THERMAL CRACKING PREVENTION WITH UNBONDED STEEL TENDONS IN CYLINDRICAL CONCRETE TANK WALL RESTRAINED AT FOUNDATION SLAB

Andrzej S. Seruga, Professor, Krakow University of Technology, Krakow.
Rafał S. Szydłowski, Assistant Professor, Krakow University of Technology, Krakow

ABSTRACT

The rigid junction of the tank wall in foundation slab is the common solution in construction of reinforced and prestressed concrete tanks. The exothermic character of cement hydration causes the increase of concrete temperature in the first period. When the cooling process is started, due to restraining of thermal volume change of the wall at bottom edge the tensile stresses increase. When thermal stresses exceed the concrete tensile strength, the concrete cracking appears. To eliminate the early-age thermal cracking authors of this paper used 8 unbonded steel tendons 7ϕ5 mm to prestress the bottom part of tank concrete wall. The prestressing was realized 46 hours after casting. The experimental research on full-scale construction during the concrete wall realization was carried out. Based on the experimental results the evaluation of concrete behaviour and conclusions are drawn.

Keywords: Concrete tank, Thermal cracking, Unbonded tendons, Early-age concrete prestressing.

INTRODUCTION

The rigid junction of the tank wall in foundation slab is the common solution in construction of the reinforced and often prestressed concrete tanks for liquids. The exothermic character of cement hydration causes the important increase of concrete temperature in the first period after casting. The plastic concrete mixture easy slides on the foundation slab and in the form. If the stiffness of concrete increase, the volume change is restrained by the bottom slab and compressive stresses appear. Visco-plastic behaviour of early-age concrete significantly reduces these compressive stresses. After the concrete temperature achieved the peak value, the concrete cooling process is started. Restraining action of foundation slab on the bottom edge causes growth of tensile stresses in the concrete tank wall. When the concrete stresses exceed the tensile strength the wall cracking appears (fig.1). In practice two type of throughcracks can be observed (fig. 2). Their occurrence depends primarily on geometrical relations. In walls with a slenderness of $L/H \leq 1$, only cracks occur which starting at the bottom only partially cut through the height of wall, type PCr. They are rather narrow ≤ 0.1 mm. The cracks, type TCr cut through the entire height of wall, they may be wide. They depend primarily on the relative stiffness of both wall and foundation relations and occur if $L/H \geq 2$ to 2.5. Control of cracking has to concentrate on the cracks type TCr.

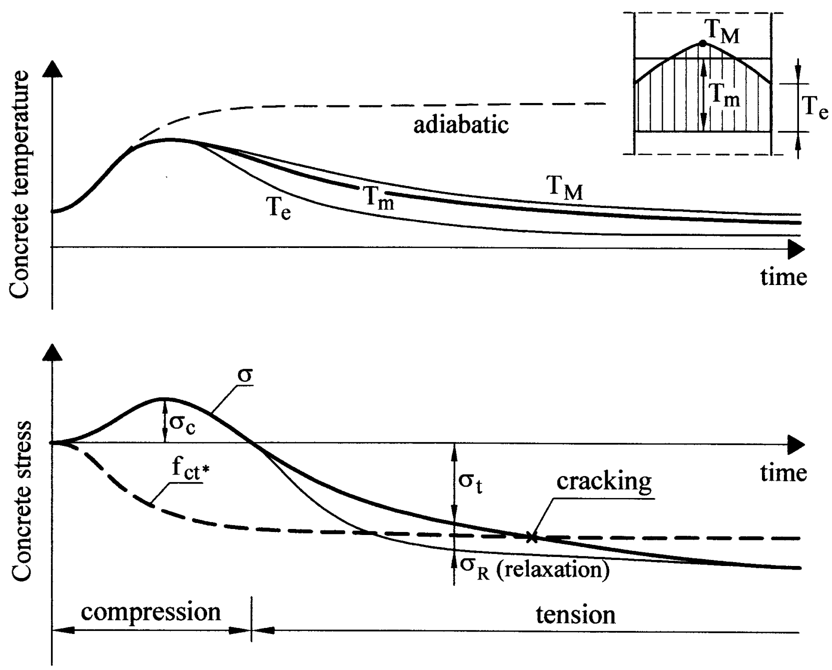

Fig. 1 Temperature and stresses in a restrained wall in the uncracked stage.

The cracking risk may be defined as the maximum value of the stress level

$$\eta^{max} = \left[\frac{\sigma_t(t)}{f_{ct}^*(t)}\right]^{max} \qquad (1)$$

where $\sigma_t(t)$ is the tensile stress at a certain time t and $f_{ct}^*(t)$ is the tensile failure stress at the same time. The tensile failure stress is a strength value reduced due to the slow loading rates.

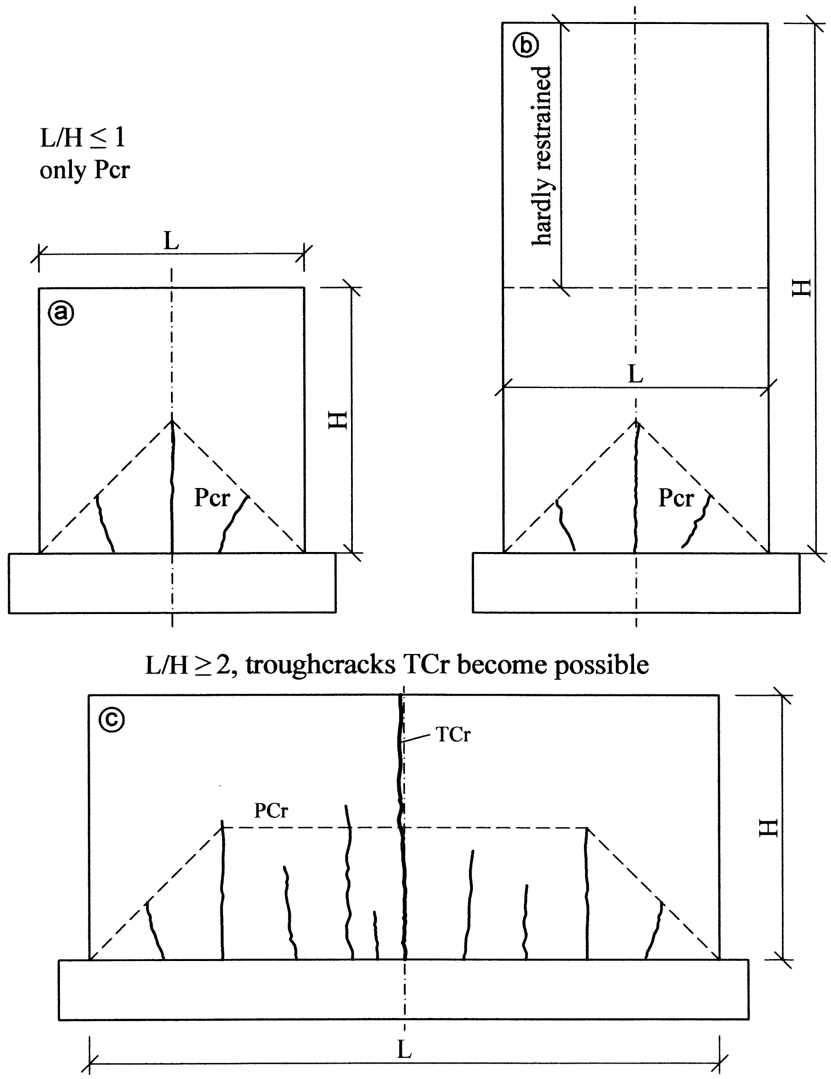

Fig. 2 Type of cracks in restrained walls.

