Floor defects in quarters over railway tunnel caused by design and construction errors

Tomasz Majewski[1,*], *Maciej* Niedostatkiewicz[2], and *Patryk* Ziółkowski[2]

[1]Pracownia Projektowo – Inżynierska Tomasz Majewski, Osiedle Sierakowskich 9B/3, 82-400 Sztum, Poland
[2]Gdansk University of Technology, Faculty of Civil and Environmental Engineering, Department of Concrete Structures, G. Narutowicza 11/12, 80-233 Gdansk, Poland

Abstract. The main subject of this paper is a floor in the quarters located above the railway tunnel in the large-area Shopping Center. The considered floor did not meet the satisfactory safety conditions, as a result of design and construction errors, which were a direct cause of the failure. In the long term, failure could lead to a construction disaster.

1 Introduction

The considered multifunctional urban complex is located in the northern part of the country. It consists of the following facilities: a tunnel over the railway track, a multi-station and multi-level car garage, a shopping centre, service and commercial building, a cinema and accompanying buildings. The subject of this paper is the floor in the rooms located above the railway tunnel in the large-area Shopping Center. As a result of design and execution errors, the floor did not meet the conditions of construction safety. The errors made were the cause of construction failure, and in the future could lead to a disaster.

During the construction of the building, the Investor raised concerns that construction works related to making the floor in the tenants' rooms are not carried out by the tender documentation [1] and the quality of the performed works is insufficient. Therefore, it was necessary to check the technical condition of floors and flooring in the entire centre building. One of the objectives was to answer the question whether the floor over the railway tunnel was made following the design documentation, applicable regulations [2-4] and technical knowledge [5-12] and whether the current technical and safety conditions are met. As part of the conducted tests, inspection holes were made, samples of embedded materials for strength tests were taken [5-9], static and strength calculations were made, analysis of the results obtained and analysis of the condition of the existing floor was carried out. On this basis, conclusions and recommendations were formulated, assuming that after their implementation it will be possible to continue the safe operation of commercial premises by their users (tenants of commercial premises).

* Corresponding author: ppi.tomimaj@gmail.com.pl

The following names and definitions have been defined for the studies carried out [12, 13]:

- **Floor** - a system of layers made on the roof above railway tracks, including thermal and hydro insulation, underlay, flooring,
- **Flooring** - the top finishing layer with stoneware tiles,
- **Base (primer) -** a layer of cement screed on which the floor was made, laid on a layer of polystyrene.

2 The analysis of outcorps and materials

In the course of local visions on the site, excavations were made to check the layout of the floor layers and samples of embedded materials for strength tests were taken. A layer system designed on the roof above the tunnel is shown in Fig. 1. The pits were made at randomly selected locations whose location was agreed with the tenants of the premises. In the outcrops, there was a different arrangement of individual finishing layers (between the rooms of tenants and public corridors), as well as the different thickness of individual layers. The substructure under the floor was made of cement screed with meagre strength. Screed did not meet the requirements of class C8/10 according to the recommendations of the standard [6]. Its average bulk density was 1871 kg/m^3, and maximum water absorption was 13.0%. The screed samples taken for testing did not contain reinforcement bars, diffused reinforcement in the form of polypropylene fibres (non-structural, fibres against plastic shrinkage) was used. In the room of tenants, underneath the base layer, expandable polystyrene (EPS) was built, the compression strength of which at 10% strain was 68 kPa. In the corridors (locally under the ramps), a grey extruded polystyrene (XPS) variety of 200 kPa was built-in. Between the individual layers of the floor insulation of black construction foil (PE), 0.2 mm thick was used. The foil was laid in one or two layers. Fig. 1 and 2 shows the layout of finishing layers [1].

