel constructions or concrete roads and composite structures which are manufactured step by step.

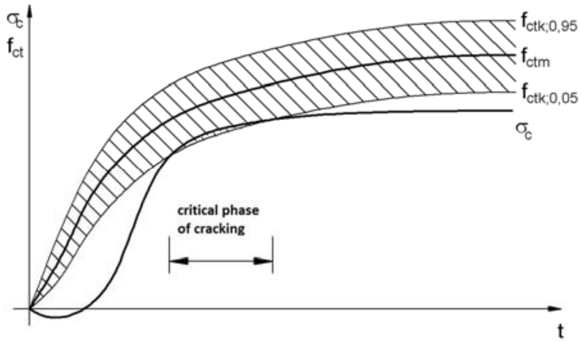


Figure 2. *Development of tensile strength in concrete f_{ctk} and tensile stresses σ_c resulting from hydration heat [4].*

Experience indicates that the possibility of keeping the occurrence of cracks low, or even of avoiding it, are certainly available. This is always striven for client-sided for construction work on transport routes for the optimisation of the quality with regard to durability and appearance. In particular, measures of concrete technology and curing must be used in order to limit Eigen- and restraint forced-stresses, especially in the first few days after the concrete is placed. Because of the exceptional high-quality requirements on construction work for concrete bridges according to DIN EN 1992-2 [2] and DIN EN 1992-2/NA [3], regular use of these possibilities should be made. Through the arrangement of suitable joint constructions (see for example [5]), restrained forced stresses and crack formation can be reduced as well.

However, experience also indicates that cracks as a result of early restraint forcing cannot be avoided with absolute reliability under real construction site conditions. Therefore, a minimum reinforcement is always to be installed as a precaution. In case of crack formation, this reinforcement ensures a limitation of the crack width, so that the serviceability and durability of the member is given.

The calculation of the minimum reinforcement for crack control has been controversial in Germany since the 1980s and is subject of research and development ever since. Especially, in the particular case of thick and restrained structural members, which frequently occur in traffic infrastructure or hydraulic-related constructions, very large reinforcement quantities result. These large reinforcement quantities endanger the cost-effectiveness of the construction design and the installation feasibility of the reinforcement on the construction site. In addition, these dimensioning results frequently do not correspond to experience of the construction involved persons, so that the responsible construction-supervision introduced own regulations according to their empirical values (e.g. [6] and [7]). With the dimensioning concept of Maurer et al [5] based on the ideas of König and Tue [8], a dimensioning concept for the dimensioning of thick structural members was proposed as a solution to this problem, which was recorded in Issues DIN 1045-1:2008 [9] for concrete structures and DIN Fachbericht 102:2009 [10], especially for Concrete Bridges. Significant elements of this approach are the consideration of an effective thickness $h_{c,ef}$ of the outer zone for thick structural members for crack control, and an appropriate construction-practical use of concrete-technological measures (cf. Section 2).

In particular, the introduction of regulations for the limitation of concrete strength development (r-values), decrease both the probability of occurrence of cracks and the requirement on minimum reinforcement due to early restraint force application. This dimensioning concept has been established very successfully in practice for thick structural members. Therefore, these regulations were transferred unchanged by NCI's into the National Appendix DIN EN 1992-2/NA:2013 [3] which is decisive for Germany (Figure 3).

7.3.2 Minimum reinforcement areas (to control cracking)

(102) Unless a more rigorous calculation shows lesser areas to be adequate, the required minimum areas of reinforcement may be calculated as follows. ...

$$A_{s,min} \cdot \sigma_s = k_c \cdot k \cdot f_{ct,eff} \cdot A_{ct}$$

where:

$A_{s,min}$ is the minimum area of reinforcing steel within the tensile zone

A_{ct} is the area of concrete within tensile zone. The tensile zone is that part of the section which is calculated to be in tension just before formation of the first crack

NCI ref. 7.3.2 (102)

$f_{ct,eff}$ the tensile strength of the concrete, effective at the time when the cracks may first be expected to occur. The mean value of the tensile strength f_{ctm} is to be used for $f_{ct,eff}$ in case of this verification. The strength class, which is to be expected with the occurrence of the cracks, is to be applied in this case. In many cases, e.g. if the restraint force arises from the outflow of the hydration heat, the crack formation in the first 3 to 5 days after the placement of the concrete can depend on the environmental conditions that arise, the shape of the member and the type the formwork. In this case, the concrete tensile strength $f_{ct,eff}$ should be set to 50% of the mean tensile strength after 28 days, provided that a more precise verification is not implemented. If this assumption is made, the strength development r = f_{cm2} / f_{cm28} of the concrete is to limited to the following values:

— $r \leq 0.30$ in case of concreting under summer temperatures

— $r \leq 0.50$ in case of concreting under winter conditions

This is to be indicated on the drawings.

For compliance with these limits, in case of concrete strength Class ≥ C30/37, the time for verification of the strength class may be arranged for a later time (e.g. 56 days).

When, in special cases e.g. for the acceleration of the construction sequence, a faster strength development is required, the concrete tensile strength $f_{ct,eff}$ is to be increased correspondingly.

