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Extending the Lifespan of Cylindrical Structures

Prolongement de la durée de vie des constructions cylindriques

Erhöhung der Lebensdauer von zylindrischen Konstruktionen

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SUMMARY

Concrete structures frequently show signs of damage such as cracks, caused, e.g. by thermally induced stresses, which usually were not considered adequately by the design provisions. The paper will attempt to summarise conclusions from the information about the most common failures and repair methods of cylindrical reinforced industrial structures such as chimneys, water tanks, silos and cooling towers.

RÉSUMÉ

Les constructions en béton armé laissent souvent apparaître des défauts, telles que fissures engendrées par des tensions amenées par des effets de température que ne sont pas souvent pris en considération lors du calcul du projet. La contribution résume les connaissances sur les défauts et sur les possibilités de réparation des constructions industrielles cylindriques, telles que cheminées, réservoirs d'eau, silos, et tours de refroidissement.

ZUSAMMENFASSUNG

Stahlbetonkonstruktionen zeigen oft Zeichen von Beschädigungen, wie zum Beispiel durch Temperaturspannungen entstandene Risse, die in den bestehenden Normen für die Bemessung nicht ausreichend berücksichtigt wurden. Der vorliegende Beitrag versucht, die Erkenntnisse über die Fehler und Sanierungsmethoden von zylindrischen industriellen Konstruktionen wie z.B. Schornsteine, Wasserbehälter, Silos und Kühltürme zusammenzufassen.

1. INTRODUCTION

Concrete structures in service may be affected by ageing, which may include changes in strength and stiffnes. Some of this ageing effects are benign, others may cause component or system strength to degrade over the time, particularly when the concrete is exposed to an aggressive environment.

Environment stressors may attack the integrity of the concrete and/or steel reinforcement in concert with or independent of operating, environmental, and accidental loads. For concrete strength, the most significant stressors are chemical reactions, freeze-thaw cycling, and temperature effects. For deformed bar reinforcement and prestressing tendons, the possibility of corrosion is the far most important factor.
The most common of all types of problems in r.c. cylindrical structures are the vertical and horizontal cracks of the walls.

Reinforced concrete will crack. In most cases this cracking is not a cause for concern and no treatment is needed. However in some instances, remedial measures may be necessary. Cracks need to be repaired if they reduce:

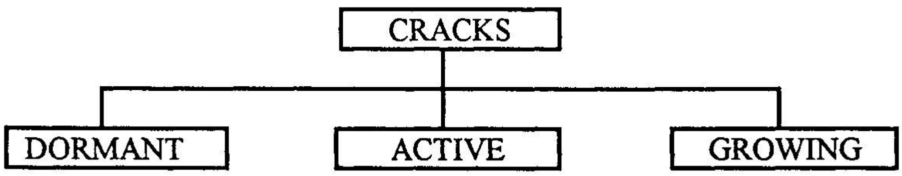
The structural safety, either the load bearing capability or the stability. As long the crack widths are not larger than approximately 0,3 mm and above all, the steel remains in the elastic region, the formation of cracks is considered as a normal phenomenon in reinforced concrete construction [1].

The serviceability. The environmental engineering concrete structures for the containment, treatment, or transmission of water, waste water, or other fluids should be designed and constructed to be essentially watertight. The ability of a structure to retain liquids will be reasonably assured if the crack width is minimised. Cracks up to 0,2 mm can be closed under the conditions which prevail in the field of water tank construction due to autogenous healing [2]. Healing will not occur if the crack is active and is subjected to movement during the healing period [3].

The durability. In the region of cracks carbonation and chlorides tend to penetrate faster towards the reinforcement than in uncracked concrete. The thickness of the concrete cover is of major importance with regard to the influence of cracks. The crack widths (if they are less than 0,4 mm) are less important. Limitation of crack widths for prestressing steel is completely different from that for ordinary reinforcement. Due to the danger of brittle failures, depassivation of the prestressing steel surface must be avoided during the entire lifetime. In most cases decompression must be asked for [4].

A suitable repair counteracts all the deficiencies which are relevant to the use of the structure.

Cracks can be divided into three categories



Dormant cracks are caused by some event in the past which is not expect to recur. They remain constant in width.
Active cracks are cracks which do not remain constant in width but open and close, perhaps as the structure is loaded, perhaps with changes in temperature.
Growing cracks are cracks which are increasing in width because the original reason for their occurrence is continuing.

Before embarking on any treatment, it is important to be aware of why cracks have occurred, otherwise an inappropriate and consequently ineffective repair method can be chosen and may do more harm than good [5].

