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SILO WITH A CORRUGATED SHEET WALL

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ABSTRACT

Silos and tanks are currently being used to create reserves of stored materials. Their importance is based on balancing the production and consumption of bulk materials to establish an adequate reserve throughout the year. The case study introduced within the framework of this paper focuses on thin-walled silos made of corrugated sheets and on an approach for designing these types of structures. The storage of bulk materials causes compression or tensile stresses in the walls of a silo structure. The effect of a frictional force in the silo walls creates an additional bending moment in a wave, which ultimately affects the resulting bending moments. Several mathematical and physical models were used in order to examine various types of loading and their effects on a structure. Subsequently, the accuracy of the computational models was verified by experimental measurements on a grain silo in Bojničky, Slovakia. A comparison of the experimental and mathematical models shows a reasonable match and confirms the load specifications, while indicating that the mathematical model was correct.

1. INTRODUCTION

Tanks are used to store material for a certain period of time while the quality of the stored material remains unchanged. Tanks and reservoirs provide sufficient reserves for both short and long-term periods during the interruption of supplies. The owners of tanks are able to react to any situation of insufficient supplies and continue with the consumption of stored materials easily with no impact on economic efficiency.

1.1 Load forces

The calculating load of a silo also requires consideration of its structure, the properties of the stored materials and the shape of the material's flow during the filling and emptying processes.

When considering the slenderness of silos, they are divided into four groups: slender silos ($hc / dc \geq 2$), silos of a medium slender-

ness ($1.0 < hc / dc < 2.0$), low silos ($0.4 < hc / dc \leq 1.0$) and very low silos ($hc / dc \leq 0.4$ with a straight bottom). The load calculations from bulk material for medium slender silos can be calculated by the following formulas (Rucknbrod, 2006) (Janssen, 1895):

– Horizontal pressure

$$P_{hf} = p_{ho} \cdot Y_R \quad (1)$$

– Frictional traction on the silo wall

$$P_{wf} = \mu \cdot P_{hf} \quad (2)$$

– Vertical pressure

$$P_{vf} = \gamma \cdot z_v \quad (3)$$

where

$$p_{ho} = \gamma \cdot K \cdot z_o \quad (4)$$

KEY WORDS

- Thin-walled silo,
- corrugated sheet,
- bulk material,
- horizontal pressure,
- friction in a wall.

Fig. 1 Types of different loads and their values according to silo height levels.

$$z_o = \frac{1}{K \cdot \mu} \cdot \frac{A}{U} \quad (5)$$

U internal circumference of silo cross-section (STN EN 1991-4, 2009).

where

- p characteristic value of bulk weight density,
- μ coefficient of friction between the stored material and the bin wall,
- K lateral-to-vertical pressure ratio,
- z depth under equivalent material surface,
- A area of silo cross-section,

Figure 1 shows various types of the loading of bulk materials and the effect of their orientation. Next to the main scheme, i.e. the loading of wheat, the traces of horizontal forces, friction forces and vertical pressure over the silo bottom are also exemplified. The pressure values and their non-linear increase, depending on the extent of their depth, can be seen.

Fig. 2 Scheme of the effect of a frictional force on silo wall waves.

1.2 Analysis of friction forces and their action on a corrugated sheet wall

In the case of calculations for thin-wall silos with horizontally placed corrugated sheets, it is necessary to consider the loading with the effective value of the angle of the internal friction, which causes an increase in the value of the frictional forces on the silo wall. Frictional traction n_z with eccentricity $e_x = b/2$ creates an additional bending moment $M_{x,1}$ at the top of a wave (see Figure 2.a).

- Bending moments $M_{x,1}(z)$ around axis-x as a result of an eccentric shear force $n(z)$:

$$M_{x,1}(z) = n_z(z) \cdot \frac{b_t}{2} \quad (6)$$

In places where $e_x=0$ is the value of the bending moment $M_{x,1}=0$, the value of force n_z is divided into a horizontal compound n_h and a vertical compound n_{zv} .

- Horizontal compound (to axis y) from the shear force in the diagonal part of a wave $n_z(z)$:

$$n_h(z) = n_z(z) \cdot \sin(\alpha) \quad (7)$$

- Vertical compound (to axis z) from the shear force in the diagonal part of a wave $n_z(z)$:

$$n_{zv}(z) = n_z(z) \cdot \cos(\alpha) \quad (8)$$

Further, additional bending moments occur even when considering the sheet thickness around axis y – see Figure 2.b.

- Bending moment $M_{y,1}(z)$ around axis y as a result of the shear force action $n_z(z)$:

$$M_{y,1}(z) = n_z(z) \cdot \frac{t}{2} \quad (9)$$

where

- t is the thickness of the wall wave.