If the time of crack formation cannot be stipulated with certainty within the first 28 days, a minimum tensile strength of 3.0 N/mm² should be assumed for standard concrete.

k is the coefficient for the consideration of non-linear distributed concrete tensile stresses and further crack-force reducing influences. Modified values for k are indicated below for different cases:

a) Tensile stresses due to forces caused in the member itself (e.g. Eigen-stresses due to outflow of hydration heat):

k = 0.8 for members with $h \leq 300$ mm;

k = 0.5 for members with $h \geq 800$ mm;

Intermediate values may be interpolated; for h the smaller value of height or width of the cross-section is to be applied;

b)- ...

NCI ref. 7.3.2

(NA,106) In case of thicker structural members, the minimum reinforcement under centric restraint force for crack control may be calculated for each member side, considering an effective outer zone $A_{c,eff}$ with Equation (NA.7.5.1):

$$A_{s,min} = f_{ct,eff} \cdot A_{c,eff} / \sigma_s \geq k \cdot f_{ct,eff} \cdot A_{ct} / f_{yk} \qquad \text{(NA.7.5.1)}$$

where:

$A_{c,eff}$ is the area of influence of the reinforcement according to Fig. NA.7.1d: $A_{c,eff} = h_{c,ef} \cdot b$;
A_{ct} is the area of the tensile zone per member side with $A_{ct} = 0.5 \cdot h \cdot b$.

The maximum bar diameter Φ_s installed in the member must be modified depending on the effective concrete tensile strength $f_{ct,eff}$ as follows:

$$\phi_s = \phi_s^* \cdot \frac{f_{ct,eff}}{2{,}9} \quad resp. \quad \phi_s^* = \phi_s \cdot \frac{2{,}9}{f_{ct,eff}} \qquad \text{(NA.7.5.2)}$$

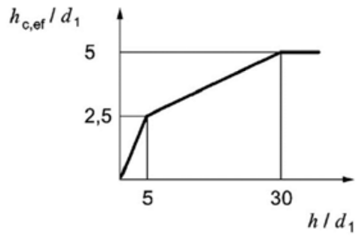
The absolute value of the maximum steel stress permitted in the reinforcement in equation (NA.7.5.1) depends on Φ_s^* as follows:

$$\sigma_s = \sqrt{w_k \cdot 3{,}48 \cdot 10^6 / \sigma_s^*}$$

(NA,107) If slowly hardening concrete with $r \leq 0.3$ is used (generally with thicker structural members), the minimum reinforcement may be reduced by a factor 0.85. The general conditions of the application prerequisites for the reinforcement decrease are then to be stipulated in the working documentation.

REMARK: Characteristic value for the strength development of the concrete $r = f_{cm2} / f_{cm28}$ according to DIN EN 206-1.

NCI ref. 7.3.2; Fig. 7.1



$d_1 = (h - d)$

Fig. NA.7.1d) Increase of the height $h_{c,ef}$ of the area of influence of the reinforcement with increasing component thickness (pure tension)
h is the overall depth of the section
d is the effective depth of the centroid of the reinforcement

Figure 3. *German design regulations for crack control due to hydration induced restraint forces in DIN EN 1992-2 and DIN 1992-2/NA for concrete bridges.*

In past years, changes to concrete ingredients were an occasion for the verification of the above described dimensioning concept. For the design of the minimum reinforcement for crack control, changes of the cement, subject to specifications for the reduction of CO_2 emissions in manufacture, as well as changes in case of concrete mixtures, can be mentioned. In particularly, these are plasticizers for flowing concrete, which can contribute to the acceleration of the strength development and to noticeable increases in the hydration heat development of the concrete.

Ten years ago, CEM I Portland cement in the strength class 32.5 r was widely distributed. Meanwhile, this cement only constitutes a small part of cement production in Germany. Today CEM I in the strength class 42.5 r is mainly available. This results from the trend towards cement production with higher fineness of the Portland cement clinker. The finer the clinker is milled, the more rapidly it reacts with the mixing water to hardened cement paste, the faster the strength and modulus of elasticity development and the higher the strength after 28 days, so that savings in the cement quantity required can result. The reduction of CO_2 emissions is a reason for this development in cement production, where it is additionally favourable when Portland cement clinker can be replaced through other cement components, such as e.g. specially processed slag sand meal, fly ash, oil shale, limestone powder or combinations. So that the strength class of such cement from several cement components remains similar to that of a CEM I Portland cement, finely ground clinker is required for their manufacture.

Consequently, it can be determined that CEM I 42.5 r Portland cement, as well as CEM II/B-S 42.5 N Portland blast furnace cement, CEM II/A-T Portland slate cement and CEM II/A-LL Portland limestone cement of strength class 32.5 r, occupy the greatest market share in Germany at this time [11].

The blast-furnace cements CEM III/A well-proven in thick structural members, with more than 50% mass content slag sand and CEM III/B of strength class 32.5 N, today indicate a comparatively small market share. Here the trend is towards CEM-III/A cements of strength class 42.5 N, which do not always indicate a comparably slow development of strength and modulus of elasticity like the well-proven CEM-III/B cements [11].

The requirements on concrete composition also make a further contribution to the faster strength development of concrete, depending on the exposure classes, in accordance with DIN EN 1992-1-1. Since the introduction of EN 206-1 in association with the German code DIN 1045-2, only concretes with reduced w/z-values are admissible. With decreasing w/z-value, the strength of concrete increases. In case of roadworks according to DIN EN 1992-2 and ZTV-ING [12], this does not take effect because, at that time, the requirements based on long-standing experience were transferred in accordance with ZTV-K [7] for concrete with exposure classes XD2, XF2 and XF4 into ZTV-ING. With that, the w/z-values remained unchanged.