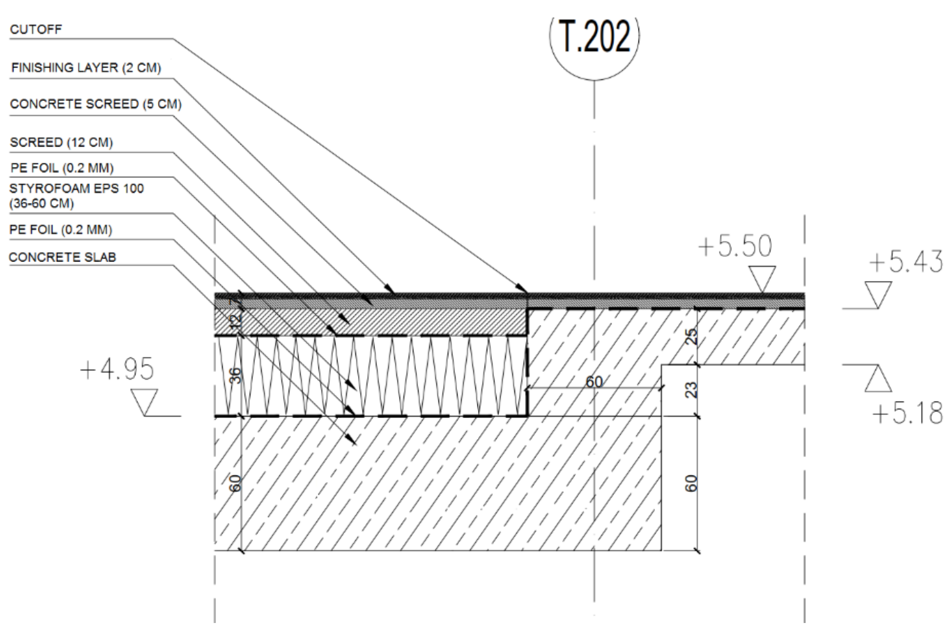


Fig. 1. The designed layout of the floor finishing layers above the railway tunnel according to [1].

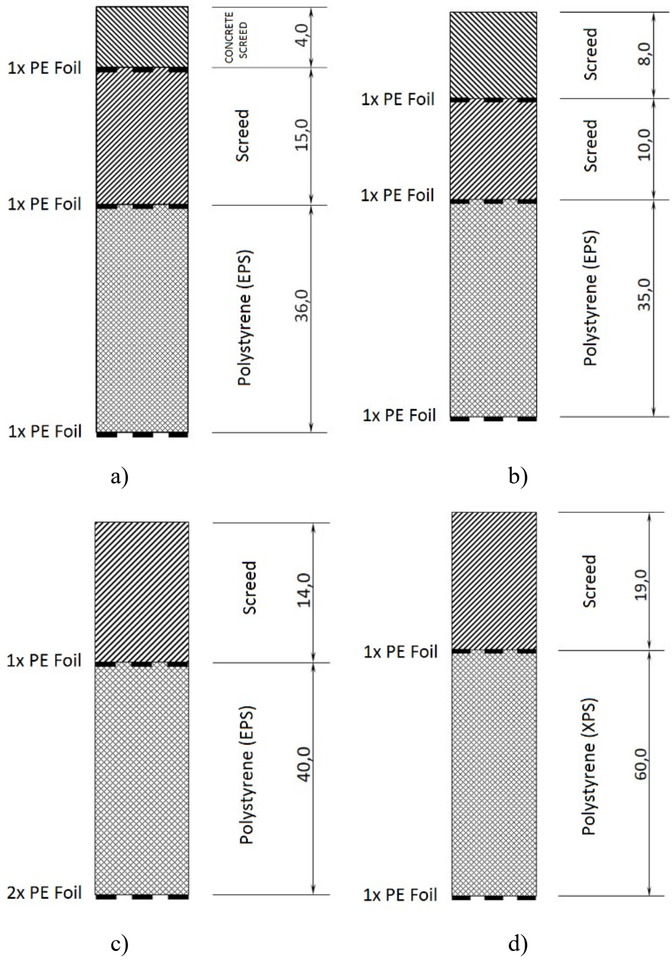


Fig. 2. The layout of the floor layers above the railway tunnel in randomly selected places: a), b) in the rooms of tenants and c), d) in generally open corridors (the drawings do not indicate the construction of the floor slab).

3 Design requirements

The available project documentation [1] included items, such as the values of point and evenly distributed loads for which the floor was designed, as well as detailed implementation requirements for the performance and acceptance of all works related to the preparation. Execution and maintenance of individual layers, in particular, the technology of conducting works as well as some acceptance requirements indicated, including the scope of partial (between different stages) loads. Detailed requirements regarding the load values for floors in public utility buildings are contained in standards and regulations [2-11], and technical requirements in different ones [11-13]. Due to the editorial limitations of the paper, these requirements have not been discussed in detail. Unfortunately, the contractor during the construction of the floor did not follow the given guidelines, and the considered floor, due to insufficient strength of the screed, did not meet the requirements of the relevant regulations [2, 3, 12].

