Int. Agrophysics, 2006, 20, 301-307

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Analysis of thermal effects in grouped silos of grain elevators

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Received July 11, 2006; accepted September 27, 2006

A b s t r a c t. The paper presents experimentally registered temperatures occurring in RC grouped silo bins for grain, corresponding to winter operation period in Polish climate conditions. A new generation wireless computerized measurement system was applied, based on the use of telemetric transceivers operating in intelligent radio network. On the basis of experimental temperature distribution, numerical analysis of the hoop thermal stresses and bending moments in reinforced concrete silo battery subjected to grain pressure and thermal gradient was carried out. In the analysis the numerical model of silo wall with interaction between wall structure and stored particulate solid was applied which had previously been developed and validated on a stand-alone ferroconcrete silo bin model.

K e y w o r d s: temperature fields, thermal stresses, silo battery, structural analysis, finite element method

INTRODUCTION

Thermal loads on silo wall should be obligatory considered in design of silo structures, and the influence of temperature fields should be carefully studied with respect to the model of thermal effects and idealized model of silo wall structure. The effects on structures of grouped silos in grain Elevators and the requirements for their structural analysis are not specified in recent codes of design (EN 1991-4:2006; PN-B-03262:2002; AS-3774-1996).

Previously the problem of thermal effects in RC cylindrical free standing silos was analysed in Canada (Muir *et al*., 1989), South Africa (Blight, 1990) and last time in Poland (Łapko, 2005; Łapko and Prusiel, 2001; 2003).

The paper presents some results of experimental and computational analysis of temperature fields and thermal effects occurring in RC grouped grain silos (arranged as 2 x 2 cylindrical bins) subjected to thermal loads, elaborated using own numerical model taking into account the interaction between wall structure and particulate solids 'en masse' (Łapko *et al*., 2001; Łapko and Prusiel, 2001).

MONITORING OF THERMAL LOADS AND THERMAL STRESSES IN GROUPED SILOS FOR GRAIN

The temperature distributions in a real silo wall in a grain Elevator were monitored using a new generation wireless system equipped with telemetric radio modules (a scheme of such a system is presented in Fig. 1) providing the possibility of testing the silo structure by measurement of mechanical stresses, deformations, displacements or temperatures – depending on sensors used.

Bi-directional wireless monitoring was carried out by radio transceivers operating with strain gauge measurement circuits (Łapko and Kołłątaj, 2003). All the measurements are performed over the radio, therefore the telemetry modules are equipped with a number of functions (zeroing, scaling, calibration, filtration) using the wireless technique.

The system is equipped with a special algorithm of data transmission. The computer program is implemented into microprocessor system in the transmission modules. The system was specially designed for operation with low level of signals in strain gauge circuits and provided with the following functions:

– running measurements – with displayed values for all sensors (without registration),
– on-line measurement (with computer registration) and displayed values for chosen channels,
– off-line registration (without main station),
– detection of strain gauge damage (shorting of the strain gauges),
– setting of sampling frequency.

Using the above mentioned wireless technique the monitoring of reinforced concrete grouped silo, consisting of a battery of 2 x 2 cylindrical silos in the grain Elevator in Bialystok (Poland), was conducted during a long winter period. The tested silo bins, K–9 and K–11, as seen in the

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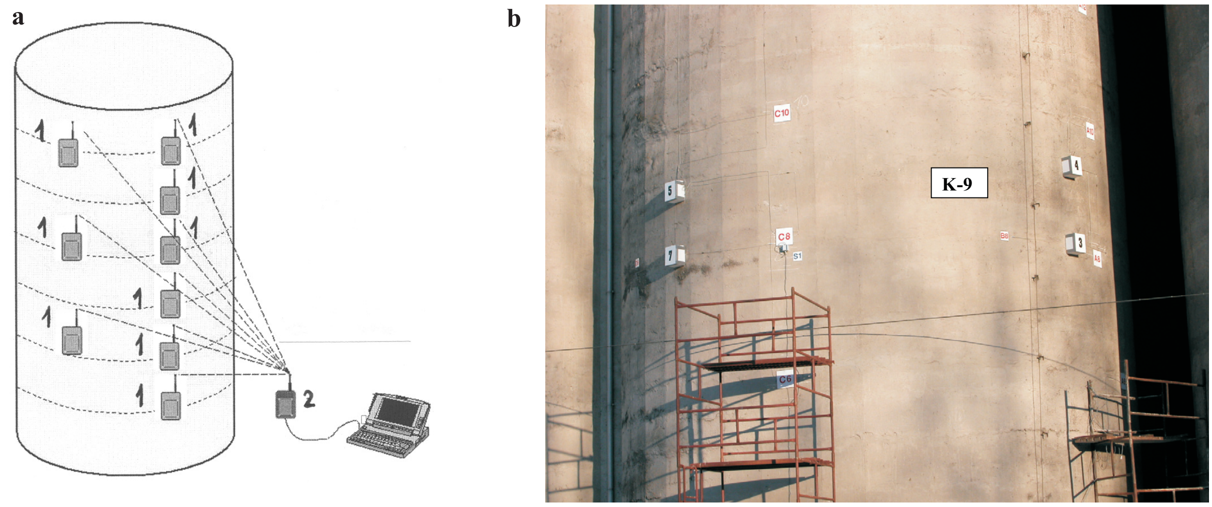

