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EXPERIMENTAL EVALUATION OF TENSILE CONCRETE STRAINS AT EARLY AGE CRACKING OF REINFORCED CONCRETE CYLINDRICAL TANK WALL

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Abstract

In the paper there are presented the program and the results of investigations carried out during the construction of reinforced concrete monolithic cylindrical tank wall. The aim of investigation was to record the mechanism of early age cracking as well as to find the ultimate concrete strains just before early age cracking. The time and the place of the first crack recorded along the wall segment is very important. For these purpose three types of mechanical strain gauges have been adopted to readings the concrete strains in about 14 m long tank wall segment. The measuring points have been located in one line at the level equal to 1,1 m on both sides of experimental tank wall. The concrete and ambient temperature were also measured. Based on obtained results the final findings are formulated.

Keywords: Concrete structures, early-age cracking, reinforced concrete tanks.

1. Introduction

Report [1] is primarily concerned with limiting the width of cracks in structural members that occur principally from restraint of thermal contraction. Particular emphasis is placed on the effect of restraint to volume change in both preventing and causing cracking and the need for controlling peak concrete temperature. This report can be applied to any concrete structure. It should be noted that general application is to massive concrete members 0,45 m or more in thickness. Reinforced mass concrete in this report refers to concrete in which reinforcement is utilized to limit crack widths that may be caused by external forces or by volume change due to thermal changes, autogenous changes and drying shrinkage.

In paper [1] there is presented the sequence of cracking for a member subject to uniform volume change and continuous base restraint. As each new crack forms at approximately the midpoint of the uncracked portions of the base, the previously formed cracks will extend vertically. The maximum width of each crack will occur at vertical locations just above the top of the previously formed cracks. Below this point there are two more times the number of cracks to balance volume change. For most structures, the hydration heat effects are dissipated during the first week after placement. The age of critical volume change will be the age which requires the minimum average crack spacing. A critical volume change in USA (similarly as in Poland) will occur for summer placement. A value for tensile strain capacity of 0,0001 for early-age cracking and 0,00015 for seasonal cracking is recommended.

The problem dealing with the tensile strain values of concrete and reinforced concrete is discussed in papers [2, 3, 4]. In paper [5] there is presented the ultimate tensile strain at early age concrete according to different sources. The presented values are equal to 0,00006 after 12 and 24 hours but only 0,00010 after 28 days in concrete element under tension. In the same paper there is presented the diagrams of ultimate tensile strain as function of tensile strength.

The problem of cracks spacing and width predicting due to the volume change cracking of base restrained concrete walls are discussed in papers [6, 7, 8, 9, 10, 11, 12, 13, 14]. There is no case that the cylindrical reinforced concrete tank for liquids was analysed. The sequence of cracking and crack width in cylindrical concrete tank wall during the prestressing is analysed in paper [15]. In codes [16, 17] it is convenient to classify liquid retaining structures in relation to the degree of protection against leakage required. Appropriate limits to cracking depending on the classification of the element considered should be selected. Any cracks which can be expected to pass through the full thickness of the wall section should be limited to w_{k1}. It should be noted that water-tightness of concrete wall is ensured for $w_{k1} \leq 0,1$ mm.

In code [17] there is presented the method of calculation of strain and stresses in concrete sections subjected to restrained imposed deformations. Moreover there is presented the procedure of calculations of crack widths due to restraint of imposed deformations. Two cases are discussed: a) restraint of member at its ends and b) restraint along one edge. It should be noted that in reinforced concrete tank the case b) is realized in the first stage of construction. The case in which wall segment is restrained at the bottom and at the end vertical edges should be taken to the analysis instead of case a) proposed in paper [17].

2. Experimental investigation

In Krakow there was realized in 2004-2006 years the greatest Sewage Treatment Plant in Poland. Four cylindrical monolithic reinforced concrete tanks constructed since May to August 2004 were monitored under construction and post construction to the water - tightness test. In spite of the tank wall was constructed in segmental system almost each segment has been cracked instantly or within a few days from formwork removal. The tank of circumference equal to 138,23 m was divided in 10 segments. Even or uneven wall segments have been constructed in first stage and others in the second stage. The wall segments realized in the first stage were restrained at the bottom only. The wall segments constructed in the second stage were restrained additionally at the end vertical edges due to the contraction joints between the adjacent wall segments and analyzed member.

The vertical cross section of analyzed structure is shown in Fig. 1. The Portland cement type CEM II B-S/32,5R was used to production of concrete class C25. The evolution of the compressive and tensile strength as well as the modulus of elasticity were tested over 90 days. In vertical direction steel bar 12 mm dia. were stabilized at the distance of 125 mm at both of the external wall faces. In horizontal direction the reinforcement ratio was equal to 0,00715 at the inside face measured from the slab top to the 2,8 m. At the outside face reinforcement ratio was equal to 0,014 at the height to 1,2 m and 0,0089 from the level 1,2 m to 2,5 m. The compressive concrete strength, direct tensile concrete strength and the modulus of elasticity after two days were equal to 10,1 MPa, 1,12 MPa and 14100 MPa accordingly. All of them have been tested on cylindrical samples $\phi 150 \times 300$ mm.