2. CAUSES OF CRACKS

Cracks in concrete have many causes. White the specific causes of cracking are manifold, the principal causes of cracking in cylindrical industrial structures are thermal stresses and corrosion of reinforcement.

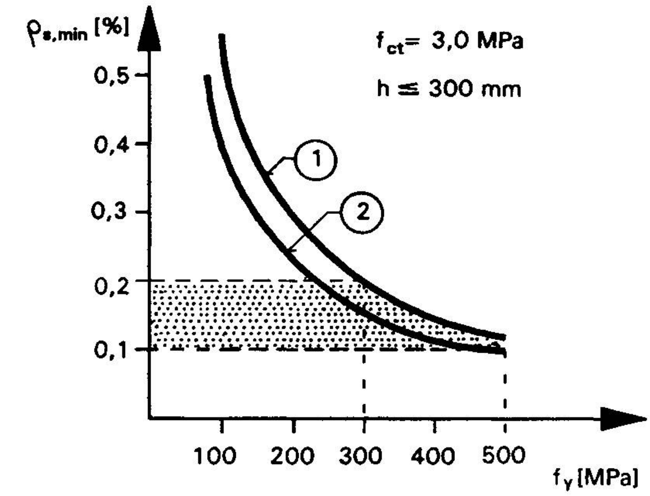
2.1 Thermal stresses

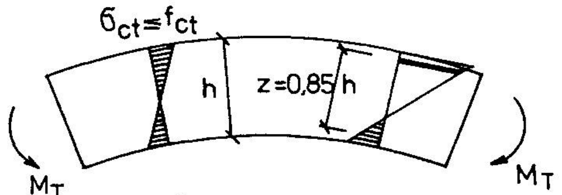
Temperature differences within cylindrical concrete structures may be due to heating up by internal influence as:

- waste gases with a temperature $T_i \leq 300°K$ (chimneys)
- steam, $T_i \leq 35°K$ (cooling towers)
- putrefactive spoilage $T_i = 37 - 55°K$ (sludge digesters)
- stored materials, $T_i \leq 200°K$ (silos)

or external weather influences like frost and solar radiation. As a consequence of the temperature differences dT between the inside and the outside surface, bending moments are activated. Bending moments starting approximately from dT = 15°K, lead to the formation of vertical crack.

Older cylindrical concrete structures, were designed and built frequently with insufficient hoops and that is the reason why, relatively often, vertical separation cracks with the yielding of the reinforcement can be observed. As shown in Figure 1, the minimal degree of reinforcement ρ_{min} depends on the relation of the tensile strength f_{ct} of concrete to the yield point f_y of steel.





$$M_T \approx \frac{f_{ct} \cdot h^2}{\sigma} = M_r \approx \sigma_{sr} \cdot A_s \cdot 0{,}85h$$

$$\sigma_{sr} \approx \frac{f_{ct}}{5\rho_s} \leq f_y$$

(1) $\rho_{s,min} = 0{,}2 \frac{f_{ct}}{f_y}$

EUROCODE 2: $A_{s,min} = k_c \cdot k \cdot f_{ct,eff} \cdot A_{ct} / \sigma_s$

(2) $\rho_{s,min} \approx 0{,}16 \frac{f_{ct}}{f_y}$

Fig. 1 The min. degree of reinforcement ρ_{min} versus yield point f_y of steel

One of the major requirements for the structure is to prevent wide vertical separation cracks which subdivide the cylindrical wall into several free-standing segments.
As shown in Fig.2, the cylindrical wall divided by separation cracks behaves with regard to its stresses and deflection much more unfavourably than a monolith structure.

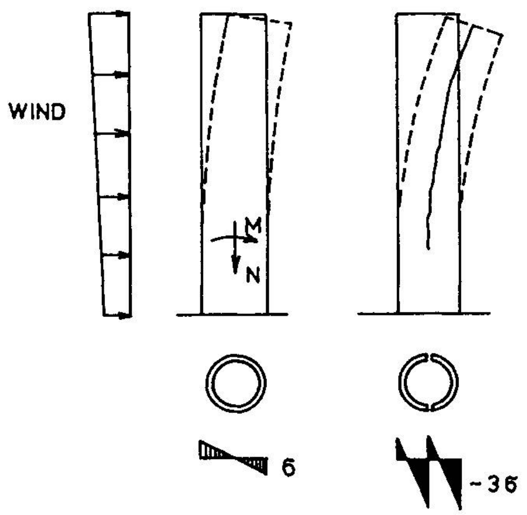


Fig.2 Effects of separation cracks on the load bearing capacity with regard to the wind