These current developments in cement and concrete manufacture have indicated an increase of early strength and hydration thermal development. Consequently, with the above-described deformation-restrained structural members, the probability of occurrence of cracks and the quantity of required minimum reinforcement has also increased due to early stress force. This effect opposes the original objective of the reduction of CO_2 emissions and the improvement of sustainability through the additional outlay for reinforcing steel. As a result, these developments led also to the adaptation of the German National Appendix DIN EN 1992-1-1/NA for the area of application of general building construction [1], [13].

In the following contribution it is examined whether adaptations, as a result of the described new general conditions in cement production also with the National DIN EN Appendix 1992-2/NA "Concrete bridges" valid for Germany, are required. It is to be considered here that, for structures for traffic routes according to the German regulatory specifications DIN EN 1992-2/NA and ZTV-ING, special concrete compositions and special dimensioning and design regulations have to be applied for a reduction of the restraint forced stresses, as is represented in the following.

2. Measures for Decreasing the Early Restraint and Design of the Minimum Reinforcement

2.1. Measures of Concrete Technology and Curing

If the contraction of the newly concreted member due to cooling down is restrained, tensile stresses result in the young concrete from restraint with increasing modulus of elasticity. In case of early and fast cooling, this results in the high probability of crack formation, cf. Figure 2. Therefore, it should be ensured that the temperature rise in the member remains as low as possible (concrete-technological measures), the concrete does not cool down too fast or non-uniformly (measures of curing) and the subsequent shrinkage of the concrete remains low.

The following measures serve generally for the reduction of the temperature rise and the time-related stretching of the restrained force stressing in the early concrete age. Restraint force induced stresses, are in part reduced by creeping of the concrete (relaxation). A low temperature of fresh concrete has a favourable effect, where the absolute value of the temperature in the core is limited. During subsequent cooling, lower stresses due to restrain arise.

Measures of concrete technology

1. Utilisation and design of concrete mixtures with slower strength development and lower hydration heat development, according to the climatic conditions to be expected (as a limitation scale the r-values of the concrete can be used, e.g. in accordance with DIN EN 206-1 in association with the German standard DIN 1045-2)
2. Lowering the cement content as far as possible
3. Lowering the w/z-value only as far as necessary
4. Lowering the fresh concrete temperature e.g. through concreting in the evening or at night

Measures for curing

1. Limitation of the temperature difference over the cross-sectional thickness in the member, e.g. by leaving it in the formwork for a longer period of time or through appropriate arrangement of a thermal-insulating covering, if the climatic conditions require this and also if surface cracks from Eigen stresses must be avoided.
2. Thermal-insulating measures are also required for protection of the concrete surface against frost in the early hardening phase

The time-related temperature development in concrete members is determined, not only by the thermal development during hydration in the member interior (design of concrete mixture, thickness of the member), but also as a function of the heat outflow and inflow at the member surface. The following influence parameters are definitive in this case for the interchange of heat at the member surface: Ambient temperature, solar radiation and wind speed [1]. For the compensation of these influences, different concrete mixtures for winter and summer are provided in the regulations DIN EN 1992-2/NA, which are clearly defined concrete-technologically using values for the concrete strength development ($r = f_{cm2}/f_{cm28}$). This specification of upper limits for the concrete strength development in the regulatory specification DIN EN 1992-2/NA is of decisive importance.

In addition, these influences can also be countered by suitable curing methods. Thus, a critical stress-generating cooling of the concrete surface at night can be prevented by thermal-insulating measures to avoid initial surface cracks in the outer zones, which would be a starting point for later separating cracks. In this way, a more uniform cooling of the concrete is achieved over the cross-section and critical temperature differences in the cross-section are avoided. A sufficiently large concrete tensile strength is available after some days to take up the forced tensile stresses. A time-related stretching of the hardening and cooling procedure through the utilisation of concrete with low hydration heat development, in association with slow strength development, in accordance with the technical regulatory specification for the implementation of concrete supporting structures DIN EN 13670, DIN 1045-3:2012 and ZTV-ING Part 3, Section 2 [12], requires a correspondingly longer curing duration. Simultaneously, stress relaxation is realised in the concrete by creep.

In tunnel construction, the curing is implemented by special post-treatment vehicles for curing [12]. The strength development of the concrete is accelerated by targeted adaptation of temperature and humidity on the concrete surface, without increasing the forced stresses inappropriately. As well as this, moisture and temperature control cause a shortening of the minimum post-treatment duration, so that the curing can be ended faster without losses in durability. Furthermore, as a result of the arrangement of the post-treatment vehicles for curing, the temperature difference in the concrete cross-section is kept low and therefore a rapid cooling down of the outer zones is prevented.

Experience indicates that the described measures contribute decisively to the reduction of crack formation due to early forced stressing. In addition, together with the construction-related measures of a structural joint arrangement (Chapter 2.3), they reduce the quantity of minimum reinforcement required for the limitation of crack widths, as is explained below.

2.2. Design of the Minimum Reinforcement for Crack Control due to Early Restraint

Since experience shows that crack formation in concrete induced by restrain cannot be avoided with certainty, a minimum reinforcement for crack control is usually provided for the limitation of crack widths. In this case, it is appropriate to differentiate between thin and thick structural members.

