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EARLY AGE CONCRETE VOLUME CHANGES AND THERMAL ACTIONS IN PRACTICE OF REINFORCED CONCRETE LIQUID TANKS DESIGN

A. HALICKA[1], D. FRANCZAK-BALMAS[2]

Due to demand of tightness, the liquid tanks should be designed with particular care. In addition to the liquid pressure, the imposed concrete strains and thermal actions should be taken into consideration. Furthermore, the verification of the ULS in persistent design situation only is not sufficient. The crack control both in persistent situation as well as in early age transient one is necessary for determination of the reinforcement.

In the beginning of the design process some assumptions, influencing the future tank performance must be made. First, the tightness class must be chosen, followed by formulation of conditions for crack width control. Next, the critical age of concrete, proper for early age transient situation should be assumed. This age determines the value of imposed strain on the one hand and the effective tensile concrete strength on the other. Then, it should be decided, if any reduction of the effective tensile strength would be applied (reduction associated with non-uniform imposed strain and reduction due to cracking under other combination of actions). Eventually, the decisions for structural analysis should be made, concerning the values of combination factors for actions both for ultimate and cracking limit state and the possible reduction of cross-section stiffness due to cracking caused by thermal actions in ULS.

The above-mentioned assumptions are listed and discussed in the paper. On the basis of the discussion the algorithm for crack control in concrete tanks is worked out and proposed. The issues are illustrated with practical example of cylindrical tank for liquid.

Keywords: reinforced liquid tank, tightness, crack control, imposed strains, thermal actions

[1] Prof., DSc., PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, ul. Nadbystrzycka 40, 20-618 Lublin, Poland, e-mail: a.halicka@pollub.pl

[2] MSc., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, ul. Nadbystrzycka 40, 20-618 Lublin, Poland, e-mail: d.franczak@pollub.pl

1. INTRODUCTION

The crack control of reinforced concrete liquid tanks is necessary not only in the interest of the structure durability but also of its tightness. Cracks in walls subjected to liquid pressure are the result of axial or eccentric horizontal tension and vertical bending. They may be also caused or intensified by imposed strains due to shrinkage and early age volume changes as well as later thermal actions associated with liquid temperature and fluctuations of environmental temperature.

That is why, the liquid tank design should be performed with particular care. Verification of the ULS in the persistent design situation only is not sufficient. The crack control both in the early age transient situation as well as the persistent one is necessary for the determination of the reinforcement.

A lot of researches on cracking of the reinforced concrete walls were carried out last years. The scientists monitored cracks of the walls restrained by foundations in the laboratory [3] as well as in the field [11] and tried to predict their behaviour using FEM [3, 5, 6, 9, 10]. The special attention was paid to self-heating and shrinkage effects for the stress-strain distribution [3, 5, 6, 9, 10, 11] and cracks prediction. The above-mentioned works were based on the analyses of temperature and dampness fields and used the precise material parameters. Such parameters are not available during the process of structural design usually.

Only few works referred directly to the Standard requirements. The rules for crack control in early age concrete members given by different Standards were compared in [7]. The recommendations for crack control regarding both cracks due to imposed strains and cracks caused by the later loads and actions were formulated in paper [8], where the addenda of German National Annex to EC2-1-1 [16] was discussed. This work is particularly valuable for designers, because the general principles of EC2-1-1 [15] and EC2-3 [17] do not give clear and ambiguous indications.

The aim of our paper is to list and discuss the assumptions which should be made in the beginning of liquid tank design process. These assumptions influence the future performance of the tank. First, the tightness class must be chosen followed by formulation of the conditions for crack width. Next, the critical age of concrete, appropriate for early age transient situation should be assumed. This age determines the values of imposed strain on the one hand and the effective tensile concrete strength on the other. Then, it should be decided, if any reduction for the effective tensile strength would be applied (a reduction associated with a non-uniform imposed strain and a reduction due to concrete cracking under other combinations of actions). Eventually, the decisions for structural analysis should be made, concerning the values of combination factors both for ultimate and cracking limit state and the possible reduction of cross-section stiffness due to cracking caused by thermal actions in ultimate limit state.

On the basis of the above discussion, the algorithm for crack control in concrete tanks is worked out and proposed. The issues are illustrated with practical example of cylindrical tank for liquid.