Fig. 1. Cylindrical silo bin structure during monitoring: a) scheme of wireless transmission: 1– transceivers, 2 – main station connected with computer; b) view of tested silo bin K–9 in Białystok Elevator.

cross section in Fig. 2, were fully filled with particulate solid (wheat) being in the storing phase. The main geometric data of the silo bins from the grouped silo were as follows:
– internal diameter d_C = 8 m,
– total height H = 26 m,
– wall thickness t = 0.2 m,
– length of contact zone between bins L = 2.4 m.

Digital temperature sensors type DS18B20 were located at the outer surface of concrete wall along the perimeter, at the level of 8 m above the ground of the silo battery. The temperature test points were distributed in horizontal distance of the bin perimeter with central angle 45°as shown in Fig. 2. The electric resistance strain gauges were localised at the silo height on uncovered outer steel reinforcement bars (with diameter of 12 mm) and located on mean average distance of 150 mm.

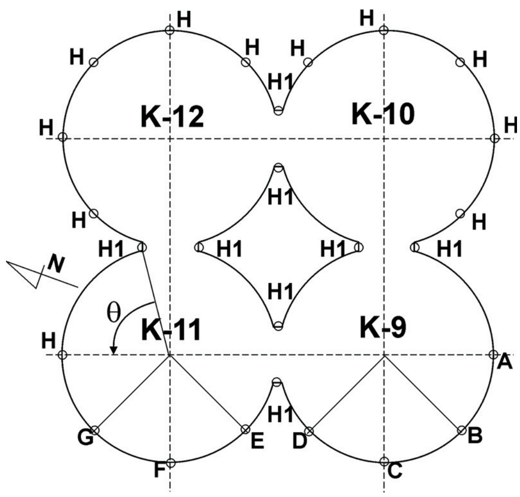

Fig. 2. Location of temperature test points on the surface of grain silo battery perimeter.

The strain test points were localised on the silo bin K–9 at selected four levels situated on two vertical lines A and C (on the levels of 12, 10, 8 and 6 m above the ground see Fig. 2) along vertical cracks observed on the concrete surface.

Example diagrams of one week temperature registration (at test points B–8, C–8, D–8 and E–8 – as shown in legend) are presented in Fig. 3a. Changes of thermal hoop strains in outer steel bars (at a few selected test points), corresponding to the registered temperature changes, are given in Fig. 3b. It can be clearly seen that the diagrams of temperature and thermal stresses are coupled *eg* for each phase of temperature drop we observe increase of tensile thermal stresses in the reinforcement and vice versa.

SIMULATION OF TEMPERATURE CHANGES IN THE SYSTEM: SILO WALL STRUCTURE – STORED BULK SOLID

During the investigations temperature changes on external surface of wall perimeter were monitored. For evaluation of corresponding temperature changes on the wall thickness the numerical program based on the Finite Difference Method (FEM) computational procedure was used. The program is based on the principles of heat transfer and moisture migration in cylindrical systems (Łapko and Prusiel, 2001; 2003), as shown in Fig. 4.

The designed system was subdivided into basic cylindrical layers (RC wall structure and grain) and the following input data were introduced:
– thickness and number of basic layers,
– initial temperature and moisture of layer,
– thermal conductivity characteristics,
– specific heat,
– density of material,
– characteristics of vapour permeability,
– isotherm of sorption of considered material.

