IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 16, Issue 1 Ser. III (Jan. - Feb. 2019), PP 01-11
www.iosrjournals.org

Evaluation of Design of RC Silos Subjected to Thermal Loads

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Abstract: *Thermal loads are very important factor in designing silos wall and can't be neglected, so it is necessary for many codes to maintain and study the effect of thermal loads in design. The evaluation of design and construction practices is an essential step in the development of design code for reinforced concrete (RC) silos, especially in the arid zones. The program of study presents some computational analysis of temperature fields and thermal effects occurring in RC silos. This study was conducted specially for this purpose and comprises two major programs. The first program is used to estimate the additional bending moment of silo structures under the effect of temperature differences over several silo wall thicknesses. In this regard, the computer program of Finite Element Model (FEM) using SAP2000 and American Concrete Institute (ACI) code were conducted to establish the current conditions of the silos. Linear and nonlinear analyses were used to evaluate the stresses and displacements for different silos configurations and different loading combinations. The second program is considered to estimate the circumferential forces of silo wall for different thermal loads over several silo wall thicknesses and several radii. This program depends on Euro and Poland codes. Further, the FEM model is also used to compare with these codes. The study results of the additional moment for ACI code and linear and nonlinear analysis of FEM showed it increases with the temperature difference and silo wall thickness increase. It can also be clearly noticed that the moment of nonlinear analysis of FEM have a good matching with the corresponding values in ACI leading to that the nonlinear analysis is good accurate rather than linear analysis. Moreover, the study results of the circumferential force showed a distinct pattern with the temperature difference, silo radii, and insignificant silo wall thickness for each of FEM, Euro and Poland codes. This study is used for rapid determination of critical areas of concern for critical loading combinations and for varying silos configurations.*

Keywords: *RC model, SAP model, RC silo, Design evaluation of RC silo, Thermal loads*

Date of Submission: 14-01-2019 Date of acceptance: 29-01-2019

I. Introduction

The big vertical stores structures or containers which storing bulk solid materials, cement and granular materials are called silos. Silo wall expands at day time as the temperature arises and contracts at night as the temperature drops. Furthermore, at night when temperature drops the silo wall will not push up the stored material, so the silo wall contraction process will be resist which leading to extra tensile stresses or extra circumferential forces. However, no adequate data or accurate figures or numbers are available, every year hundreds of silossuffer serious damage partially or completely. Cracks, deformations and harming triggers are considered a partially damage, even if it may appear harmless to the structure purpose, but it is a sign of needing more data and measures to accurately define the root causes. Any damage to the silo structure causes economic loss by any means, cost of losing structure, stored material, repair cost or rebuild cost, beside all that the man loss.

Silos can be considered one of the special structures subjected to unconventional loads with various loading conditions, which causes failure if one or more of the input loads have not taken into consideration, resulting in partial or total collapse. A thermal load on silos is one of the main input loads in design process. So it is necessary for many codes to maintain and study the effect of thermal loads in each phase (analysis, design, construction, and maintenance). Codes put many restraints in the design and analysis phases in the form of extra input loads or pressure and/or additives output straining actions.

The American Concrete Institute (ACI) standard practice devote a section gives design, material, and construction recommendation and requirements for pre-cast, convention cast-in-place, and post-tensioned concrete silos, stave silos, and stalking tubes for storing granular material. ACI (313-97) is the code for "standard practice for design and construction of concrete silos and stalking tubes for storing granular material". ACI recommends calculating an additional moment because of thermal effect under several Conditions [1]. The thermal moment can be calculated according to [2].

Variation in air temperature around silo wall with ensiled granular material is a very important load; it increases the wall stress because wall radially does not undergo free contraction. Laboratory studies prove that lateral pressure vary with ambient temperature decline and static pressure [3]. There are two ways to calculate the additional moment and thus steel reinforcement rebar. The first one is the resulting moment equation [2]. The second is according to shrinkage and temperature steel requirements of ACI 318 applying the silo design consideration [4]. An additional area of reinforcement shall satisfy the minimum ratio of deformed temperature reinforcement area to gross concrete area [5].

The thermal effect caused by the stored hot or cold material can be calculated in a form of extra moment. But, in design structural member for temperature differences for hot or cold material usually a certain amount of temperature variation can be neglected, thus in silo the authors agree to neglect the first (80°F) or (26.67 °C) of the temperature difference (ΔT), and can be calculated as [6].

The temperature of the ensiled granular material drops significantly at the inner face of the silo wall, because of that the granular material, cement for example, acts as an insulating material at which the temperature drops linearly; this thickness can be estimated as 8 inches. Lapko and Prusiel [7] showed the linearly drop across the conforming insulating thickness of the ensiled cement and the silo concrete wall.

From the above and from the principles of heat transfer, the thermal resistance of the silo wall can be estimated according to [8] based on the assumptions shown in [9].