The result of investigation carried out on reinforced concrete tank No 4 are presented in paper [18]. The wall of tank No 3 was constructed from 15.07.2004 to 2.08.2004. The date and sequence of construction of wall segments are listed in Table 1. The concrete compressive strength was evaluated after 28 days (cubic samples 150×150×150 mm). $A_{c,ave}$ denotes rhe temperature of concrete mix at the time of casting. It should be noted that each wall segment

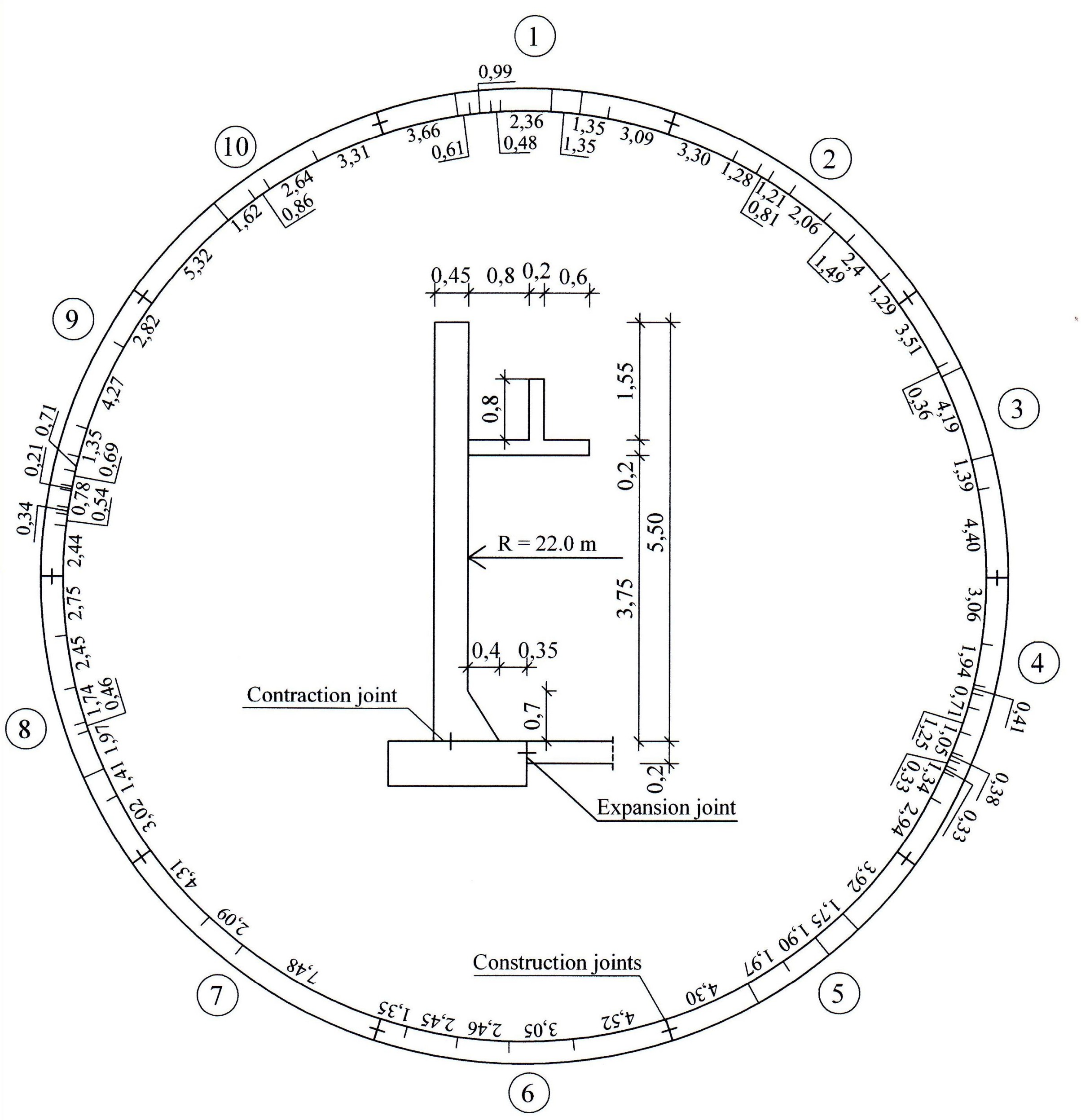

Fig.1 Cross section of the tank No 3 and contraction joints layout.

was cracked at the inside face. The cracks spacing at the circumference of tank wall is shown in Fig. 1. Some of cracks are through wall thickness.

Sequence of crack propagation and distribution of cracks width along the height of the wall segment 5, for an example only, are shown in Fig. 2. The distribution of total cracks widths in particular wall segment measured in November 2004, at the inside and outside face of the tank wall are presented in Fig. 3 and 4 accordingly.

The wall segment 9 and 8 were subjected to particular investigations. The measuring points were localized at the level of 1,1 m in total length of segment 9 in the distance 100 mm at the inside face and in the middle part 2 m long at the outside face. Moreover the measuring points were localized in the distance 200 mm at the outside face. In case the wall segment 8 the measuring points were localized in the distance 100 mm at the inside face and in the distance 200 mm at the outside face. The wall segment 8 was constructed the 26 of July 2004.