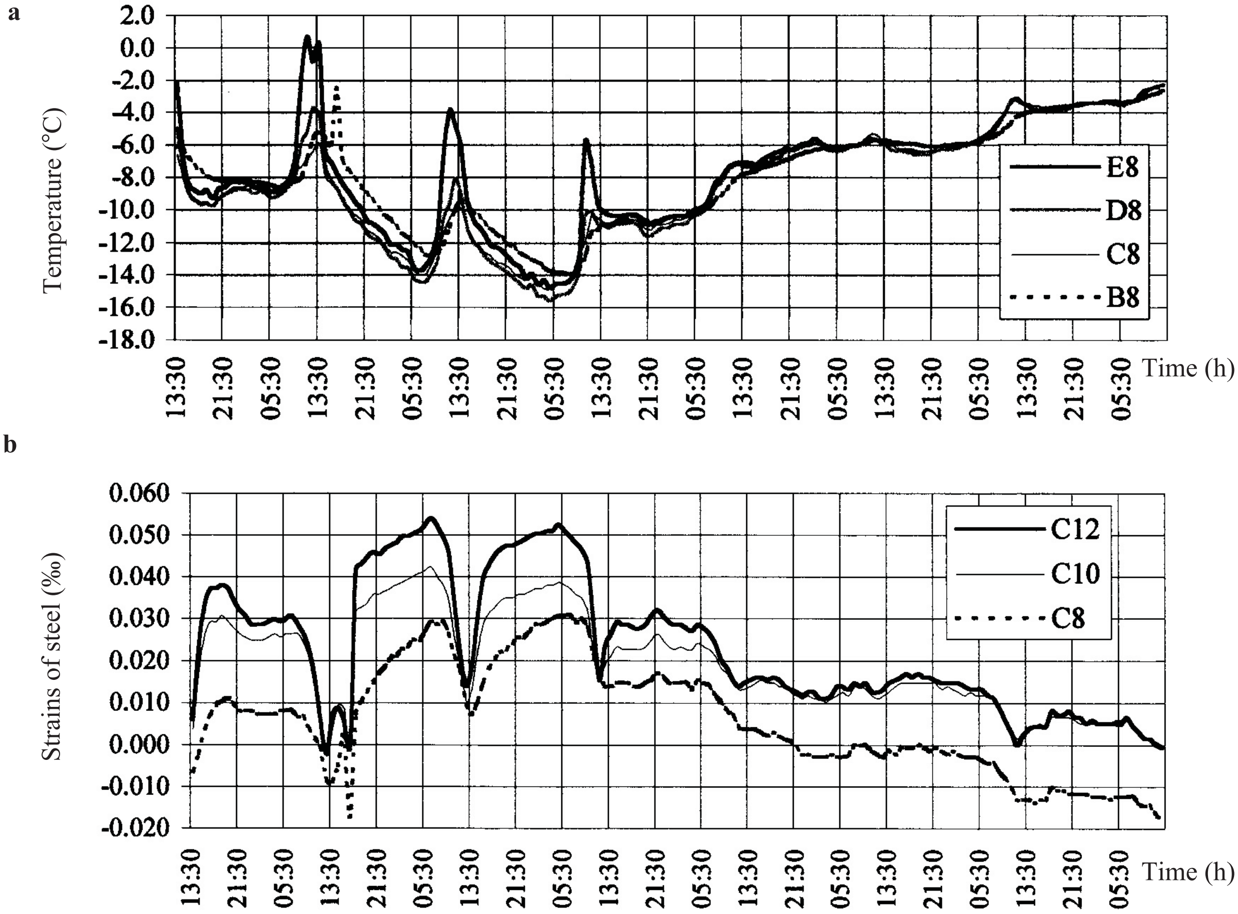

Fig. 3. Temperature distributions on silo battery perimeter (December 2002) (a) and corresponding thermal strain changes in reinforcing steel at selected test points (b) (Łapko, 2005).

