Imposed Deformation Reduction in Semimassive Walls of RC Tanks by Internal Cooling

Mariusz Zych and Trong-Chuc Nguyen

Abstract Early-age cracks in the RC walls of the tanks very often cause leaks. In turn, limiting the value of imposed strains reduces the risk of cracking or the width of cracks if cracking is not to be excluded in general. In the paper the analysis of the impact of a cooling pipe system (CPS) on the changes of temperature and strains in a RC semimassive wall was presented. In the numerical calculations a model covering non-linear and non-stationary temperature field variations resulting from cement hydration, internal cooling and heat exchange with the surroundings was used. It was demonstrated that during concrete maturing CPS contributes not only to mean temperature changes reduction but also to the reduction of temperature gradients, which helps effectively limit or eliminate concrete cracking. The analysis of the so-called "self-equilibrated stress" inducing temperature indicated that the application of CPS contributes to the reduction to zero the positive temperature difference in the immediate surroundings of the cooling pipes and to the reduction of temperature extreme changes, i.e. positive changes in the wall interior and negative ones in its corners. As a result, the restrained part of the imposed strains, to a greater extent, may remain below the tensile strain capacity of concrete. This solution can protect the tank wall from cracking or significantly reduce it.

Keywords Cracks · Cooling pipe system · Wall · RC tank · Early-age concrete

1 Introduction

The period of concrete hardening, i.e. of cement hydration, is the time when significant imposed strains occur in massive and semimassive structures. According to

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the definition proposed by Falga [8], structures for which 2 $m^{-1} < m_c < 15$ m^{-1} are considered semimassive. This approach is based on determining the surface area-to-volume ratio $m_c = u_c/v_c$, where: u_c is the surface area of element that is exposed to air and v_c is the volume of the element. The number of variable parameters in the concrete mix as well as the variety of possible hydration conditions make it difficult to find optimal solutions. The issue of the complexity of the cement hydration process together with the influence of the currently used concrete admixtures was extensively presented by Aitcin and Flatt [1]. For example König et al. [13] described the early temperature changes in maturing concrete which result in self-equilibrating strains of a structural member as well as mean strains. The effect of excessive imposed strains in structures with a significant degree of external restraint are cracks, which are responsible for leakage in reinforced concrete (RC) tanks. Knoppik-Wróbel [12], proposing her own advanced numerical model for cracking risk assessment, verified it on semimassive wall members. This allowed a parametric analysis of the distribution of the degree of external restraint to be performed. Jeon [10] described the phenomenon of crack formation as a result of the release of the heat of hydration in members restrained by internal restraints. They proposed a hypoelastic model that can incorporate an incremental constitutive equation. The issue was discussed taking into account various mixtures and construction conditions. Seruga and Zych [20, 21] carried out extensive research studies on the material, temperature changes, strain and cracking during the execution of semimassive cylindrical and rectangular tanks. Further numerical analyses of these tanks carried out by Zych [25, 26] demonstrated the expected compliance of the advanced numerical model with the study results.

In the case of massive structures, one of the design solutions is the use of CPS, thanks to which the temperature rise resulting from cement hydration can be effectively lowered. However, the use of a CPS in mass concrete blocks also has many drawbacks such as local stress formation around large pipes, rapid reduction of concrete temperature can affect the strength development of concrete as presented by Bofang [5]. For a CPS to be efficient it is necessary to monitor the parameters affecting the working process of the CPS in concrete blocks [16, 22] such as: start and end time of water flow in the cooling pipe, water velocity, the type of water pipe, layout of the water pipe along the wall height (for example, in a concrete dam, the vertical and horizontal layouts are in the range of 1.5–3.0 m as proposed by Bofang [5]), water temperature in the cooling pipe, etc. Bofang [5] recommends that for a dam structure the height of the cooling area not be less than 0.4 times the height of the dam. Water temperature control in the pipes is very important to avoid a sudden drop in temperature in concrete blocks. In the studies by Bofang [5], Tang et al. [23], and Aniskin and Chuc [2] it is shown that the difference between water temperature and the initial temperature of concrete mixture should not exceed 10 °C.