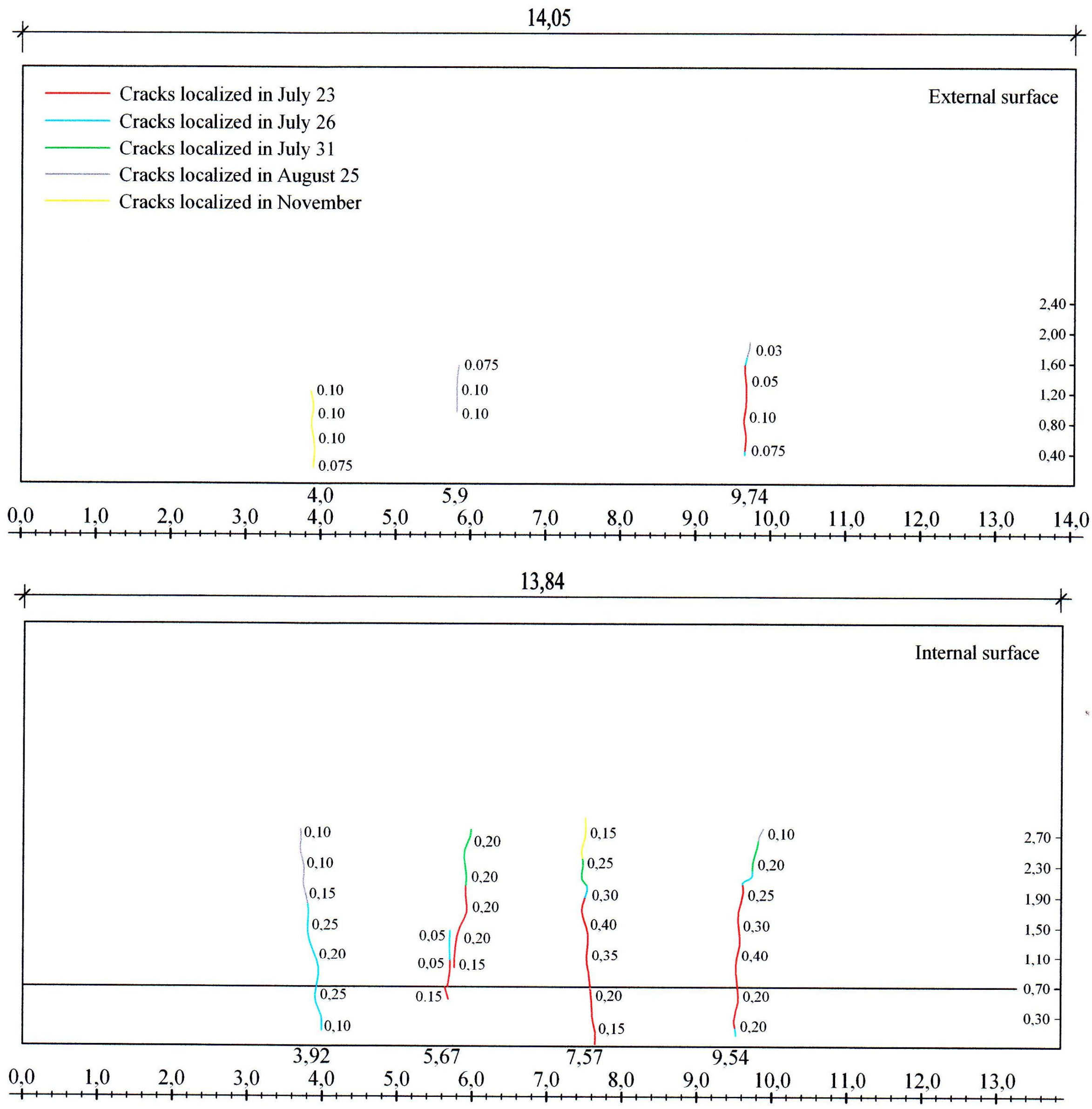

Fig. 2 Sequence of crack propagation and distribution of crack widths along the height of external and internal faces of the wall segment 5.

Next day the formwork was removed. The surface concrete temperature measured at both sides was equal to 36°C. First readings with mechanical strain gauges Demec 400, 200 and 100 mm at the inside and with Demec 400 and 200 mm at the outside surfaces were taken the 27 of July at 15^{00}. After 40 hours from construction of wall segment 8 i.e. the 28 of July at 7^{00} it was found the tensile concrete strains at the inside surface in one of measuring base signed as 11 (a-b). The crack width measured with Brinell's magnifier was equal to 0,02 mm. In that situation it was decided to stabilize the additional measuring points in three vertical cross-sections at the base 11-12, 17-18 and 26-27 in distance 200 mm in both directions. Three measuring nets (200 × 200 mm) in the base 11-12, 17-18 and 26-27 are shown in Fig. 5. In the same Figure it can be seen the propagation and cracks distribution at the inside face.

Concrete strains recorded in initial 6 day are listed in Table 2. The essential difference in concrete strain values measured in different base are visible. This fact is illustrated in Fig. 6, 7

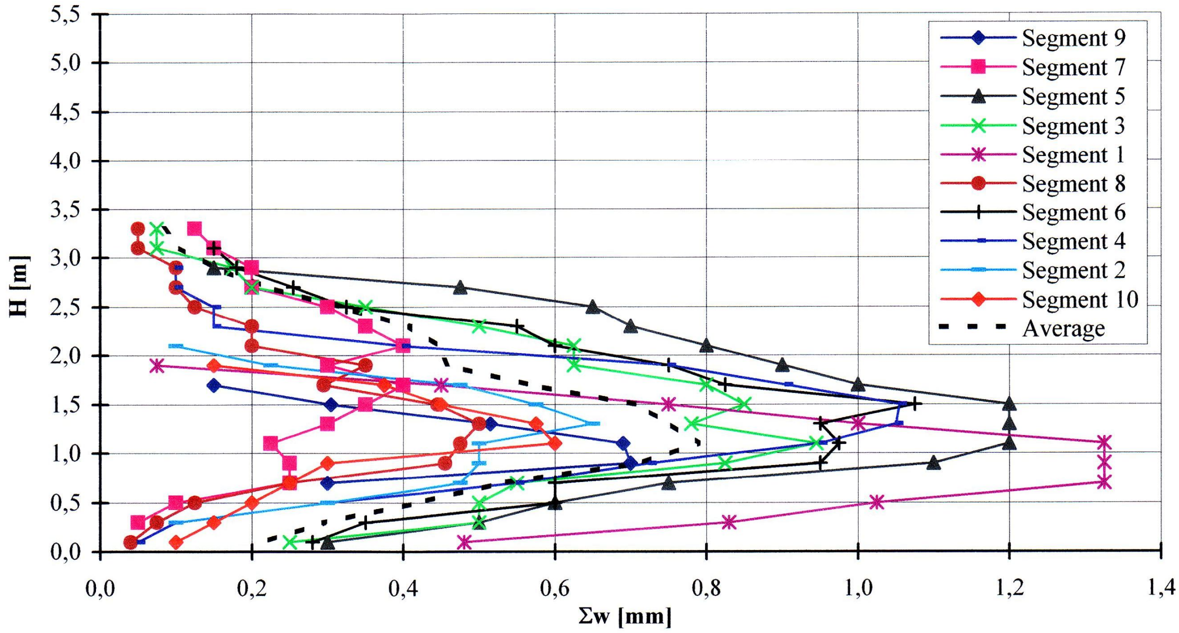

Fig. 3 The distribution of total cracks widths in particular wall segment measured at the inside face of the tank wall.