The European committee for standardization created and published many parts and sections of general regulations and recommendation in design and construction. Eurocode 1: Actions on structures, part 4: Silos and tanks, [10] is the part concerns in loads and actions on concrete silos. Eurocode assigns an additional horizontal pressure when a fall in ambient temperature. The additional horizontal pressure should be calculated as in [10]. There are two ways to calculate the unloading effective elastic modulus of the stored granular material. The first is the direct assessment from laboratory testing as in [10] annex C section C10.1. The second is indirect assessment depending on the vertical pressure at the base of silo wall [10].

The Poland norm provides static calculations, design, construction and operation for reinforced concrete silos. [11] is the Poland standard that concerns in loads and actions on R.C silos. Poland norm recommended an additional latitudinal tensile force due to decline in temperature.

This paper evaluates the effect of thermal loads on silo wall design in terms of applied forces and stresses. Thermal loads affect silo walls in two main manners; tangential oriented stresses (Circumferential stress) due to thermally induced surcharge pressure during cooling of a filled silo structure, and stress due to differences of temperature at wall thickness.A computation analytical finite element model (FEM) has been applied using a computer program SAP 2000 version 16. Various codes provisions are used comparably with FEM results. For oriented stresses in silo wall, the American concrete institute (ACI) provisions are used in comparison with a linear and non-linear FEM with two parametric study wall thickness and temperature difference. For hoop forces, the European Union regulation and Poland norm provisions are used in comparison with a linear FEM with two parametric study wall thickness and temperature difference. These will be used for rapid determination of critical areas of concern for critical loading combinations and for varying silos configurations. In the following, the methodology set, and the results and discussions are presented.

II. Materials and Methods

Thermal loads are very important factor in designing silos wall and can't be neglected, so it is necessary for many codes to maintain and study the effect of thermal loads in each phase (analysis, design, construction, and maintenance). This study includes two main programs. The first comprises the estimation of the additional moment due to the thermal loads over the silo wall thickness. The second estimates the circumferential force under the same conditions of the first program with different silo radii. The programs suggested, use several codes of practice (ACI, Euro, and Poland codes). Moreover, Finite Element Model (FEM) using SAP2000 is used to compare with the mentioned codes to evaluate the thermal loads for the RC silos on their design effects.

2.1 Code of Practice

In this part, The study presents the required precautions and practice for design of the American Concrete Institute (ACI), the European Union code (Eurocode), and Poland code in the concrete silos subjected to thermal loads. Each of these codes put some precautions in form of equations as additional input loads or output straining actions, therefore different parametric element for each equation.

2.1.1 American Concrete Institute, ACI

The additional moment assigned by ACI equation [6], required to resist the additional stresses due to thermal loads is a function in temperature difference (ΔT) and silo wall thickness (t) as,

$$M_t=(E_w\, t^2\, \alpha_w \Delta T)/\,(12\,(1-\vartheta)) \tag{1}$$

Where (M_t) is the thermal bending moment per unit of wall height or width, (E_w) is the modulus of elasticity of silo wall, could be reduced to express the developing of cracks (cracked moment of inertia) or/and demolishing of concrete, (t) is the silo wall thickness, (α_w) is the thermal coefficient of expansion of silo wall, (ΔT) is the temperature difference between inside face and outside face of silo wall, and (ϑ) is the Poisson's ratio for concrete, may assume to be 0.2. Thus, (ΔT) and (t) will be the parametric study elements in the ACI equation, so cases study will be performed on them separately. Fixing one of the two parametric elements and changes the other to study its effect on the resulted moment from the FEM computer program compared to the calculated ACI moment. Wheat is the stored granular material which is used in case study inputs data.Firstly, it can be possible to classify the temperature difference into two divisions:

- Uniformandnon-uniform: Uniform temperature difference means that the temperature is equal throw the inner and the outer of the silo wall, despite the difference comes from the variation of temperature day to day or month to month or season to season with increasing (positive) or decreasing (negative). But, the non-uniform temperature difference means that there are a difference between the inner and the outer face of the silo wall at any instant. It is worth to be mentioned that the moment resulted from the case of non-uniform temperature difference is bigger and more critical than uniform case.
- Positiveandnegative: Positive temperature difference means that the temperature inside the silo wall is lower than the temperature outside (ambient temperature); consequently silo wall tends to expand outward generating stresses due to thermal loads. Vice versa for negative temperature difference, so silo wall tends to contract resulting in more stresses due to thermal load and granular material reaction pressure. Obviously, negative temperature difference is more critical than the positive because it generates more lateral pressure on silo wall in the case of full load of granular material.

In this regard, the assumptions of temperaturedifferencecan be included as; the tensile strength of concrete will be neglected. In addition, it can be neglected the effect of, wind direction on temperature difference, temperature variation between different elevations, and the direction of sun rays (shady or sunny). With another way, assume that temperature varies only radially.