2. RECOMMENDATIONS OF EC1-4, EC2-1-1 AND EC2-3

2.1. TIGHTNESS CLASSES

According to EC2-3 [17], the tank tightness is ensured by fulfilling the specified conditions. In the tank of class 0 some level of leakage is acceptable, in class 1 leakage should be limited, in class 2 leakage should be minimum and in class 3 leakage is no permitted. The conditions regarding the compression zone and crack width are compiled in Fig.1. Special requirements are given for the early age stress. In class 1 early age stress should not exceed the tensile early age concrete strength. In class 2 the entire cross section should be compressed, which is usually not possible due to tensile character of shrinkage stress through the whole wall thickness.

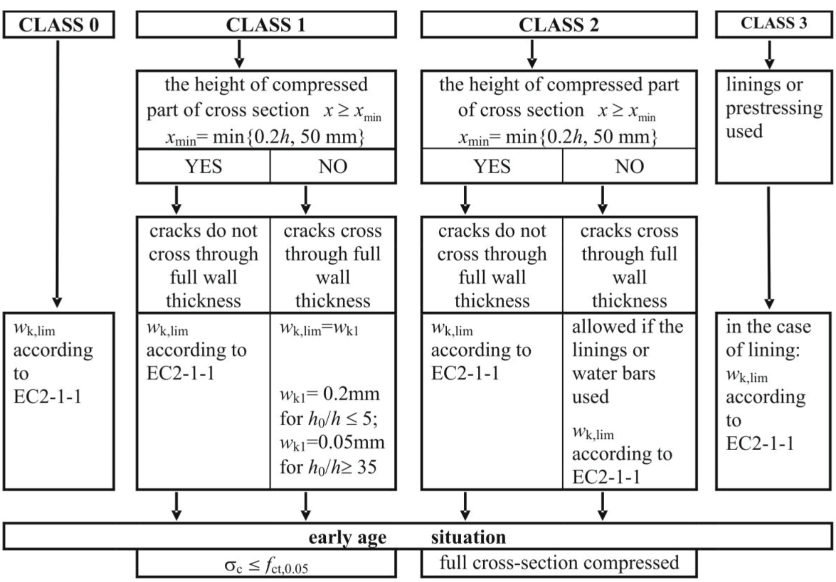

Fig. 1. Liquid tanks classification regarding the tightness according to EC2-3

The above rules are quite different from the traditional approach, consisting in assuming the wall thick enough to avoid any cracks. Now, cracks passing through whole cross section are essential. The first option is to design thick or prestressed wall in order to avoid of such cracks and the second one is to use inner linings. As a matter of fact, the decision is based on the economic reasons.

2.2 STRUCTURAL ANALYSIS

2.2.1 DESIGN SITUATIONS AND COMBINATION FACTORS

The structural analysis of liquid tank should include: persistent situation of tank under liquid pressure and accompanying actions, transient situations (successive concreting, stages of prestressing, unburying of underground tank) and accidental situations (tightness test and vehicle impact). In this paper the persistent situation and the transient early age one are analyzed only.

The EC1-4 Standard [14], dedicated to actions applied onto silos and liquid tanks, recommends to consider the internal pressure as dominant variable action, whereas the foundation settlement, wind, snow, imposed load and thermal actions as accompanying actions. The combinatory factors for accompanying actions ψ_0, ψ_1 and ψ_2 are given here for silos only and they are the same as in EC0 [12] for buildings.

The combinatory factors in EC1-4 for thermal actions needs discussion. It should be emphasized that thermal actions (difference between temperatures of wall sides ΔT_M and difference between the actual temperature and the initial one ΔT) are calculated assuming the stationary heat flow through the wall. This assumption is questionable because of fluctuations of environmental temperatures and thermal inertia of concrete. That may be a reason why the factor of combination value $\psi_0 = 0.6$ is recommended for silo. But there is a difference regarding heat flow through the wall between silos and liquid tanks. The hot powder e.g. cement clinker poured into a silo cools down and the extreme temperature inside is of short-term nature. In opposite, the temperature of liquid in a tank is usually constant (e.g. drink water tanks, fermentation chambers in savage plants), therefore the heat flow through a wall better suits here the stationarity assumption.