The beneficial effect of internal cooling with air-filled prestressing ducts on the reduction of the risk of cracking in a massive wall was presented by Azenha et al. [3]. The authors demonstrated that in spite of the acknowledged limitations of air cooling, it may prove quite feasible in relatively cool climates and small lengths of embedment. Besides, the water pipe layout not only affects the cooling efficiency in concrete but also the economy of the project. In the case of a small water pipe, the temperature difference will be small, which can lower the maximum temperature in the concrete block significantly, thus reducing the formation of thermal stress.

This research paper analyses in detail the effect of CPS on temperature changes and imposed strains in a semimassive wall of a RC tank. A detailed analysis of the effect of CPS on changes in stresses was presented by the authors in Zych and Chuc [27].

2 Structure

The subject of analysis is one of the wall segments of a RC tank. This tank, due to the occurrence of cracks during the hardening of concrete and the resulting leaks, was the subject of the analysis presented by Zych [24]. Therefore, this tank was also a very good example for verifying the efficiency of internal cooling in order to reduce imposed strains. From the practical point of view, this has a large effect on the possibility of reducing the degree of reinforcement, which is usually very high in structures that are required to be watertight. The necessity of using a very high amount of reinforcement in a classic construction solution, has been experimentally confirmed in tests on a real object e.g. by Seruga and Zych [20]. The subject of the analysis is one of the wall segments (Fig. 1). This wall was constructed in stages, i.e. by executing subsequent segments. The second wall segment (which is being analyzed) that was 0.75 m thick, 1.4 m high and 30.3 m long was concreted in one cycle without a vertical construction joint in the middle of it. Despite the procedure of introducing horizontal and vertical construction joints in the rest part of the wall, numerous vertical cracks were observed on the outside and inside surfaces of the wall during concrete hardening (Fig. 1a, b).

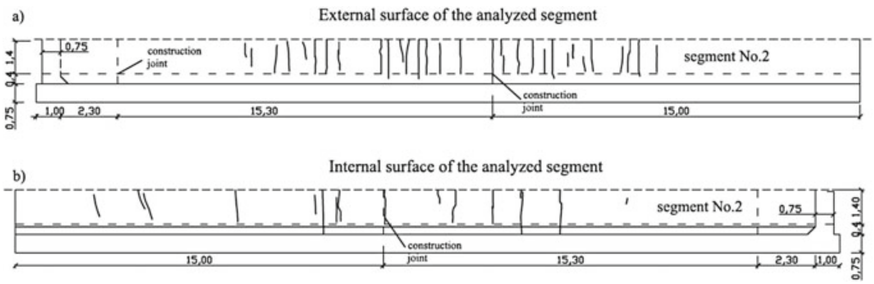

Fig. 1 Layout of cracks and their widths on the **a** outside and **b** inside segment surfaces

3 Numerical Model

The changes in the temperature field in the wall containing CPS were calculated by solving two basic differential equations, i.e. the Fourier equation taking into account the heat of hydration of cement and the equation taking into account the heat transfer between CPS and concrete, by following the principle of energy balance and described by Myers et al. [15] and Qiu et al. [18]. Convection is expressed by Newton's law of cooling as presented by Nguyen and Aniskin [17]. A detailed description of this model is presented by Zych and Chuc [27]. Its main simplification was to perform calculations in 2D. The 2D finite element model to determine temperature fields in mass concrete structures with CPS was presented in details by Lagundžija and Thiam [14]. Possible differences may result from the heating of the flowing water, therefore the obtained results in this respect should be treated as approximate. The tank was designed using C20/25 concrete. The concrete mix was used as specified in Seruga and Zych [21]. Segment No. 2 of this wall was made from CEM IIIA/42.5 cement. The following basic mechanical properties of concrete were tested: the secant modulus of elasticity, the mean value of concrete cylinder compressive strength and mean value of axial tensile strength of concrete [21]. In order to analyze the temperature changes in the early-age concrete hardening, it was necessary to know the amount of heat released in the concrete hardening process. Pursuant to Kiernożycki [11], the average values of clinker and GGBS content in the type of the cement CEM III A/42.5 was used, i.e. 55% clinker and 45% GGBS. Figure 2 illustrates the FEM mesh and the numbering of the nodes for which the results of the calculations are presented further in this paper. The calculations take into account both the influence of the changing ambient temperature as well as the thermal boundary conditions in line with the technology of the construction of this segment, i.e. the presence of formwork and the fact that the segment was built on the