When applying negative thermal loads to the silo walls, extra stresses generated not only the temperature difference, but also the extra horizontal pressure from the stored granular material similar to passive earth pressure. The extra horizontal pressure depends mainly on the properties of the granular material as (stiffness, density, friction coefficient, etc.). In the analysis of silo under negative temperature difference using the FEM model, the contact between silo walls and the stored granular material will be modeled by elements having radial oriented elastic area constrains under compression only (-ΔT) as illustrated in Fig. 1.

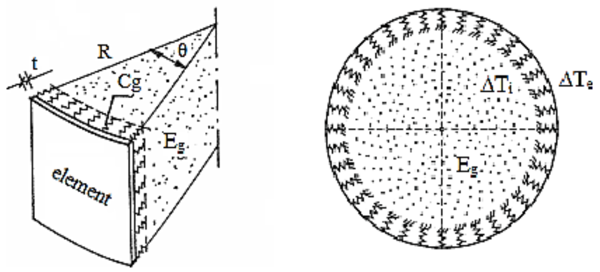


Figure 1. FEM model simulation of interaction between silo wall and grains [7]

The granular material stiffness (C_g) can be calculated according to the equilibrium of deformations of an elastic ring in contact with the ensiled granular material, also with the validation of applied spatial stress relationships [7] as,

$$C_g= E_g/(r(1-\vartheta_g)) \tag{2}$$

Where (C_g) is the stiffness of the stored granular material, (E_g) is the modulus of elasticity of the stored granular material, (r) is the inner radius of silo, and (ϑ_g) is the Poisson's ratio of the stored granular material. Since the granular materials have properties similar to soil for evaluation the grains modulus of elasticity, it can be used Table 1 to get values of $E_g$and ϑ_g.

Table1. Values of modulus of elasticity and Poisson's ratio for granular soils [7]

Type of soil	Modulus of elasticity, E_g(MPa)	Poisson's ratio, ϑ_g
Loose sand	10 24	0.2-0.4
Medium dense sand	17-28	0.25-0.4
Dense sand	35-55	0.3-0.45
Silty sand	10-17	0.2-0.4
Sand and gravel	69-170	0.15-0.35

2.1.2 The European Union Regulation

The Eurocode assigns an additional horizontal pressure (P_h) [10], required to resist extra stresses due to thermal loads. The horizontal pressure equation (3) is a function of temperature difference (ΔT), silo wall thickness (t), and silo radius (r). Thus, (ΔT), (t) and (r) will be the parametric study elements in the Eurocode equation as,

$$P_h=(C_T\ \alpha_w\ \Delta T\ E_w)/\ ((r/t) + (1-\vartheta)\ (E_w/E_{su})) \tag{3}$$

Where (C_T) is the temperature load multiplier. It equals 1.2 where laboratory testing is used to obtain the unloading effective elastic modulus. It also equals 3 where the unloading effective elastic modulus is simplified from the density, (α_w) is the coefficient of thermal expansion of silo wall, (E_w) is the elastic modulus of elasticity of silo wall, (ϑ) is Poisson's ratio of the stored material, can be assumed equal 0.3, and (E_{su}) is the unloading effective elastic modulus of the stored material. There are two ways to calculate the unloading effective elastic modulus of the stored granular material. The first is "Direct assessment from laboratory testing as in EN 1991-4:2006 annex C section C10.1". The second is "Indirect assessment". An estimated value for E_{su}can be calculated as,

$$E_{su}=\chi\,P_{vft} \tag{4}$$

Where (P_{vft}) is the vertical pressure at the base of silo wall, (χ) is the modulus contiguity coefficient as,

$$\chi= 7\gamma^{\,3/2} \tag{5}$$

Where (γ) is the density of the stored material in kN/m^3, (γ) may be alternatively estimated as 70 for dry grains, 100 for small mineral particles, 150 for large hard mineral particles. P_{vft}may be calculated first as,

$$P_{vft}= (P_{ho}\,Y_J)/K \tag{6}$$
$$P_{ho}=\gamma\,K\,z_o \tag{7}$$
$$z_o=1/(K\ \mu)(A/U) \tag{8}$$

Where (P_{ho}) is the horizontal pressure at the big depth due to stored material, (Y_J) is the Janssen pressure depth variation function, (K) is the Lateral pressure ratio, (z_o) is the Janssen characteristic depth, (z) is the depth below the surface of the stored material, (μ) is the Coefficient of wall friction for material sliding on the vertical wall, (A) is the cross section area of the silo plan, (U) is the internal perimeter of the cross section of the silo plan.For circular plan silos A/U=r/2,

$$Y_J= 1-\exp(z/z_o) \tag{9}$$
$$z= h-2/3r\tan\phi_r(10)$$

Where, (h) is the height of the silo wall, and (ϕ_r) is the angle of repose of stored material. Fig. 2 explains the equations' variables on the silo elevation.