Next, the ψ_2 factor for *quasi*-permanent values of thermal actions is recommended to be equal to 0. This means that thermal actions are not taken into consideration in *quasi*-permanent combination at all. This assumption for liquid tanks raises concerns, because it is the *quasi*-permanent combination which is proper for tightness assurance.

Despite the above-mentioned doubtfulness, the authors decided to use $\psi_0 = 0.6$ and $\psi_2 = 0$ for thermal actions in the design example (p.3).

Indirect actions connected with shrinkage and early age concrete volume changes are not mentioned in EC1-4 at all, therefore they should be treated as permanent ones in accordance with EC0 [12]. This implicates the combinatory factors for these actions $\psi_0 = 1.0$ and $\psi_2 = 1.0$, as well as safety factor $\gamma_f = 1.35$.

2.2.2 IMPOSED AND THERMAL ACTIONS IN FEM ANALYSES

The crucial for calculation of imposed actions is an average value of free shrinkage strain ε_{cs}. The rules for calculation ε_{cs} are given in EC2-1-1 [15] and updated in MC2010 [18]. The update of EC2-1-1 rules is necessary due to present-day changes in cements and mix compositions (this problem is discussed in e.g. [1]).

The long-term shrinkage strain ε_{cs}' should be assessed regarding the concrete creep [2]:

(2.1)
$$\varepsilon'_{cs} = \frac{\varepsilon_{cs}}{1 + \chi\varphi(\infty, t_0)}$$

where $\varphi(\infty, t_0)$ – creep coefficient, χ – age coefficient (may be taken as 0.8).

In the FEM analyses it is convenient to simulate the average shrinkage strain with decrease of the wall temperature ΔT_s, which may be calculated as follows:

(2.2)
$$\varepsilon'_{cs} = \frac{\alpha_t \Delta T_s l}{l} = \alpha_t \Delta T_s \rightarrow \Delta T_s = \frac{\varepsilon'_{cs}}{\alpha_t} = \frac{\varepsilon'_{cs}}{1 \cdot 10^{-5}},$$

where α_t – coefficient of thermal expansion depended on e.g. aggregate type. .

If the effects of concrete self-heating are included, the equivalent temperature ΔT_{s+h} is equal to:

(2.3)
$$\Delta T_{s+h} = \Delta T_s + \Delta T_h = \frac{\varepsilon_{cs}'}{1 \cdot 10^{-5}} + \Delta T_h .$$

The temperature decrease ΔT_h is related to cooling of concrete from the maximum temperature achieved due to self-heating to current environmental temperature.

The increase of temperature due to self-heating lasts 1–3 days from the beginning of setting [4]. Its value depends on the massiveness M, defined as the ratio of external member area being in contact with environment to its volume [2]. If $M > 15$/m the temperature marking ^{o}C increases of 1 to 5^{o}, for $M = 2$–15/m of 5 to 35^{o} and for M< 2/m even of 20 to 50^{o}. Next, concrete cools until the temperature of environment is achieved. Only if the environmental temperature is constant, the temperature decrease ΔT_{h} is equal to increase. In the design process one can not predict precisely the environmental temperature fluctuations and therefore it seems reasonable to assume that ΔT_{h} is equal to temperature increase.

The critical parameter is the age of concrete appropriate for verification limit states is early age design situation. This age determines the shrinkage strain on one hand and concrete maturity and strength on the other hand. This problem constitutes the subject of sophisticated analyses e.g. [5, 6, 10] and it is very difficult to give a simple recommendation, which critical age should be considered in particular design. It is justified to assume t_{crit} as concrete age when concrete and environment temperatures equalize after self-heating. The scope of 3 to 7 days seems to be reasonable for t_{crit} assumption.

2.2.3 CRACK WIDTH CONTROL

According to EC2-3, the formal conditions for tightness should be fulfilled for quasi-permanent combinations of actions in all design situations. Therefore, besides the persistent situation including liquid pressure as the dominant action, the transient early age situation should be regarded. In MC2010 [18] it is stated: “where cracking is due also to imposed deformations, the steel stress at cracks due to imposed loads should be increased by that caused by imposed deformations”. Therefore, in all design situations an autogenic and drying shrinkage should be taken into consideration and in transient early age situation self-heating should be regarded additionally.