Alternatively, the restrained tensile strain $\varepsilon_t(t)$ may be compared with the ultimate tensile strain $\varepsilon_u(t)$ at the same time

$$\chi^{max} = \left[\frac{\varepsilon_t(t)}{\varepsilon_u(t)}\right]^{max} \tag{2}$$

The safety factor against cracking may be expressed as

$$\Gamma = \frac{1}{\eta^{max}} \qquad \text{or} \qquad \Gamma = \frac{1}{\chi^{max}} \tag{3}$$

It is difficulty to define which stresses level that is acceptable regarding cracking risk. Considering general uncertainty in early age concrete behavior and material modeling as well as simplifications and approximations done in application to structural analysis, Emborg [5] suggests a maximum value for stress level $\eta^{max} = 0.7$. This corresponds to a safety factor $\Gamma \approx 1.4$.

Even though, the cracked concrete is common and acceptable by building engineers, in specific types of concrete structures e.g. tanks for liquids, underground floors of building, early-age concrete cracking is undesirable and persistent problem. The thermal cracks are reason to leakages in the liquids tanks, foundations slabs and walls of underground floors of the buildings. Costs of sealing the early-age cracked concrete in EU countries is estimated about billion EUR per year.
The problem of thermal early-age cracking of the concrete is minimized by different means, mainly technological modifications:

- modification of mixture content: application of low-heat hydration cement, decrease of water/cement ratio,
- dividing the wall in segments,
- by cooling the wall with the water, nitrogen or air pipe system,
- by cooling the wall and heating up the bottom slab.

The authors of this paper propose the new solution for thermal cracking avoiding. It is suggested, to introduce into concrete wall the compressive stresses reducing the further tensile stresses caused in changing the volume restrained at bottom edge concrete wall (fig. 3). It is necessary to introduce of compressive stresses before the thermal stresses exceed the effective concrete tensile strength. But, if it will be done too early, the compressive stresses will be lost because of the visco-plastic behaviour of early-age concrete. Appearance of unbonded tendons in Poland about fifteen years ago gave possibility to applications new type of prestressing to avoiding the thermal-cracking in the fixed in bottom slab concrete walls. The authors of this paper used the eight unbonded steel tendons to eliminate early-age cracking in bottom wall segment during construction the prestressed concrete tank in sewage treatment plant.

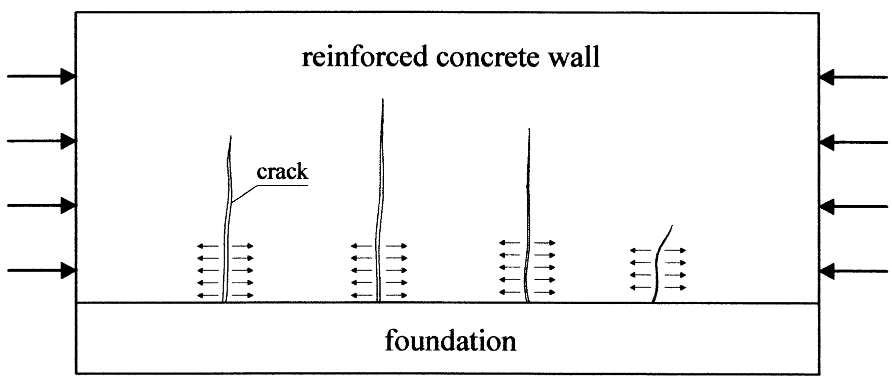

Fig. 3 Reduction of thermal stresses in the concrete wall by prestressing.

STRUCTURES GEOMETRY AND REALIZATION PROCESS

The cylindrical prestressed concrete tank for sewage was built in 2008 year in sewage treatment plant in Poland. The tank was designed as 18.0 m inner diameter, 19.44 m cylindrical wall high and 0.3 m concrete wall width. The cylindrical concrete wall was fully

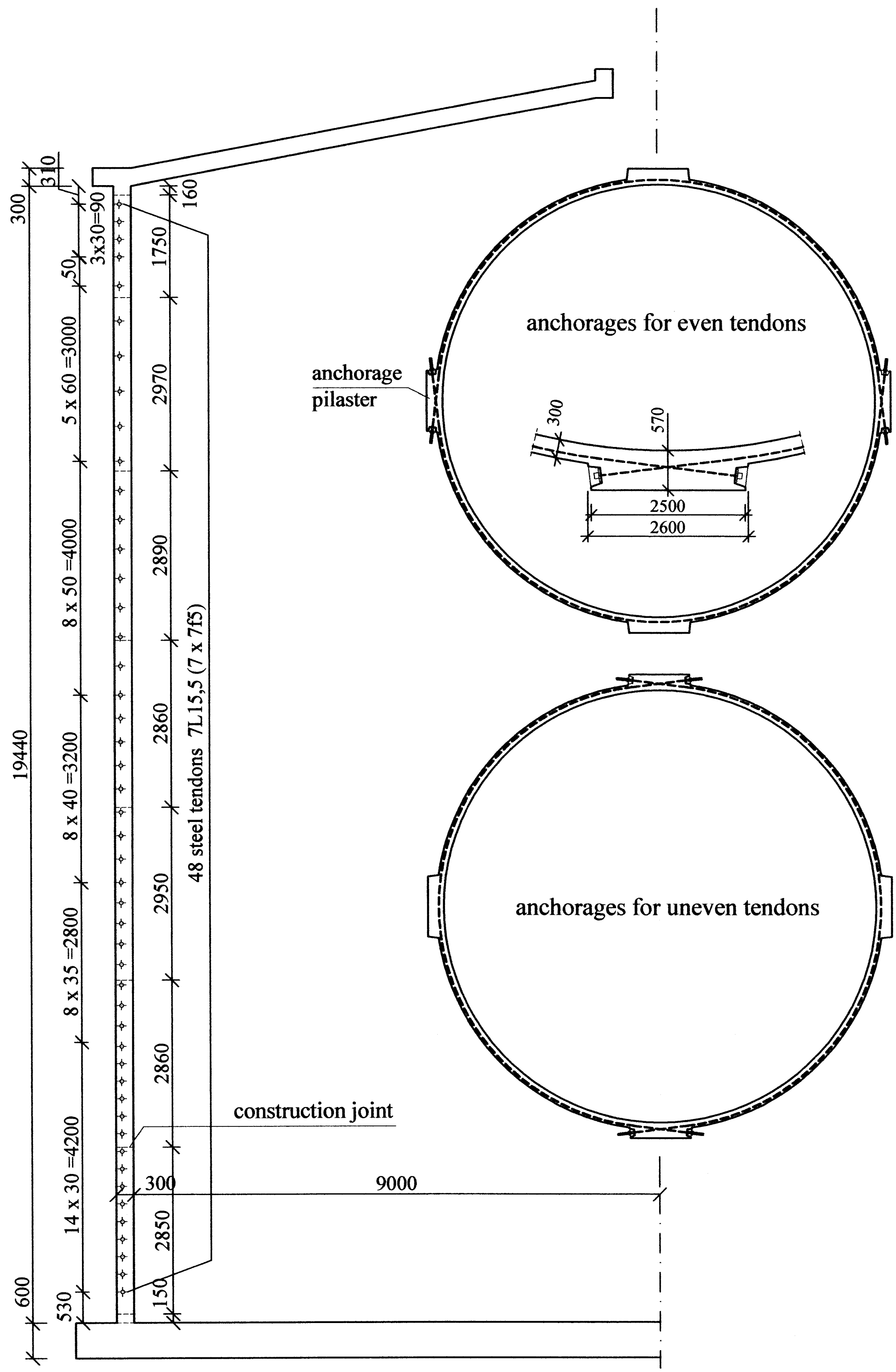

Fig. 4 Geometry of prestressed concrete cylindrical tank (length in millimeters).