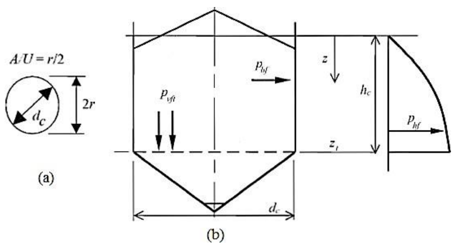


Figure2. Silo forms showing various variables on silo elevation and plan [10]

P_{vft} may be calculated also second as,

$P_{vft}=\gamma\ z_v$(11)
$z_v = h_o - 1/(n+1)[z_o - h_o - \{(z + z_o - 2h_o)^{n+1}/(z_o - h_o)^n\}]$(12)
$n = -(1 + \tan\phi_r)(1 - h_o/z_o)$(13)
$h_o = r/3\tan\phi_r$(14)

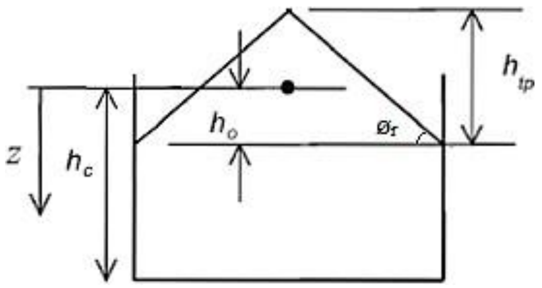


Figure3. Silo elevation illustrates dimensions [10]

Where, (z_v) is the depth which used for vertical stress calculations, (h_o) is the depth below the equivalent surface to the base of the top pile, and (n) is the power in hopper pressure relationship. These variables are shown in fig. 3.

Then, the circumferential force (F_E) according to Eurocode [10, 12],is using structural mechanics equilibrium principles as,

$F_E = r\ P_h$(15)

2.1.3 Poland Norm

The Poland norm provides static calculations, design, construction and operation for reinforced concrete silos. PN-B-03262: 2002 is the Poland standard that concerns in loads and actions on R.C silos. Poland norm[11],recommended an additional latitudinal tensile force (F_P) due to decline in temperature as,

$F_P=(rE_g\ \alpha_w\ \Delta T_m)/((r\ E_g)/(t\ E_w) + 1 - \vartheta_g)$(16)

Where, (r) is the internal radius of the cylindrical silo wall, (t) is the thickness of the silo wall, (E_g) is the modulus of elasticity of the stored granular material, (E_w) is the modulus of elasticity of silo wall, (α_w) is the coefficient of thermal expansion of the silo wall, (ϑ_g) is the Poisson's ratio of stored granular material, (ΔT_m) is the average daily temperature at the thickness of the wall of the silo, as shown in fig. 4.

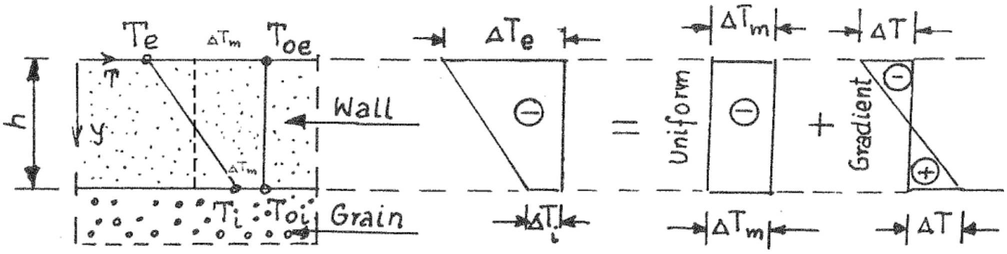


Figure4: Distribution of temperature through the silo wall [7]

2.2 Finite Element Method

The finite element method (FEM) is a numerical technique to solve complex problems in structural analysis and structural mechanics by divided the geometry into smaller parts (finite elements) for boundary problems by having approximate solution for the partial differential equation [13]. This study uses the FEM by a computer program SAP 2000 v. 16.

2.2.1 Linear and Nonlinear Analyses of Silo Walls under Thermal Analysis

The RC silos are considered as load bearing members divided into elements according to finite element method. Thestiffness of these structures are independent on the value of applied loads. The applied loads are proportional to the deformation, and while the loads have been removed, the body has its known shape back [14].This behavior is known as linear theory based on some assumptions included in [15].That leads to the term called elasticity which is the proportion of the strain resulting from applying a known stress (Hook's law [16]). Most of codes provide empirical equations to calculate modulus of elasticity of concrete usingthe compression strength as,

$E_c = k\,(f_{cu})^{1/2}$(19)

Where (E_c) is the concrete modulus of elasticity (N/mm^2), (f_{cu}) is the compressive strength of concrete cube at 28-day (N/mm^2), and (k) is the empirical constant, which equals 4400 [17], 4733 [5], and 5000 [18].

