prof. dr hab. inż. Mieczysław Kamiński[1)]
ORCID: 0000-0002-0639-7534
mgr inż. Marek Drzazga[2)]
dr inż. Michał Drzazga[3)*)]
ORCID: 0000-0002-9989-7123
dr inż. Maciej Kaźmierowski[3)]
ORCID: 0000-0002-8977-4154

Failure of a reinforced concrete silo – reconstruction project using elements of BIM technology

Awaria silosu żelbetowego – projekt przebudowy z wykorzystaniem elementów technologii BIM

DOI: 10.15199/33.2022.07.

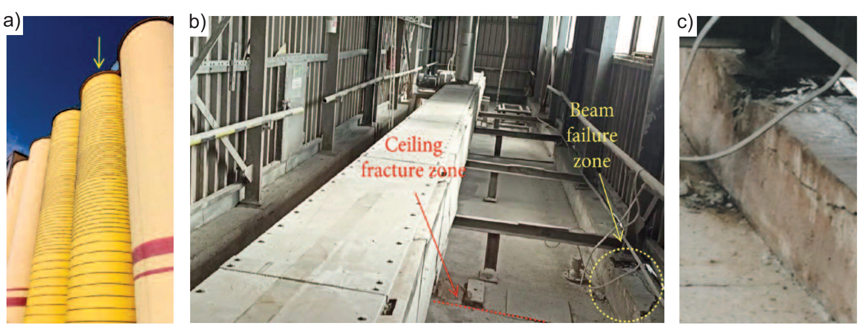
Streszczenie. W artykule opisano awarię żelbetowego stropu silosu na śrutę rzepakową. Omówiono przyczyny oraz zakres uszkodzeń. Na podstawie rozwiązań technologii BIM (ang. *Building Information Modelling*) przedstawiono główne elementy projektu przebudowy konstrukcji silosu obejmujące demontaż uszkodzonej części oraz wykonanie nowej.
Słowa kluczowe: awaria; silos; BIM; projekt.

Abstract. The article describes a case study of a failure of reinforced concrete ceiling of a rapeseed meal silo. The causes and extent of damage are discussed. On the basis of BIM technology (*Building Information Modelling*) the main elements of the project of reconstruction of silo's structure are presented, including disassembly of the damaged part and making a new one.
Keywords: accident; silos; BIM; project.

The BIM (*Building Information Modelling*) technology enables the creation of complex, n-dimensional models described by the parameters related to the planning, design, construction, and use of building objects [1]. This also applies to projects that involve the reconstruction of industrial objects that have suffered from failures. Silos are significantly more prone to failures than other industrial objects [2]. This is strongly connected to the influence of the stored material on the structure of the silo both during loading and unloading [3]. The smooth flow of loose material depends, among others, on the occurrence of: the arch effect, overhangs and cavities in the storage chamber and zones where the material is deposited permanently. The main conditions that cause these phenomena include: the properties of the stored material (grain size distribution and moisture content), the period of storage, the geometric properties of the chamber (slenderness, the parameters of the discharge hopper and outlet) and the equipment applied to support the discharge. The paper presents a case study of a failure of the silo ceiling and the application of the BIM technology in designing its reconstruction (the ceiling and the gallery).

Description of the structure

The group of silos was constructed at the beginning of the 1970s. It consists of five monolithic, cylindrical chambers built from reinforced concrete (Photo 1). The 38 m high chambers with hopper bottoms, of an external diameter of 9.2 m and 0.4 m thick walls are filled with use of belt conveyors and designated for storing rapeseed meal. The covering of the chambers is a trough slab ceiling, supported on the bottom T flanges of prefabricated reinforced concrete beams of the cross-section of 45 x 60 cm (web width: 25 cm, flange thickness: 15 cm). The slabs, of a span of 8.45 m, total length of 9.94 m, and spacing of 3.25 m, are made from concrete of the compressive strength of 200 ATM (≈ 20 MPa), reinforced with rods 6 ϕ 18 (stretch zone) and 2 ϕ 14 (compression zone) of a yield strength of 4000 ÷ 4200 ATM (405 ÷ 425 MPa). The ceiling of the silo is loaded with the redler conveyor and the gallery. The structure of the gallery consists of steel frames spaced at 2.2 m in form of columns and channel-section beams. The columns are connected to the beams with gussets. The frames of the gallery, inside the chamber, were braced in one of the four fields and decoupled. The columns of the gallery are supported by the pre-