4 Checking calculations

Due to the inadequate strength of the screed (C8/10), the checking calculations of the floor for the actual material parameters determined from the samples taken from the outcrops was performed, i.e., for the actual screed class and the strength of the expanded polystyrene. The other essential concrete parameters were calculated under the recommendations of the standard [10], the commonly used Finite Element Method (FEM) was also used for calculations. The stiffness of the substrate on which the screed layer was made was calculated using the OSZD and Westergard-Eisenmann method described in detail in [13-16]. The main material parameters adopted for calculations are presented in Table 1.

Table 1. Material parameters used for calculation.

	Concrete Screed	Screed	Expanded polystyrene (EPS)
f_{ck} [MPa]	8,53	5,44	-
$f_{ctm,flex}$ [MPa]	2,23	0,93	-
E [MPa]	25520	23983	610
ρ [kg/m^3]	1856	1871	16,6
$\sigma_{10\%}$ [kPa]	-	-	61

Substrate susceptibility:

- Concrete screed no 5,5 cm k_1=25520/0,055=464000 kN/m^3
- Screed nop 12,5 cm k_2=23983/0,125=191864 kN/m^3
- Expanded polystyrene (EPS) k_3=610/0,36=1694 kN/m^3

$$k_s = \frac{1}{\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}} = \frac{1}{\frac{1}{464000}+\frac{1}{191864}+\frac{1}{1673}} = 1694$$

Fixed spring (k_s) accepted for the slab calculations: k_s=1694 kN/m^3.

The paper presents selected results of calculations regarding the part of the floor in the premises of tenants separated by a corridor (due to differences in the layout of the floor, as well as in the type of embedded materials). The corridor was separated from the space by massive masonry partition walls that did not cooperate with the foundation slab. Due to the lack of sufficient information on the performance of expansion joints in the floor and their location in the foundation slab (cement screed with a thickness of 12.5 cm), calculations were made for two extreme cases: unfavorable and favorable according to to the level of the foundation slab material stress (the foundation slab is covered with screed):

Case I - this was the most unfavourable case (bottom envelope) when as a result of shrinkage the plate (undercoat) cracked all its thickness in the places of apparent expansion joints. The calculation model consisted of 12 independent concrete slabs (Fig. 3) based on a Winkler spring substrate with constant stiffness k_s. The dimensions of individual expansion joints were 4.00 × 4.22 m. It was assumed that the neighbouring slabs would not cooperate in transferring loads.

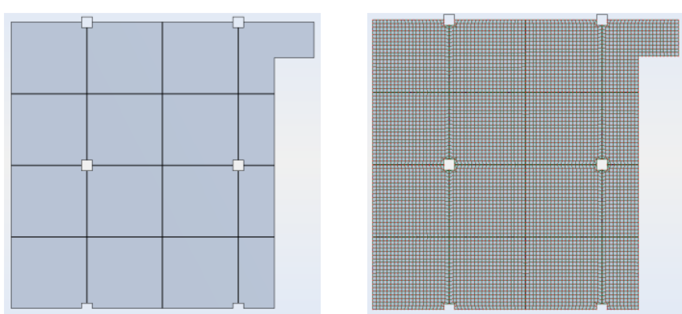
Case II - it was the most advantageous case (upper envelope) when the foundation slab did not completely break in the places of apparent expansion joints. The cooperation of neighbouring expansion fields in transferring loads was assumed. The calculation model consisted of two concrete slabs separated by a brick wall (marked with a red line in Fig. 4), based on a Winkler substrate with a constant stiffness k_s. In the place of the wall, there was an expansion joint, and the neighbouring plates had the freedom of deformation.

