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Experimental Verification of Stress State in Selected Steel Load-Bearing Elements of Silo

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Abstract. When evaluating the service life of already operated silos, information about the history of the current load is needed. Although we have sufficient information about the history of the operating load, with unforeseen stresses, its impact on future operational safety needs to be evaluated. Such a case is the assessment of silo S1 in the immediate vicinity of which the adjacent silo S2 collapsed. Although the structure of silo S1 did not show any signs of damage at first sight, the operator decided to assess its future operational safety and reliability through the analysis of experimental measurements. This paper describes strain gauge measurements in selected areas. The aim was to compare measured values with results of numerical modelling and to draw conclusions about future operational safety of the silo based on such comparison.

Introduction

Among other vessels, steel tanks or silos are used to store liquids, gases or bulk materials. Their shells are formed by thin sheets reinforced with vertical steel reinforcing elements [1,2]. The total breakdown of steel structures is preceded by the occurrence of local plastic deformation, which causes the loss of stability of the entire object. Published analyses of possible causes of breakdowns document that such deformation often occurs not only due to incorrect operation but also due to incorrect construction [3,4,5]. In rare cases, local plastic deformation allows further operation without the need for major structural repair [6]. However, there are many cases where, due to overloading, the occurring local deformation subsequently caused a global loss of stability of the entire structure. An example hereof is the collapse of the supporting roof structure of a hot water storage tank due to underpressure, Fig. 1 [7]. In this case, a structural modification was necessary to ensure its future operational safety. The last and most critical situation occurs when a load-bearing structure breaks down completely. Such situation often occurs with silos, Fig. 2. Silos are used in agriculture to store grain or fermented feed known as silage. The load is caused by the weight of the stored material. When designing silos, several design situations are considered [8,9]. In addition to loads in the state of complete filling, the following limit states are also evaluated:

- maximum normal stress on the vertical wall of the silo,
- maximum friction thrust (traction) on the vertical wall,
- maximum vertical pressure on the bottom of the silo,
- maximum load of the discharge hopper.

a)  b) 

Fig. 1: a) View of storage tanks, b) collapsed roof of the storage tank

a)  b) 

Fig. 2: Steel silos a) without failure, b) collapse of a silo for the storage of approximately 120 t of wheat

The paper presents the procedure of experimental measurement on steel supporting structure of the silo S1 (Fig. 3a) located near the collapsed silo S2 (Fig. 3b). As presented in Fig. 3b, the collapse of silo S2 also caused the breakdown of the adjacent silo S3. Although the structure of silo S1 did not show any signs of damage at first sight, the operator decided to assess safety and reliability of its future operation through the outputs of the analysis of experimental measurements. The circumferential walls of the silo are made of steel profiled sheets, the corrugated profiles of which run in the horizontal direction. The structure is reinforced around the perimeter with vertical stiffening profiles. The stiffeners are evenly distributed around the circumference of the silo along the entire height of the cylindrical part.

Basic dimensions:

- diameter: 32.08 m,
- total high: 32.00 m (cylindrical part 22.88 m, conical roof 9.12 m),
- volume 20 924 m^3.

The measurement was done under operational load in order to validate the results of numerical modelling performed by the facility operator. The aim of the first stage was to evaluate the impact of temperature changes on the steel structure of the empty silo during one day. In the second stage, the stress inside the steel shell of the silo was monitored as the silo was gradually filled until its subsequent complete emptying.

a) 

b) 

Fig. 3: View of the analysed silo S1, a) before breakdown, b) after breakdown

Strain measurement and determination of the size of stress components

The resistance strain gauge method was chosen for the experimental stress analysis, while in application areas of strain gauges' solo devices 1-LY11-6/120, k = 2.05 were used, also regarding technical possibilities of their application. The strain gauges were applied in places with assumed maximum exploitation of the cross-section near the lower part in the "second field" at a height of approx. 1.7 m using a concrete support. The "first field" above the concrete support was excluded because of possible local influences due to placement, i.e. due to uneven expansion causing possible uneven distribution of forces and measurement distortion or uneven stress distribution in monitored elements. The areas of strain gauge application were located on the south and the north side of the steel structure (opposite each other). Fig. 4a shows a location diagram of strain gauges. For experimental determination of strain components by means of the strain gauge method in locations of strain gauges, the gauges were connected to half-bridges, while the active branch was formed by a strain gauge applied to the silo structure. The compensation gauge connected in the second branch of the bridge was applied to a steel plate fixed at the measuring point. Fig. 4b shows the orientation of active grids of strain gauges.