Silo battery: a) general view with indication of chamber failure; b) ceiling damage; c) crushing of concrete in a beam
Bateria silosów: a) widok ogólny z zaznaczeniem awarii komory; b) uszkodzenia stropu; c) zmiażdżenie betonu w belce

1) Expertus BRB Mieczysław Kamiński
2) KONSTRUKTOR group Sp. z o.o.
3) Wrocław University of Environmental and Life Sciences, Department of Civil Engineering
*) Correspondence address: michal.drzazga@upwr.edu.pl

viously described reinforced concrete beams. The single-pitched roof made from trapezoidal sheet metal is supported on beams spaced at 1.1. m. The shielding walls are also made from trapezoidal sheet metal. Four ventilation stacks were installed in the ceiling. The technological equipment is supported by two steel I-beams, connected by flat bars welded to the top chords.

Description and causes of the failure

During the use of one of the chambers of the silo, a failure of the ceiling structure occurred (Photo 1). The failure involved a crack in the ceiling slab (Photo 1b) and crushing the compression zone of concrete in the span of the beam (Photos 1b and 1c). As a result of significant deformation, the connection between the column of the gallery and the beam was lost. Due to safety reasons, no visual inspection of the beams was conducted on the inside of the chamber, so the extent of damages in the stretch zone of the beams remained unknown.

The direct cause of the failure was the spontaneous collapse of the arch of rapeseed meal, which caused a negative pressure with a vertical force directed towards the bottom of the chamber (in spite of the existing ventilation stacks). As a result of the emerging load, the bearing capacity of the ceiling was exceeded. The arch effect in silos may take the form of either overhang or arches that cause significant negative pressure at the moment of spontaneous or induced detachment [4, 5]. This is caused by the fact that, after the collapse of the arch, the volume of air in the space under the ceiling of the chamber increases to the end value that equals approximately the total volume of the air above and below the arch prior to the collapse. After some time, the emerging negative pressure equalizes with the atmospheric pressure, provided that the ventilation equipment has been designed and functions correctly. The negative pressure in the part of the silo located under the ceiling is the higher, the more the silo is filled and the higher the arch was located above the discharge hopper. A common cause of the emergence of arches is the caking of the loose material as a result of humidity. Even materials with low moisture content may demonstrate arching behaviour, if the material is stored motionless for a sufficiently long time. The time of storage after which the arching processes begin is the shorter, the higher the moisture content in the material. Another factor that influences the rate of the arching behaviour is the consolidation pressure of the stored material. The level of this pressure also influences the degree of cohesion and the internal friction angle [4].

The application of BIM solutions in the reconstruction project

The conducted visual inspection revealed a large scale and extent of damages to the ceiling. Repairing and reinforcing the damaged parts of the structure raised justified doubts in the technical and economic aspect. Hence, it was decided to prepare a design of reconstruction of the ceiling and the gallery. At the first stage, the plan of disassembly of the gallery and the ceiling was developed, followed by the second stage, which was the reconstruction design. The designs were created with the use of BIM solutions that consist in creating 3D models in the Autodesk Revit software. In BIM-supported design, each object is assigned multiple parameters, including material characteristics, geometric properties, and parameters related to the schedule of construction and realisation of the design [1]. Assigning the appropriate scheduling pa-