The disc was discretised with a grid of flat, four-piece finite elements (plate with constant thickness). There were 6 degrees of freedom defined in each node (three displacements and rotations), the material (screed) was described as a linear elastic material with a constant thickness of 12.5 cm. Four simple load cases were declared (self-weight, the weight of finishing layers, the weight of partition walls and service load) (Fig.5), by which the most unfavourable load combinations in the *Ultimate Limit State (ULS)* and the *Serviceability Limit State (SLS)* were defined. As a result of the calculations, detailed maps of the distribution of stresses on the entire surface and the thickness of the underlying panel for given load combinations were obtained. The sample results in the map are shown in Figs. 6-9:

- Fig. 6 - the map of the principal tensile stresses (σ_1) on the upper surface of the foundation slab for the most unfavourable combination of loads in the *Ultimate Limit State (ULS)* - case I, independent boards,
- Fig. 7 – the map of deformation (subsidence) of the foundation slab for the most unfavourable combination in the *Serviceability Limit State (SLS)* - case I, independent boards,
- Fig 8 - the map of principal tensile stresses (σ_1) on the upper surface of the underlying panel for the most unfavourable combination of loads in the *Ultimate Limit State (ULS)* - case II, cooperating plates,
- Fig. 9 – the map of deformation (subsidence) of the underlay for the most unfavourable combination in the *Serviceability Limit State (SLS)* - case II, cooperating discs.

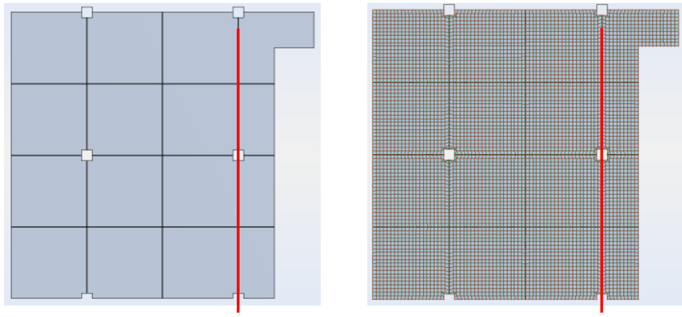
Based on the analysis of the results obtained for case I, it was found that the maximum tensile stress in the screed plate is 0.63 MPa (on the upper surface of the board) and less than 0.93 MPa concrete tensile strength, thus the board fulfilled the conditions of the *Ultimate Limit State (ULS)* capacity [10]. The maximum calculated subsidence of the slab corner was 0.6 cm.

Based on the analysis of the results obtained for Case II, it was found that the maximum tensile stress in the screed plate is 1.13 MPa (on the upper surface of the board) and is 21% higher than the concrete tensile strength equal to 0.93 MPa, thus the slab does not meet conditions of the *Ultimate Limit State (ULS)* [10]. The maximum calculated subsidence in the centre of the slab was 0.7 cm.



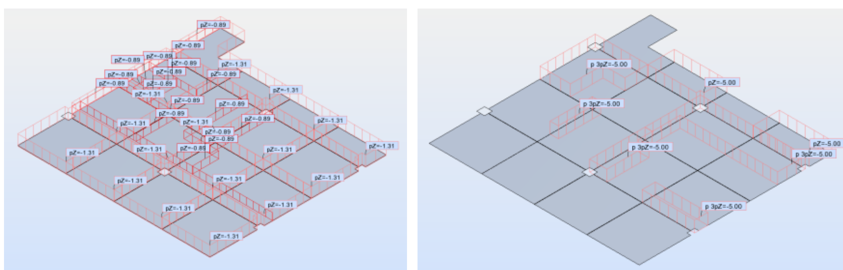
a) b)

Fig. 3. Calculation model (case I - independent plates): a) location of expansion joints, b) division into finite elements.



a) b)

Fig. 4. Calculation model (case II - cooperating plates): a) location of one expansion joint, marked in red, b) division into the finite element.



a) b)

Fig. 5. Examples of load diagrams (characteristic values): a) permanent, b) service load in corridors.