To fully understand linear and nonlinear analyses, it can be applying a well-known stress-strain relationship[8].Thestress-strain behavior is divided into: Pre-peak, the structurebehaves linear elastic response for a very minor strain, and Post-peak, excessive deformation (strain) occurs with low stress level and this stage can be called nonlinear as plastic response. From these analyses, it is obvious that, most of structures behavior is nonlinear, but using linear analysis for such cases doesn't make a great divergence (may be neglected) from the results come out of nonlinear analysis. Using linear analysis in cases need nonlinear analysis may be conducted and preferred if the accuracy is low or to have an overview of the structure behavior or displacement orientation. However, linear analysis is not accurate and not perfect in some analysis cases, it is money and time saving and such factors are more important in the preliminary analysis.The exact opposite, nonlinear analysis is pretty accurate and takes all the applied stress and resulting strains, even if it exceeds the yielding strength. In addition to that, the changes resulting from deformations may cause changes in the structure shape and stiffness, furthermore loads may change their orientation and supports would be changed in regards with the large deformations during loading [19].

III. Results and Discussions

The main goals of this study concern with the estimation of the maximum vertical bending moment and the circumferential force of RC silos subjected to temperature difference. In this regard, Table 2 shows the Silo dimensions, concrete characteristics and granular material (wheat) properties.

Table 2.Silo dimensions, concrete characteristics and granular properties

Silo dimensions and concrete characteristics	Granular material (wheat) properties
Total height of the silo wall, H = 30 m	Density, $\gamma = 0.9\ t/m^3$
The inner radius, r = 5 m	Angle of internal friction, $\phi_i = 30^o$
Concrete compressive strength, $f_{cu} = 3000\ t/m^2$	Coefficient of friction, f = 0.38
Modulus of elasticity, $E_c = 2617789.2\ t/m^2$	Modulus of elasticity E_g = 30Mpa = $3060 t/m^2$
Poisson's ratio, $\vartheta = 0.2$	Poisson's ratio, $\vartheta_g = 0.35$
Thermal coefficient of expansion, $\alpha_w = 1.2*10^{-5}$	

Before presenting the whole results of both additional moments and circumferential forces, it can be possible to show the effect of thermal loads on silo walls using one scenario of the FEM computer program according to the data shown in Table 2 and considering the silo wall thickness equals 0.2 m. The outputs of the FEM analysis are: F11 is the circumferential (hoop) force in silo wall, M11 is the circumferential (hoop) moment in silo wall, F22 is the vertical force in silo wall, and M22 is the vertical moment in silo wall. Table 3 and fig. 5 shows the result of the mentioned scenario for ($\Delta T = \pm 30ºC$).

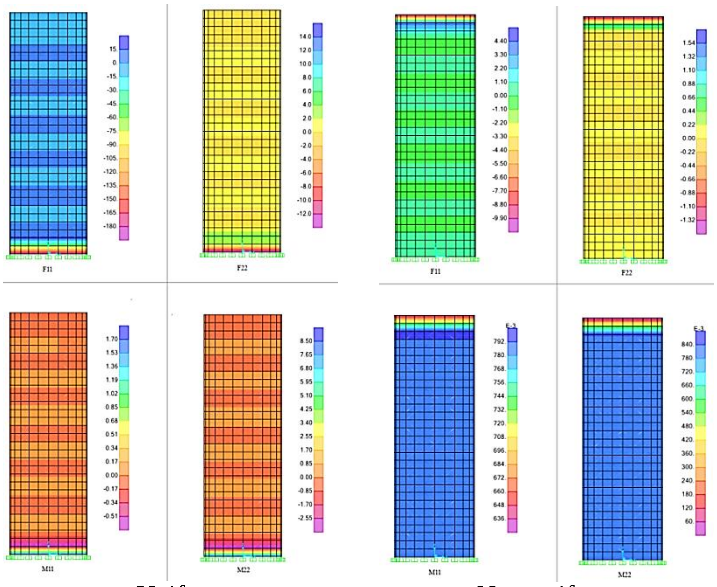
Table 3.Silo dimensions, concrete characteristics and granular properties

Temperature Difference	ΔT=+30ºC		ΔT=-30ºC	
	Uniform	Non-uniform	Uniform	Non-uniform
M_{ACI} (t.m)	3.93	3.93	-3.93	-3.93
M11 (t.m)	0*	0.798	0*	0.798
M22 (t.m)	0**	0.849	0**	0.849
F11 (t)	0***	0	50	0
F22 (t)	0****	0	0	0

*For the last 0.5 meters, an extra moment appears ascending to reach its maximum value at the base M11=1.65 t.m.
**For the last 2 meters, an extra moment appears ascending to reach its maximum value at the base M22=8.26 t.m.
***For the last 2 meters, an extra compression force appears ascending to reach its maximum value at the base F11=-191.1 t.
****For the last 0.5 meters, an extra compression force appears ascending to reach its maximum value at the base F22=-13.54t.