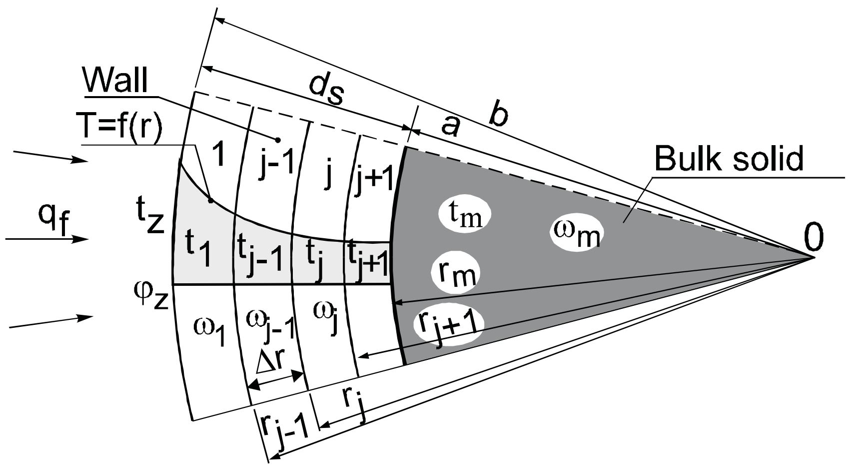

Fig. 4. Assumptions for the numerical computation of temperature in the system: silo wall – bulk solid (Łapko and Prusiel, 2001); T = f(r) temperature function against silo wall radius.

Temperature changes predicted numerically along the silo bin radius during 19 h long phase of dropping winter temperature (see Fig. 3) are shown in Fig. 5.

External temperature changes, ΔT_e, needed in the simulation were taken from experimental works and on this basis the internal surface wall temperature changes, ΔT_i, were predicted (Fig. 6).

From here the thermal effects components for considered silo battery (linear thermal gradient, ΔT_g, and uniform temperature changes, ΔT_m) were established for some selected points on silo wall circumference. The respective results are given in Table 1.

FEM ANALYSIS OF THERMAL FORCES IN SILO WALL

The structure of a grouped silo is very complex and therefore the known solutions for evaluation of thermal stresses in a freestanding cylindrical silo cannot be used even for symmetrical loads.

The FEM was used in structural analysis of considered silo battery subjected to grain pressure and previously predicted thermal effects. In the analysis the discrete numerical model of grouped silo, taking into account interaction between wall structure and stored particulate solid, was applied. This model was previously developed

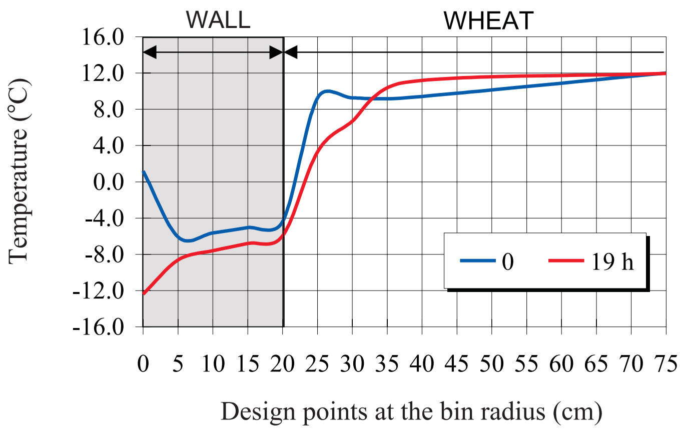

Fig. 5. Temperature distribution along the radius of silo bin.

