Zeszyty Naukowe Politechniki Częstochowskiej
Budownictwo
ISSN 0526-5916

Zeszyty Naukowe Politechniki Częstochowskiej nr 26 (2020), 156-161
DOI: 10.17512/znb.2020.1.23

Cracking state analysis of reinforced concrete grain silos structures

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ABSTRACT:
Silo structures are classified as objects with a higher degree of risk and disaster hazard compared to other engineering structures. In reinforced concrete silos, the following may occur: excessive cracks or strains, exceeding capacity of the wall or the floor to withstand bending moments and normal forces, corrosion of structural members, or explosions of a part or the whole silo bin. Silo failures may be caused by yet not fully recognized stress and strain states in sections of the silo chambers, which result from random and variable interactions of stored granular media in combination with temperature fields. Circadian fluctuations of ambient temperature that occur particularly during early winter and spring coupled with the static pressure of the granular medium produce overload states in the silo wall structures. As a result, additional tensile stresses combined with bending are produced. All these factors cause increased cracking in reinforced concrete silo walls, which may reduce the load capacity and durability of the silo structure. The paper presents assumptions and design procedures regarding verification of the cracking state in reinforced concrete silo chambers based on the latest recommendations given in EN 1992-3, EN 1992-1-1 and *fib* Model Code 2010.

KEYWORDS:
cracking state; silos; RC structures

1. Introduction

Complex stress states that occur in walls and hoppers of reinforced concrete silos result from random and variable interactions caused by such factors as the pressure of a bulk solid during the silo's filling and discharge phase [1, 2], coupling of static loads exerted by bulk materials and by drops in ambient temperature [3, 4]. These factors create eccentric tensile stress in the walls and hoppers of reinforced concrete silos thus leading to their cracking.

In accordance with EN 1990:2004 [5] standard RC silos should be designed to last 100 years (S6 structure class), which means that during their expected service lifespan, silo structures must fulfill all the requirements of load capacity, stability and serviceability without incurring excessive, unforeseen costs of their maintenance and repairs. To ensure an appropriate level of durability and reliability of silos, Eurocode 1, Part 4 [6], describes a variety of procedures for determining the load induced by bulk material pressure depending on the class of impact assessment for which the silo has been classified (Table 1). In the case of silos with high storage volumes (over 10,000 tons) as well as silos discharged or filled on a large eccentricity (class AAC3, class AAC2), the procedure for determining the impact on the walls and hopper of the silo has been significantly expanded. However, simplified procedures can be used in silos of the AAC1 class.

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Table 1
Classification of silo action assessment according to EN 1991-4 [6]

Action assessment class	Class description
Action assessment class 3 (AAC3)	Silo with storage volume of more than 10 000 tons Silo with storage volume of more than 1 000 tons, with any of the following calculation situations: a) non-centric emptying at $e_0/d_c > 0.25$ b) low silos, with eccentric of the upper fill cone $e_t/d_c > 0.25$
Action assessment class 2 (AAC2)	All silos mentioned in EN 1991-4 which are not qualified for a different class
Action assessment class 1 (AAC1)	Silo with storage volume of less than 100 tons

The paper presents variable interactions in silos caused by asymmetrical pressure of a bulk solid during emptying as well as due to weather factors, such as temperature, under which scratches in RC silo structure elements occur. The up-to-date standard procedures for calculating crack widths in reinforced concrete silo walls (serviceability limit state) are also discussed in the paper.

2. Variable action in silos

2.1. Local pressure in silo chambers during emptying

RC silo action involves two phases of structure operation, i.e. silo filling and discharge phases in which loads induced by the pressure of stored bulk material can be determined. The pressure of a bulk solid in the silo chamber depends on the following parameters: the properties of the bulk solid, dimensions and shape of the silo chamber and the magnitude of the filling and emptying eccentricity. Detailed guidelines regarding the determination of actions in silos are included in Eurocode 1, Part 4 [6].