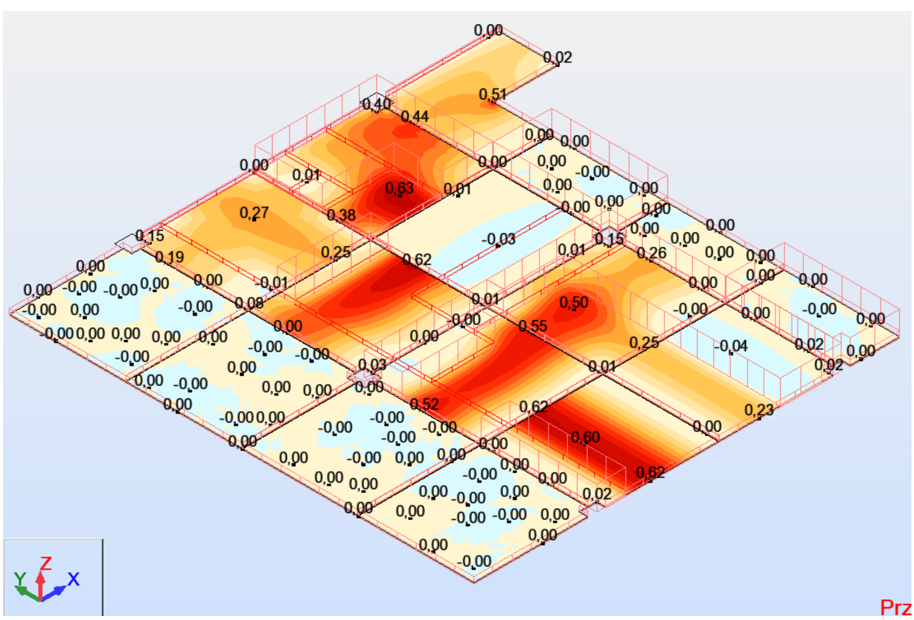


Fig. 6. Principal stresses σ_1 on the upper surface of the underlay for load combinations in the *Ultimate Limit State (ULS)* - case I, independent plates.

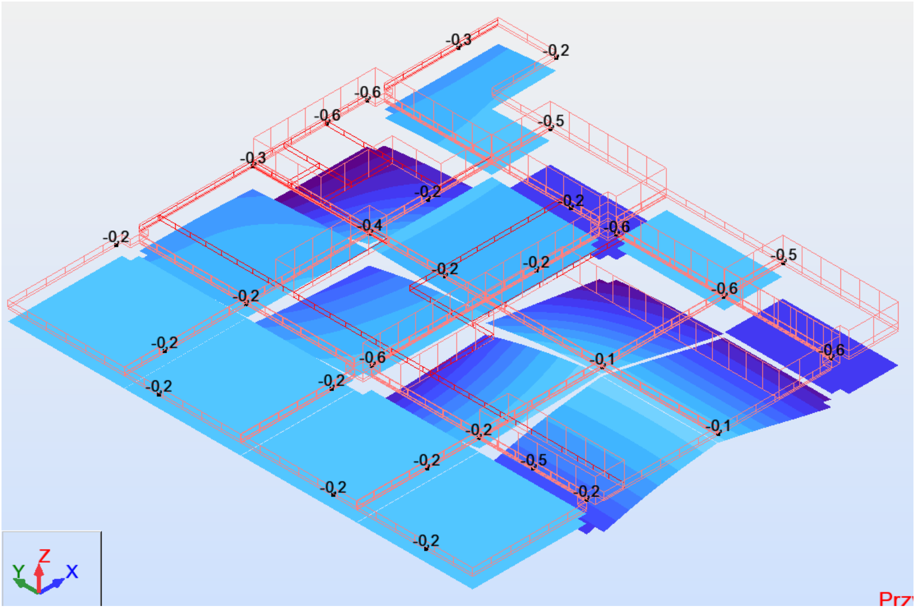


Fig. 7. Deformation of the backing plate for the combination of the *Serviceability Limit State (SLS)* - case I responding to a situation where, as a result of shrinkage, the plate (undercoat) has cracked over its entire thickness in the places of expansion joints (apparent).