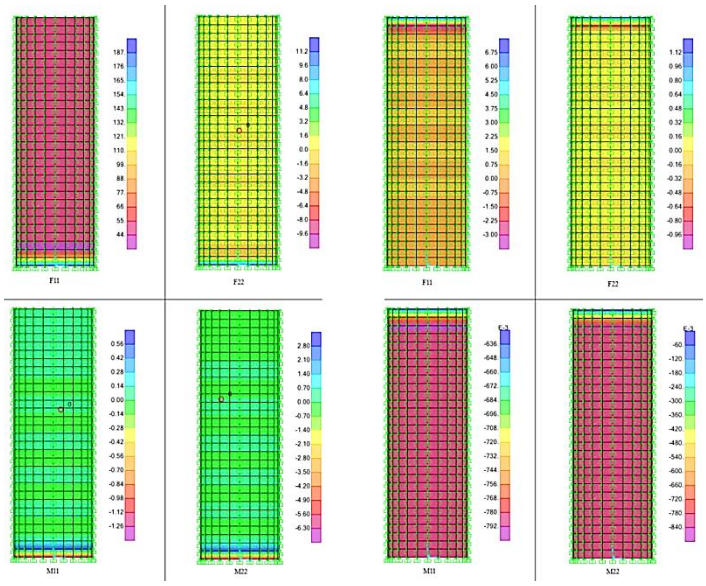
3.1 Moment due to Thermal Loads

To estimate the additional maximum vertical moment over the silo wall, the authors present two systems for estimation. The first is throughout ACI code. The second is Finite Element Model (FEM) using SAP2000 v.16 (Linear and Nonlinear Analysis).It is obvious from ACI equation (1) that the additional moment is directly proportioned to the square of the silo wall thickness. Taking the same silo data from Table 2, the calculated moment can be rewritten as a function of (ΔT) and (t) as: ($M_t = 3.272*t^2*\Delta T$ t.m/m). Taking (t)-valuesare (0.15, 0.20, 0.25, 0.30, 0.35) Meters and (ΔT)-values are (10°, 20°, 30°, 40°, 50°) Celsius. Figure 6 illustrates the resulted linear and nonlinear analysis of FEM moments and the calculated ACI moments with different values of (ΔT) and (t). Likewise, Table 4 shows the standard deviations for the two groups. The first is for (t=0.15~0.35 m) versus the (ΔT)-values and the second is for (ΔT=10~50°C) versus each of the (t)-values.



Uniform Non-uniform

Figure5a. FEM model outputs for (ΔT=+30ºC)



Uniform Non-uniform

Figure5b. FEM model outputs for (ΔT= -30ºC)

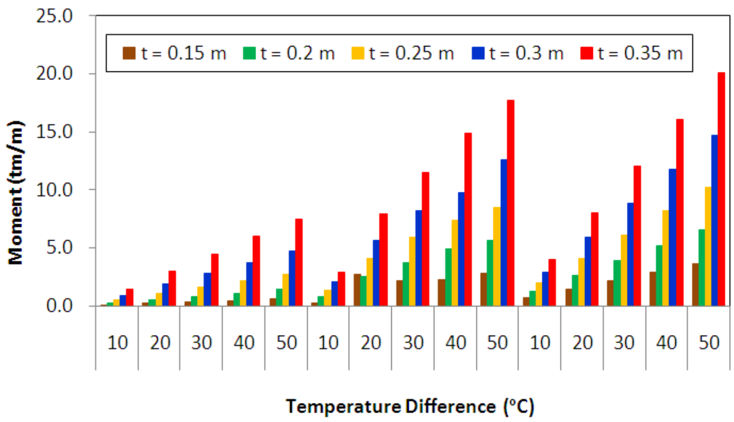


Figure 6: Linear & Nonlinear FEM and ACI moments verses temperature differences (1 ton=9.806 kN)

In figure 6, it can be obviously noticed that the moments for linear and nonlinear FEM and ACI code increase with the temperature difference and silo wall thickness increase. These results are clearly shown as in Table 4 whereas the standard deviations (σ) increases for FEM and ACI code with increasing of temperature differences and silo wall thickness. These standard deviations mean that the moment varies greatly with the increasing of temperature differences and silo wall thickness. Further, it can be clearly noticed that the moment of linear analysis of FEM have a great gap less that the corresponding values in ACI, especially in higher values of the temperature difference and silo wall thickness. Furthermore, it can be clearly noticed that the moment of nonlinear analysis for FEM have a good matching with the corresponding values of ACI results (σ-values of Nonlinear FEM are much closer to ACI). These results leads to that the nonlinear analysis is good accurate to ACI results rather than linear analysis.