In case of thin structural members under pure tension, the area of influence of the reinforcement crossing the crack includes the entire tension zone according to the uncracked section. The cracks run through the entire cross-section as separating cracks (Figure 4). The tensile stresses, which arise from an existing crack, propagate with an inclination of 1:2 and are distributed uniformly over the cross-section at the end of the transmission length.

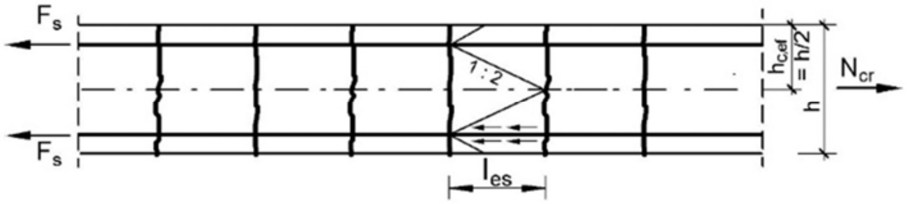


Figure 4. *Thin Member with separation cracks under pure tension.*

In the case of thick structural members, the crack mechanism is characterised in that, as well as the continuous primary separating cracks in the outer zone, secondary cracks arise in addition (Figure 5) since, at the end to the transmission length l_{es}, the necessary tensile stresses for the formation of the next continuous separating crack are not yet distributed uniformly over the entire cross-section width, rather are concentrated in the outer zone.

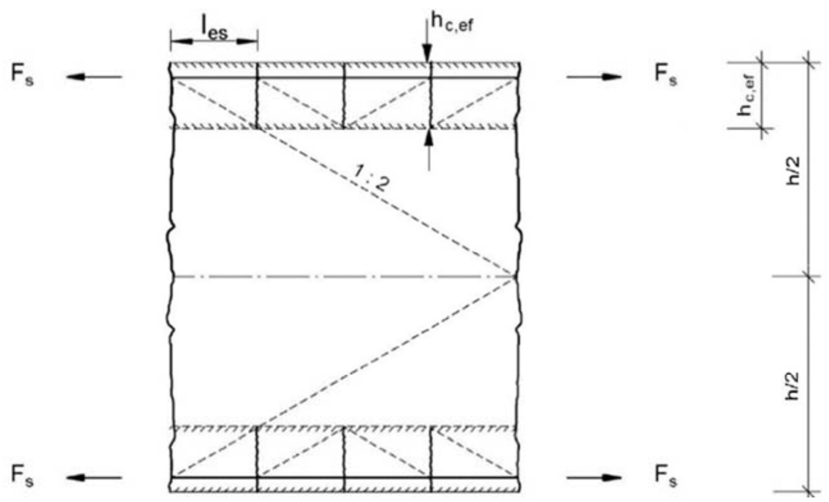


Figure 5. *Mechanism of cracking in thick structural members with secondary cracks between two primary separation cracks..*

In case of thin structural members, the minimum reinforcement for the limitation of crack width may be determined according to equation 1 as written in DIN EN 1992-2/NA, 7.3.2., Equation (7.1).

$$A_{s,min} \cdot \sigma_s = k_c \cdot k \cdot f_{ct,eff} \cdot A_{ct} \tag{1}$$

For the determination of the crack force within thicker structural members required for the formation of secondary cracks, the idealised model of the effective concrete surface at the edge of the cross-section in the area of influence of the reinforcement according to equation 2 is referred to.

$$A_{c,eff} = h_{c,ef} \cdot b \tag{2}$$

It is to be ensured in addition that, with the formation of a primary separating crack, the reinforcement does not yield.

In case of thicker structural members, the minimum reinforcement may be calculated with equation 3 (NA.7.5.1) under centric force stressing for the limitation of crack widths per member side, considering the effective outer zone $A_{c,eff}$ per member side.

$$A_{s,min} = f_{ct,eff} \cdot \frac{A_{c,eff}}{\sigma_s} \geq k \cdot f_{ct,eff} \cdot \frac{A_{ct}}{f_{yk}} \quad (3)$$

where

1. $A_{c,eff}$ is the effective area of concrete in tension surrounding the reinforcement of depth, $h_{c,ef}$ according to Figure 6

$$A_{c,eff} = h_{c,ef} \cdot b;$$

2. A_{ct} is the area of the concrete within tensile zone before formation of a separation crack due to pure tension (half member side)

$$A_{ct} = 0.5 \cdot h \cdot b.$$

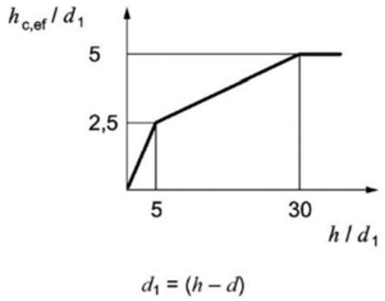


Figure 6. *Effective height $h_{c,ef}$ of concrete in tension surrounding the reinforcement, depending on member thickness (pure tension).*

The effective tensile strength of the concrete in both equations at the time considered is $f_{ct,eff}$, where the mean value of the tensile strength f_{ctm} is to be used If the definitive force stressing arises from the outflow of the hydration heat, the crack formation can arise as early as in the first 3 to 5 days (in case of thicker structural members also longer). If no further precise verification is implemented, the concrete tensile strength, according to applicable regulatory specification DIN EN 1992-2/NA, may be set to $f_{ct,eff} = 0.5 f_{ctm}$ after 28 days. Prerequisite for this, in accordance with DIN EN 1992-2/NA, is that concrete with slow strength development is used (cf. Section 2.1). This is to be limited as follows:

1. $r \leq 0.30$ with concreting under summer temperatures
2. $r \leq 0.50$ with concreting under winter temperatures

with $r = f_{cm2} / f_{cm28}$ as a characteristic value for the strength development of the concrete, according to DIN EN 206- 1 in association with DIN 1045-2.