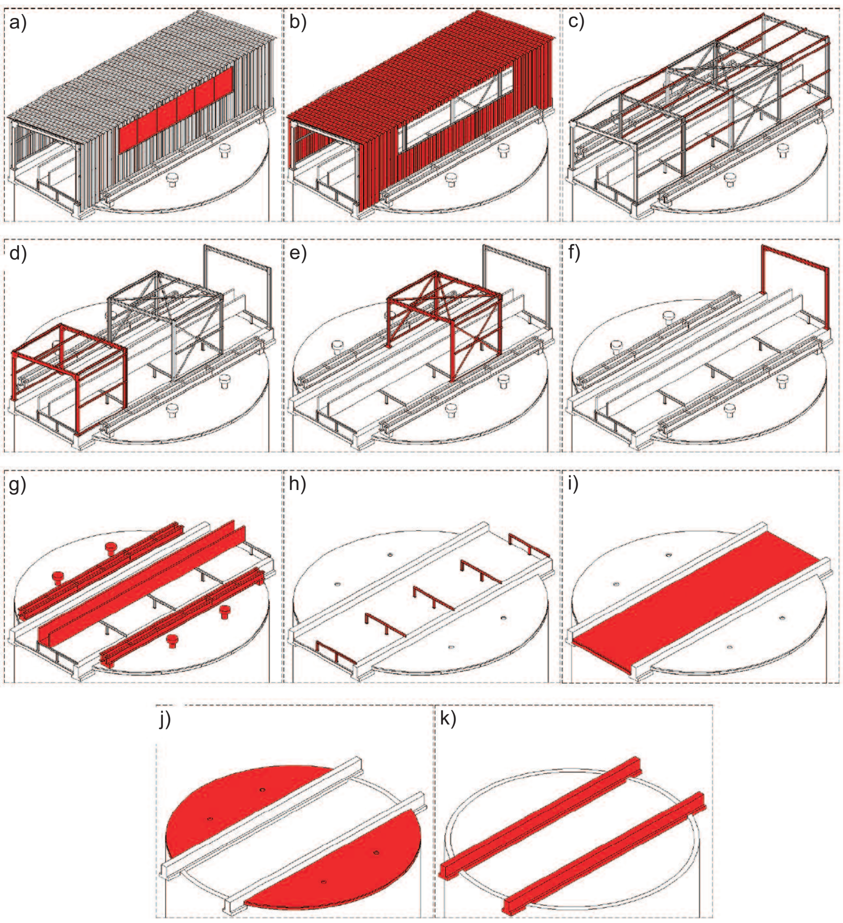


Fig. 1. Gallery and silo ceiling disassembly steps (fill indicates item being disassembled): a) windows; b) trapezoidal sheeting; c) purlins and rafters; d) section 1 (4 columns, 2 rafters, 4 purlins and 6 wall rafters); e) section 2 (4 columns, 2 rafters, 4 purlins, 6 wall rafters, slope bracing and inter-pillar bracing); f) section 3 (2 columns, 1 rafter); g) ventilation equipment, equipment support beams, redler; h) redler substructure; i-j) chamber floor; k) floor beams

Rys. 1. Etapy demontażu galerii i stropu silosu (wypełnienie oznacza demontowany element): a) okna; b) blacha trapezowa; c) płatwie i rygle; d) sekcja 1 (4 słupy, 2 rygle, 4 płatwie i 6 rygli ściennych); e) sekcja 2 (4 słupy, 2 rygle, 4 płatwie, 6 rygli ściennych, stężenie połaciowe oraz międzysłupowe); f) sekcja 3 (2 słupy, 1 rygiel); g) urządzenia odpowietrzające, belki podtrzymujące urządzenia, redler; h) podkonstrukcja redlera; i-j) strop komory; k) belki stropowe rameters in the analysed model enabled us to present the course of actions during demolition works (Figure 1) and during the reconstruction process (Figure 2). The 3D model was also the basis for estimating the weight of specific elements to select the suitable transport equipment.