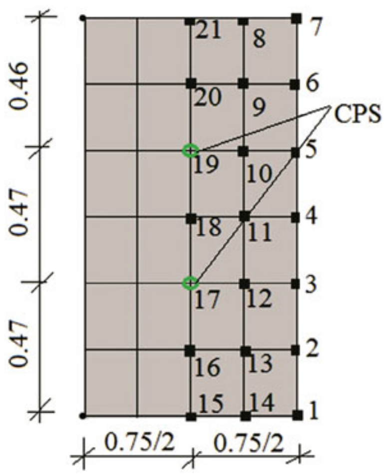

Fig. 2 Segment FEM mesh [m]

Table 1 Characteristics of the pipe cooling system [23]

Parameters	Values
Heat transfer coefficient on the border with concrete (W/(m^2 °C)	381.20
Specific heat (J/kg °C)	4200
The coefficient of thermal conductivity W(m °C)	0.64
Volume (m^3/h)	1.08
The water velocity in the pipe (m/s)	0.6
The water temperature in pipe (°C)	15
Water density (kg/m^3)	1000
Diameter (m)	0.025
Section area (m^2)	0.00008

foundation slab. It was assumed that the cross-section includes two cooling pipes at a height of 0.47 and 0.94 m. The CPS characteristics contained in Table 1 were used.

4 Results

4.1 Temperature Changes

In Fig. 3 examples of temperature changes $T_i(y, z, t)$ for both calculation variants are compared (i.e. without and with CPS). Figure 3a, b concern ordinate $y = 0.47$ m

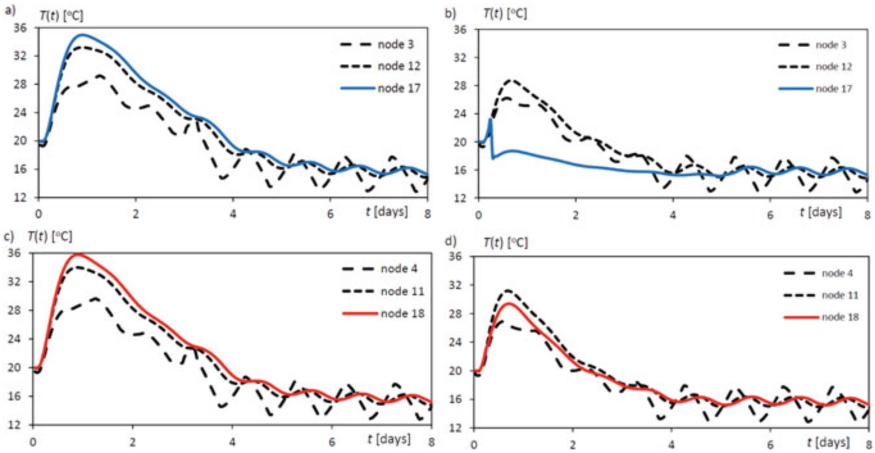

Fig. 3 Temperature changes in nodes on ordinate y = 0.47 m for: **a** variant without CPS, **b** variant with CPS and ordinate y = 0.7 m for: **c** variant without CPS, **d** variant with CPS

(measured from the wall base) on which in the variant with CPS the cooling pipe is located (cf. Fig. 2). The results are presented in the central node (node 17), in front of the extreme node (node 12) and on the wall surface (node 3). The comparison of Figs. 3a and b indicates a substantial reduction of the value of temperature changes $T_{17}(t)$ in the place of the location of the cooling pipes and slightly lower in the nodes more remote $T_{12}(t)$ and $T_3(t)$. The temperature changes shown in Fig. 3c, d concern the ordinate at mid-height of the wall (i.e. $y = 0.7$ m), and the ordinate is at an equal distance between ordinates $y = 0.47$ m and 0.94 m, on which the cooling pipes are located (cf. Fig. 2). The differences between the two variants observed on this ordinate are definitely smaller.