The fulfillment of the limit crack width conditions (Fig. 1) may be ensured using EC2-1-1 methods. The first method, a precise one, consists in comparison the calculated width with limit value. The second one is a simplified method which allows to choose the maximum bars diameter and spacing corresponding to limit crack width (this method is not proper for liquid tanks, where the tightness is crucial). The third method consists in calculation of minimum reinforcement, which should be applied in regions where tension is expected. The horizontal tension is usually expected in whole liquid tank, so the minimum reinforcement should be applied along a whole wall height.

In liquid tanks design, it seems reasonable to use combination of two methods – the minimum reinforcement method in transient early age situation and precise method in persistent situation. The algorithm proposed for crack control in design process is presented in Fig. 2.

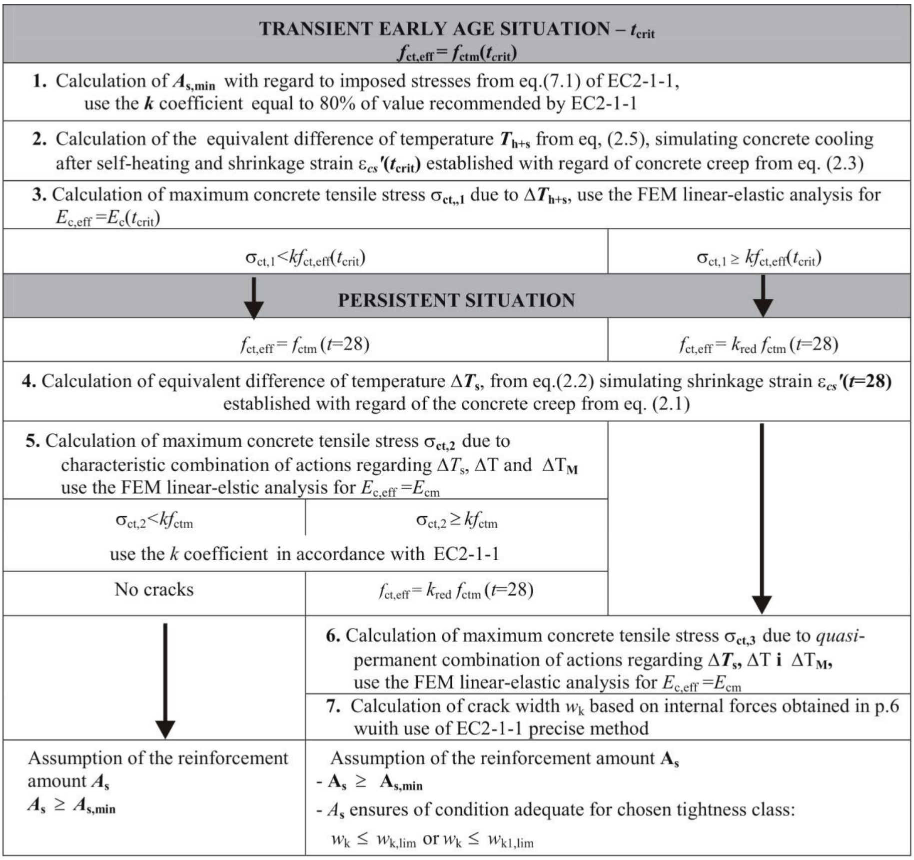

Fig.2 Proposed algorithm for crack control in liquid tank

The basic problem in the both accepted methods is proper assessment of effective tensile concrete strength. Analyzing the German National Annexes to EC2-1-1 [15] and discuss in [7] it seems reasonable to apply the following reductions of $f_{ct,eff}$:

- $f_{ct,eff}$ reduction with coefficient k in expressions for $A_{s,min}$ in early age situation due to the self-equilibrating stresses; according to [7, 15] k=0.8 for cross-section height $h \leq 0.30$ m and k=0.52 for $h > 0.80$ m (the intermediate values should be interpolated); this reduction decreases $A_{s,min}$,
- $f_{ct,eff}$ reduction with coefficient $k_{red} < 1.0$ in expression for $(\varepsilon_{sm}-\varepsilon_{cm})$ if the concrete element was cracked earlier (in [7] the k_{red}=0.5 was given); this reduction increases the crack width and lead to increase the reinforcement ratio.