Table 4: Linear & Nonlinear FEM and ACI Standard Deviation (σ)

ΔT (°C)	FEM (Linear)					FEM (Nonlinear)					ACI code				
	10	20	30	40	50	10	20	30	40	50	10	20	30	40	50
t = 0.15-0.35 m	0.5	1.1	1.6	2.2	2.7	1.0	2.2	3.7	4.8	5.8	1.3	2.6	3.9	5.2	6.5
ΔT (°C)			10-50					10-50					10-50		
t = 0.15 m			0.19					1.01					1.16		
t = 0.20 m			0.45					1.91					2.07		
t = 0.25 m			0.86					2.81					3.23		
t = 0.30 m			1.49					4.00					4.66		
t = 0.35 m			2.37					5.82					6.34		

3.2 Circumferential Force

To estimate the circumferential force over the silo wall, the authors presents three systems for estimation. The first is throughout FEM using SAP2000 v.16. The others are the Poland and Eurocodes.In Eurocode, the calculation of the unloading effective elastic modulus of the stored material (E_{su}) is mainly depends on the granular material properties (wheat), the depth at which it is calculated (z) – this depth will be the highest depth to be conservative – and the silo inner radius (r). Table 5 shows the unloading effective elastic modulus calculations due to radius changing.Then the circumferential force using Eurocode as shown in Equation (15), is compared to the Poland Norm as shown in Equation (16), and the circumferential force from FEM taking into account the grain stiffness.

Table 5: Calculation of the unloading effective elastic modulus due to radius changing

r (m)	z_o (m)	z (m)	First method				Second method					E_{su}max (t/m^2)
			P_{ho} (t/m^2)	Y_J	P_{vft} (t/m^2)	E_{su} (t/m^2)	h_o (m)	n	z_v	P_{vft} (t/m^2)	E_{su} (t/m^2)	
2.5	6.09	28.88	2.959	0.99	5.424	1025	0.562	-1.52	7.05	6.35	1200	1200
5	12.18	27.75	5.919	0.89	9.755	1844	1.124	-1.52	11.2	10.08	2041	2041
7.5	18.27	26.63	8.879	0.77	12.66	2393	1.686	-1.52	13.8	12.42	2347	2393

Table 6: FEM, Poland code, and Eurocode Standard Deviation (σ)

ΔT (°C)	FEM					Poland code					Eurocode				
	10	20	30	40	50	10	20	30	40	50	10	20	30	40	50
r = 2.5 m, t = 0.15-0.35 m	0.03	0.06	0.10	0.13	0.16	0.01	0.02	0.03	0.04	0.04	0.01	0.01	0.01	0.02	0.02
r = 5.0 m, t = 0.15-0.35 m	0.07	0.14	0.21	0.28	0.35	0.04	0.07	0.10	0.14	0.17	0.05	0.09	0.14	0.18	0.23
r = 7.5 m, t = 0.15-0.35 m	0.12	0.24	0.35	0.45	0.57	0.07	0.15	0.22	0.29	0.36	0.14	0.28	0.41	0.55	0.68
ΔT (°C)	10-50					10-50					10-50				
r = 2.5 m, t = 0.15 m	3.92					2.17					2.60				
r = 2.5 m, t = 0.20 m	3.87					2.19					2.61				
r = 2.5 m, t = 0.25 m	3.83					2.19					2.61				
r = 2.5 m, t = 0.30 m	3.92					2.20					2.61				
r = 5.0 m, t = 0.15 m	4.99					4.21					8.59				
r = 5.0 m, t = 0.20 m	4.83					4.28					8.68				
r = 5.0 m, t = 0.25 m	5.10					4.31					8.73				
r = 5.0 m, t = 0.30 m	4.96					4.34					8.76				
r = 7.5 m, t = 0.15 m	6.58					6.15					14.69				
r = 7.5 m, t = 0.20 m	6.67					6.28					14.93				
r = 7.5 m, t = 0.25 m	6.89					6.36					15.08				
r = 7.5 m, t = 0.30 m	6.96					6.41					15.18				

The figure 7 shows the values of the circumferential force, resulted from thermal stresses, verses variable values of silo wall thickness (t), silo inner radius (r), and temperature difference (ΔT) for the three systems. It is obviously clear, from this figure, that the value of the ring force using any of FEM,Poland code, and Eurocode are slightly affected by the silo wall thickness (t), the force difference at variant wall thicknesses does not exceed one ton. In addition, Table 6 shows the standard deviation for several groups of silo wall thickness, silo inner radius, and temperature difference for the three systems.

For the figure 7, it can be obviously noticed that the circumferential force increases with the increasing of temperature difference and silo radii (σ increases from 3.92 to 6.96 for FEM, from 2.17 to 6.41 for Poland code, and from 2.60 to 15.18 for Eurocode) but no significant for silo wall thickness showing a good matching values of FEM and Poland code, especially in higher values of silo radii (see Table 6).It can be outlined clearly the effect of temperature difference on the circumferential force results as in figure 8.