connected with bottom slab of 0.6 m high. The concrete wall was prestressed by 48 half circumference long steel tendons 7L15.5 (7×7ϕ5 mm) anchored alternate in four pilasters (fig. 4). The concrete wall was casting into 7 full perimeter long segments of 2.85, 2.86, 2.95, 2.86 2.89, 2.97 and 1.75 m high. The concrete class was C35/45. The special concrete mixture design for prestress concrete structures has been used. The concrete mixture was designed based on Portland cement CEM I MSR NA 42.5 in quantity 433 kg/m^3, w/c = 0.39. To improve the concrete modulus of elasticity basalt aggregate has been used. Because of the high quantity of hydration heat cement had been used and time of realization (summer months), the thermal cracking was expected. To prevent the wall concrete from early-age cracking 8 unbonded steel tendons located regularly in distance 0,3 m in bottom segment of the cylindrical wall. Localization of unbonded tendons and its anchorage scheme are shown in figure 5. All of these tendons were tensioned about 46 hours after casting up to 20 tons.

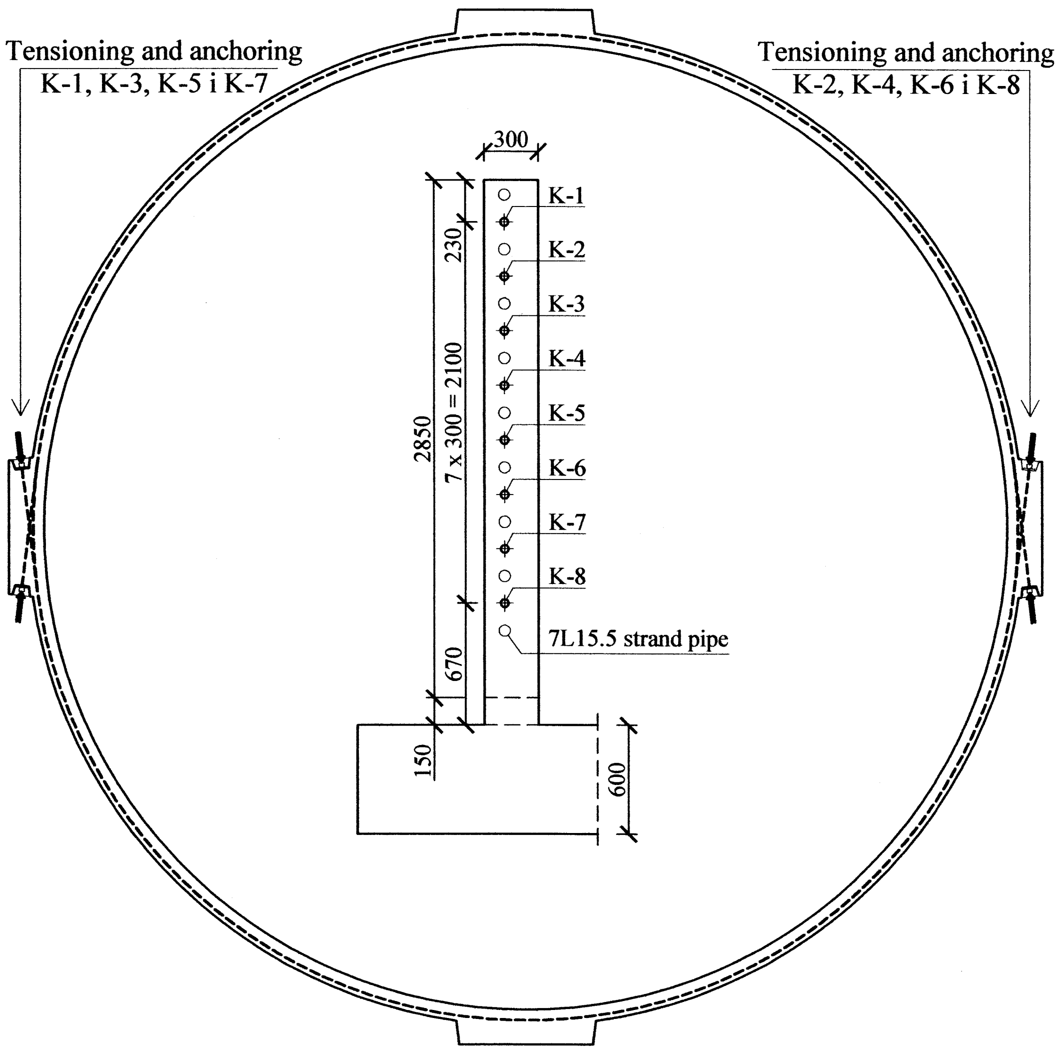

Fig. 5 Localization in cross-section and anchorage scheme of unbonded tendons (length in millimeters).

TEST PROGRAM

Because of the prototype character of this application the large test program was conducted. The prestressing of concrete tank wall with service load tendons type 7×7ϕ5 mm was realized 210 days from casting. The following values were monitored from casting through 280 days:

- concrete strains and temperatures distribution in bottom wall segment in two cross-section: first: mid-span of the wall between the pilasters, second: pilaster cross-section,
- concrete stresses in the wall cross-section at the high 2.72 m from the foundation slab,
- prestress force in all of 8 unbonded steel tendons.

During the wall casting the concrete sample set was made. Simultaneously with in-situ test the development of mechanical properties of concrete in day-time was determine in the Laboratory. The following mechanical properties of the concrete were monitored:

- compressive strength (cube samples 150 mm × 150 mm ×150 mm),
- compressive strength (cylindrical samples ϕ150 mm × 300 mm),
- axial tensile strength (cylindrical samples ϕ150 mm × 300 mm),
- splitting tensile strength (cube samples 150 mm × 150 mm ×150 mm),
- modulus of ruptures (beam samples 150 mm × 150 mm × 600 mm), two points bending,
- modulus of elasticity of concrete (cylindrical samples ϕ150 mm × 300 mm),
- concrete shrinkage (beam samples 100 mm × 100 mm × 500 mm).

Because of the strains in real structures are caused by temperature volume change, concrete shrinkage and creep, it is difficult to evaluate the visco-elastic concrete behavior. To separate the creep strains, the two additional concrete wall samples 0,3×0,9×1,2 m were casted on sliding base to eliminate the restraining effect. The both elements were reinforced similarly to concrete tank wall (fig. 6). One of them was prestressed by 3 unbonded tendons located in the same distance to receive exact the same stress level as in concrete tank wall. The second was unloaded, and the shrinkage and thermal strains were monitored. The special type of screw anchorage was adopted to eliminate the slip losses.