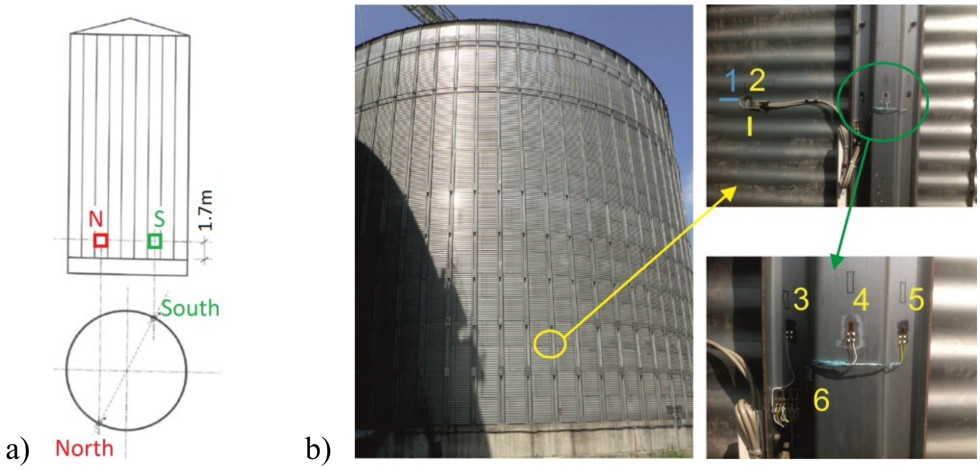


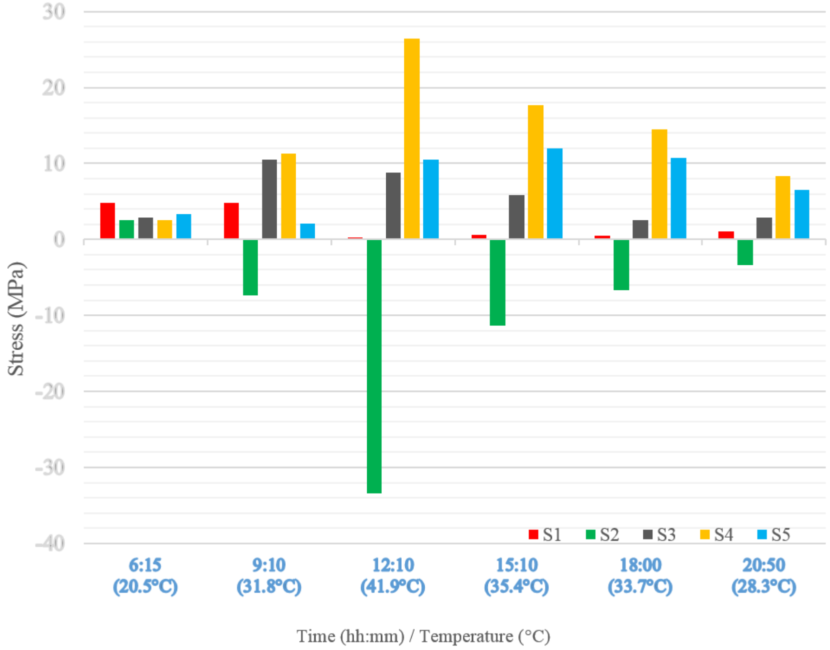
Fig. 4: a) Location diagram of strain gauges, b) orientation of grids

Fig. 4b shows a detailed view of the applied strain gauges on a corrugated sheet (areas 1 and 2) and on a stand (areas 3 to 5). In addition to the mentioned strain gauges, a temperature sensor type FNA611L0100 was used in the vicinity of strain gauges.

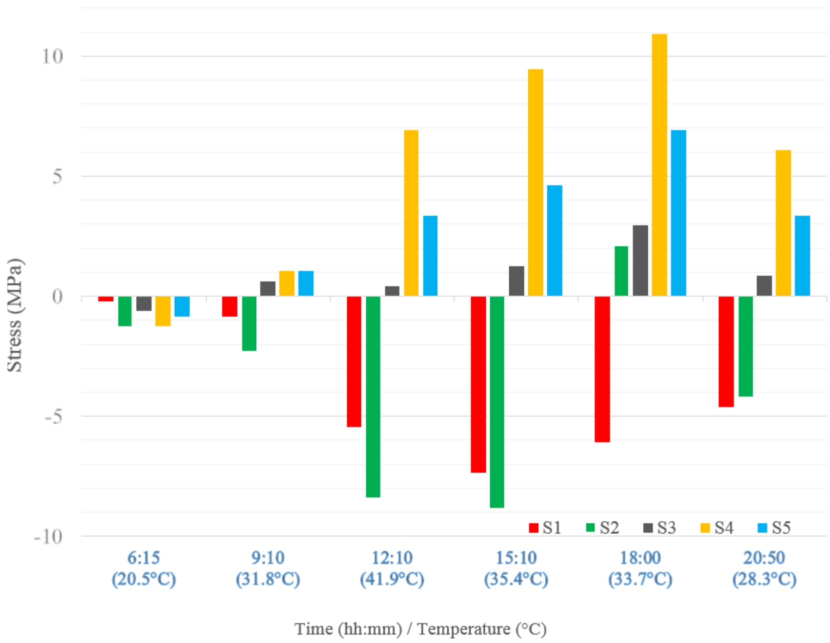
The application of strain gauges to an already existing empty structure allows us to measure strain increments under operating load after connecting the strain gauges to the measuring apparatus. Calibration of the used measuring chain was performed before and after the strain gauge measurement. Strain gauge measurements provided us with strain values at locations of applied strain gauges during filling or discharging of the silo according to operator's instructions. The proposed methodology assumed that the regulation of operating parameters is sufficiently accurate, and data provided by the operator are relevant to actual values. From strain values measured by strain gauges, stress increments since the change of load caused by internal pressure as well as stress increments due to temperature changes were determined using constitutive equations.