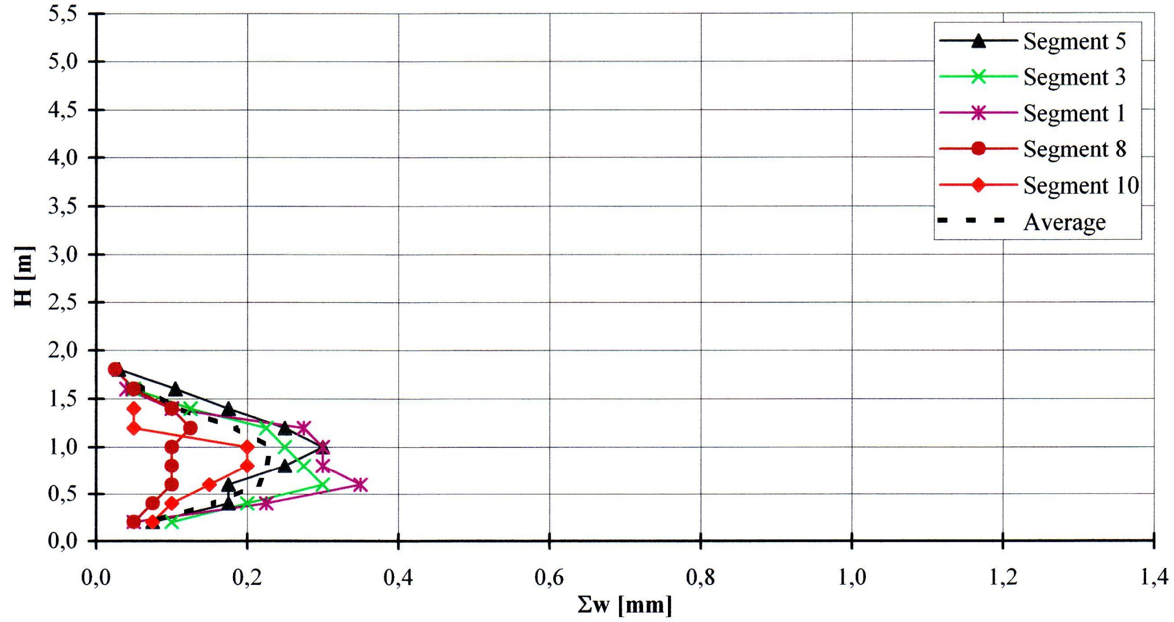

Fig. 4 The distribution of total cracks widths in particular wall segment measured at the outside face of the tank wall.

and 8. It can be found that concrete tensile strain values recorded at the time of cracks registered are equal to $-11{,}13\times10^{-5}$, $-12{,}78\times10^{-5}$, and $-11{,}85\times10^{-5}$ in measuring sections 11 (a-b), 17 (a-b) and (b-12) accordingly. It should be noted that measuring points were stabilized 24 hours since concrete casting in formwork.

The development of the crack width at the level 1,1 m at the inside face measured with mechanical strain gauge and by Brinell's magnifier are shown in Fig. 9. It is visible the influence of time and method of measuring on crack width value. The development of the crack width in the same vertical cross-section along the height of the thank wall at the inside face is presented.

The 2 August 2004 the last wall segment 10 was constructed. The measuring points in base 100 mm have been stabilized along the height of the last vertical contraction joint between wall segments 10 and 9 at both sides. Concrete strains registered with mechanical gauge Demec are presented in Fig. 11. It is visible that vertical joint in the lower part (up to 1,0 m) is opened after three days since time of casting the last wall segment.

Table 1 Program of construction, crack widths, compressive strength and temperature data.

Wall segment	L_{ws} [m]	$T_{c,ave}$ [°C]	$T_{a,ave}$ [°C]	$f_{c,ave}$ [MPa]	Meteorological Station Balice		W_{max} [mm]	
					T_{max}[°C]	T_{min}[°C]	Inside	Outside
9 - 15.07.04	13,81	22,75	17,1	37,0	18,3	9,7	0,15	-
7 - 19.07.04	13,88	24,30		29,9	28,0	16,0	0,20	-
5 - 20.07.04	13,84	31,50	32,7	31,0	30,2	15,5	0,40	0,15
3 - 22.07.04	13,85	27,80	31,3	31,0	30,2	16,3	0,35	0,15
1 - 26.07.04	13,89	27,80		36,0	24,2	12,4	0,35	0,15
8 - 26.07.04	13,80	27,80		36,0	24,2	12,4	0,20	0,125
6 - 28.07.04	13,83	23,10	17,0	36,8	17,7	12,5	0,30	-
4 - 28.07.04	13,74	23,70	18,2	38,6	17,7	12,5	0,30	-
2 - 02.08.04	13,84	25,40	23,1	36,3	22,4	14,4	0,25	-
10 - 02.08.04	13,75	25,40	23,1	36,8	22,4	14,4	0,30	0,10

Table 2 Concrete strains $\varepsilon \times 10^{-5}$ measured at the surfaces of wall segment 8, in initial 6 days.