From a general comparison of temperature changes $T_i(y, z, t)$, between the two calculation variants it can be concluded that an effective impact of internal cooling, that is a reduction of the maximum temperature in each node of the section is clearly noticeable. For the presented nodes No 17, 12, 3 (i.e. $y = 0.47$ m) and nodes No 18, 11, 4 (i.e. $y = 0.7$ m) the reduction was 34, 14, 10% and 18, 8, 9%, respectively. In conclusion, the temperature reduction rate heavily depends on the position of the given node relative to the cooling pipe.

Most of the analytical (e.g. [4]) and standard (e.g. [9]) methods of determining thermal strain induced stresses in members restrained by external restraints based on the 1D model, i.e. averaging the temperature changes along the wall thickness. Therefore in the first stage the changes of mean temperatures $\Delta T_{i\_y\_mean}$ were determined for individual ordinates subtracting the current mean temperature from the initial temperature of concrete in the wall. The mean temperature changes $\Delta T_{i\_y\_mean}$ thus obtained for individual wall ordinates as a function of time for the variants without and with CPS are shown in Fig. 4. As is most clearly seen, the application of internal cooling results in a considerable reduction of temperature variations in the mid-wall and the temperature decrease in the wall section, in the variant with internal cooling, begins five hours earlier.

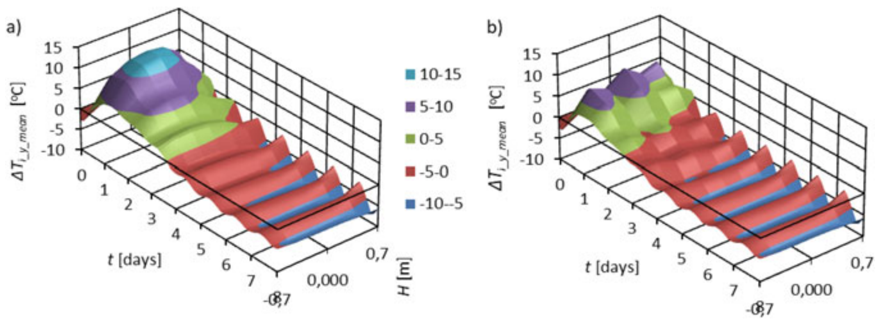

Fig. 4 Mean temperature variations $\Delta T_{i\_y\_mean}$ for individual wall ordinates in function of time for variants: **a** without CPS and **b** with CPS

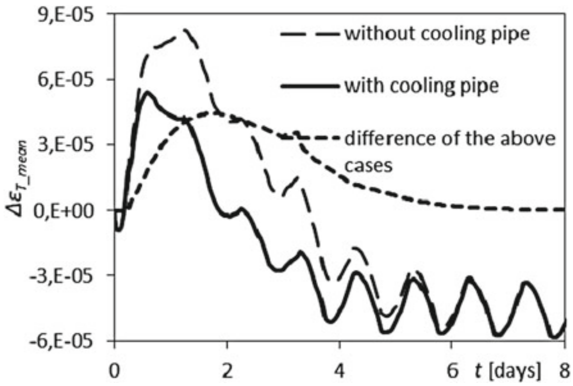

Fig. 5 Variations of free mean strain $\Delta\varepsilon_{T\_mean}$(t) in the cross-section of segment no 2

4.2 Mean Strains

Figure 5 illustrates changes of free mean strain $\Delta\varepsilon_{T\_mean}(t)$ of segment No 2 for both variants, without and with CPS. In the calculations the value of the coefficient of thermal expansion $\alpha_T = 1 \cdot 10^{-5}$/°C recommended by Eurocode 2 [6] was adopted. Major differences in free strains occur in the period of up to four days of concrete maturing, and their maximum value of about 50% is for the time $t = 2$ days. Free mean strain $\Delta\varepsilon_{T\_free\_mean}(t)$ is an important factor in the case of a high degree of restraint which, in turn, depends mainly on the type of external restraints and geometry of the member. In the case analyzed here both these conditions are extremely unfavorable as the external restraints are constituted by the slab of 0.75 m thickness, and the wall length to height L/H ratio is as high as 24. Despite, however, the final value of free strain, in both variants without and with CPS, in the case of nearly complete restraint of strains, concrete creep will additionally take place. Since concrete creep takes the highest value in the period of positive strains formation, the restrained part of imposed strain for the variant without CPS will be definitely higher. In the design practice [7] the period of positive imposed restraints increase is disregarded, therefore on the basis of the comparison of strains after reaching $T_{\max}$ only, it can be concluded that the internal cooling reduces the mean free strain of thermal shrinkage by ca. 20%.