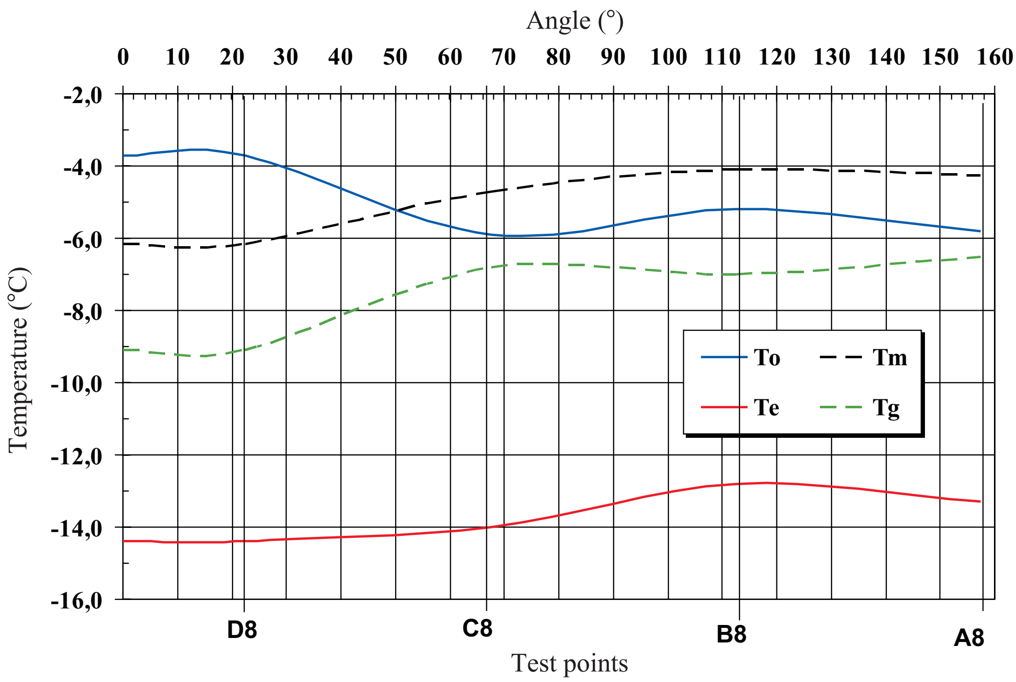

Fig. 6. Wall temperature distribution over the wall perimeter taken in computer simulations; T_o, T_e – external surface temperature at the start and the end of monitoring, respectively, T_m – mean wall temperature; T_g – temperature difference at the wall thickness.

T a b l e 1. Thermal loads on silo battery wall from monitoring and numerical analysis

ΔT	Thermal effects (°C)						
	H-G	F	E	D	C	B	A
ΔT_e	-6.1	-13.6	-11.5	-10.7	-8.1	-7.6	-7.5
ΔT_i	-1.6	-1.6	-1.5	-1.6	-1.3	-0.6	-1.0
ΔT_g	-4.5	-12.0	-10.0	-9.1	-6.8	-7.0	-6.5
ΔT_m	-3.85	-7.6	-6.5	-6.15	-4.7	-4.1	-4.25

*H, G, F, E, D, C, B, A – temperature test points (see Fig. 2).

and validated on a silo model (Łapko and Prusiel, 2001; 2003). Numerical scheme of analysed horizontal cross-section of silo battery structure is presented in Fig. 7. The contact between adjacent silo bins in grouped silo was modelled assuming real increase of wall stiffness in this zone.

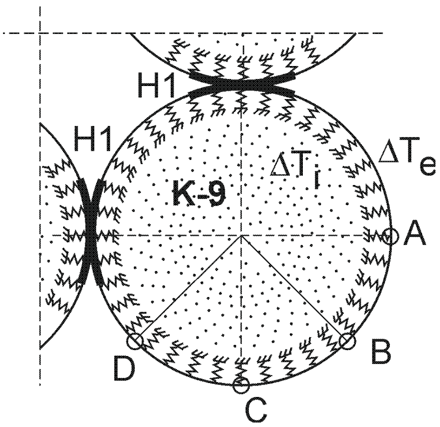

Fig. 7. Scheme for FEM analysis of silo battery using discrete model of interaction between wall structure and bulk solid.

The numerical FEM model of the 2 x 2 bins silo battery is based on the shell plate Finite Elements having radial oriented constrains in the nodes modelling the bulk solid stiffness in the nodes. The elastic stiffness characteristic, C, of stored grain in silo bin was defined considering the equilibrium of deformations of elastic ring in contact with elastic bulk solid core separated from cylindrical silo wall with the diameter, d_C, and the wall thickness, t. From the equilibrium of strains we obtain:

$$C = \frac{E_s}{0.5(d_c + t)(1 - \nu_s)}, \qquad (1)$$

where: E_S and ν_s are modulus of given bulk solid and its Poisson ratio, respectively.

The effective modulus of given particulate solid can be determined experimentally or predicted by indirect assessment depending on unit weight, γ, of stored solid.

European Standard final draft (EN 1991-4: 2006) proposes the following empirical formula for evaluation of unloading effective modulus of particulate solid:

$$E_{sU} = \chi \, p_{vft}, \qquad (2)$$

where: p_{vft} – vertical stress due to bulk solid pressure at the base of the vertical walled section, χ – modulus contiguity coefficient.