The newly designed structure of the gallery is built of frames that consist of roof rafters and columns (spaced at 2.44 m). In the plane of the arrangement, a rigid connection was installed between the rafters and the columns and articulated connections between the bases of the columns. The frames were braced in the longitudinal direction with transverse bracing and inter-column bracing. Roof beams (of a span of 3.25 m) and columns made of CE180 and CE140 S235 steel sections in internal and external frames, respectively, were designed (height of the lower column – 2.43 m; and of the higher – 3.00 m). To support the gallery wall and window casing, C65 section wall transoms, with a span equal to the main frame spacing (2.44 m) and a spacing of 1.30 m, were used. The designed roof cladding was made from 1.00 mm thick, three-span T55 trapezoidal sheet metal laid in negative. It was supported by single-span purlins of C65 sections of a span equal to the main frame spacing (2.44 m) and a spacing of 1.10 m.

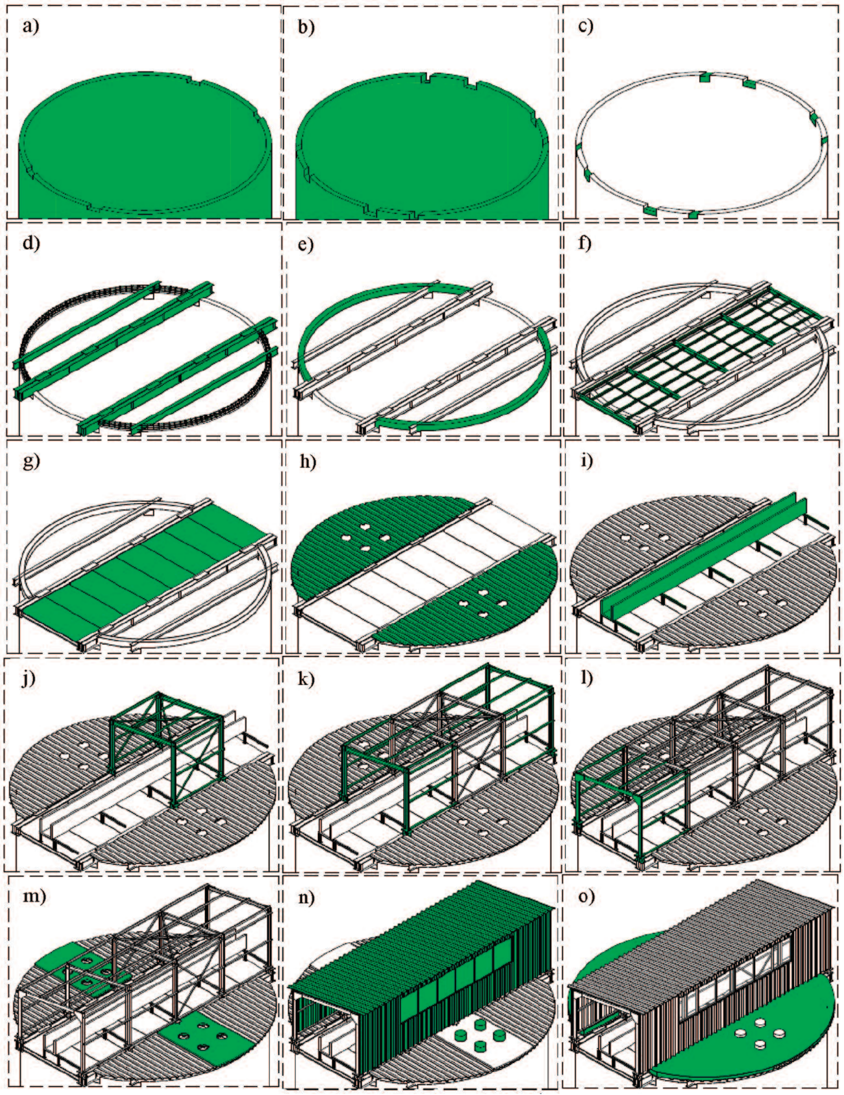


Fig. 2. Stages of execution of the designed structure: a) state after disassembly of the ceiling; b) sockets of ceiling beams; c) epoxy-mineral mortar under steel beams; d) steel ceiling beams; e) rim on silo jacket; f) grate in the gallery area; g) ribbed sheeting in the gallery area; h) trapezoidal sheeting of the ceiling in the area outside the gallery; i) redler with subconstruction; j-l) structure of the gallery – section 1÷4; m) monolithic slab on the trapezoidal sheet; n) housing of the gallery and installation of venting devices on the silo ceiling; o) finishing layers of the silo ceiling