- Bending moment $M_{y,2}(z)$ around axis y as a result of the shear force action $n_z(z)$ in the diagonal part of a wave:

$$M_{y,2}(z) = n_{zv}(z) \cdot \frac{t}{2} \quad (10)$$

According to STN EN 1991-4, the intensity of a friction force as well as the intensity of the horizontal force affecting the silo walls can be defined in each depth level of a silo. The intensity of a circumferential stress σ_y is defined as follows:

- when $e_x = b/2$

$$\sigma_y = \frac{n_y}{t} \quad (11)$$

- when $e_x = 0$

$$\sigma_y = \frac{n_y}{t} + \frac{n_h(z)}{A_v} \quad (12)$$

where

- n_y is the circumferential force from horizontal loading;
- A_v surface of a wave, where the wave dimensions are not greater than $15t$, counting the full wave surface;
- σ_v circumferential stress;

Consequently, the meridional stress σ_z when $e_x=0$ and $e_x=b/2$ can be expressed as follows:

- when $e_x = b/2$

$$\sigma_z = \frac{n_z(z)}{A_t} + \frac{M_{x,1}}{W_y} + \frac{M_{y,1}}{W_y} \quad (13)$$

- when $e_x = 0$

$$\sigma_z = \frac{n_{zv}(z)}{A_t} + \frac{M_{y,2}}{W_y} \quad (14)$$

where

- A_t surface, where a wall's thickness is multiplied by a unit of length of a silo perimeter;
- W_y wave intersection model;
- σ_z meridional stress.

The effect of the resulting equivalent stress from a circumferential stress, a meridian stress and a shear stress in any depth level of a silo can be expressed by the von Mises formula:

$$\sigma_E = \sqrt{(\sigma_y^2 - \sigma_y \cdot \sigma_z + \sigma_z^2 + 3 \cdot \tau_{yz}^2)} \quad (15)$$

where

- τ_{yz} shear stress due to membrane-bending hypothesis $\tau_{yz}=0$ (Martens, 1988), (STN EN 1993-1-6, 2007), (Schulze, 2006), (Rotter, 2008), (Rotter, 2011).

2. THEORETICAL MATHEMATICAL MODEL OF A SILO

The experimental measurements were realized on grain silos in Bojničky, Slovakia. Therefore, an adequate mathematical-physical model of a silo in Bojničky was created. The theoretical calculations were developed by the Scia Engineer 2011.1 computational software.

Scia Engineer 2011.1 is a user-friendly 3D modeling solution for the analysis and design of steel, timber and reinforced concrete buildings, slab, rafts and other elements. It is based on a powerful Finite Elements Engine.

The silo consists of a circular ground plan with a 16.69 meter diameter. The height of the silo is 12.0 meters up to the roof base. The silo wall was modeled with a membrane element (Shell 89) – a corrugated sheet with a wave height of 70mm and a width of 16mm. For

Fig. 3 Static diagram and wave diagram.

the analysis linear elastic shell analysis (LA) was used. The shape of the wave was created by 13 points, which were allied by a straight line. The silo was designed to be made of S355 material. The loading force on the silo was calculated in compliance with STN EN 1994-1. Colza seeds were considered as the content. The values of the stored material's properties were taken from the German standards DIN 1055 Teil 6, where $\rho = 700 \text{ kg/m}^3$, $\mu = 0.55$ and $\varphi = 30^\circ$. A joined anchoring of the silo was considered (DIN 1055 Teil 6, 1987) (DIN 18914, 1990).

Graphs 1.a and 1.b show the values of an equivalent stress in the silo wall. Graph 1.a shows the values recorded during fulfillment in four stages: stored material up to 0.8 m, 4.0 m, 9.5 m and 12.0 m, which is the maximum storage capacity of the subject silo. The great differences in the values of the stress are caused by changes in the thickness of the wall sheet. The greatest stress was measured in the lowest row, where in certain positions the peaks of the values increased over 400 MPa, which is the material's plastic limit. Graph 1.b shows the results of the stress values according to the calculation procedure listed in article 1.2. The values of an equivalent stress are calculated on the peaks of the waves and on the walls of the waves. The stress values are taken from the characteristic load values. Following the graph it is clear that the stress values from the manual calculations are smaller in the higher parts than the values achieved by the computational software. The maximum values from the manual calculation exceed 300 MPa. Approximately 3 meters above the anchorage, where tensometers had also been installed, the start of the calculation results align and develop in a similar way down to the anchorage. Consequentially, the manual calculations can be used as a preliminary projection for the maximum stress calculations in the silo.