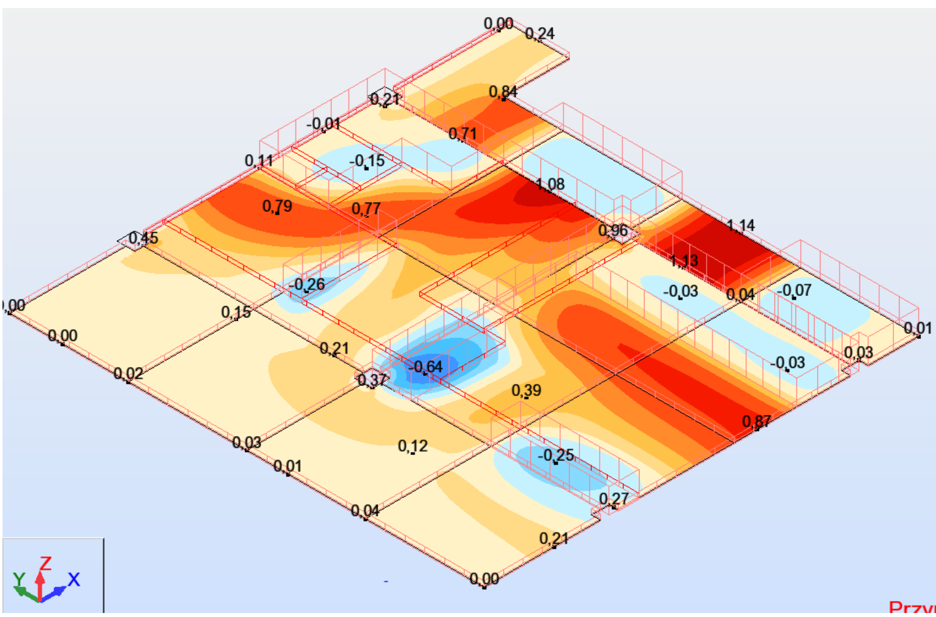


Fig. 8. Principal stresses σ_1 on the upper surface of the underlay for load combinations in the *Ultimate Limit State (ULS)* - case II, cooperating plates.

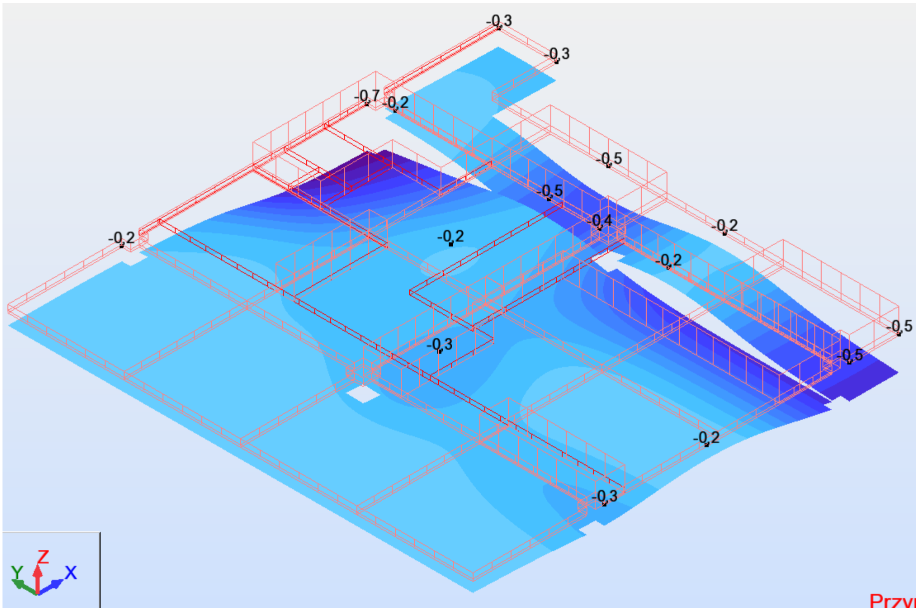


Fig. 9. Deformation of the backing plate for load combinations in the *Serviceability Limit State (SLS)* - case II corresponding to the situation when the foundation slab did not completely break in the places of expansion joints (apparent).

In both analyzed cases (I and II), the screed plate, which is a load-bearing layer did not meet the tender requirements set out in the project documentation [1] and requirements specified in [2] due to surface deformations as well as recommendations contained in [17-24] due to the planned durability.

5 Analysis of the existing state

Fig. 10 shows the implemented in [1] way to support partition walls on the ceiling/floor.