In the absence of experimental data from tests, the modulus contiguity coefficient, χ, may be estimated as:

$$\chi = 7\sqrt{\gamma^3}, \qquad (3)$$

where: γ – unit weight of the stored solid in kN m^{-3}; for wheat we have γ = 7.8 kN m^{-3}.

The value of coefficient, χ, may alternatively be taken as 70 – for dry agricultural grains, 100 – for small mineral particles, and 150 – for large hard mineral particles.

The vertical stress in Eq. (2) may be computed from formula based on Janssen pressure:

$$p_{vft} = \frac{p_{ho}}{K} Y_j(z), \qquad (4)$$

where:

$$p_{ho} = \gamma K z_o,$$

$$z_o = \frac{1}{K\mu}\frac{A}{U},$$

$$Y_j(z) = 1 - e^{\frac{-z}{z_o}},$$

where: μ – coefficient of friction between silo wall and bulk solid, K – characteristic value of the lateral pressure ratio, z – depth below the equivalent surface of the solid, A – plan cross-sectional area of the silo, U – internal perimeter of the plan cross-section of the silo.

Assuming the standard approach for the needs of numerical analysis we obtained in the paper:

$$\chi = 7\sqrt{7.8^3} = 152,$$

$$p_{vft} = 62.12 \text{ kN m}^{-2},$$

$$E_{sU} = 9.4 \text{ MPa}.$$

The numerical FEM scheme of considered grouped silo was modelled with 4096 finite wall elements having dimensions of 800 x 800 mm and the same number of constrains modelling the core of grain. The silo battery consisted of four cylindrical bins made of concrete class B20. Thermal effects were assumed to be linear across the wall thickness and not uniform on silo battery perimeter (Fig. 2), as given in Table 1.

Example diagrams of thermal stresses and bending moments in considered silo bin K–9 structure (for outer arch of the wall), assuming the experimentally registered daily thermal effects, are presented in Fig. 8a (thermal uniform stresses on the wall thickness) and in Fig. 8b (thermal bending moments). The diagrams marked with (C=0) denote the results of numerical tests neglecting interaction between the wall structure and bulk solid stored (for the stiffness characteristic parameter C=0).

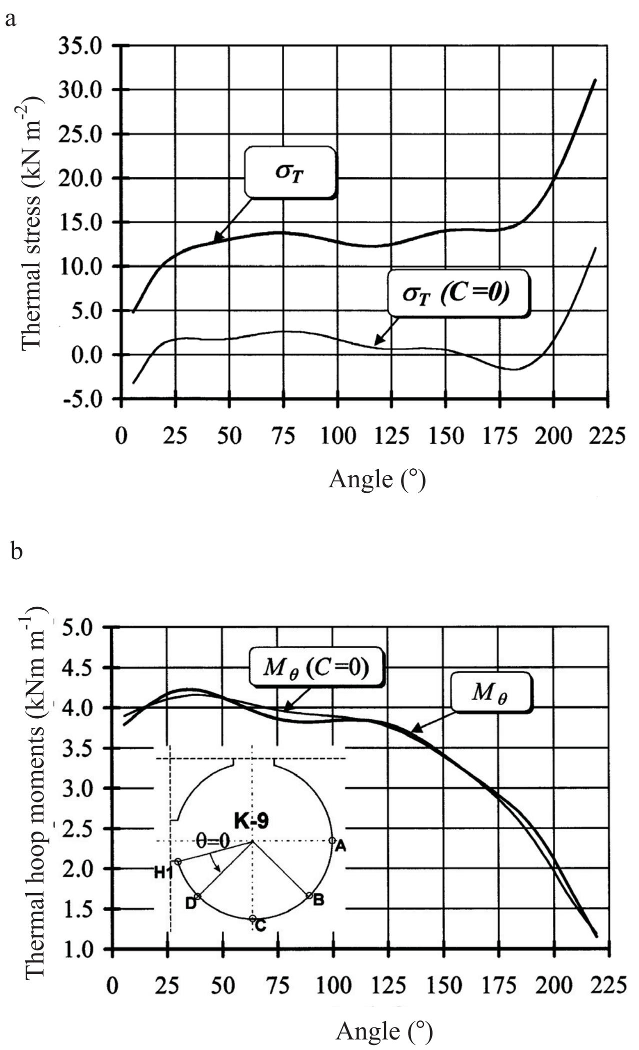

Fig. 8. Selected diagrams for outer arch of silo bin K–9 at the level of 5.5 m: a) uniform thermal hoop stresses in concrete, b) thermal hoop moments.