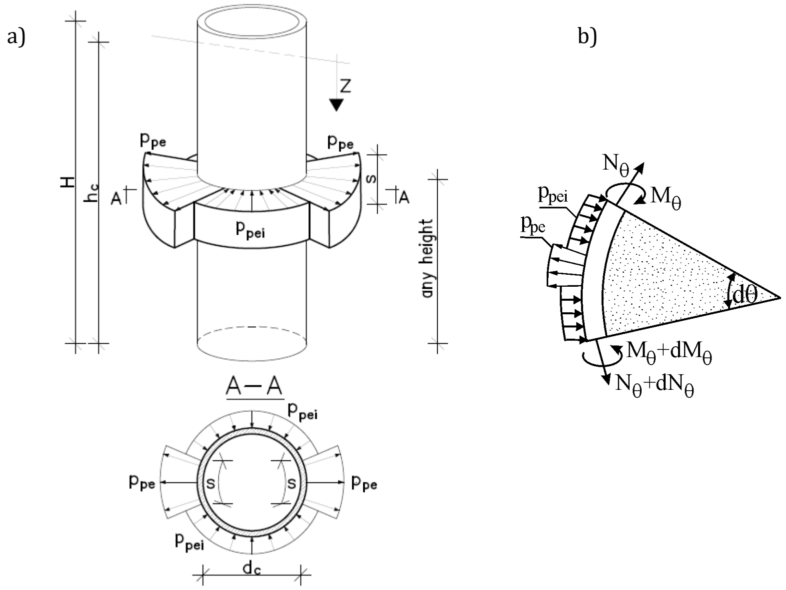

Fig. 1. Rules for loading reinforced concrete silo structures with local pressure according to EN 1991-4 [6]: a) distribution of local pressure in the cylindrical silo chamber, b) internal forces in the silo wall structure

In a silo chamber during its discharge, in addition to the symmetrical pressure, there is an increased local pressure, the distribution of which is shown in Figure 1. The components of the local pressure, i.e. p_{pe} – increased pressure directed outside the silo chamber and p_{pei} – local pressure directed inside the silo, are determined from the following formulas:

$$p_{pe} = C_{pe} \cdot p_{he} \tag{1}$$

$$p_{pei} = \frac{p_e}{7} \tag{2}$$

where C_{pe} is the increasing coefficient when calculating the local pressure depending on the eccentricity magnitude of filling and discharge, chamber geometry and the properties of the bulk medium; p_{he} is the horizontal pressure on the silo wall during discharge.

The EN 1991-4 [6] standard specifies the procedures for determining the local pressure only for a free-standing silo. Lapko and Prusiel [7] proposed a procedure for determining the local pressure component for corner and inner chambers in a battery of grouped silos.

2.2. Pressure during discharge on a large eccentricity

When dealing with discharge on a large eccentricity (i.e. when the discharge eccentricity e_0 exceeds the value $0.25d_c$; where d_c is the inner diameter of the silo chamber) apart from the local pressure, it is necessary to account for the increased pressure caused by non-centric flow channel of the bulk material in the silo chamber (Fig. 2).

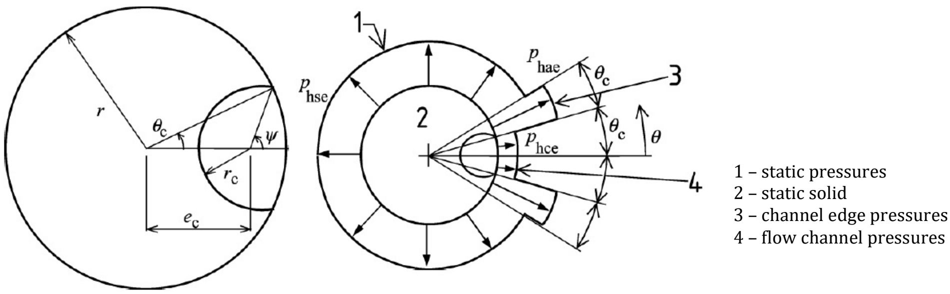

Fig. 2. Distribution of pressure on the silo wall at a non-centric flow channel of the bulk solid during discharge [6]

Under the influence of asymmetrical pressure in the silo during emptying, bending moments with variable signs several times greater than normal are created in the reinforced concrete wall. Also, considerable circumferential forces arise in the reinforced concrete wall, which may cause cracks in the silo wall [8].

2.3. Thermal actions

The walls and hoppers of RC grain silos during operation are subjected to cyclically variable fields of ambient temperature. Significant diurnal ambient temperature drops, occurring especially in early winter and spring periods in conjunction with the static pressure of a bulk solid can cause overloading of silo wall structures.

