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NON-DESTRUCTIVE TESTING AND ANALYSIS OF A XIX-CENTURY BRICK MASONRY BUILDING

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The article presents the results of non-destructive testing and analyses carried out for a brick masonry building from the 19th century, which has many irregularities that involve a lack of inspections and tests of its technical condition for many years, as well as a failure to carry out necessary repairs. The conducted organoleptic tests enabled the most significant building damage to be indicated, and its causes were determined on the basis of the results of non-destructive tests and analyses. These causes include mainly wall cracks, ceiling deflections and excessive dampness. It also contains the relationships, which were developed using non-destructive dielectric and resistive methods when testing the moisture content of the brick walls. These results may be useful for other researchers dealing with brick masonry buildings from a similar period of time. The authors' intention was to present the existing poor technical condition of the brick masonry building and indicate its causes, as well as to present that a lack of appropriate maintenance can lead to a situation in which the life or health of residents is threatened.

Keywords: brick masonry building; wall cracks; ceiling deflections; excessive dampness; non-destructive testing

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1. INTRODUCTION

Many countries in Europe are struggling with the problem of an unsatisfactory, or even poor, technical condition of multi-family residential buildings that were built before World War II [1-3]. These brick masonry buildings, in many cases, do not meet basic functional and utility requirements, regarding e.g. mechanical resistance and stability, safety in case of fire, appropriate hygiene and health conditions, environmental protection, safety in use, protection against noise and vibration, energy economy and heat retention of partitions as well as sustainable use of natural resources [4-8].

Compliance with all the above-mentioned requirements is important, however, due to the health and life of residents, it is particularly important to ensure the safety of the structure (it is not maintained when the ultimate limit states of the basic structural elements are exceeded) and appropriate hygiene and health conditions. In order to comply with the above-mentioned requirements, buildings should be kept in an appropriate technical condition. Therefore, systematic periodic inspections and tests are necessary, which allow interference in the tissue of an object to be significantly reduced [9-12]. Such inspections therefore minimize the amount of local damage resulting from diagnostic tests [13].

Nowadays different non-destructive testing (NDT) methods are used in the assessment of different types of masonry. For example ultrasonic testing has been successfully used to evaluate the mechanical properties of clay masonry units [14] and weathered granites [15]. Also ground-penetrating radar (GPR) has been applied to measure the moisture in full-scale stone and brick masonry models after simulated flooding [16]. On the other side GPR, thermography and sonic tests were applied successfully to evaluate the moisture distribution in the masonry after flooding and during natural drying [17]. In [18] the infrared radiation has been used for thermal and mycological active protection of baroque building.

Based on the results of the inspections and tests, it is possible to prepare a correct assessment of the condition of the entire building and its individual elements, and thus conduct a proper renovation policy [19-22]. However, it often happens that inspections and tests are not carried out regularly, and in some cases, these omissions go back many years. It is also not uncommon that the recommended repairs, based on the conducted inspections and tests, are not carried out.

This may result e.g. from an inefficient property management model, which especially applies to buildings that have many co-owners, or even from a lack of funds that are needed to finance the renovation [23-25]. The results of periodic inspections and tests should also be recorded in the building's logbook, which is not always observed, and many buildings - especially those that are centuries old or older - do not even have a building logbook.

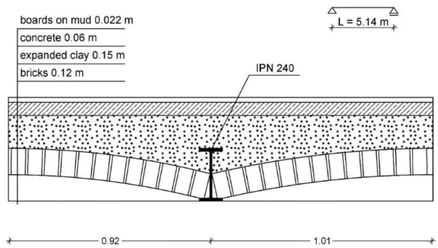
Referring to the above statements, this article presents the case of a 120-year old brick masonry building, which has irregularities within the basic functional and utility requirements indicated above. This building, for many years, was not subjected to the necessary periodic inspections, tests and renovations. The purpose of the paper is to present the existing poor technical condition of the brick masonry building and to indicate its causes, as well as to highlight that a lack of proper maintenance can lead to a situation in which the life or health of residents is endangered. The article contains the results of tests and analyses, including non-destructive tests, on the basis of which the causes of damage were determined.