The comparison of numerical tests obtained from numerical FEM analysis using the model with interaction ($C\neq0$) and classic FEM model without interaction (for C=0) shows significant influence of the bulk solid stiffness on the hoop thermal stresses in the silo wall sections.

Assuming the reinforced concrete section of silo wall for the computed uniform hoop thermal stress, σ_T, and thermal bending moment, M_T, the following formula for evaluation of thermal stresses, σ_{sT}, in outer hoop reinforcement can be used:

$$\sigma_{sT} = \left(\frac{M_T}{W} + \sigma_T\right)\frac{E_s}{E_{cm}}, \tag{5}$$

where: W – is the silo wall section modulus and E_s/E_{cm} – is the ratio of steel and concrete moduli.

Taking the values of M_T and σ_{sT} from diagrams (Fig. 8) and assuming for cracked wall concrete modulus E_{cm} = 13.5 GPa, for steel modulus E_s = 210 GPa and wall thickness t = 0.2 m in the wall cross-section (for the angle θ = 150°) we obtain the value of thermal stresses in hoop tension reinforcement:

$$\sigma_{sT} = 8.2\,\text{MPa}. \tag{6}$$

To compare this value with the thermal stress changes registered during silo wall monitoring (see Fig. 3b for test point C-8 at the considered level of 8 m of silo wall height) for the measured change of steel strains, $\Delta\varepsilon_s$, related to daily temperature drop we obtain:

$$\sigma_s = \Delta\varepsilon_s E_s = 0.047\cdot 210 = 9.9\,\text{MPa}. \tag{7}$$

The discrepancies of thermal stresses in hoop reinforcement of silo battery due to daily drop of ambient temperature predicted experimentally and taken from FEM analysis are not significant and validate the proposed numerical approach for silo battery structural analysis.

CONCLUSIONS

1. Experimental analysis of temperature distribution and thermal effects on real silo batteries can be very efficiently carried out using new generation wireless monitoring system.

2. Structural analysis of silo battery structure under bulk solid pressure and non-uniform thermal actions proved that the thermal forces and moments in silo wall sections should be evaluated taking into account the numerical FEM silo bin model assuming the interaction between wall structure and bulk solid.

3. It can be clearly seen from numerical analysis that short time (daily) winter temperature drop influences hoop stresses resulting from bulk solid pressure in the wall section of silo battery and this effect must be considered in design of silo battery structure.

REFERENCES

AS-3774-**1996.** Australian Standard. Loads on bulk solid containers. Published by Standards Australia.

Blight G.E., 1990. Temperature surcharge pressures in rein forced concretre silos. Powder Handling and Processing, 2, 4, 303-305.

EN 1991-4: **2006**. Eurocode 1 – Actions on structures – Part 4: Silos and tanks.

Łapko A., 2005. Thermal fields in grain during storage – their sources and effects on silo structures reliability. Int. Agrophysics, 19, 141-146.

Łapko A. and Kołłątaj J., 2003. The wireless technique of examination of silo wall structures during operation. Proc. 4th Int. Conf. Conveying and Handling of Particulate Solids. Budapest, Hungary, 27-30 May, 1, 6.77-6.82.

Łapko A., Nikitin V., Prusiel J.A., and Kowalczyk R., 2001. Prediction of temperature fields and thermal forces in cylindrical shell of silo chamber. Proc. 4th Int. Cong. Thermal Stresses, Osaka, Japan, 537-540.

Łapko A. and Prusiel J.A., 2001. Studies on thermal actions and forces in the cylindrical storage silo bins. Handbook of Conveing and Handling of Particulate Solids. Elsevier, Amsterdam.

Łapko A. and Prusiel J.A., 2003. Experimental and theoretical analysis of thermal effects in full – scale grain silo battery. Proc. 5th Int. Cong. Thermal Stresses and Related Topics Blacksburg, Virginia, USA, 8-11 June, 1, MM-2-1-1-MM-2-1-4.

Muir W.E., Jayas D.S., Britton M.G., Sinha R.N., and White N.D.G., 1989. Interdyscyplinary grain storage research. Powder Handling and Processing, 3, 281-295.

PN-B-03262: **2002**. Reinforced concrete silos for granular substances. Statistic calculations and drafts (in Polish). Polish Standard Committee, Warsaw.