The exothermic hydration process of the fresh concrete takes place far more slowly under winter conditions and the hydration heat development in the construction work is far lower as a result. The r-value determined under laboratory conditions should therefore be approved to 0.5 for these in-service conditions.

Winter temperatures are considered to be present if daytime temperatures sink below 0°C and summer temperatures increase above 25°C. Outside of summer, r may exceed the value 0.3 somewhat.

The above-designated limit values for the characteristic value r have proved themselves well in practice. For the determination of r, the time for the verification of the strength class may be arranged as e.g. 56 days as an exceptional case at a later time. The verification of the concrete strength class at an even higher age than 56 days is impracticable in the normal case for cast-in-place concrete constructions and therefore, according to ZTV-ING, is not admissible. If use is made of the extension of the verification time period, the slower strength development of the concrete associated with this is to be considered as early as in the design phase. Thus, for example, effects on the schedule planning of initial tests and suitability tests, as well as concreting plan, formwork-boarding periods, curing duration and construction sequence, are to be tracked [12].

If slow hardening concretes are used with the designated r-values (normal case with thicker structural members), as a simplification the minimum reinforcement may be additionally reduced with a factor 0.85. The decisive influence for the crack formation is the temperature difference between T_{max} in the young concrete and the temperature T_{min} at the time point when cracks may be expected to occur. Therefore, concreting in the cool season with relatively low fresh concrete temperatures, unlike concreting in the warm season, from experience means lower crack formation.

The smaller the temperature difference after exceeding the maximum temperature, up to the reaching the equivalence temperature with outflow of the hydration heat, the lower is the opening of an individual crack with the same reinforcement in case of this deformation-controlled process, as indicated in Figure 7 in the example of a restrained wall. In the first place, all measures, which lead to a reduction of this temperature difference, therefore take effect favourably. Favoured are slowly hardening concretes with low hydration heat development and minimum low fresh concrete temperature.

In the case of sufficiently designed reinforcement for crack control, this can distribute the deformations to further secondary cracks with innocuous crack width. It involves a geometrical problem of compatibility. In this case, starting from the primary crack, over the reinforcement, so much tensile force must be initiated that the secondary cracks can form themselves in the outer zone.

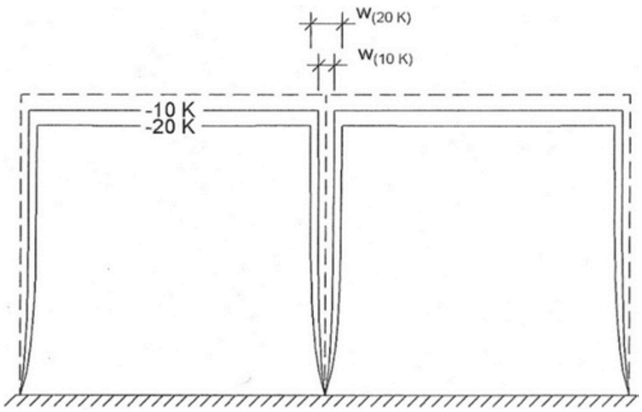


Figure 7. *Impact of the drop of temperature ΔT on the crack width.*

The general conditions of the application prerequisites for reinforcement decrease at a minimum, in particular the r-values taken as a basis, are to be indicated definitively in the working plans. In accordance with DIN EN 1992-2/NA section 2.8, these must also include the building specification and be explained.

However, if a faster strength development is necessary due to the construction sequence (e.g. acceleration of the time taking down formwork), so that the above-recommended r-values cannot be kept, the corresponding values of the concrete tensile strength $f_{ct,eff}$ are also to be increased with the large r-values. This is e.g. frequently the case when, according to DIN EN 1992-2, 7.3.2 (NA,110), in superstructures which are manufactured span by span, parallel to the working joint to control restraint cracking due to hydration heat, the minimum reinforcement has to be designed and arranged in the new concreted section.

In these cases, in particular against the background of the described current developments with usual cement, the total approach $f_{ct,eff} = 0.5.f_{ctm}$ in case of concrete constructions according to DIN EN 1992-2 is not to be ·presupposed. Then the concrete tensile strength $f_{ct,eff}$ taken as a basis, in accordance with DIN EN 1992-2/NA, Section 7.3.2, NCI ref. (102), is to be correspondingly increased. The following Section 2.4 gives more detailed recommendations regarding this. The latter led to the A1-Issue DIN EN 1992-1-1/NA December 2015 [12] for structural members of general building construction in Germany.

2.3. Influence of Expansion Joints

In the case of traffic structures according to DIN EN 1992-2 and ZTV-ING, which are subject to recurring annual and daytime-related temperature changes, the arrangement of joints for the limitation of the restraint forced stresses has traditionally been of very great importance. With appropriate spacing, they can effectively reduce the probability of the occurrence of restraint cracking and the required minimum reinforcement for crack control.