The subject structure was verified for an ultimate limit state of load-carrying capacity in three different load combinations. The loads were multiplied by a partial factor of reliability. Dead weight loadings, wind loading and the bulk material loading at the maximum storage capacity were summed up for the first combination. Within the frame of the second load combination, an empty silo and wind loading was considered. The third load combination included the dead weight loading, the bulk material loading, and the effect of the temperature. Graphs 2 and 3 introduce an equivalent stress of various load combinations. The greatest tension values are around 600 MPa in the middle part of the silo. In this part, the maximum load-carrying capacity utilizations of the corrugated sheets are reached and even exceed the designed strength of the silo walls. The second combination shows that the maximum stress values reached values of up to around 150 MPa, which occur in the upper part of the structure. It is obvious that the wind loading design is not determinative for this type of silo. The third combination introduces increasing stress values compared to the first load combination. This is caused by the effect of the temperature. In the final calculations for each of the three different types of loads, the same thickness of silo walls was used as the silos in Bojničky. We also took into consideration the partial factor of reliability, which was not taken into account during the experimental measurements; therefore, the maximum equivalent stress was 600 MPa. The high stress values were caused by the effect of the bending moments from the eccentric action of the friction. This construction was highly under-dimensioned, even under the same initial conditions (Moran, 2002), (STN EN 1993-1-3, 2010), (STN EN 1993-4-1, 2007).

Graph 1.a Equivalent stress σ_{E+} .

Graph 1.b Equivalent stress σ_{E-} - manual calculation.

Graph 2 Equivalent stress values for combinations Nos. 1 and 2.

Graph 3 Equivalent stress values for combination No.3.

3. EXPERIMENTAL MEASUREMENTS

The calculations listed above have been verified by experimental measurements. The grain silos in Bojničky were chosen as appropriate structures to apply the mentioned measurements. The subject silos are filled once a year with colza seeds, which are stored throughout the year. The experimental measurements lasted for one year, i.e., from the first fulfillment till the whole emptying. The basic dimensions of the silo are as follows: width 16.69 m and the cylinder height 12.0 m. The silos are made of corrugated sheets of variable thicknesses. The thicknesses vary from 1.6 mm to 4 mm. The roof construction is also made of corrugated sheet of an approximately 1.5 mm thickness. The structure is equipped with neither lateral nor vertical reinforcements.

3.1 The measurement results

The measurements were made on one of the mentioned silos in Bojničky, where foil tensometers were installed. The measuring devices were installed in three places on the silo and were located approximately 6 meters from each other. They cast about $\frac{1}{4}$ of the silo perimeter (see Figure 5). The tensometers were located approximately 2.5 meters high, where the maximum stress values were assumed to occur. The measuring devices were only protected from moisture. The silo's fulfillment took place at the beginning of July 2011.

Type of wave

Fig. 4 The roof construction and wave diagram.

Fig. 5 Ground plan of the silos- the silo used and the location of the measuring device are marked.

Fig. 6 The scheme of the location of the tensometers.

Graph 4 Stress values recorded at point No.1.

Graph 5 Stress values recorded at point No.2.

The filling lasted for five days. The measurements were performed at various height levels of the stored colza seeds: 0 m, 0.8 m, 4 m, 9.5 m and the maximum storage capacity – 12.0 m. Eventually, eighteen measurements were made. In Figure 6, the position of certain tensometers can be seen. Two tensometers were placed vertically on the wall of a wave, and the other two were located vertically on the wave peaks.

The individual measurements are introduced in the following charts. The graphs for each measurement point are introduced separately, and the stress values on the walls and peaks of the wave in MPa are shown.

Graph No.4 shows stress values from measuring point 1. These are stress values captured from the peak and from the wall of the wave. Figure No. 6 has two measuring points marked: 1 and 4.

Graph 6 Stress values recorded at point No.3.

Graphs Nos. 5 and 6 show stress values from the measuring points 2 and 3. The values vary up to the eighth measurement, which was leveled up afterwards due to stable climate temperatures.

The first two measurements were made at the 0 m height; the third was at 0.8 m; the fourth at 4 m; the fifth at 9 m, and the sixth was made when the silo was full – 12 m. All the measurements were made during the day. The following chart captures the temperature values measured on the silo wall's surface during the silo's filling.

The values received from the tensometers show a difference between the emplacements. The values from the tensometer placed on

the wall of the wave are more stable than the values from the tensometers situated on the peak of the wave, which vary.

3.2 Comparison of the experimental measurements with the theoretical models

The following charts introduce a comparison of the values gained by the measurements with the values from the mathematical models. Graph 8 introduces a comparison of the stress values on the wave walls. Each measuring point has two curves, which represent

Graph 7 The course of the temperature on the surface structure.