Tests conducted on the silos used in the Bialystok grain elevator in winter and spring have shown that, in the zone of intensive sunlight, an increase in tensile stress in the silo wall reinforcement up to several MPa occurs (Table 2). Making use of variable temperature field distributions and changes in reinforcement deformations registered by the SensoNet telemetry system [9], it was possible to determine temperature drops on the wall surface and corresponding stress increases in the horizontal reinforcement of the chamber [4].

Table 2
Extreme temperature drops on the wall surface at measuring points and corresponding thermal stress increments in the horizontal reinforcement of the grain silo battery wall

Measuring point	Spring season			Winter season		
	ΔT_{spring} [°C]	$\Delta\varepsilon_t$ [‰]	$\Delta\sigma_t$ [MPa]	ΔT_{winter} [°C]	$\Delta\varepsilon_t$ [‰]	$\Delta\sigma_t$ [MPa]
C10	–17,9	0,080	16,8	–8,1	0,045	9,5
C8		0,073	15,3		0,047	9,9
C6		0,052	10,9		0,032	6,7

Variable actions causing complex stress states in the silo structures can cause cracks in the reinforced concrete silo walls, often leading to numerous building failures and disasters [1].

3. Crack analysis of RC grain silo walls

3.1. Procedure according to EN 1992-1-1:2004 and EN 1992-3:2006

Eurocode EN 1992-3:2006 [10] distinguishes four classes of tightness for liquid tanks and concrete silos: class 0, 1, 2 and 3. The reinforced concrete silos for storage of dry bulk materials can be classified into tightness class 0. For storing bulk materials that are particularly susceptible to moisture (e.g. grain, flour), the silo should be designed in class 1, 2 or 3.

The serviceability limit state (SLS) of a reinforced concrete silo structure regarding cracking is maintained if the following condition is met

$$w_k \le w_{max} \tag{3}$$

where: w_k – computational crack width [mm]; w_{max} – maximum crack width [mm], the recommended value according to EN 1992-1-1:2004 [11] depends on the environmental conditions in which the structure is operated.

For RC silos designed in tightness class 0, the computational crack width can be calculated in accordance with Eurocode guidelines [11], and the maximum crack width is 0.3 mm. The computational crack width in a RC silo wall is calculated from the formula

$$w_k = \left(\varepsilon_{sm} - \varepsilon_{cm}\right) \cdot s_{r,max} \tag{4}$$

where: ε_{sm} – average steel strain taking into account the effect of “tension stiffening” and ε_{cm} – average concrete strain between cracks; $s_{r,max}$ – maximum spacing cracks.

For silo structures belonging to tightness class 1-3, if the crack cuts the entire cross-section of the wall, when calculating the wall crack, we apply the same procedure as for a reinforced concrete structure according to EN 1992-1-1 [11]. Additionally however, the conditions specified in the Eurocode EN 1992-3 [10] regarding the design of concrete silos must be met

$$x_{\min} \ge 50 \text{ mm and } x_{\min} \ge 0.2h \tag{5}$$

where: x_{min} – minimum range of the compressed concrete zone in the eccentrically stretched section of the silo wall; h – cross-sectional height of the silo wall (Fig. 3).

The range of the compressed concrete zone and the stress in reinforcing steel in cross--section through the crack are calculated using linear-elastic analysis based on the theory of elasticity.

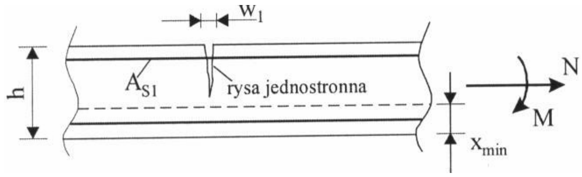

Fig. 3. Computational diagram for cracking the reinforced concrete structure of silos in tightness class 1-3

3.2. Procedure according to fib Model Code 2010

To ensure the durability and serviceability of RC silos, the SLS condition must be met

$$w_d \le w_{\lim} \tag{6}$$

in which the computational crack width w_d is determined from dependence

$$w_d = 2l_{s,\max} \cdot \left(\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs}\right) \tag{7}$$

where: $l_{s,max}$ – the section where slippage occurs between concrete and steel; ε_{sm} – average steel strain on the section $l_{s,max}$; ε_{cm} – average concrete strain on the section $l_{s,max}$; ε_{cs} – strain of the concrete due to free shrinkage.