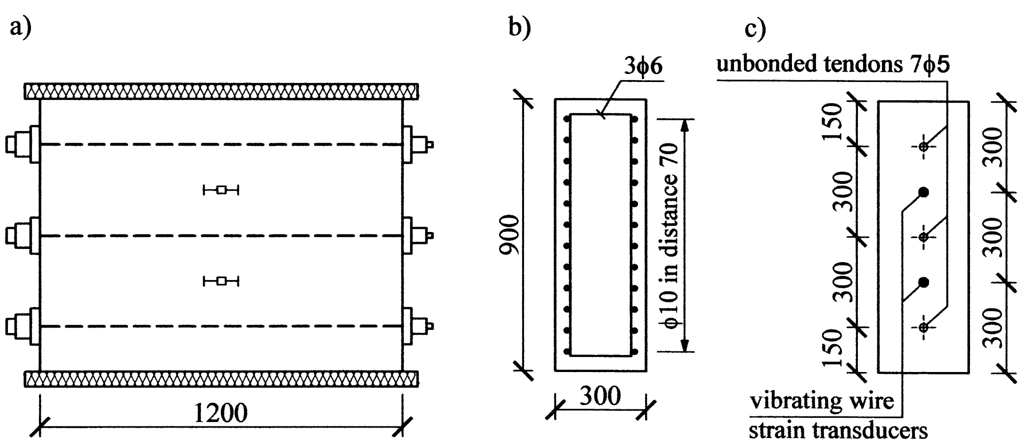

Fig. 6 Concrete samples wall for comparative analysis (length in millimeters).

The general view of first wall segment and the arrangement of prestress tendons and strain transducers is shown in fig. 7.

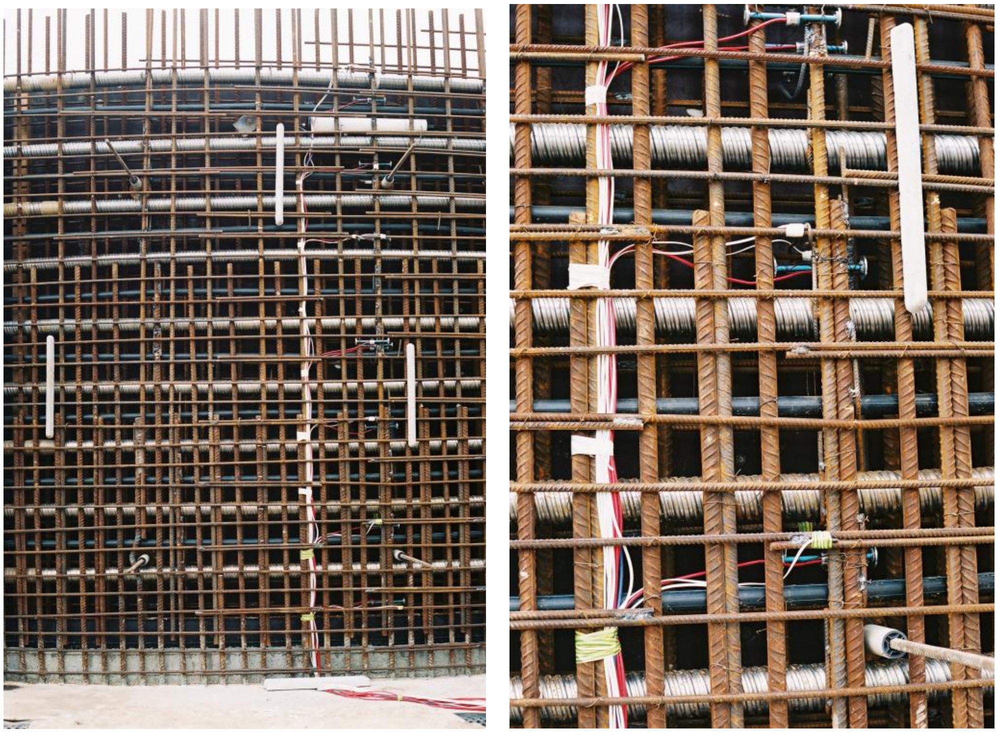

Fig. 7 View of localization of unbonded tendons and strain transducers.

DEVELOPMENT OF CONCRETE MECHANICAL PROPERTIES AND TEMPERATURE

The development of concrete mechanical properties were tested up to period of total prestressing of concrete tank wall. The concrete compressive strength (a), tensile strength (b) and modulus of elasticity (c) tested on the samples set during the first 28 days are presented in fig. 8. The development of concrete shrinkage during 250 days is shown in fig. 8d.

The concrete strains as well as temperature changes in the first horizontal segment of tank wall were recorded in vertical cross-section localized at mid-span of the wall with Geokon vibrating wire system. The concrete temperature development is drawn in fig. 9. The highest value of temperature was recorded 17 hour from casting. After that, it was observed the cooling process effect. The three local minimum values of temperature T_{min1}, T_{min2}, T_{min3} were recorded 39, 60 and 84 hours after casting accordingly. The highest risk of concrete cracking was in the first three days from concreting because of insufficient tensile strength of young concrete. 24 Hours from concreting it was started to remove the formwork. After stabilization of the anchorage system on each tendon it was started to tensioning the tendons K-2, K-4, K-6 and K-8 fixed in uneven pilasters. In the second stage the prestressing force

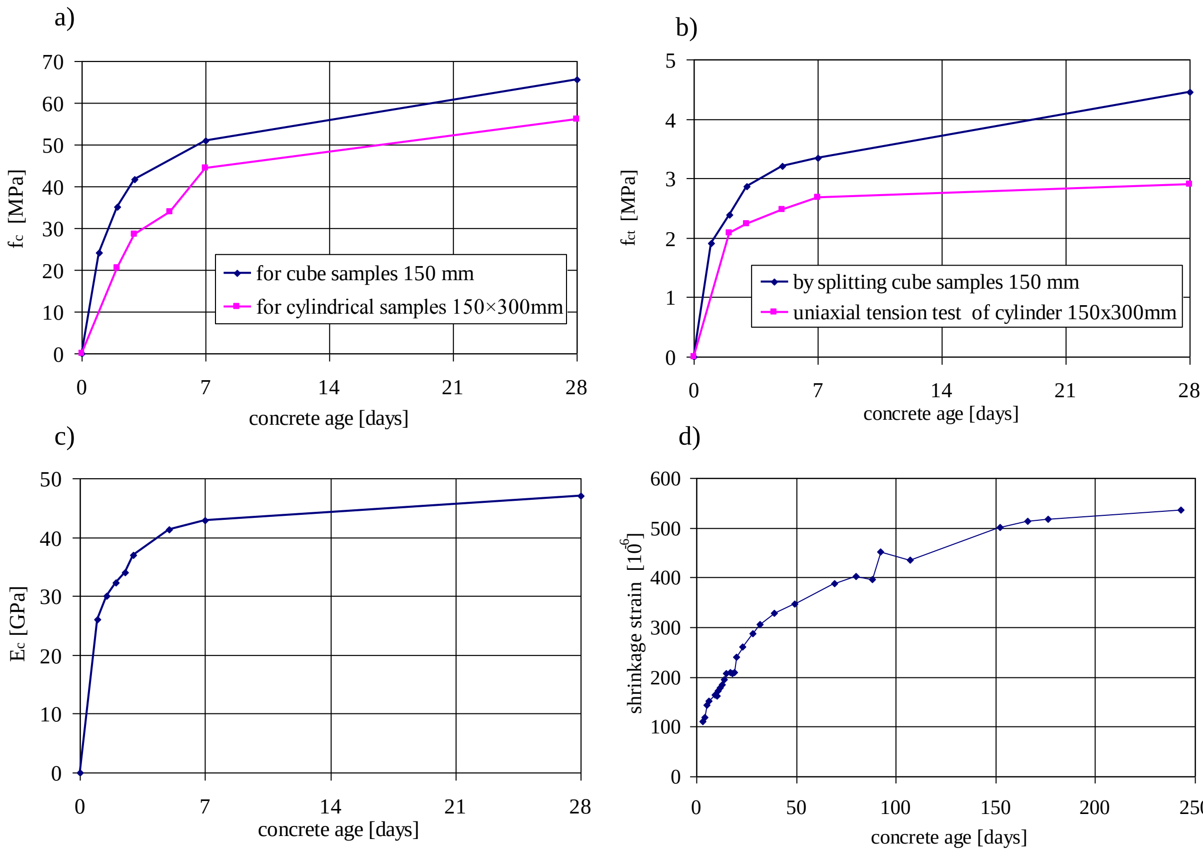

Fig. 8 Development of concrete mechanical properties on day-time: tensile strength (a), compressive strength (b), modulus of elasticity (c) and shrinkage strain (d).