Graph 8 Comparison of the measured values with the results of the calculations – wall of the wave.

the values from an upper part of the wave wall and a lower part of the wave. These location points are marked with numbers 1 and 4 in Figure 6. The tensometers were installed vertically.

The continuous thick curve, which is figured in the graphs, represents the values of a meridional stress calculated by the Scia Engineer 2011.1 software in MPa. The stress values are calculated from the characteristic load values. The loads were also considered from the bulk material and the difference in the temperature range of 25°C in the calculations.

The meridional stress values calculated manually by the procedure specified in section 1.2 are marked with a thick dotted line. The thin curves represent the values gained from the measurements. The equivalent stress values calculated on the wall of the wave, where the eccentricity is zero, were gained by manual calculations that are marked with a thin line. The equivalent stress values calculated by the software are marked with a thin dotted line.

The values of the meridional stress calculated by the software are similar to the values gained from the measurements. On the contrary, the values from the manual calculations are lower in this case. The differences in the meridional stress values between the manual calculations and the software are that in the manual calculations (on the silo walls), we only considered the vertical part of the horizontal force. In reality, there are also stresses from eccentric frictional forces and bending moments. The differences between the calculated values and the values from the experimental measurements are caused by the actual position of the tensometers. They are never mounted in an ideal way – horizontally or vertically; they always

carry some values from the other direction. From the results, it is obvious that the calculated equivalent stress values are similar to the values gained from the measurements.

Graph 9 introduces a comparison of the equivalent stresses measured in the wave peaks. The continuous thick curve figured in the graphs represents the values of the circumferential stress calculated by the Scia Engineer 2011.1 software in MPa. The thick dotted line refers to the circumferential stress values calculated manually. The values gained by the measurements are represented by thin lines. At each measurement point, a tensometer was placed on both the outside and the inside peaks of the wave. These tensometers were installed horizontally. These places are marked Nos. 2 and 3 in Figure 6. The equivalent stress values from the peak of the wall of the wave, achieved by manual calculations, are marked with the thin line. The equivalent stress values from the software calculations are marked with a dotted line. In this case, both the manual and software calculations show lower values than the values gained by the measurements.

The difference in the circumferential stress results between the manual calculations and the software is that the software calculations on the wave peak also create the horizontal parts of friction traction, which cause the mentioned difference. On the other hand, the equivalent stress values become more similar to the values gained from the measurements.

As a result, the graphs show that the measured values on the silos in Bojničky are sufficiently close to the software calculations.

Graph 9 Comparison of the measured values with the results of the calculations – Peak of the wave.

The expected stress values were achieved by the tensometers. These stress values correspond with the actual values that may occur in the structure from various combinations. The equivalent stress needs to be put into consideration when comparing the values from the experimental measurements and the values from the calculations. If so, the measured values are sufficiently equivalent with the values calculated from the software.

The wave wall values gained by the manual calculations are sufficiently close and did not confirm the load-carrying capacity. The stress values calculated by the software were mostly on the safe side and were sufficiently close to the values gained by the measurements. The stress values from the 6th to the 14th measurements are adequate for the calculated stress values. The climate conditions during this period were stable, and the tensometers gave the stable stress values. After the 14th measurement, the stress values started to cross the calculated values due to the changing climate. This could be caused by the increased moisture in the installed tensometer, so the measured stress values started to vary.

4. CONCLUSION

This study focuses on the design of thin-walled cylindrical shell structures made of corrugated sheets and the problems that can emerge. The theoretical analysis procedure determined a procedure for calculating the equivalent stress forces in the silo walls made of

thin-wall corrugated sheets. The computational procedure allows for the calculation of the resulting equivalent stress by its own weight, the load from the bulk materials, and the temperature. It is possible to calculate the stress at any height of the silo by the use of this computational procedure. In the mathematical and physical models, the effects on the structure from various load types were examined. The dimensions of the modeled silos were the same as the dimensions of the Bojničky silos, so the results from the FEM can be compared with the measurement experiment. The width of a wave affects the value of the bending moments, which result from an eccentric friction force. Therefore, the bending moments affect the resulting equivalent stress on a bigger scale. The silo was verified by considering various load combinations, which proved the fact that this silo is under-dimensioned under these specific boundary conditions. The experimental measurements confirmed the correctness of the computational models and procedures. Foil tensometers were installed on the walls and peaks of the waves. The stress values and deformations caused by the bulk material and the effect of the temperature were recorded. These results were compared with the results from the computer model. The expected stress values were given by the tensometers. These stress values correspond with the actual values that may occur in a structure from various load combinations. The experimental measurements proved that the mathematical and physical models applied sufficiently describe the actual action in a silo structure. The temperature caused a great amount of dispersion in the measured values, thus influencing the accuracy of the measured values the most.

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