The maximum value of permissible crack width in silos according to *fib* Model Code 2010 [12], similarly to EN 1992-1-1 [11], depends on the environmental exposure class and is 0.3 mm. The section is determined from the formula

$$l_{s,\max} = k \cdot c + \frac{1}{4}\frac{f_{ctm}}{\tau_{bms}} \cdot \frac{\phi_s}{\rho_{s,ef}} \tag{8}$$

where: k – experimental parameter, taking into account the effect of concrete cover (can be adopted); c – concrete cover; τ_{bms} – average adhesion strength between concrete and steel (Tab. 7.6-2 [12]); f_{ctm} – average concrete tensile strength; ϕ_s – diameter of tensile reinforcement; $\rho_{s,ef}$ – effective degree of tensile reinforcement.

According to the procedure *fib* Model Code 2010 [12], the average strain in equation (7) is described by dependence

$$\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs} = \frac{\sigma_s - \beta\sigma_{sr}}{E_s} + \eta_r \cdot \varepsilon_{sh} \tag{9}$$

where: σ_s – stress in steel in cross-section through the crack (calculated in silos for the case of stretching with a large or small eccentricity); σ_{sr} – maximum stress in steel in the crack, in the state of crack formation in the case of pure stretching; ε_{sh} – shrinkage strain; β – experimental coefficient depending on the type of load; η_r – coefficient accounting for shrinkage impact; coefficients β and η_r are given in Table 7.6-2 [12].

The presented analysis of the crack calculation of reinforced concrete silos should take into account additional recommendations related to the adopted tightness class of the silo according to Eurocode [10].

4. Conclusions

1. At the silo's design stage, it is important to correctly determine the loads caused by asymmetrical pressure of the bulk solid, as well as the loads due to thermal actions that may lead to increased cracking of the reinforced concrete walls and silo hoppers.

2. Excessive cracking combined with fatigue effects or corrosion of concrete and reinforcing steel will ultimately reduce the durability of RC silos.
3. Use of accurate procedures for calculating crack widths in a silo structure according to EN 1992-1-1:2004 and *fib* Model Code 2010 and taking into account the guidelines of EN 1992-3:2006, makes it possible to check the serviceability limit state with respect to cracking.

Acknowledgements

The paper was prepared at Bialystok University of Technology within a framework of the WZ/WB-IIL/4/2020 project sponsored by Ministry of Science and Higher Education.

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Analiza stanu zarysowania konstrukcji żelbetowych silosów na zboże

STRESZCZENIE:
Konstrukcje silosów są klasyfikowane jako obiekty o wyższym stopniu ryzyka i zagrożenia katastrofą w porównaniu z innymi konstrukcjami inżynierskimi. W silosach żelbetowych mogą wystąpić: nadmierne zarysowania lub odkształcenia, przekroczenie nośności ściany lub dna na momenty zginające i siły normalne, korozja elementów konstrukcyjnych, eksplozje części lub całej komory silosu. Awarie silosów mogą być spowodowane jeszcze nie do końca rozpoznanymi stanami naprężeń i odkształceń w sekcjach komór silosu, które wynikają z przypadkowych i zmiennych oddziaływań składowanych ośrodków ziarnistych w połączeniu z polami temperatury. Dobowe wahania temperatury otoczenia, które występują szczególnie wczesną zimą i wiosną, w połączeniu ze statycznym parciem ośrodka ziarnistego, powodują stany przeciążenia konstrukcji ścian silosu. W rezultacie powstają dodatkowe naprężenia rozciągające połączone ze zginaniem. Wszystkie te czynniki powodują zwiększone zarysowanie ścian żelbetowych silosów, co może wpływać na obniżenie nośności i trwałości konstrukcji silosu. W artykule przedstawiono założenia i procedury projektowe dotyczące weryfikacji stanu zarysowania w żelbetowych komorach silosów w oparciu o najnowsze zalecenia podane w EN 1992-3, EN 1992-1-1 oraz *fib* Model Code 2010.

SŁOWA KLUCZOWE:
zarysowanie; silos; konstrukcje żelbetowe