The second reduction is suitable for crack width calculations in persistent situation, if crack appeared in transient situation due to early age concrete imposed actions. It is also suitable for cracks caused by *quasi*-permanent combination of actions, if cracks occur under characteristic combination of actions. This is possible in liquid tanks due to thermal actions. As it was described in p. 2.2.1, in *quasi*-permanent combination thermal actions are not considered, whereas characteristic combination of actions including thermal actions may cause cracks.

Another problem of structural analysis related to cracking due to thermal actions should be mentioned also. Cracks result in decrease of cross-section stiffness followed by decrease of internal forces. That is why in EC2-1-1 the calculation of internal forces due to thermal actions for the ULS is allowed with use of the lower stiffness than assumed for homogeneous concrete. There is no precise suggestion for the level of stiffness decrease, therefore it is the designer who decides if this possibility would be used. However, usually the use of this reduction does not decrease the reinforcement ratio, because the final amount of reinforcement depends on the SLS (as in p. 3).

3. THE EXAMPLE OF LIQUID TANK CALCULATIONS

3.1 THE ANALYZED TANK

The cylindrical concrete tank, of 8.0 m in height and of 22.4 m in diameter, for sewage of specific gravity γ_c=10.8kN/m^3, made of C30/37 concrete is analyzed (Fig.3). Such tanks, covered with tilt roofs, are built in biogas plants. They are made as reinforced concrete or prestressed ones. The problems of cracking of reinforced tanks, coming to light during tightness tests, are reported from time to time.

Tightness class 3 was assumed, therefore in reinforced (not prestressed) tank the linings would be necessary and $w_{k,lim}$= 0.3mm. Assumed temperatures are the following: sewage temperature +30^{o}C, tank initial temperature T_o=+15^{o}C, environmental temperature in winter T_{min}=–30^{o}C and in summer

T_{max} = +38°C, wall surfaces temperature in winter T_{out} = –30°C and in summer T_{out} = 56°C, soil temperature in winter T_{out} = –3°C and in summer T_{out} = +6 °C.

The internal forces were calculated with use of the FEM Autodesk Robot Structural Analysis software assuming the linear-elastic model of concrete. The tank was modeled with „panel" elements, covered by 40 cm mesh, twice diminished near the bottom. The bottom slab was modeled also as "panel" element with polar mesh. The coefficient of soil reaction was assumed as 50 000 kN/m^3.

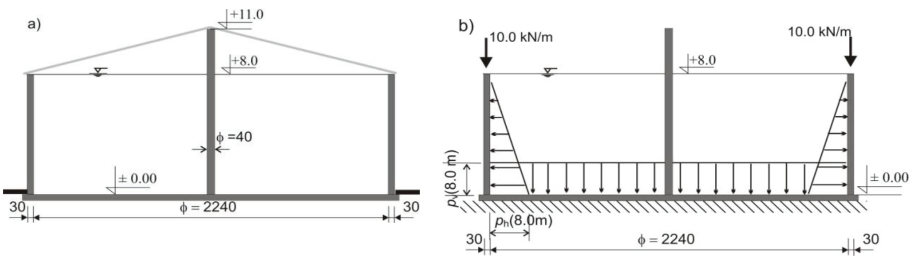

Fig. 3 Analyzed cylindrical tank (dimensions in centimeters): a) vertical cross-section, b) calculation scheme

3.2 TRANSIENT EARLY AGE SITUATION

It was assumed, that during concreting the wall would be divided into four successively concreted horizontal rings of 2 m height. First ring would be made 21 days after concreting of bottom plate.