If structural members cannot deform freely under imposed deformation, restraint forces and stresses arise. On reaching the tensile strength of the concrete, crack formation results, as already represented in the introduction. Restraint force stressing due to the outflow of the hydration heat is "early restraint force" and a main cause for these cracks. However, under certain circumstances cracks can also arise at a later time, for example due to year-related temperature deformations, subsidence or time-dependent concrete characteristics, such as e.g. non-completed shrinkage deformations. In case of tunnel frames or tunnel internal shells which are deformation-restrained in a special manner, computation values are therefore indicated for temperature extremes in the concrete and road surfaces for the determination of the effects of late force stressing [12].

With the determination of the minimum reinforcement, it is assumed in general that the tensile stresses in the concrete are relocated to the reinforcement immediately after the crack formation. The distribution of the restraint tensile stresses is very strongly dependent on the l/h ratio of the wall (Figure 8). While restraint stresses in case of short walls (e.g. l/h = 1) only build up in the lower third, long walls (e.g. l/h = 8) are almost constantly stressed over the high progressing tensile stresses. At the free edges, a more favourable stress distribution results with far lower restraint stresses.

The l/h ratio and thus the stress distribution can be influenced favourably through the arrangement of suitable expansion joint spacing. This is used e.g. by the regulation for the arrangement of structural joints in ZTV-ING, Part 3, Section 3 [12], since, with a prescribed joint separation distance of 6 - 8 m for most abutment walls, an l/h ratio between 1.0 and 2.0 results, cf. Figure 8. According to the same principle, the restraint forced stresses are limited per block length through arrangement of expansion joints in tunnel and trough constructions.

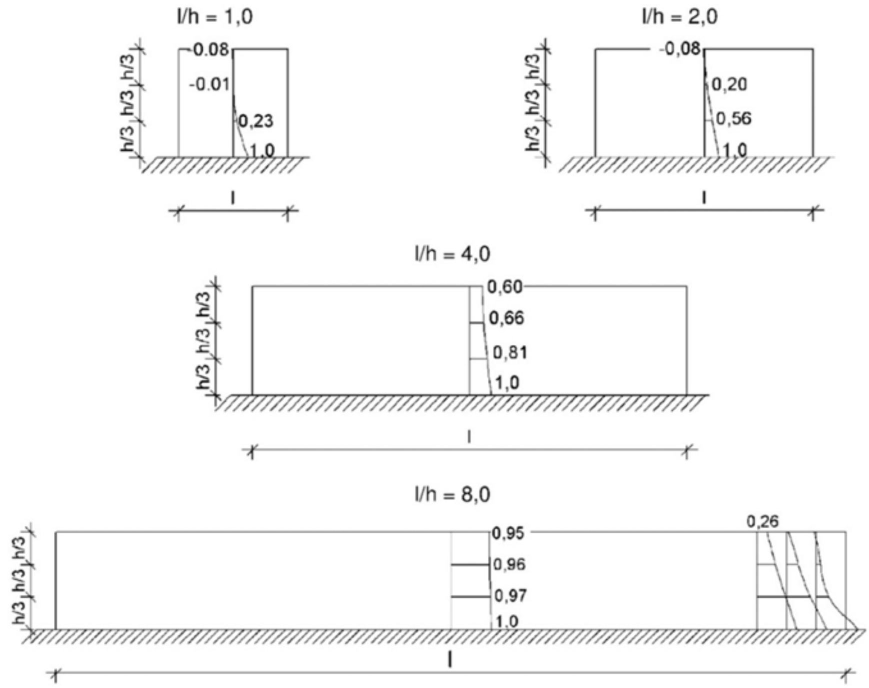


Figure 8. *Stress distribution for base wall restraint at l/2 dependent on l/h due to cooling of the wall.*

The largest tensile stress occurs in l/2 at the wall footing. The stress there reaches the value according to equation 4.

$$1{,}0 \cdot \sigma_c = f_{ct,eff} \quad (4)$$

This stress distribution can be taken as a basis of calculation for the crack formation. The minimum reinforcement is to be designed according to this at the wall footing for the crack section variable and can be graduated in agreement with DIN EN 1992-2 NCI to 7.3.2 (102) over the wall height, according to the progress of the concrete tensile stresses.

A possible reinforcement classification over the wall height is represented as an example in Figure 9:

1. Ratio l/h = 3
2. Selected grading of the horizontal wall reinforcement for the limitation of the crack widths to h/2

The minimum reinforcement may be adapted to the restraint stress distribution. It does not have to be inserted over the full wall height. If the elastic behaviour of the ground is additionally considered, a further reduction of the required minimum reinforcement results.