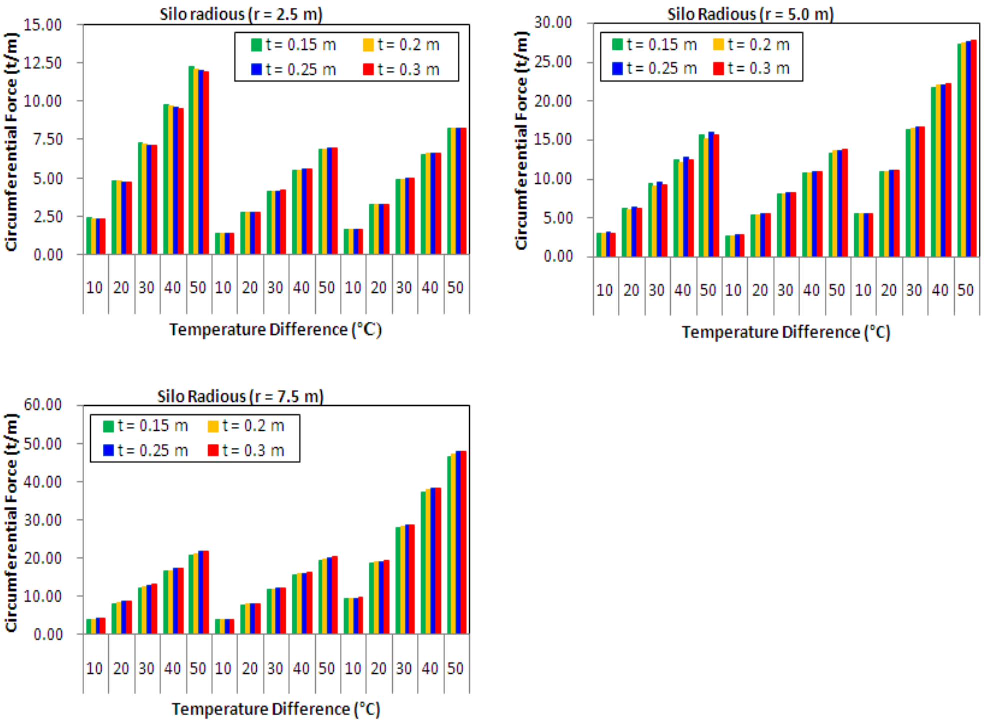


Figure 7: FEM-Poland-Euro circumferential forces verses temperature differences (1 ton=9.806 kN)

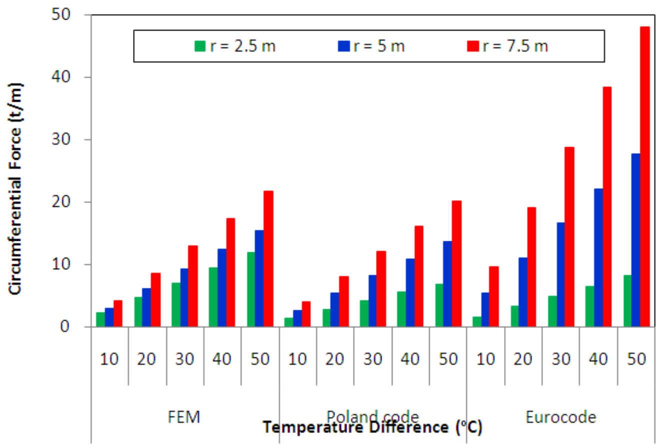


Figure 8: FEM-Poland-Euro circumferential forces verses silo wall radius (1 ton=9.806 kN)

IV. Conclusions

This study has been conducted to presents some computational analysis of temperature fields and thermal effects occurring in RC silos using the design formula adopted by ACI, Euro, and Poland codes. These codes are used to estimate the additional moments and circumferential forces of silo wall for different thermal loads. Further, the computer program of Finite Element Model (FEM) using SAP2000 is used to compare with these codes in linear and nonlinear analysis. The study results of the additional moment for ACI code and linear and nonlinear analysis of FEM increase with the temperature difference and silo wall thickness increase. It can also be clearly noticed that the moment of nonlinear analysis of FEM have a good matching with the corresponding values in ACI leading to that the nonlinear analysis is good accurate rather than linear analysis. In addition, the circumferential force results showed a distinct pattern with the temperature difference, silo radii for each of FEM, and Euro and Poland codes. But the silo wall thickness has no significant effect in the circumferential force. Regardless, the study showed a good evaluation for the RC silo design subjected to thermal loadings.

Nevertheless, the research performed in the area of silos has been very extensive and covers many disciplines, more work remains to be done: new problems need to be tackled and older ones need to be analyzed with less simplified methods. It is recommended that the load combinations to be considered for silos incorporate the following aspects: Load combinations and combination factors should be set by dividing silos into different categories, at least according to the following: the relative thickness of the silo walls; the aspect ratio of the silo; whether the silo is on-ground or elevated and operating conditions.

Acknowledgments

The research reported herein was funded by the Deanship of Scientific Research at the University of Hail, Saudi Arabia, under the contract (E-3-CE). The authors would like to express their deepest gratitude to the Deanship of Scientific Research and to the College of Engineering at the University of Hail for providing necessary support to conducting this research.

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Walid M. A. Khalifa."Evaluation of Design of RC Silos Subjected to Thermal Loads." IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) , vol. 16, no. 1, 2019, pp. 01-11