Date	Time [h]	Inside face/measuring base (mm)						Outside face	
		11-12	11-b	11 a-b	17-18	17-b	17 a-b	11-12	b-12
		400	200	100	400	200	100	400	200
26.07.04 - 15^{00}	0	-	-	-	-	-	-	-	-
27.07.04 - 15^{00}	24	-	-	-	-	-	-	-	-
28.07.04 - 7^{00}	40	-1,20	-2,37	-11,13	4,00	5,53	3,18	9,20	10,27
28.07.04 - 17^{00}	50	5,20	-11,06	-36,57	10,00	3,16	-1,59	10,00	10,27
29.07.04 - 9^{00}	66	-34,0	-67,15	-162,2	1,20	7,90	1,59	-5,20	-11,85
29.07.04 - 17^{00}	74	-33,6	-78,21	-181,3	0,80	7,11	1,59	-3,60	-11,85
01.08.04 - 15^{00}	144	-28,4	-75,84	-189,2	8,00	-2,37	-12,72	20,00	-10,27

(-) minus – denotes tensile strains

Taking into consideration the temperature difference for wall segment (temperature of wall segment surface after formwork removed minus T_{min}) equal to 25°C, concrete creep coefficient $\phi = 3$, $E_{cm} = 17285$ MPa (after 3 days), calculated $E_{c,eff} = 4321$ MPa, $R_{ax} = 0,5$, $z = 1,5$ m, $z_1 = 2,75$ m and $r = 1,54\times10^{-4}$ m, the calculated tensile strain is equal to $12,5\times10^{-5}$ for $R_m = 1$. For this concrete strain the suitable concrete tensile stress is equal to 0,54 MPa. In the case of $R_{ax} = 1,0$ and $R_m = 1,0$ the concrete tensile strains is equal to 0 and tensile stress 1,08 MPa. The direct concrete tensile strength tested after 3 days was equal to 1,32 MPa. It should be noted that real tensile concrete strength in structures is lower than one tested at the samples.

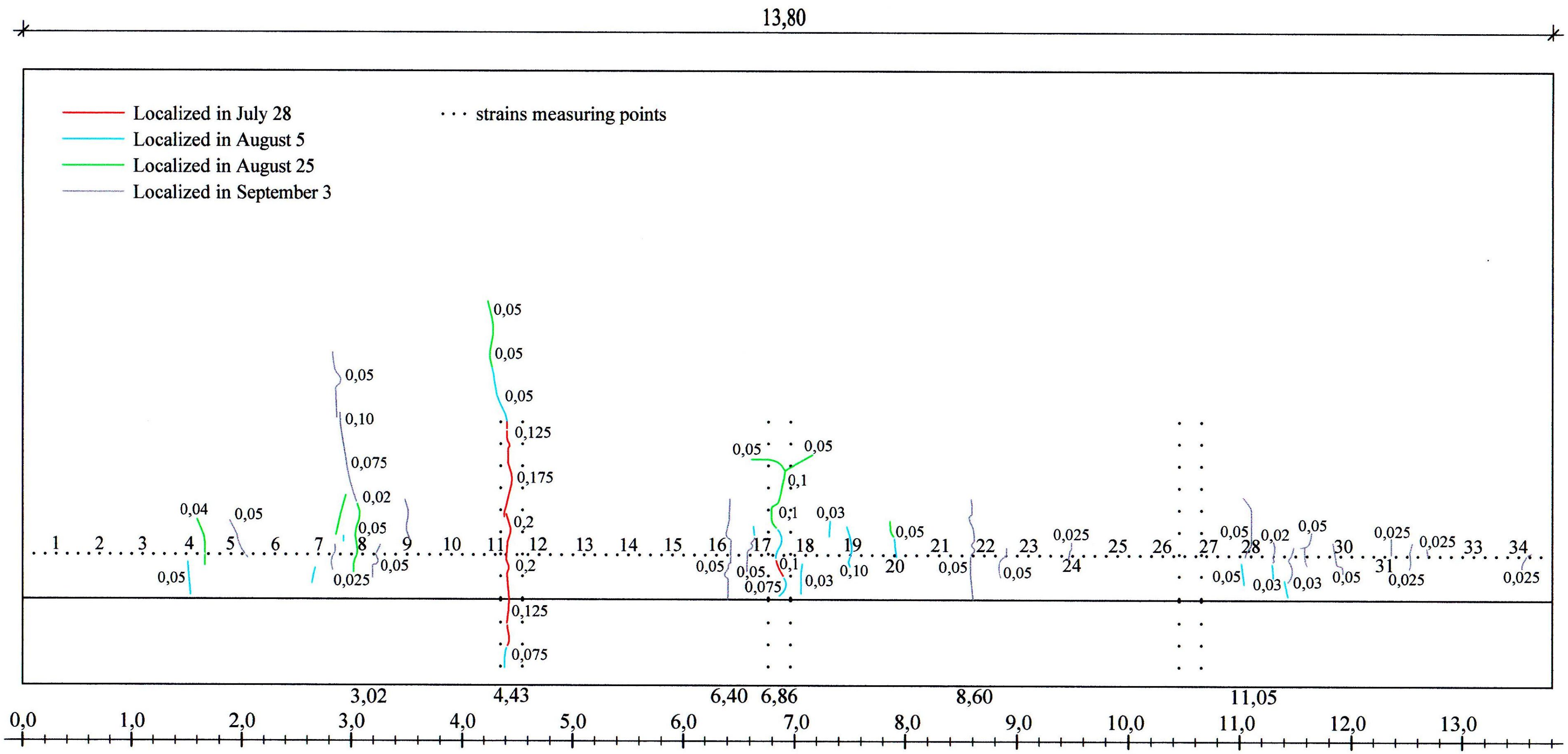

Fig. 5 Stable state of cracking recorded at the inside wall segment 8.

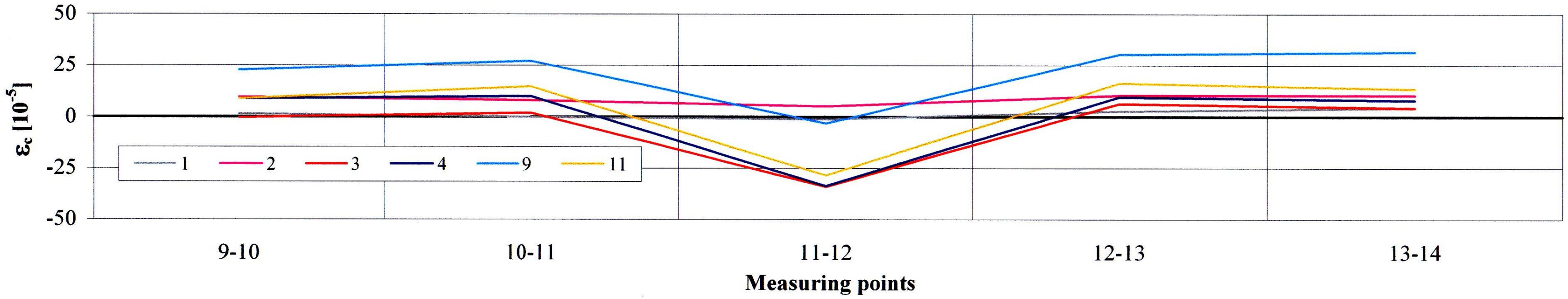

Fig. 6 The distribution of concrete strains recorded in measuring base 400 mm at the level 1,1 m on inside face of wall segment 8.