4.3 Strain Gradient

Another component of strains, i.e. free strain gradient in the function of time $\Delta\varepsilon_{T\_free\_grad}(t)$ for both variants is shown in Fig. 6. Similarly to the case of free mean strain $\Delta\varepsilon_{T\_free\_mean}(t)$, free strain gradient $\Delta\varepsilon_{T\_free\_grad}(t)$ is a significant factor in the case of external restraints an unfavorable geometry of the member. In RC tank walls the geometry factor is of essential importance as mainly the gradient in

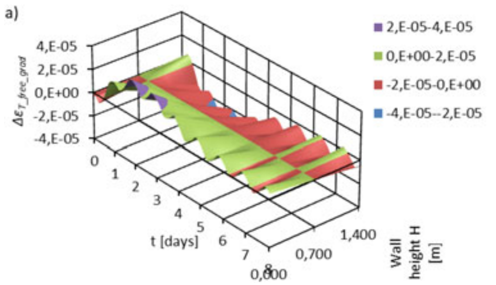

Fig. 6 Variations of free strain gradient $\Delta\varepsilon_{T\_free\_grad}$(t) in vertical section of segment no 2 in the function of time for cases: **a** without CPS, **b** with CPS

vertical direction is analyzed. In some cases even if there are no external restraints, the substantial role is played by the self-weight of the member, which itself can effectively increase the restrained part of the strain gradient [19].

In the case analyzed here the external restraints, apart from free shortening of the segment, restrain the possibility of free rotation. In segment No 2 the effect of both the member's geometry and the monolithic connection with slab foundation is that the degree of restraint of rotation derived after JSCE [9] is 1.0, which means that 100% of strains resulting from temperature gradient are restrained strains that lead to the occurrence of stress gradients in the vertical section of the wall.

Figure 7 illustrates the gradients of restrained strains (which are 100% of the value of strain in unrestrained member) in the vertical section of segment No 2 for selected points in time. As in the case of free mean strains covering the period of both temperature increase and drops, from the presented values the time in which restrained strains causing tension occur cannot be deduced, because it depends on the full history of strains and changes of the mechanical properties of concrete over this period of time.

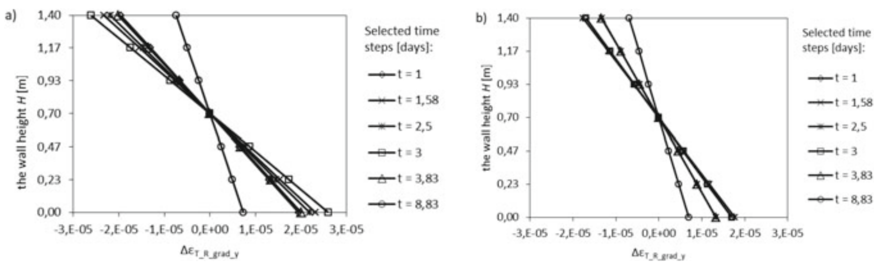

Fig. 7 Gradient of strain restrained part $\Delta\varepsilon_{T\_R\_grad\_y}$(t) in vertical section of segment no 2 for cases: **a** without CPS, **b** with CPS

4.4 Self-equilibrated Strains

The last component of thermal strains $\Delta\varepsilon_{T\_eq}(t)$ concerns restrained self-equilibrated strains which regardless of the presence or lack of external restraints are an effect of temperature non-linear variations occurring in the section. These strains are 100% restrained part of the strain because it results directly from the design assumption of plane sections before and after the load has been applied to the member.