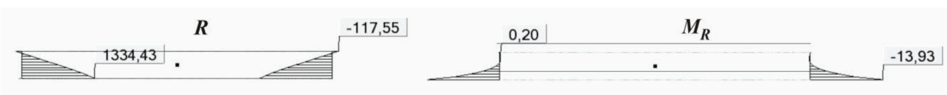

Fig. 4. Distribution of internal forces in numerical model of wall segment of 2 m height, concreted as the first one on the bottom plate, due to early age imposed concrete deformations in transient situation at t_{crit} = 6 days (hoop force R in kN/m, hoop bending moment M_R in kN·m/m)

The critical term for early age situation of wall was assumed as t_{crit} = 6 days, when the bottom slab would be 27 days old. The difference between shrinkage strain of walls (6 days old) and increase of shrinkage of bottom slab between 21 and 27 days was calculated. Autogenic and drying shrinkage were calculated in accordance with EC2-1-1 RH = 80% and N cement. The obtained difference was equal to $\Delta\varepsilon_{cs} = 16\cdot10^{-6}$, so equivalent cooling ΔT_s = 1.6°C. The constant environmental temperature was assumed, therefore the cooling after self-heating was equal to increase of temperature due to self-heating. The wall massiveness M=3.8 /m, so ΔT_h = 14° [1]. Finally ΔT_{h+s} = ~16°C.

Due to early age, the internal forces in numerical model were calculated assuming the elasticity modulus of the concrete of wall $E_{c,eff}$ = 0.88E_{cm}. The imposed strain was simulated with the software function "thermal surface load" for ΔT = 16 °C. The obtained hoop force and hoop bending moment distributions are shown in Fig. 4.

The cracking force (for $e = M_R/R$ = 0.001m, and tensile strength of 6 days old concrete $f_{ct,eff}$ (t_{crit}) = 2.1 MPa):

(3.1) $$N_{cr} = \frac{f_{ct,eff}(t_{crit})}{\frac{e}{W_c} + \frac{1}{A_c}} = \frac{2100}{\frac{0.001}{1.0 \cdot 0.3^2/6} + \frac{1}{1.0 \cdot 0.3}} = 630\,\text{kN/m}$$

is far lower than hoop force equaled to 1334,43 kN. Therefore, the wall cracking is expected.

The minimum reinforcement in one cross-section side (for bars ϕ=22 mm, standardized diameter ϕ_s*=32 mm, steel stress σ_s=160 MPa, A_{ct}= 0.3 m^2 , k_c=1.0 and k = 0.8) is equal to:

(3.2) $$A_{s,\min(cr)} = 0.5\frac{k_c k f_{ct,eff} A_{ct}}{\sigma_s} = 0{,}5\frac{1.0 \cdot 0.8 \cdot 2{,}1 \cdot 0{,}3}{160} = 0.001575\,\text{m}^2 = 1575\,\text{mm}^2/\text{m}$$

For other bars: for ϕ=18 mm $A_{ss,min(cr)}$=1313 mm^2/m and for ϕ= 14 mm $A_{s,min(cr)}$=1146 mm^2/m.

3.3 PERSISTENT SITUATIONS

3.3.1 APPLIED ACTIONS AND DISTRIBUTIONS OF INTERNAL FORCES

The numerical model was loaded with self-weight, liquid pressure, imposed strain and thermal actions (Tab. 1). The distributions of internal forces proper for ULS and SLS are shown in Fig. 5.

Table 1. Imposed and thermal actions applied to finite element model of tank

Action	Characteristic values		Combination			
			basic for ULS		characte-ristic	*quasi*-permanent
	wall	bottom	ψ_0	γ_F	ψ_0	ψ_2
Shrinkage (equivalent cooling ΔT_s)	–25.0°	–6.0°	1,0	1.35	1.0	1.0
Difference between temperatures of wall sides ΔT_M in winter / summer	+27,6 /–12.0	+18.1° /+13.1°	0,6	1.5	0.6	0
Difference between the actual temperature and the initial one ΔT in winter / summer	–23,1 /+31.5°	–6,5° /–0.2°	0,6	1.5	0.6	0