2.2 Corrosion of reinforcement

Reinforcing steel may corrode, however, if the alkalinity of the concrete is reduced through carbonation or the passivity of this steel is destroyed by aggressive ions (usually chlorides). Corrosion of the steel produces iron oxides and hydroxides, which have volume much greater than the volume of the original metallic iron. This increase in volume causes high radial bursting stresses around reinforcing bars and results in longitudinal cracks, or spalling of the concrete.
The cracking time of concrete cover can be calculated approximately from following formula [6]:

$$t = 80 \frac{c}{d_s . r}$$

where: t is the cracking time (years)
c the thickness of concrete cover (m)
d_s the diameter of the reinforcing bar (m)
r the rate of steel corrosion in concrete (μm/year).

The rate of corrosion at the temperature of 20°K with regard to the relative humidity is presented in Table 1.

Table 1 The rate of corrosion in concrete

RH (%)	Carbonated concrete (μm/year)	Chloride contaminated concrete (μm/year)
99	2	34
95	50	122
90	12	98
85	3	78
80	1	61
75	0,1	47
70	0	36
65		27
60		19
55		14
50		9

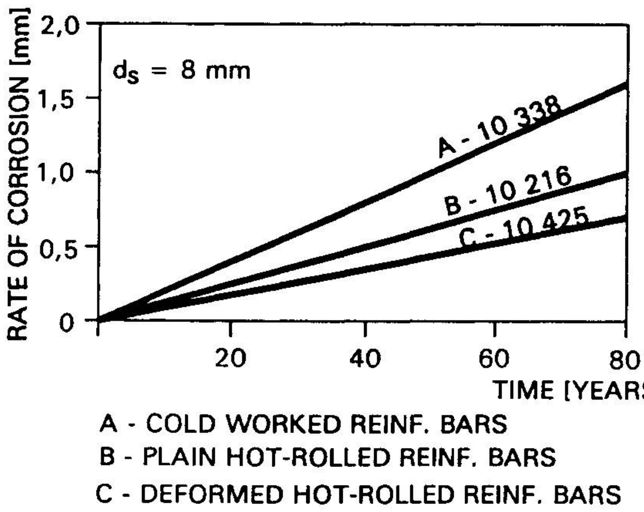


Fig.3 Mean atmospherical corrosion rate as a function of time [7]

Once the concrete cover has been cracked and spalled of, corrosion of the exposed steel will freely proceed like atmospherical corrosion. The mean values for the atmospherical corrosion rate are presented in Fig.3.

The design engineer may set a limit for the minimum cross-sectional area of the main reinforcement steel bars. It may depend on the requirement that the actual stresses in the steel bars can't exceed the yield point.

3. REPAIR METHODS

Following the evaluation of the cracked structure and the determination of the cause of the cracking a suitable repair procedure can be selected. Procedures can be selected to accomplish one or more of the following objectives:
1. Restore the original stiffness;
2. Improve functional performance (e.g. watertightness);
3. Improve appearance of the concrete surface; and/or
4. Improve durability.

Depending on the nature of the damage, one or more repair methods may be selected. For example tensile strength can be restored across a crack by injecting it with epoxy. However, it may be necessary to provide additional strength by adding reinforcement or using post-tensioning. The key methods of crack repair, particularly for cylindrical walls are described in Chapter 3.1 and 3.2.

3.1 A new outer reinforced concrete shell

The obvious solution for cylindrical r.c. structures is to provide the cracked shaft with an additional thin shell (Fig.4). The new outer shell comprises all envisaged repair measures, so that no separate crack pressure - grouting and improvement of concrete surface are necessary[8]. However, unless the cracks are dormant (or the cause of cracking is removed), they will probably recur. In order to restrict the crack width at the outer shell, high amount of reinforcement must be inserted. In view of the increase in dead weight the foundation pression must be verified.