was realized in the tendons K-1, K-3, K-5 and K-7 fixed in even pilasters. The total process of prestressing took two hours between 46 and 48 hour after casting. The temperature development during the first seven days is shown in fig. 9. Three characteristic points (T_{min1}, T_{min2}, T_{min3}) related to the greatest average temperature drop in time rates are the moments of the time when the concrete cracking was expected. The distribution of the temperature at the analyzed vertical cross-section in four characteristic time points are drawn in fig. 10.

The development of concrete strains in time were measured also on two additional wall samples. The obtained results are plotted in fig. 11. Because of concrete shrinkage is independent on loading state, the difference of concrete strains values recorded in both wall samples is equal to the concrete creep strains. The development of these concrete creep strains is plotted by red solid line in fig. 11. Because of tendons prestressing was realized simultaneously it gave possibility to evaluate the reliable value of modulus elasticity in real construction. The stress level due to prestressing was 2.17 MPa. The increase of concrete strains after 39 hours from concreting visible in fig. 11 represents the instantaneous strain caused by prestressing (124×10^{-6}). The value of modulus of elasticity determined in this way is equal to 17,500 MPa. It should be noted, that this value is 0.56 of the value obtained from the test of cylindrical samples $\phi150\times300$ mm presented in fig. 8c (30,600 MPa). The same

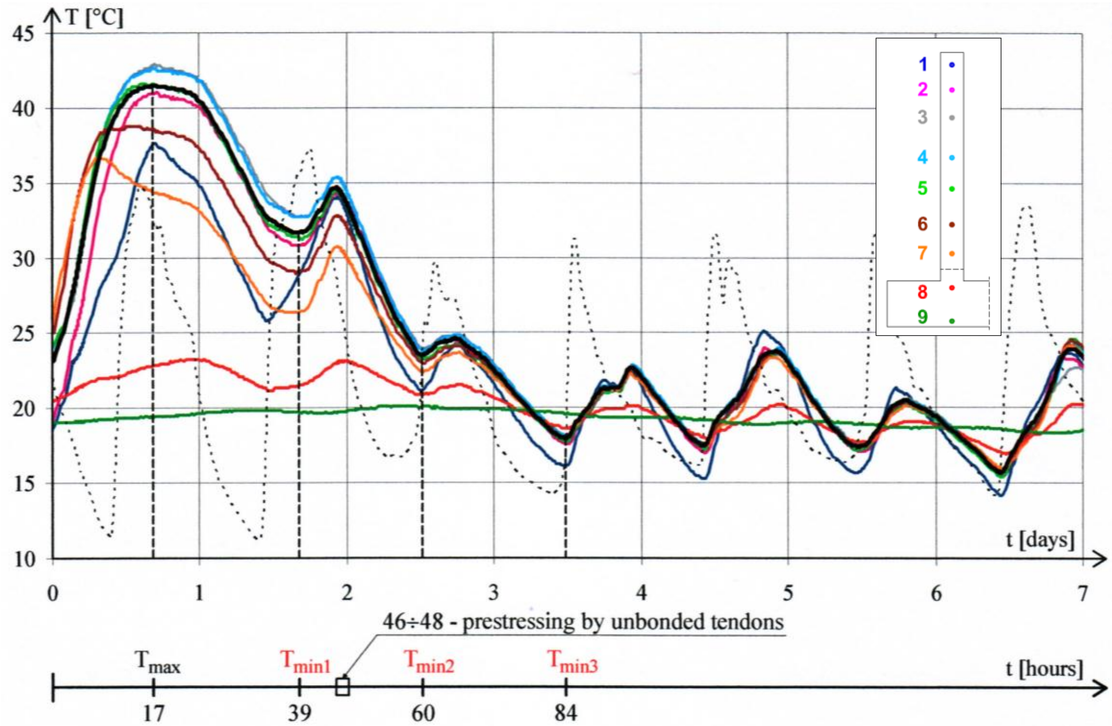

Fig. 9 Development of concrete temperature recorded on transducers in the middle of the wall cross-section and bottom slab (point 8 and 9), the average temperatures from point 2÷6 (black solid line) and ambient temperature (black dashed line).

value of modulus of elasticity was determined with the strain and stress of concrete in tank wall. It was 16,900 MPa and it is lower than value obtained from additional wall samples. This problem was often discussed in many publications. When the load is applying, the creep strains appears simultaneously with instantaneous strain before the loading is completed. Because of this fact, is difficult to unique separate the instantaneous and creep strains. Regarding of this phenomena, it is obvious that the modulus of elasticity values is affected the load rate. The tensioning of unbonded tendons took several minutes in case of additional wall sample and about two hours in case of tank wall. Therefore, the value obtained from the wall samples seems to be more reliably and was taken to further analysis of thermal stresses. Based on this value of concrete modulus of elasticity the FEM model was built in DIANA system. The concrete temperature drops from value T_{max} up to T_{min1}, T_{min2}, T_{min3} calculated from measured values and plotted in fig. 10 were applied in FEM model as well as loading from prestress tendons.

The fig. 11 presents the values of concrete strains caused by prestressing obtained from FEM analysis (red line) in compare to value recorded on the strain transducers. It can be observed the good agreement of both theoretical and experimental results. This confirms the correctness of assumption of the modulus of elasticity. The same figure includes the concrete strains calculated for the modulus of elasticity obtained from sample test equal to 30,600 MPa. We can seen, that these values are strong underrated in comparison to experimental