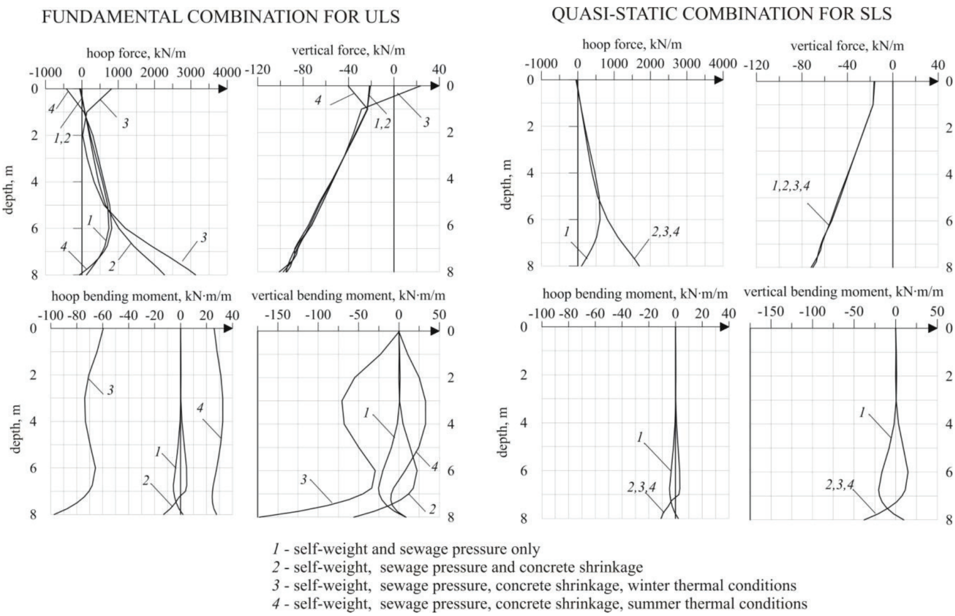

Fig. 5 Comparison of internal forces distributions in different persistent situations: for ultimate limit state and for serviceability limit state

3.3.2 HOOP REINFORCEMENT RESULTING FROM ULTIMATE LIMIT STATE

Hoop reinforcement amount was calculated for winter and summer conditions in accordance with algorithm for dimensioning of eccentrically tensioned cross-sections. It was compared with minimum reinforcement established in p. 3.3.1. In lower part of wall of 3.0 m height reinforcement in the outer side of wall was higher then minimum (it was assumed ϕ22/95, ϕ22/135, ϕ18/135 in consecutive one meter height rings). In the upper part of outer side and in the whole inner side of the wall the minimum reinforcement was sufficient (ϕ14/100 mm was assumed).

Diminishing of reinforcement amount in ULS would be possible in lower part of tank if the reduction of cross-section stiffness due to cracking was used (see p. 2.2.2). If the stiffness was reduced twice the hoop forces would be diminished of 59% and hoop bending moment of 79%. This fact however does not make any difference because the reinforcement calculated in crack control process is crucial (see p .3.3.3).

3.3.3 CRACK CONTROL

The first step was to find out if cracks due to characteristic combination of actions would be possible. For the calculation of cracking force the $f_{ct,eff}$ = 2.9MPa was used and it was proved that cracks may appear through the whole wall height.

In the consequence, the reduction of $f_{ct,eff}$ was used in crack control for quasi-permanent combination of actions (k_{red} = 0.5 was assumed resulted in $f_{ct,eff}$ =1.45 MPa). It was found that cracks would be possible in the lower part of four meters height (if the reduction were not used the cracking would appear along the two meters only).

Crack width exceeded limit value w_k = 0.3 mm in the ring sections 1.0–2.0 m and 2.0–3.0 m from the bottom, therefore the enlargement of the reinforcement in relation to that obtained from ULS in these parts was necessary. Finally, in the outer side of lower wall part, the reinforcement ϕ22/95, ϕ22/100, ϕ18/100 in consecutive one meter height rings were designed, whereas in the upper part of outer side and in the inner side of the wall the minimum reinforcement ϕ14/100 mm was left.

The obtained large amount of tank reinforcement suggests, that the prestressing of analyzed tank should be taken into consideration and probably is the better solution.

4. CONCLUSIONS

On the basis of the discussion of standard rules for design of liquid tanks and the obtained results of design calculation for an illustrative tank, the following conclusions may be formulated:

1. In liquid tanks the tightness and the following crack control is crucial for the amount of reinforcement. In order to ensure the tightness, the persistent situation concerning the imposed strains as well as the transient early age situation should be taken into consideration.
2. Detailed design of liquid tanks with consideration of the imposed strains, demands assumption of some initial parameters necessary for calculations of strain values, both in early age situation as well as in persistent one. It is not easy to precise predict these parameters in the stage of the design. However, in the illustrative tank the assumptions lead to equivalent cooling simulating difference of shrinkage strain of wall and bottom in persistent situation equal to 15^{o}C. This value is the same as given in earlier Polish Standard recommendations [18].
3. Values of safety and combinatory factors for imposed and thermal actions are decisive for calculations of internal forces in tanks for hot liquid. The values given in EC1-4 seem to be questionable to some extend.