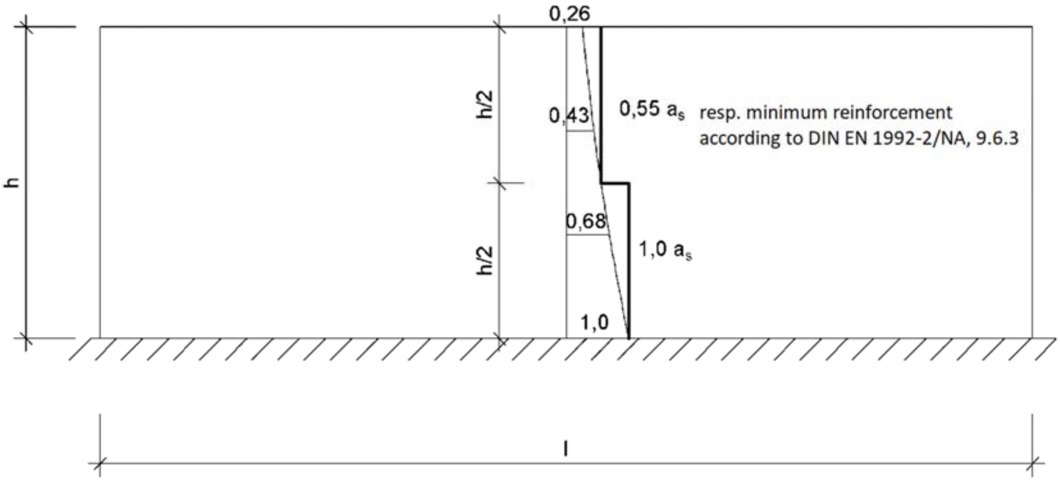


Figure 9. *Arrangement of the horizontally reinforcement over the wall height dependent on the tensile stress distribution.*

The decrease of the restrained forced stresses through the arrangement of joints can be used on this basis for the computational reduction of the minimum reinforcement. The construction-related minimum reinforcement, based on empirical values, may not be undershot in this case, however, in accordance with Figure 10 for wall-like structural members. For road tunnels, a minimum reinforcement in accordance with ZTV-ING Part 5 [12] may not be undershot.

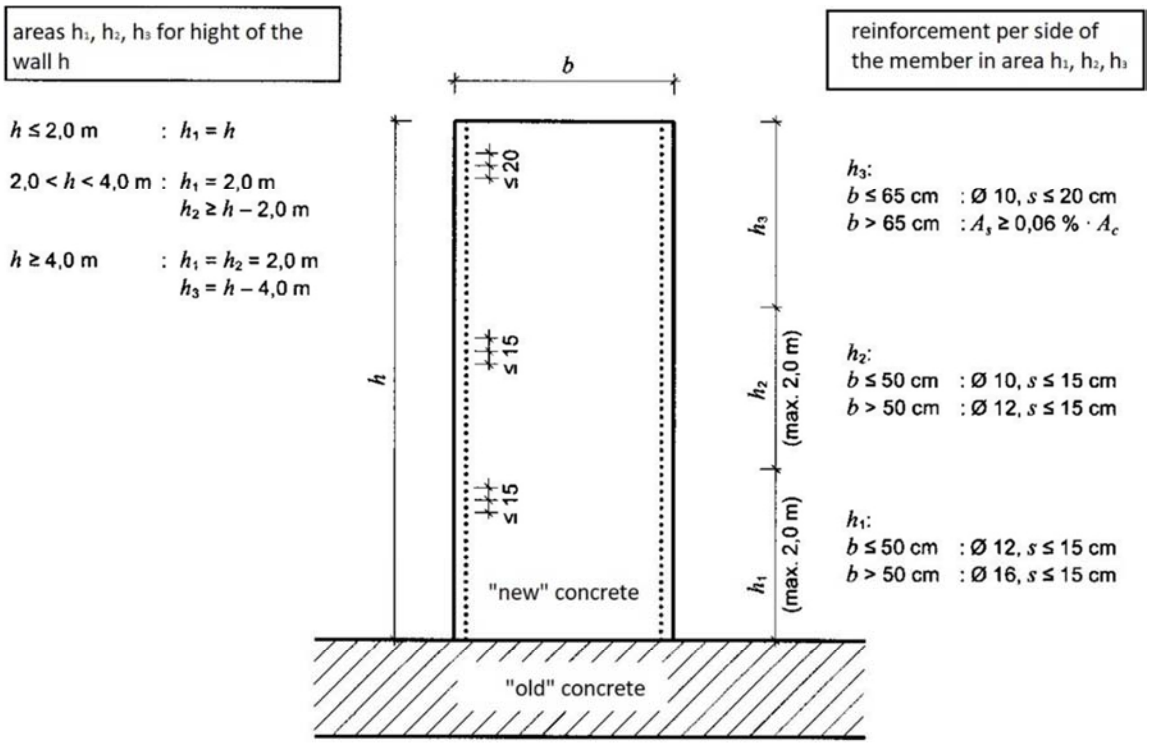


Figure 10. *Construction related minimum reinforcement in restrained structural members according to DIN EN 1992-2/NA (figure NA 9,110.1DE).*

2.4. On the Use of the Concrete Tensile Strength with Early Restraint Cracking

In case of utilisation of concrete with slow strength development, DIN EN 1992-2/NA includes clear dimensioning specifications for the computational approach of $f_{ct,eff}$ (cf. Section 1, Figure 3) and application regulations for those participating in the construction. For more rapid hardening concretes deviating from this, a corresponding increase for the use of $f_{ct,eff}$ must be carried out. As a result of this, however, the probability of the occurrence of cracks increases and the required minimum reinforcement for crack control increases, while on the other hand for example the formwok boarding periods are shortened.

For bridges, tunnels and other structural engineering works according to DIN EN 1992-2, the following Table 1 recommends provisional values for $f_{ct,eff}$. It is planned to apply these values first within the framework of initial practical applications, in co-ordination with the responsible building supervisory authorities, and to check them without undue delay through investigations for crack formation in already implemented construction work.