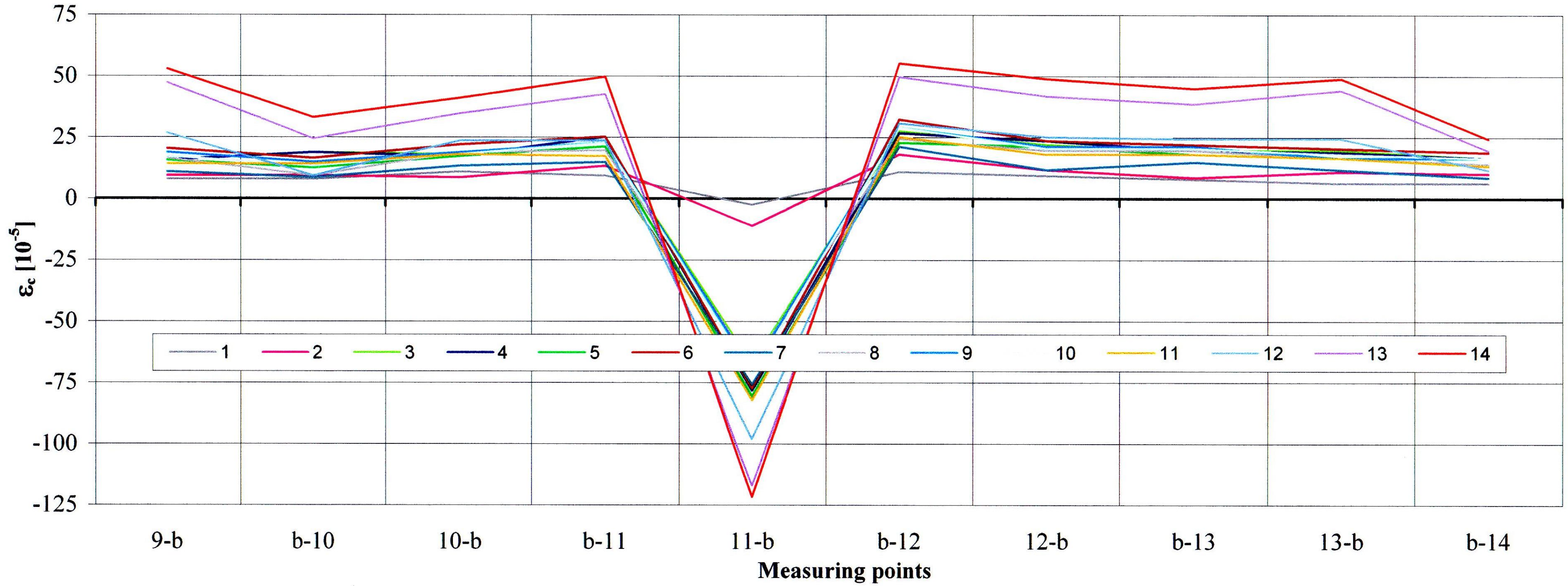

Fig. 7 The distribution of concrete strains recorded in measuring base 200 mm at the level 1,1 m on inside face of wall segment 8.