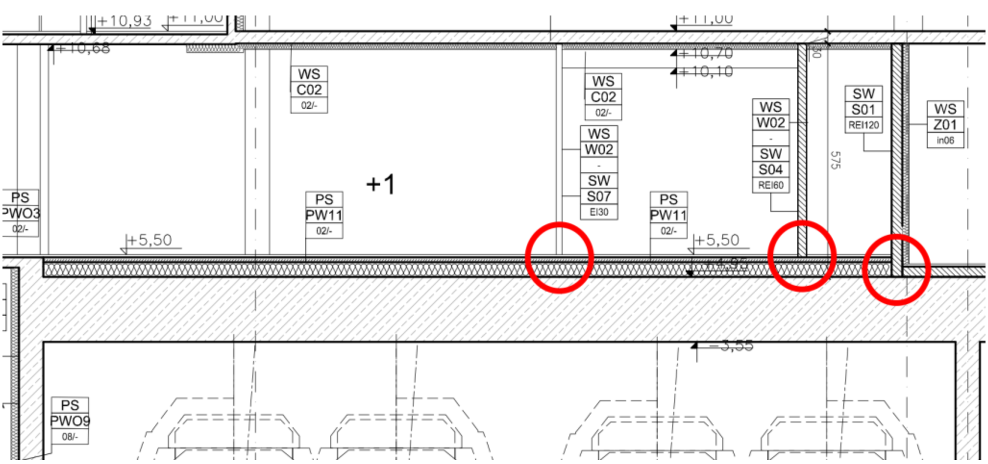


Fig. 10. Method of supporting walls on the ceiling above the tunnel according to [1].

In the finished outcrops, the S01 was a constructional wall (reinforced concrete wall set directly on the reinforced concrete ceiling).

The S04 wall was a partition wall, made of lime-sand brick (silicate) 18 cm thick, which according to the design should be built on the floor construction layer (cement screed 12 cm thick - Fig. 10). However, it was found that the wall was placed on a reinforced concrete floor slab, not on the floor layer. That was inconsistent with [1] but allowed for the continued safe use of this wall. The excavations made revealed intense moisture of all the walls set on the ceiling over the entire height of the floor layers (foamed polystyrene and cement coat). In the dilatation areas of the ceiling slab, expansion joints of the walls were also made, i.e., the dilatation of the ceiling and the walls overlapped, which was a correct solution consistent with the principles of technical knowledge.

The S07 wall was a system partition wall with a thickness of 15 cm made of G.-K. Fastened to system steel profiles with a width of 100 mm, double-sided coated with plasterboard, two plates with a thickness of 1.25 cm on each side). The space between the plates was filled with mineral wool. The S07 wall was set on the floor layer (ceramic tiles or carpet). Additionally, on the floor, in the rooms of the tenants, any arrangement of partition walls made of gypsum-cardboard boards with a height of up to 3.5 m is provided by the arrangement designs.

The design [1] adopted in the project to support the walls S04 and S07 on the ceiling above the railway tunnel provided that they were to be based directly on the floor underlay (screed/ concrete screed), which was an erroneous solution with a high risk of failure. In the case of insufficient load capacity of the floor, e.g., due to the low strength of the underlay, which occurred or insufficient stiffness of polystyrene, the adopted solution would fail or even cause a disaster. The contractor arbitrarily, without consulting with the building inspector, built up all the walls directly on the ceiling, which ultimately enabled safe exploitation of the premises by the tenants.

An arrangement of the floor layers in the outcrops did not comply with [1]: the screed thickness was different and ranged from 7.0 cm to 19.0 cm, the screed itself was made in one or two layers separated from each other by a layer of black PE foil. Under the screed, expandable EPS and extruded expanded polystyrene (with different strength parameters) were laid out.

In all the excavations made, intense moisture was found in the part of lime-sand (silicate) blocks sunk in polystyrene (the entire height of the wall under the floor). The technological moisture was introduced between the floor layers during the construction. Incorrect floor layer layout resulted in moisture condensation on the cold tunnel ceiling (because the thermal insulation is placed on the ceiling from the warmer side of the barrier). Lack of effectiveness is indicated as probable causes of the source of moisture — horizontal insulation made of foil or leakage of building installations.

Based on the calculations made, it was found that the screed plate (in both analysed cases - I and II) used as load-bearing floor layer does not meet the tender requirements set out in [1] and the requirements specified in [2, 11-13] due to acceptable deformations. Based on the calculations made, it was found for the II case that the screed plate, which is used as load-bearing floor layer, does not meet the conditions of the *Ultimate Limit State (ULS)* according to the standard [10].