Rys. 2. Etapy wykonania projektowanej konstrukcji: a) stan po demontażu stropu; b) gniazda belek stropowych; c) zaprawa epoksydowo-mineralna pod belki stalowe; d) stalowe belki stropowe; e) wieniec na płaszczu silosu; f) ruszt w obszarze galerii; g) blacha żeberkowa w obszarze galerii; h) blacha trapezowa stropu w obszarze poza galerią; i) redler wraz z podkonstrukcją; j-l) konstrukcja galerii – sekcja 1÷4; m) płyta monolityczna na blasze trapezowej; n) obudowa galerii oraz instalacja urządzeń odpowietrzających na stropie silosu; o) warstwy wykończeniowe stropu silosu

The ceiling structure in the gallery area was designed from steel beams consisting of two I-beams of IPE360 of S235 steel, with a length of 9.8 m and a span at the support axes of 8.4 m. A grid of IPE 180 beams (span 3.25 m, spacing 2.44 m) and IPE 80 beams (span 2.44 m, spacing 0.6 m) was designed on the beams.The external layer of the roof is constructed from 6 mm thick ribbed sheet S235 steel, composed of 1.22 x 3.00 m sheets in a five-span arrangement.

Outside the gallery area, the roof structure was designed in form of a double--span slab of 1 mm thick trapezoidal sheet metal T55, laid in positive. Due to the need to reinforce the trapezoidal sheet metal at the planned ventilation stacks (safety dampers); a 6.5 cm thick reinforced concrete slab (made on trapezoidal sheet) was designed. The reinforced concrete slab made from C25/30 concrete is reinforced with Φ16 rods in folds and with a Φ6 188/188 grid on the top. The indirect support of the trapezoidal sheet metal was designed from IPE270 beams of the span of 6.7 m at the support axes. Figure 2 presents the selected stages of construction of the newly designed structure.

Static and strength calculations were performed with the use of Autodesk Robot Structural Analysis Professional software, with a separated spatial model of the structure. Simultaneously with creating the geometric model in the Autodesk Revit software, an analytical model was created that was exported directly to the Autodesk Robot Structural Analysis Professional calculation software (Figure 3).