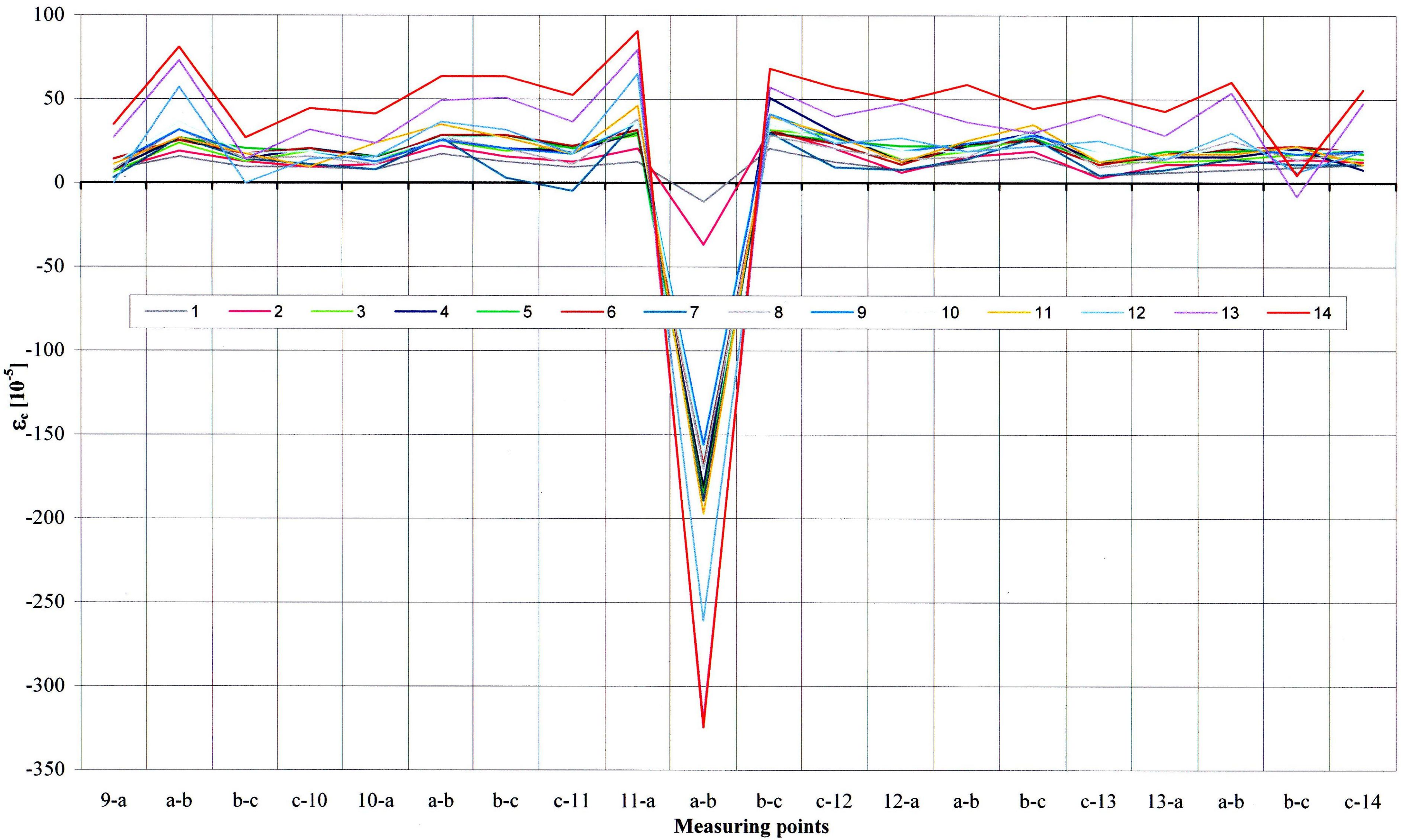

Fig. 8 The distribution of concrete strains recorded in measuring base 100 mm at the level 1,1 m on inside face of wall segment 8.

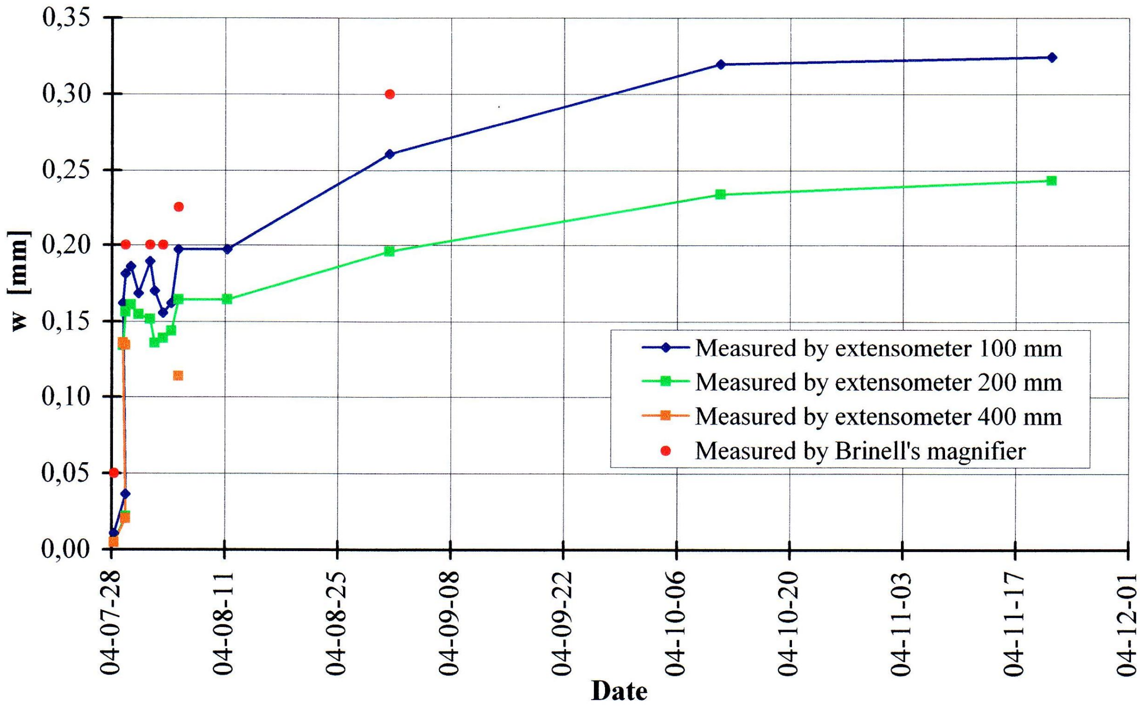

Fig. 9 The development of the crack width at the level 1,1 m in measuring base 11-12 at the inside face.