Figure 8 illustrates strains $\Delta\varepsilon_{T\_eq}(t)$ for wall variants without and with CPS. Definitely higher strains $\Delta\varepsilon_{T\_eq}(t)$ are recorded at the initial period of concrete maturing for the variant without CPS. From the comparison of the obtained values of $\Delta\varepsilon_{T\_eq}(t)$ with the tensile strain capacity of maturing concrete $\varepsilon_{ctu\_e\text{-}a} = 70$ με [4] it follows that in the variant without CPS the wall may undergo cracking at the bottom edge where the self-equilibrating temperature induced restrained strains are 75 με after time $t = 18$ h. The restrained parts of mean strains, strain gradients and self- equilibrated strains occur at different periods of time, so the likelihood of cracking can be finally stated when the impact of other strains has been taken into account. Nevertheless, also in the case of RC tank walls it should be stated that the values of self-equilibrated strains are an important component and should not be disregarded in the assessment of the crack risk.

Figure 9 illustrates self-equilibrating strains $\Delta\varepsilon_{T\_eq}$ for selected points in time in the vertical section of segment No 2. As in the previously discussed strain components, i.e. mean strains and strain gradients that covered the periods of temperature increases and drops, at this stage of analysis it cannot be concluded on the time of the initiation of tensile stress inducing strains because it depends on the full history of strains and changes of the mechanical properties of concrete over this period of time.

The presented strain components of imposed strain and self-equilibrated strain occur simultaneously over the entire period of concrete maturing but their extreme values are shifted in time. Consequently, the following sub-section of the paper will deal with, inter alia, the combined effect of these strains for the entire period of concrete maturing.

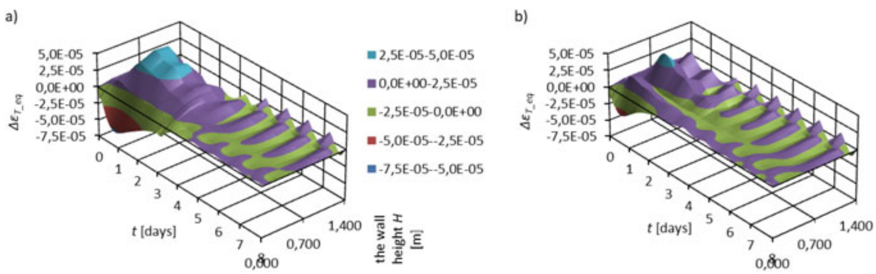

Fig. 8 Variations of self-equilibrating strains $\Delta\varepsilon_{T\_eq}(t)$ in vertical section of segment no 2 in the function of time for variants: **a** without CPS, **b** with CPS

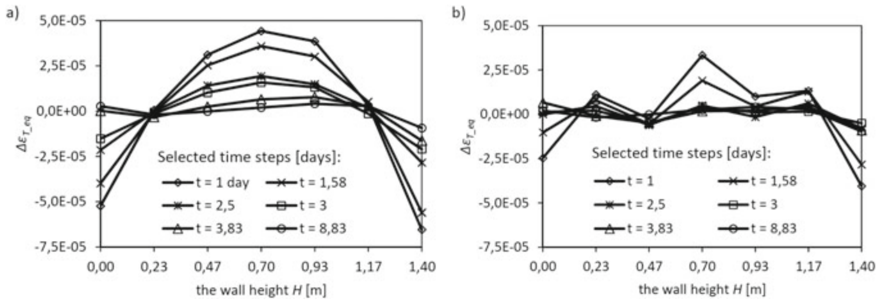

Fig. 9 Variations of self-equilibrating strains $\Delta\varepsilon_{T\_eq}$ in vertical section of segment no 2 for selected points of time for variants: **a** without CPS, **b** with CPS

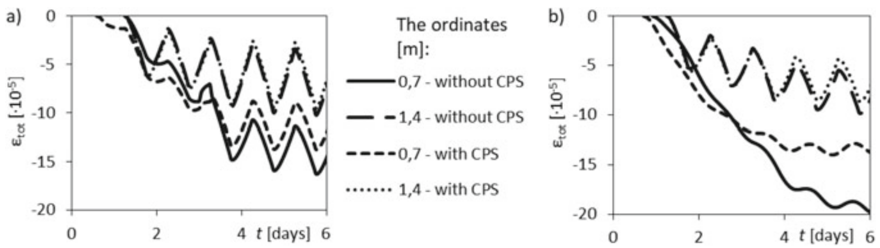

Fig. 10 Total strains **a** on the vertical edge of the wall, **b** along the wall axis