6 Conclusions

By the carried out analyses, it was found that the floor over the railway tracks was not able to safely transfer the service loads foreseen in the design project that in practice excluded it from use. There was a probability that in the course of use, the floor slab, with an unfavourable load pattern, would crack uncontrollably, which in the long term would hurt its durability. The surface of the floor may have been detached from the substrate. Cracks, deflections in the areas of expansion joints, chipping and loss of concrete could occur. It was recommended to reduce the permissible loads, which was a significant operational deficiency, and in the later period to replace all floor layers including the thermal insulation layer. For this purpose, the project documentation was to be developed, which will also take into account the thermal and moisture calculations, i.e. temperature and moisture distribution on the partition thickness and the probability of so-called "dew point" occurrence. The floor replacement has been included in the renovation plan of the facility.

References

1. Document: Fragmentaryczna archiwalna dokumentacja powykonawcza obiektu, tymczasowo udostępniona przez Zamawiającego [in Polish]
2. Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie (Dz.U. Nr 75, poz. 690 z późniejszymi zmianami) [in Polish]
3. PN-EN 13318:2002: Screed material and floor screeds. Definitions
4. PN-EN 1991-1-1: Eurocode 1: Actions on structures - Part 1-1: General actions - Densities, self-weight, imposed loads for buildings
5. PN-EN 12504-1:2001: Testing concrete in structures - Part 1: Cored specimens - Taking, examining and testing in compression
6. PN-EN 13791:2008: Assessment of in-situ compressive strength in structures and precast concrete components
7. PN-EN 206-1:2003 Concrete - Specification, performance, production and conformity
8. PN-B-06250:2004 Krajowe uzupełnienia normy PN EN 206-1:2003 [in Polish]
9. PN-B-06250:1988 Beton zwykły [in Polish]
10. PN-B-03264:2002 Konstrukcje betonowe, żelbetowe i sprężone. Obliczenia statyczne i projektowanie [in Polish]
11. A. Ujma, z zespołem, *Warunki techniczne wykonania i odbioru robót budowlanych. Poradnik projektanta, kierownika budowy i inspektora nadzoru* (Wydawnictwo Verlag Dashofer, Warszawa 2008) [in Polish]
12. Report: *Concrete industrial ground floors. Technical Report Nr 34. A guide to design and constructions* (Concrete Society, 2003)
13. P. Hajduk P, *Projektowanie podłóg przemysłowych* (Wydawnictwo Naukowe PWN, 2013) [in Polish]
14. E. Motak, Inżynieria i Budownictwo, **5-6** (1989)
15. J. Świniarski, Inżynieria Morska i Geotechnika **5**, pp. 314÷319, (2003)
16. J. Ślusarek, *Wybrane rozwiązania strukturalno-materiałowe betonowych nawierzchni przemysłowych* (Proceedings of XIX Ogólnopolska Konferencja Warsztaty Pracy Projektanta Konstrukcji, pp. 129÷154, 2004)

17. B. Chmielewska, L. Czarnecki L., *Materiały i wymagania dotyczące posadzek* (Proceedings of XXVI Conference „Warsztaty Pracy Projektanta Konstrukcji”, pp. 239÷280, 2011) [in Polish]
18. J. Mierzwa, *Kształtowanie i obliczanie posadzek przemysłowych na gruncie* (Proceedings of XXIII Conference „Warsztaty Pracy Projektanta Konstrukcji”, 2008) [in Polish]
19. D. Bajno, A. Małasiewicz, Czasopismo techniczne, **1**, pp. 3-11, (2007) [in Polish]
20. A. Małasiewicz, I. Boukerou, *Typowe uszkodzenia posadzek przemysłowych* (Proceedings of II Konferencji Technicznej Technologie i Materiały Budowlane XXI wieku. Gdańsk, 1999) [in Polish]
21. Z. Ściślewski, *Trwałość konstrukcji żelbetowych* (Wydawnictwo Techniki Budowlanej, Warszawa, 1995)
22. M. Substyk, *Utrzymanie i kontrola okresowa obiektów budowlanych* (Wydawnictwo ODDK, Warszawa, 2012)
23. G. Fegerlund, *Trwałość konstrukcji betonowych* (Wydawnictwo Arkady, Warszawa, 1997) [in Polish]
24. Joint publication, *Trwałość i skuteczność napraw obiektów budowlanych* (Dolnośląskie Wydawnictwo Edukacyjne, Wrocław, 2007)