Table 1. *Recommended values for tensile strength in case of early restraint cracking, if the requirements for slowly hardening concrete according to DIN EN 1992-2/NA are not complied ($r = f_{cm2}/f_{cm28}$ where f_{cm2}; f_{cm28} mean value of concrete cylinder compressive strength at 2 resp. 28 days).*

Strength development of the concrete	**Member thickness h [m]**		
	≤ 0.50 m	**≤ 1.00 m**	**≤ 2.50 m**
slow ($r \leq 0.30$)	$0.50 \cdot f_{ctm}$ 2)	$0.50 \cdot f_{ctm}$ 2)	$0.50 \cdot f_{ctm}$ 2)
medium ($r < 0.50$)	$0.50 \cdot f_{ctm}$ 1) $0.65 \cdot f_{ctm}$ 2)	$0.50 \cdot f_{ctm}$ 1) $0.75 \cdot f_{ctm}$ 2)	$0.50 \cdot f_{ctm}$ 1) $0.85 \cdot f_{ctm}$ 2)
rapid ($r \geq 0.50$)	$0.80 \cdot f_{ctm}$	$0.90 \cdot f_{ctm}$	$1.0 \cdot f_{ctm}$

1) Concrete work subject to winter temperatures
2) Concrete work subject to summer temperatures

3. References on Planning and Execution

In the case of thicker structural members according to DIN EN 1992-2, due to the very high-quality requirements, it is assumed that slowly hardening concretes are generally to be used (DIN EN 1992-2/NA, Section 7.3.2), in order to keep the probability of occurrence of cracks low and to appropriately limit the quantity of the minimum reinforcement for crack control required.

For the unambiguous clarification of these general conditions, it is provided in DIN EN 1992-2/NA that corresponding notes in the building specifications and on the working plans must be carried out (cf. DIN EN 1992-2/NA), so that possible effects on, for example, construction planning, quantity bases of the performance description and cost estimates of the participants in the construction, can be considered and monitored in accordance with the relevant technical regulatory specifications. A specification of the strength development of the concrete (r-value) must always be included in the plans which are approved for execution on the construction site, so that the construction site personnel can order the matching concrete from the supplier.

Since, in case of structures for bridges, tunnels, etc. according to DIN EN 1992-2 and ZTV-ING [12] in Germany, the construction contract will usually be awarded in combination with the structural analysis and drawings for execution and it is ultimately the task of the contractor to send the specifications in time to the concrete manufacturer instructed by him for the definitive r-values, so that he can stipulate a suitable design of concrete mixture within the framework of aptitude testing, and arrange and supply the concrete materials in good time. As a result of the described, changed general conditions during cement production, it obviously can no longer be presumed that the required cement with slow strength development is always in stock with the concrete manufacturer. Different than the case of concrete of general building construction, a preparation time which is possibly a little longer must therefore be included. However, this was also normal in the past for the normal case of concrete for bridges, due to its special requirements.

In case of traffic structures according to DIN EN 1992-2 [2] and ZTV-ING [12], the division of the construction work into structural members is known and the effects of deformations, due to time-dependent concrete characteristics or temperature effects during the effective life of the construction work, are easily and clearly visible. Therefore, member-related and dependent on the ambient conditions, early and late restraint force stressing are to be clearly differentiated and considered separately in calculations.

A random-sampling type survey with different road construction administrations, as well as cement and concrete manufacturers in Germany, has indicated that the procurement possibility of slowly-hardening cement is basically provided everywhere in Germany. With most cement manufacturers, the required cement types are included in the quotation. Possible additional costs can result for longer transport haulage or inventory maintenance in an internal silo, which are to be included in the quotation presentation. This is also experienced in the manufacture of hydraulic engineering works, where there are a lot of further demands on the concrete technology. However, exceptions can be appropriate when the required quantities delivered are very small or delivery schedules are very short. This should be clarified on an individual basis in the planning of the structural members.

In case of concrete, the concrete compressive strength required as standard in general is considered as owed performance. Sizes derived from this generally do not represent acceptance sizes. Generally, it has proven appropriate to require as contractually-agreed only those material characteristics which are arranged as standard. The determination of characteristic values in the member, especially if they are derived approximately from the compressive strength, should be limited to cases of damage.

For the mean tensile strength of the concrete the following relationship according to equation 5 may be used:

$$f_{ctm} = 0{,}3 \cdot f_{ck}^{\frac{1}{3}} \tag{5}$$

An explicit verification of the concrete tensile strength of the selected concrete type is not necessary. According to [13], the selection of suitable concrete types can be further assigned to the compressive strength development (r-values). With a view to the scattering of the strength values and the other, in-part rough, assumptions in the design model, this approach appears sufficiently exact.

4. Summary

The design concept for thick structural members, in accordance with DIN EN 1992-2/NA, for the determination of the minimum reinforcement for crack control in case of early restraint force stressing, in combination with the limitation of the probability of occurrence of cracks, has proved very successful in practice in Germany. The short-term availability of the cement required for this, with low hydration heat development, is provided everywhere in Germany even if, in case of cement and concrete manufacture from current developments, it cannot always be presupposed that this cement is always immediately in stock with the concrete manufacturer.

If the area of application of the design concept for thick structural members, in accordance with DIN EN 1992-2/NA, should be additionally extended in reasonable individual cases, and cement with faster hydration heat development used, the probability of occurrence of cracks increases significantly due to early restraint force stressing and a larger quantity of minimum reinforcement for crack control must be installed. For the determination of this reinforcement, computational values of concrete tensile strength are indicated above (Table 1) as recommendations. It is planned to verify these values first of all within the framework of initial practical applications and in co-ordination with the responsible building supervisory authorities.

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