4.5 Total Strains

The total restrained strains resulting from changes in the temperature of the maturing concrete are the sum of the strains that are calculated above. Figure 10 presents a comparison of the total strains ε_{tot} calculated for selected points in the wall segment for the variants without CPS and with CPS. However, the presented results include only those strains which occurred due to the temperature drop at a given point of the cross-section. This approach is a conservative one, yet it is recommended by some guidelines. Moreover, due to the occurrence of shrinkage strains in practice that were not included in this analysis, the calculated values were not compared with the tensile strain capacity of the concrete. Figure 10a and b refer to the ordinates 0.7 and 1.4 m on the vertical edge of the wall and along the wall axis, respectively. In general, it can be stated that after 3 days, in the variant with CPS, the strains are smaller. It also means that the cooling intensity during the first 3 days should be limited by the possibility of the occurrence of premature tensile strains. By using CPS, a much greater reduction of strains was obtained for the central part of the wall, i.e. the place where the influence of ambient cooling is the smallest.

The strain ratio for the variants without and with CPS for analogous places in the wall cross-section is illustrated in Fig. 11. It demonstrates that CPS reduces strains in the central part of the wall by almost 50%, while at the remaining points this

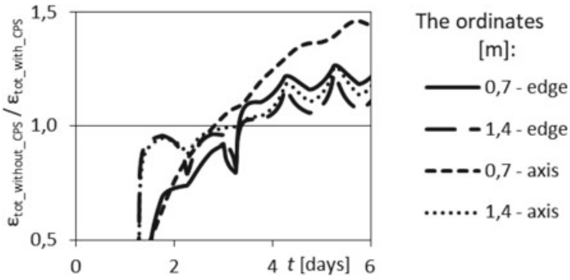

Fig. 11 Total strain ratio for variants without and with CPS

reduction is locally limited to 25%. It should be noted, however, that earlier cooling of the wall results in the occurrence of early-age strains which are larger at some initial stage, mainly in the wall axis. Despite the significant percentage differences observed between these strains (Fig. 11), their absolute values do not differ much (Fig. 10a, b).

5 Conclusions

The analysis of the impact of a cooling pipe system (CPS) on temperature changes in a semimassive wall of a RC tank provides a basis for both scientific conclusions suggesting further research aims and practical implications for design engineers:

- The novelty in this research paper is the analysis of the effect of CPS on the state of strains in a semimassive structure on the example of a RC tank wall.
- In RC semimassive tank walls internal cooling reduces very effectively the temperature rise of maturing concrete only in the immediate vicinity of the cooling pipes. The temperature variations reduction in the other areas is definitely smaller, which may result in locally higher self-equilibrated stresses. Therefore, cooling pipes' spacing should be determined by, inter alia, local temperature changes in the wall section.
- In the process of concrete maturing internal cooling contributes to a reduction of mean strain changes and strains gradient. In the analyzed semimassive wall of a RC tank these reductions are 19 and 35%, respectively, which enables concrete cracking to be limited or eliminated.
- The analysis of self-equilibrated strains indicates that the application of CPS contributes to the reduction to zero of the positive (compressive) strain difference in the immediate vicinity of cooling pipes. Moreover, a CPS helps reduce the extreme strain changes, i.e. positive (compressive) in the wall interior and negative (tensile) in its corners.
- The analysis presented herein provide a basis for further studies on the identification of the most effective/optimal engineering solution employing internal cooling in semimassive RC tank walls, including changes of key parameters such as cooling pipes spacing, cooling rate and duration. These parameters will be

determined by, inter alia, the wall geometry, composition of concrete mix, external conditions and expected results, i.e. complete elimination or merely limiting of the range of early-age concrete cracking.

- CPS results in a significant reduction of thermal strains after 3 days of concrete hardening. During the first 3 days, however, CPS causes greater increments of these strains. Hence, the cooling intensity is limited by the possible occurrence of premature tensile strains.

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