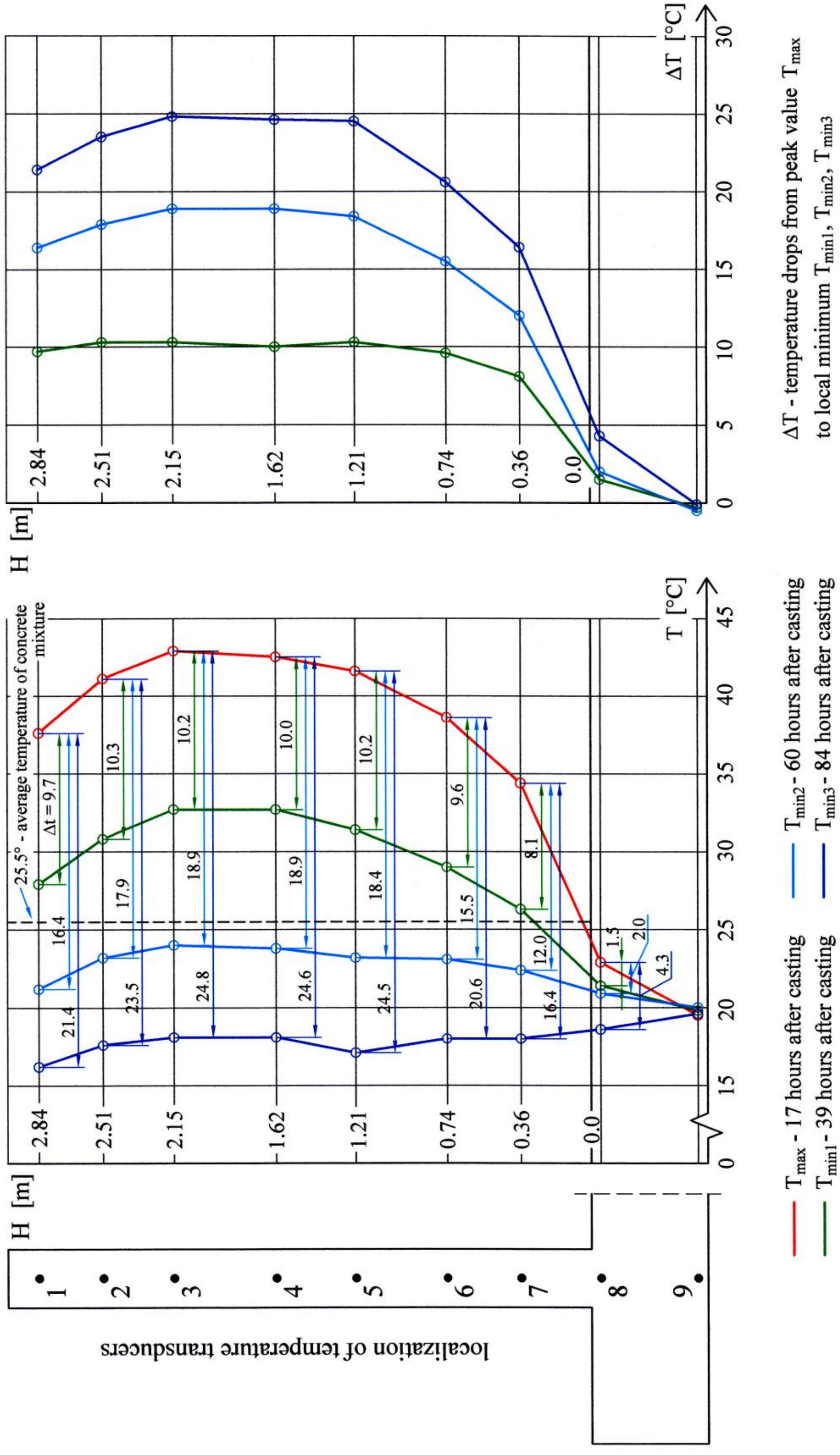

Fig. 10 Temperature distribution in the wall cross-section at significant points of the time.

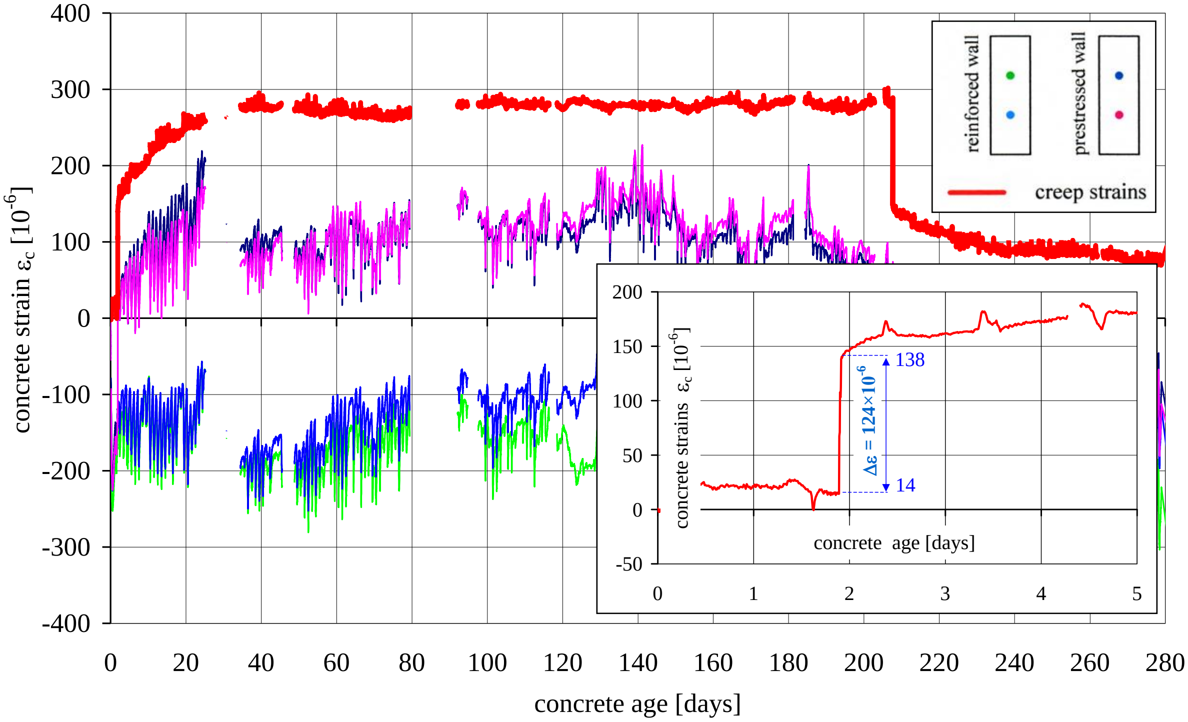

Fig. 11 Concrete strains in wall samples and the creep strains development (the color of the curve responds to color of measuring point presented on top-right figure).