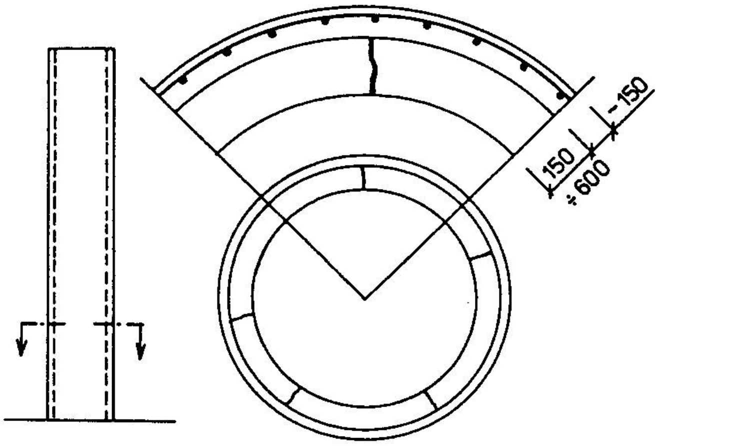


Fig.4 Shaft modification by means of reinforced concrete-jacketing

3.2 Transverse prestressing

Post-tensioning is often the desirable solution when the cracks that have formed must be closed. This technique uses prestressed concrete rings at intervals of about 10 m (Fig.5). They are post - tensioned by means of single unbounded tendons [9]. The local transverse prestressing must be restricted in view of additional vertical and tangential stresses which can lead to a additional crack formation. More uniform circumferential precompression can be achieved with external prestressing tendons at intervals about 2 m (Fig.6). This stressing technique is particularly beneficial when the wall is insufficiently reinforced at the inner surface.

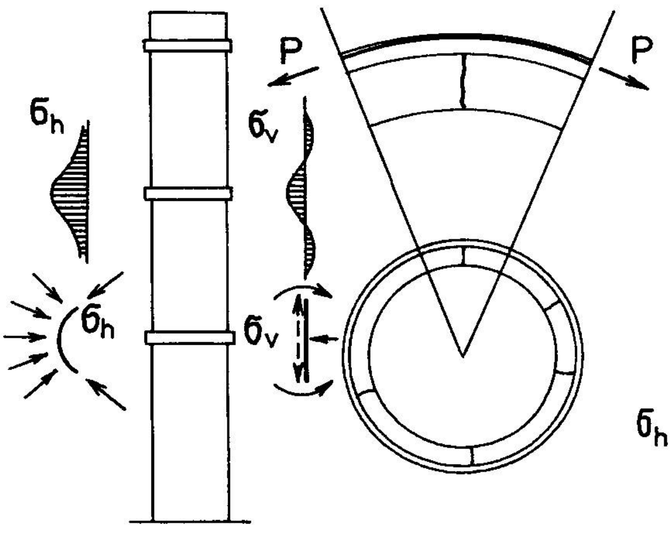


Fig.5 Shaft modification by means of prestressed concrete-rings

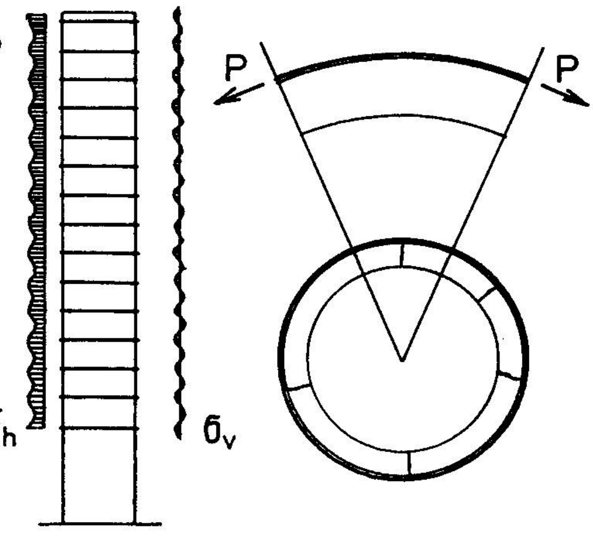


Fig.6 Shaft modification by means of prestressed external tendons

4. CONCLUSIONS

Primary causes of cracks and available actions to extend the functional life of cylindrical r.c. industrial structures are discussed. It has been shown that:

1. Temperature gradient between the inside and outside surface is the most likely cause for the development of vertical cracks and corrosion of reinforcement is the most likely cause for spalling of the concrete cover,
2. Some of these problems are due deficiencies in the previous or present standards, while others are due to the designers failure to comprehend fully the requirements of the standard. Still other problems result from the fact that many structures under inspection were not reinforced as designed,
3. The selection of successful repair techniques should consider the causes of cracking, whether the cracks are dormant, active or growing, and the need for repair of structures whose designed lifetime is over, while they are still in function, and
4. Application of external prestressing for restoring the orginal stiffness, improving the functional performance and durability is a very economical procedure and may be used on the cylindrical industrial structures.

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