4. In crack control process performed for *quasi*-permanent combination of actions, the fact of cracking in transient early age situation and cracking in persistent situation under characteristic combination of actions should be considered. Such cracking results in the reduction of effective tensile concrete strength.
5. The appropriate algorithm for crack control in liquid tank has been proposed in the paper (see Fig. 2).

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LIST OF FIGURES AND TABLES:

Rys. 3 Analizowany zbiornik cylindryczny: a) przekrój pionowy, b) schemat obliczeniowy

Fig.4 Distribution of internal forces in the down segment of tank wall due to early age imposed concrete deformations in transient situation at t_{crit} = 6 days

Rys. 4 Rozkład sił wewnętrznych w dolnym segmencie o wysokości 2.0 m betonowanym jako pierwszy na płycie fundamentowej, powstałych w wyniku wczesnych odkształceń wymuszonych betonu w sytuacji przejściowej w wieku t_{crit} = 6 dni

Fig. 5 Comparison of internal forces distributions in different combination of actions: for ultimate limit state and for serviceability limit state of cracking

Rys. 5 Porównanie rozkładów sił wewnętrznych powodowanych różnymi kombinacjami obciążeń dla stanu granicznego nośności i stanu granicznego zarysowania

Tab. 1. Imposed and thermal actions applied to finite element model of tank

Tab. 1. Odkształcenia wymuszone i termiczne przyłożone do modelu numerycznego zbiornika

ODKSZTAŁCENIA MŁODEGO BETONU I ODDZIAŁYWANIA TERMICZNE W PRAKTYCE PROJEKTOWANIA ŻELBETOWYCH ZBIORNIKÓW NA CIECZE

Słowa kluczowe: zbiornik żelbetowy, szczelność, kontrola zarysowania, odkształcenia wymuszone, oddziaływania termiczne

STRESZCZENIE

Ze względu na wymaganie szczelności, zbiorniki na ciecze należy projektować ze szczególną starannością. Pod uwagę powinno być wzięte nie tylko ciśnienie cieczy, ale także odkształcenia wymuszone betonu i oddziaływania termiczne. Projektowanie w oparciu jedynie o sprawdzenie stanu granicznego nośności w stałej sytuacji obliczeniowej jest niewystarczające. Dla ustalenia przekroju zbrojenia należy przeprowadzić szczegółową kontrolę zarysowania zarówno w sytuacji stałej, jak i w sytuacji przejściowej charakteryzującej okres kilku dni po betonowaniu.

Na początku procesu projektowania trzeba podjąć kilka decyzji związanych z założeniami projektowymi. Po pierwsze należy ustalić klasę szczelności determinującą warunki obliczeniowe dla sprawdzenia szerokości rys. Później trzeba założyć wiek betonu, w którym rozważana będzie sytuacja przejściowa. Wiek ten determinuje wartość odkształceń wymuszonych z jednej strony, a wytrzymałość betonu z drugiej. Następnie należy zdecydować, czy przy sprawdzaniu stanu granicznego zarysowania dla *quasi*-stałej kombinacji obciążeń zastosowane zostaną redukcje wytrzymałości (redukcja związana z odkształceniami samorównoważącymi i redukcja związana z wcześniejszym zarysowaniem wskutek innej kombinacji). Wreszcie, przyjęte muszą być założenia do analizy statycznej - ustalić należy wartości współczynników kombinacyjnych dla stanów granicznych nośności i zarysowania oraz zdecydować, czy w obliczeniach dla stanu granicznego nośności zastosowana zostanie redukcja sztywności przekrojów ze względu na zarysowania np. wskutek oddziaływań termicznych.

W niniejszym artykule powyższe problemy zostały zestawione i przedyskutowane. Zaproponowano algorytm postępowania przy projektowaniu zbiorników ciecze. Cale zagadnienie zostało zilustrowane praktycznym przykładem obliczeń cylindrycznego zbiornika na ścieki. Received: 28.08.2020, Revised: 01.10.2020