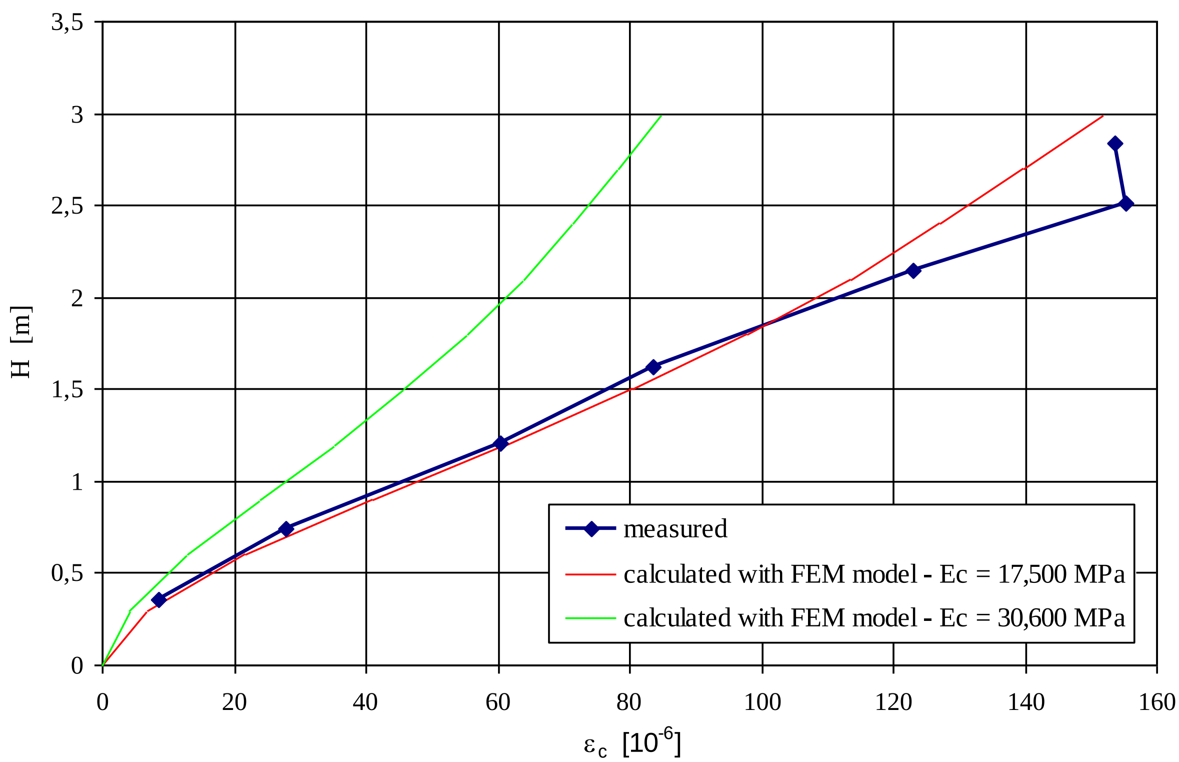

Fig. 12 Measured and calculated with FEM model.

results. It is evidence, the modulus of elasticity in full-scale construction is lower than secant modulus in concrete samples. The assumption of modulus from laboratory tests is the fault and will provide to incorrect estimation of shell deformation and prestressing losses.

PRESTRESSING LOSSES

Because of the difficulty in prediction of the visco-elastic and visco-plastic behavior of very young concrete (< 2 days) it was impossible to predict the loss of prestressing force. For this reason, each unbonded tendon was equipped with vibrating wire force transducer Geokon type. The force cells were located on the strands anchorages. The values of prestress forces were monitoring during the 280 days period.

The figure 13 shows the change of prestress force in all of 8 unbonded tendons. The prior value of the force was 200 kN. The values plotted in fig. 13 started from the lower level than prior values. It is caused by the slip losses near the anchorages. The value of prestress force in the analyzed wall cross-section was calculated based on measured values and friction factor equal to 0.05. The numerous values of forces and losses are listed in Table 1. It can be seen, the prestress force losses aren't high significantly. The highest value of prestress loss after 210 days is 8.52 % (K-1), the average value is 6.5 %. The maximum prestress force loss due to tensioning of service load tendons is 1.4 % (K-5). The maximum and average values after prestressing of full tank wall are 9.32 and 7.6 % accordingly.

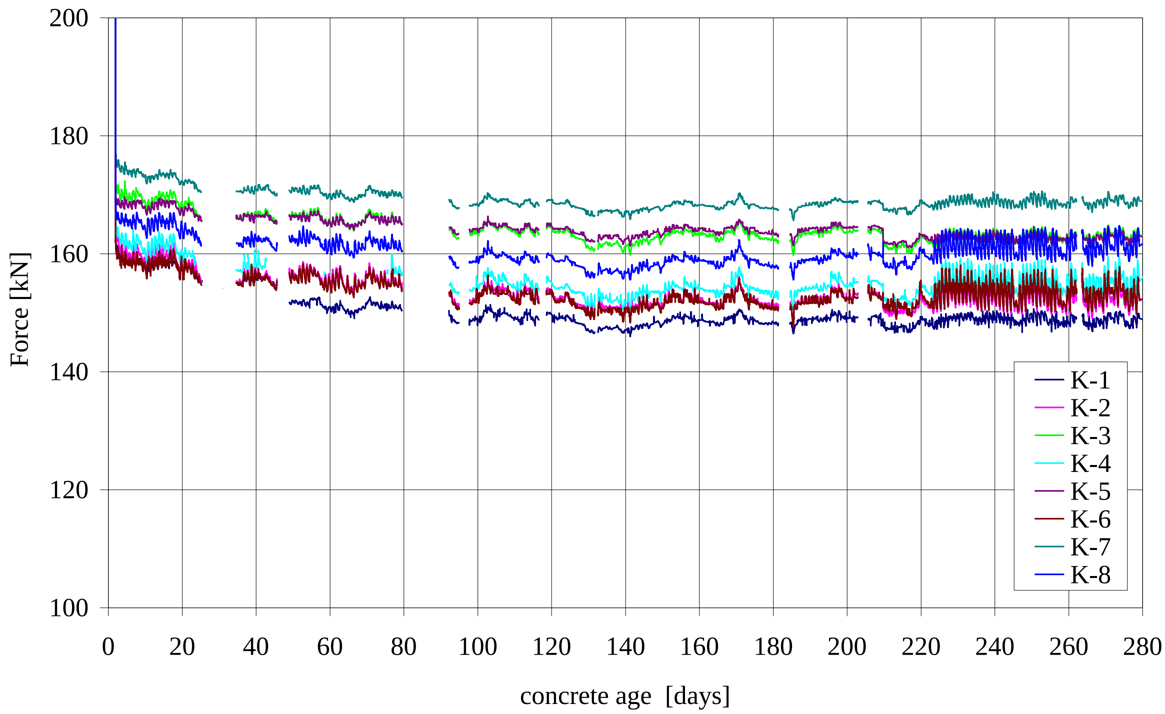

Fig. 13 Change of prestress force values in unbonded tendons.

Table 1 The values of prestress forces and losses in unbonded tendons.

Strand No	After anchoring	210 days later				Losses caused by service load strands tensioning	
		Before service load tensioning		After service load tensioning			
	[kN]	P_t [kN]	ΔP_t [%]	P_t [kN]	ΔP_t [%]	ΔP [kN]	ΔP [%]
K-1	163,1	149,2	8,52	147,9	9,32	1,3	0,80
K-2	166,2	153,2	7,82	151,0	9,15	2,2	1,3
K-3	173,3	162,3	6,35	160,0	7,67	2,3	1,3
K-4	167,2	155,1	7,24	153,4	8,25	1,7	1,0
K-5	170,4	161,2	5,40	158,9	6,75	2,3	1,4
K-6	162,9	152,6	6,32	150,8	7,43	1,8	1,1
K-7	177,8	168,8	5,06	167,8	5,62	1,0	0,6
K-8	169,2	160,3	5,26	158,7	6,21	1,6	1,0
Average	168,7	157,8	6,5	156,1	7,6	1,8	1,1

Nevertheless, the compressive stress was applied in very early-age concrete (< 2 days) the prestress forces aren't intended to large decreasing. It seems to be a right decision to involve the prior compressive stresses in the concrete (inserted in purpose of early-age thermal cracking prevention) in the service load carrying in future realization of this type construction.