As already mentioned, the measurement was divided into two stages. The focus of the first stage was to determine the effect of temperature changes on the steel structure of the empty silo within one summer day with intense sunlight. The measurement started at 3:25 o'clock. when all strain gages were balanced. The recording of values during the day was at about 3 hours' intervals.

An overview of the values of recalculated stresses is given in Graph 1 and 2. The given values imply that during that day both tensile and compressive stresses were recorded. The maximum values were measured on the south side at noon, as expected.



Graph 1: Stress values depending on the influence of ambient temperature within one day – south side



Graph 2: Stress values depending on the influence of ambient temperature during one day – north side

The aim of the second stage was to monitor and then assess stress inside the steel shell of the silo as the silo was gradually filled until its subsequent complete discharge during normal operation. It was a long-term measurement. The first measurement was performed on November 12 and the last on August 31 of the following year. The values of strains were not registered permanently but only in 7 characteristic stages. An overview of the values of recalculated stresses is given in Tables 3 and Table 4.

Table 3: Stress values during filling and discharging of the silo – south side

Date / time	Mass [t]	Measurement area S-I [MPa]	S-II [MPa]	S-III [MPa]	S-IV [MPa]	S-V [MPa]	S-VI [°C]
12.11. / 10:35	7099	52.08	-58.17	7.98	31.50	-0.42	30.18
14.11. / 14:15	10800	73.08	-47.04	6.51	38.01	3.36	16.32
27.11. / 14:05	12164	57.33	-54.81	-6.51	26.04	-15.54	6.84
29.12. / 12:35	15574	119.91	-78.75	-25.41	19.74	-38.01	2.77
21.07. / 15:35	12050	73.92	-73.92	-9.87	45.15	-16.17	36.40
05.08. / 11:55	9055	67.83	-45.99	6.93	49.77	-13.44	38.40
31.08. / 08:15	0	18.7	-2.1	-8.8	-30.2	-29.4	23.84

Table 4: Stress values during filling and discharging of the silo – north side

Date / time	Mass [t]	Measurement area N-I [MPa]	N-II [MPa]	N-III [MPa]	N-IV [MPa]	N-V [MPa]	N-VI [°C]
12.11. / 10:35	7099	58.17	-57.75	2.10	10.71	-10.08	10.80
14.11. / 14:15	10800	74.97	-72.87	-0.63	16.80	-12.81	11.30
27.11. / 14:05	12164	99.96	-98.49	-6.72	17.43	-24.99	4.62
29.12. / 12:35	15574	118.65	-129.99	-18.69	18.69	-39.69	1.72
21.07. / 15:35	12050	125.72	-132.93	-36.33	-30.24	-39.06	31.67
05.08. / 11:55	9055	105.48	-101.22	-18.48	-31.08	-21.21	28.66
31.08. / 08:15	0	27.94	-30.3	-9.7	-17.7	-15.1	14.10

Strain gauges applied in the meridional direction from both sides of the structure enabled the assessment of a possible change in shape (geometry) due to possible eccentricity of the stored material. The correctness of the proposed methodology of experimental measurements was confirmed by different values of stresses corresponding to excessive deformations of the whole structure identified even by the naked eye. The values of compressive normal stresses in vertical direction did not exceed 40 MPa (Table 4). In addition to compressive stresses, tensile stresses due to bending of the structure, which was visible to the naked eye at the time of measurement, were also recorded in the same areas. The maximum values of these tensile stresses in vertical direction did not exceed 50 MPa (Table 3). After complete discharge of the silos, non-zero stress values were recorded in the measurement areas, which is documented by the fact that permanent structural deformations occurred during operating load. The task of the authors was not to draw conclusions on future operational safety of the silo, but to provide the operator with information about stress inside the structure for further analysis performed by the operator. It should be noted that the measuring points as well as stress directions were determined according to operator's requirements.

Conclusions

When assessing service life of steel tanks (silos), information, among other things, about the history of the current load is necessary. Based on verified analyses, it can be stated that the greatest influence on damage accumulation have stress amplitudes which exceed the fatigue limit of the supporting element in the examined area. In this case, in order to evaluate operational safety and reliability of silo S1, an experimental stress investigation was performed in selected areas on both the southern and the northern side of the silo during its filling or discharging. It was a long-term measurement lasting about 1 year in total. Based on the measured strain, stress values were recalculated. Based on the measured data, it can be stated that the limit safety values of the evaluated structure were not exceeded in any of the analysed areas. It should be noted, however, that these were local values which were forwarded to a further analysis of the supporting structure carried out by an operator who subsequently examined the silo and its safety.

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