Conclusion

The direct cause of the silo failure was the spontaneous collapse of an arch of

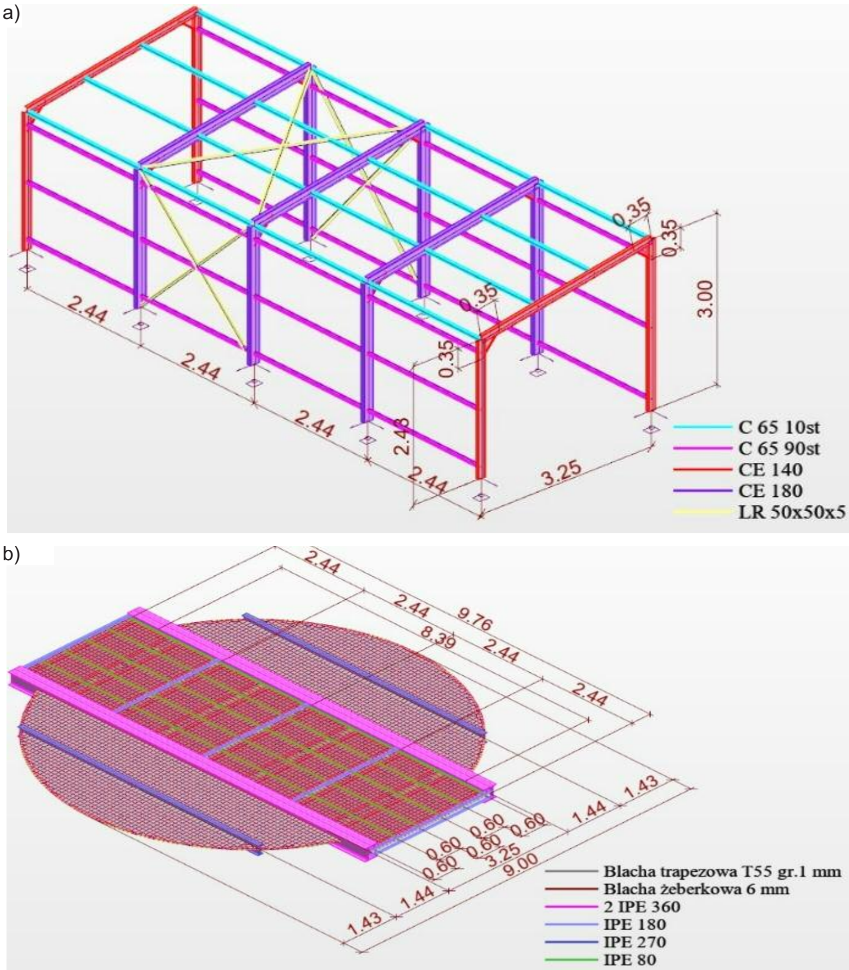


Fig. 3. Calculation models for: a) gallery structure; b) silo floor structure
Rys. 3. Modele obliczeniowe w zakresie: a) konstrukcji galerii; b) konstrukcji stropu silosu

rapeseed meal, which resulted in significant negative pressure. This, in turn, led to an overload and, in consequence, damaged the structural elements of the ceiling of the chamber. The application of BIM technology solutions in the reconstruction process enabled the presentation of the stages of realisation of the construction project, so that the documentation became transparent for all participants of the construction process. Apart from that, any interpretation errors were eliminated. Thanks to the BIM technology, the client was presented with a spatial model of the object, which, if necessary, allows analysing the influence of various modifications on the overall status of the project and the costs. Exporting the 3D geometrical model to calculation software accelerates the creation of the analytical model. As a result, the designing process is shorter, and thus less expensive. The presented design is an example of the application of the BIM technology in the construction process to create a design of disassembly and reconstruction of a structure. The BIM process enables defining and managing information both for newly erected and reconstructed buildings.

Bibliography

[1] Drzazga M. BIM – zapis informacji o przedsięwzięciu budowlanym (projektowanie 5D). Przegląd Bud. 2016; t. 87, 9: 33 – 37.

[2] Carson JW, Holmes T. Silo failures: why do they happen. TASK Q. 2003; t. 7, 4: 499 – 512.

[3] Prusiel JA. Analiza naprężeń termicznych w żelbetowych ścianach silosów na zboże. Mater. Bud. 2015; 9: 55 – 56, doi: 10.15199/33.2015.09.17.

[4] Hotała E. Nośność graniczna nieużebrowanych cylindrycznych płaszczy silosów stalowych. Pr. Nauk. Inst. Budownictwa Politech. Wroc. Monogr. Oficyna Wydawnicza Politech. Wroc. 2003; t. 83, 35: 166 – 166.

[5] Bywalski C, Kamiński M. A case study of the collapse of the over-chamber reinforced concrete ceiling of a meal silo". Eng. Struct. 2019; t. 192: 103 – 112, doi: https://doi.org/10.1016/j.engstruct.2019.04.100.

Przyjęto do druku: 17.06.2022 r.