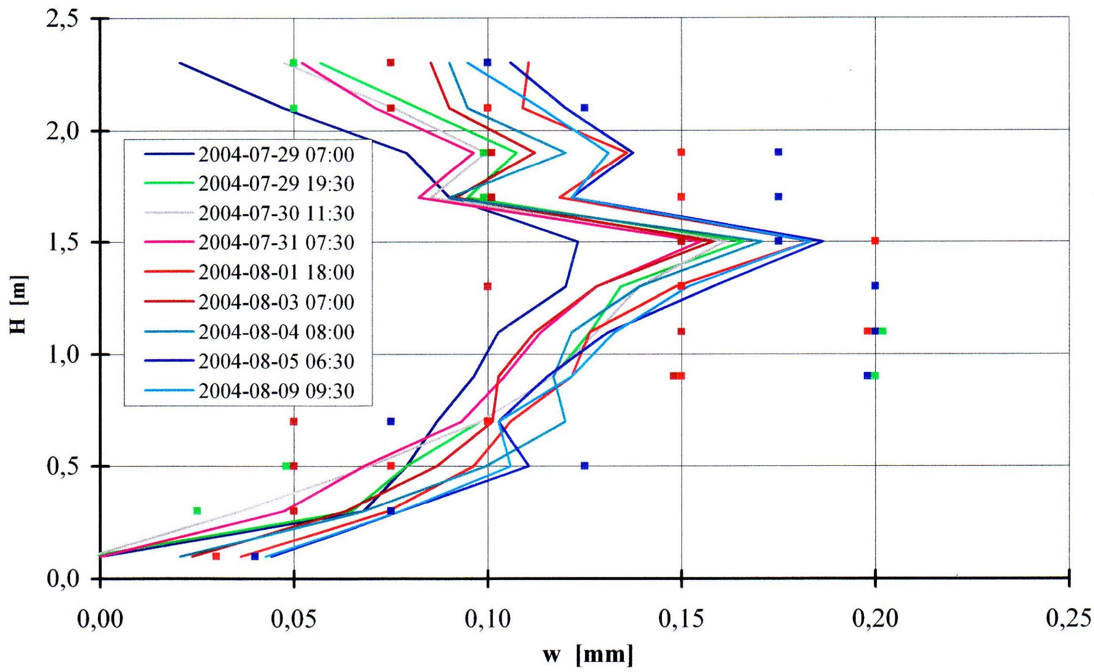

Fig. 10 The development of the crack width in vertical cross-section along the height of wall segment, at the inside face in measuring base 11-12.

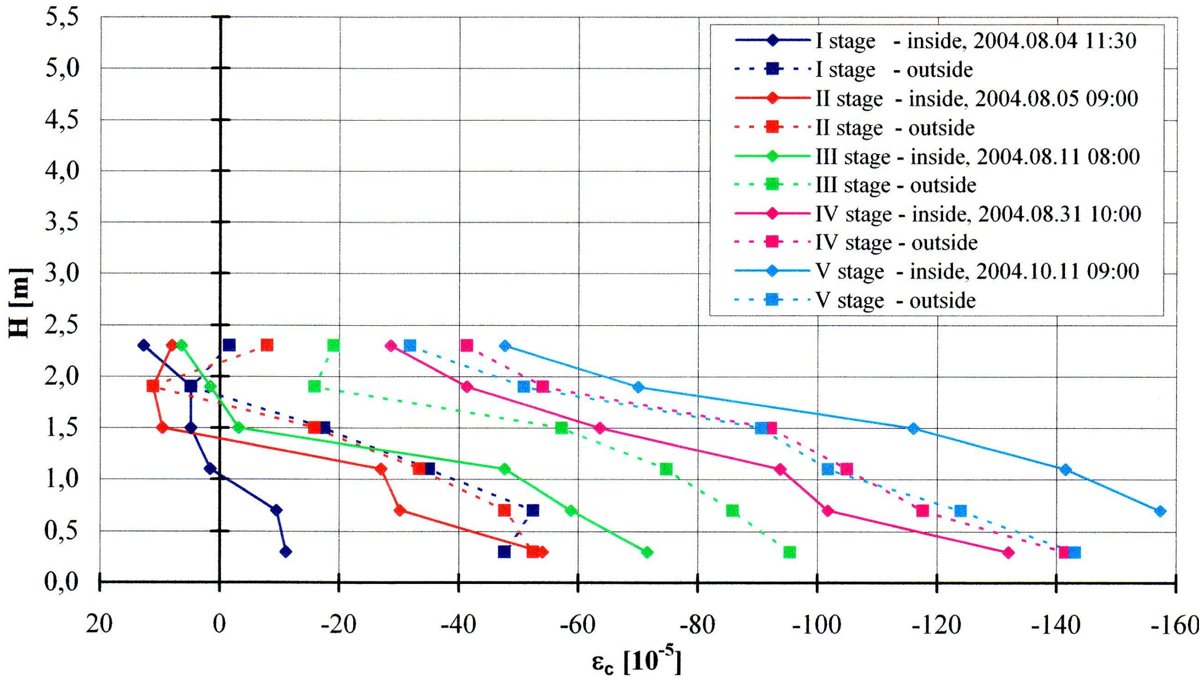

Fig. 11 The development of horizontal concrete strains in measuring base localized at vertical contraction joint between segment 9 and 10.

3. Final conclusions

Continuous restraint exist along the contact surface of concrete and any material against which the concrete has been cast. The degree of restraint depends primarily on the relative dimensions, strength, and modulus of elasticity of the concrete and restraining material. The stress at any point in an uncracked concrete member is proportional to the strain in the concrete. The horizontal stress in a member continuously restrained at its base and subject to an otherwise uniform horizontal length change varies from point to point in accordance with the variation in degree of restraint throughout the member. The distribution of restraint varies with the length-to-height ratio (*L/H*) of the member. When stress in the concrete due to restrained volume change reaches the tensile strength of the concrete, a crack will form. If a concrete member is subjected to a uniform reduction in volume but is restrained at its base or at an edge, cracking will initiate at the base or restrained edge where the restrained is greatest and progress upward or outward until a point is reached where the stress is insufficient to continue the crack [1].

In paper [1] it is stated that for *L/H* greater than about 2,5 if there is enough tensile stress to initiate a crack, it should propagate to the full height. In analyzed case (*L/*H = 2,55) the maximal height of cracking evolution was observed at the level 3,3 m (Fig. 3) at the inside face and 1,8 m (Fig. 4) at the outside face of the tank wall. Based on the obtained results the following conclusion can be drawn:

1) Methodology of crack control available in technical papers can't be directly adopted into the reinforced concrete cylindrical tanks walls fixed in the bottom slab. Reinforced concrete cylindrical tanks for liquids should be water-tight what means that the maximum width of crack through the wall thickness should not exceed 0,1 mm. In above case the reinforcement ratio should be ranged from 0,012 to 0,014. These both factors should be included in modelling of restraint cracking propagation at early-age concrete.
2) It was found, that measuring base not greater than 100 mm is suitable for concrete tensile strain monitoring in reinforced concrete structures. Obtained values were very closed to

these recommended in papers [1, 2, 4, 5].

3) Further investigations are needed to solve the problem of effect the boundary conditions (at the bottom and end edges), reinforcement ratio and wall curvature on tensile force and crack distribution.

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