THE EVALUATION OF PROPOSED METHOD

The figure 14a presents the concrete stresses in time point when the value T_{min1} was achieved. The effective tensile concrete strength is plotted in this figure, too. Take into consideration the load application rate which appears in thermal stresses phenomena, according to Emborg [5], the value of tensile concrete strength was reduced to effective concrete tensile strength equal to 0.7 the value obtained in laboratory tests. The both values of thermal concrete stresses, obtained from elastic and visco-elastic analysis, are plotted in fig. 14a. It can be seen, that the concrete stresses are lower than concrete strength in this time. The stress/strength ratio (visco-elastic analysis) was 1.04/1.47 = 0.71. It is sufficient value to avoid a thermal cracking. In next characteristic time points T_{min2} and T_{min3} when the concrete temperature dropped again the stresses (without prestress compression) exceed the concrete tensile strength. In point T_{min2} the stress/strength ratio was 1.67/1.52 = 1.1 (fig. 14b). It was reduced due to prestressing to level 1.32/1.52 = 0.87. In point T_{min3} the stress/strength ratio was 2.07/1.61 = 1.29 without and 1.69/1.61 = 1.05 with prestressing.
It may be concluded that without application of prestressing by unbonded tendons, the concrete wall thermal cracking would be appear at the moments when the concrete tempera-

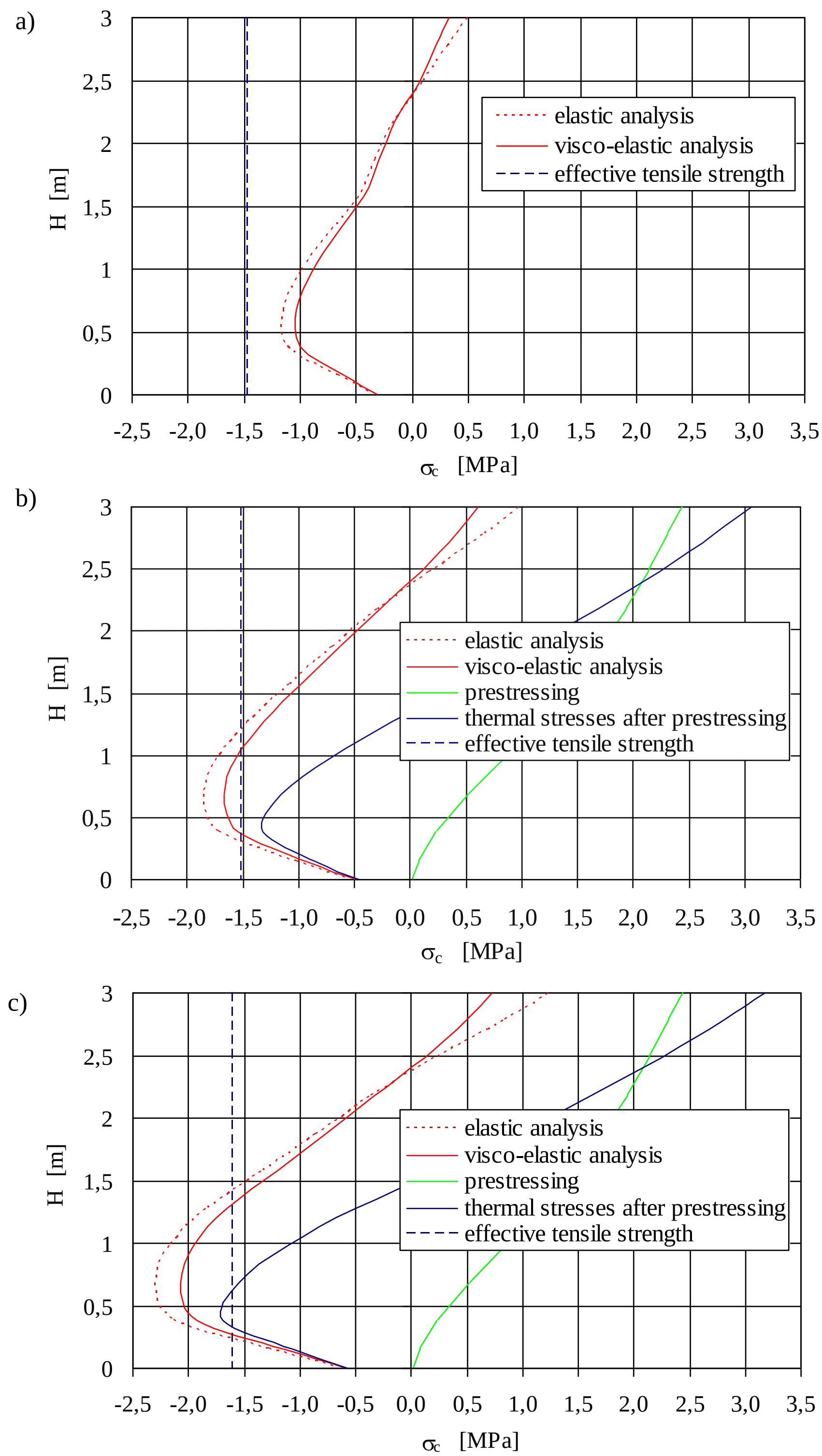

Fig. 14 Concrete stresses in the wall cross-section as well as effective tensile strength at the moment when T_{min1}, T_{min2}, T_{min3} were achieved ((a), (b), (c) accordingly).

ture achieved values T_{min2} and T_{min3} (60 and 80 hours from casting). Though, the prestressing didn't reduce the concrete stresses to value below the effective concrete tensile strength, the thermal cracking was not observed. It is obvious, the prestressing by unbonded tendons let to reduce the cracking risk. The lack of cracking in time when T_{min3} appeared may by explained by the accidental character of young concrete behaviour and the conservative assumption of tensile concrete strength.

FINAL CONCLUSION

Based on the results obtained from experimental and analytical tests as well as the experience from the first application of unbonded tendons to prevent the early-age thermal cracking in prestress concrete wall, the following conclusions may be drawn:

- The proposed method of prevention of thermal early-age concrete cracking is very simple in application and fully effective.
- It is shown on presented experimental results, that it should be applied between 40 and 60 hours from the first horizontal segment tank wall is concreted.
- The formwork would be removed from tank wall segment before the process of unbonded tendons tensioning is started.
- Preparing of pockets for anchorage system in the pilasters' faces is much time consuming process because of presence of anchorages for designed tendons.
- Because of difficulties in theoretical determination the concrete behaviour in the time of construction, the application of prestressing of early-age concrete structures should be always based on the full scale experimental tests independently of laboratory tests.

REFERENCES

1. Nishio, H., "Prestressed concrete tank – OHNA regulation reservoir," Proceedings of Congress of the FIP, Hamburg, 1990, pp. 97-100.
2. Okai, D., Kitamura, H., Hasegawa H., Hamada, F., „Computer based construction techniques applied to prestressed concrete dike for LNG Storage", Proceedings of FIP Symposium Modern Prestressing Techniques and Their Applications, Kyoto, Japan, 1993, V.3, pp. 1299-1306.
3. Staffa, M., "Zur Vermeidung von Hydratationsbedingten Rissen in Stahlbetonwänden," *Beton und Stahlbetonbau*, H. 1, 1994, pp. 4-8.
4. Morimoto, H., Koyangi, W., "Estimation of stress relaxation in concrete at early ages," *Thermal Cracking in Concrete at Early Ages* Proceedings of RILEM International Symposium, edited by R. Springenschmid, E&FN Spon, London, 1995, pp. 95-102.
5. Emborg, "Development of Mechanical Behaviour at Early Ages," *Prevention of Thermal Cracking in Concrete at Early Ages* State-of-the-Art Report prepared by RILEM Technical Committee 119: Avoidance of Thermal Cracking in Concrete at early Ages, edited by R.Springenschmid, E&FN Spon, London and New York, 1998, pp. 76-148.