2. General description of the brick masonry building

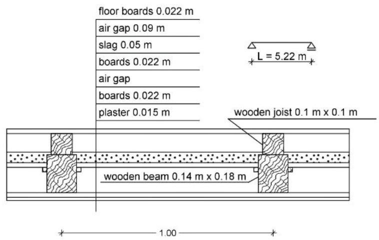
The analysed building is located in the close vicinity of a street and was erected at the end of the 19th century as a four-storey multi-family brick masonry building with a basement and an attic. It has no foundation benches - it was founded on rocky ground. The basement walls had a thickness of about 550 mm were partly made of granite elements and partly of solid burnt clay brick. The view of building location, facade with the main entrance to the building, facade from the yard and gable wall of the building were presented in Fig. 1.

Fig. 1. View of: a) building location, b) facade with the main entrance to the building, c) gable wall of the building, d) facade from the yard

In turn, the walls of the over-ground storeys - internal with a thickness of 250 mm and 150 mm and external with a thickness of 500 mm - were made of solid burnt clay brick and lime mortar. The ceiling above the basement is segmental, built of brick with a thickness of 120 mm, expanded clay with a thickness of 150 mm, 60 mm thick layer of concrete and 22 mm thick layer of boards on mud (Fig. 2a). This ceiling is based on both the external walls and a steel 240 mm height IPN-beam running through the central part of the basement. Above the other storeys there are wooden beam ceilings with sound boarding (Fig. 2b). The load-bearing beam of this ceiling had dimensions of 140 x 18 mm. On this beam the wooden joist with a dimensions of 100 x 100 mm are placed.



(a)



(b)

Fig. 2. Cross-section of: a) the segmental ceiling above the basement, b) the wooden ceiling above the first floor

The building is also covered with a roof queen post truss. The building has a staircase, the runs of which are made of stone up to the first floor, while on the upper floors they are wooden. The building has no damp insulation of its walls and basement floors, however, there is a perimeter drain that was executed around it during its construction.

3. Results of the conducted tests and analyses

3.1. Organoleptic tests

As a result of organoleptic tests (visual inspection), the condition of the brick masonry building was assessed and the most significant damage was pointed out, namely:

- numerous vertical cracks and bulging towards the outside of one of the gable walls of the brick masonry building. Deep cracks were also noticed in one longitudinal outer wall. There was also local deformation and a deep crack along the entire height of the internal transverse wall, as a result of which the brick lintel that is based on it is distorted above the entrance to the basement, with the bricks being loose in the zone above the lintel. The locations of the wall cracks are shown in Figure 1,
- strong corrosion of the I-section steel beam in the sectional ceiling in the basement. Rust layers of 2 mm thick were easily detached from the bottom flange of this beam, and as a result of which the cross-section of the beam was reduced by about 40%. In addition, a significant deflection of the beam and its rotation in the plan were found. Therefore, it was recommended to support it with a wooden support in order to prevent the ceiling above the basement from collapsing,
- significant deflections of wooden ceilings over all the above-ground floors,
- a significant deviation regarding the level of the stone stairs that run from the ground floor to the first floor, and which are based on the deformed and cracked transverse wall,
- strong dampness of the walls at the ground floor level, with salt efflorescence and mould fungi on their surfaces.

The most important damage - cracked walls, significantly deflected ceilings, deformed stairs, and also heavily damp ground floor walls covered with efflorescence of mould fungi that are harmful to human health - clearly indicated the poor condition of the brick masonry building. Therefore, due to the threat to the life or health of the residents, it was decided to move them out.

Figure 3 presents the wall cracks and deformed stone stairs, as well as a sketch of the second floor of the brick masonry building, on which the direction of the support of the wooden ceilings is marked. In the photo of the stairs, a dashed line shows a significant deviation of the stone treads from the original level.

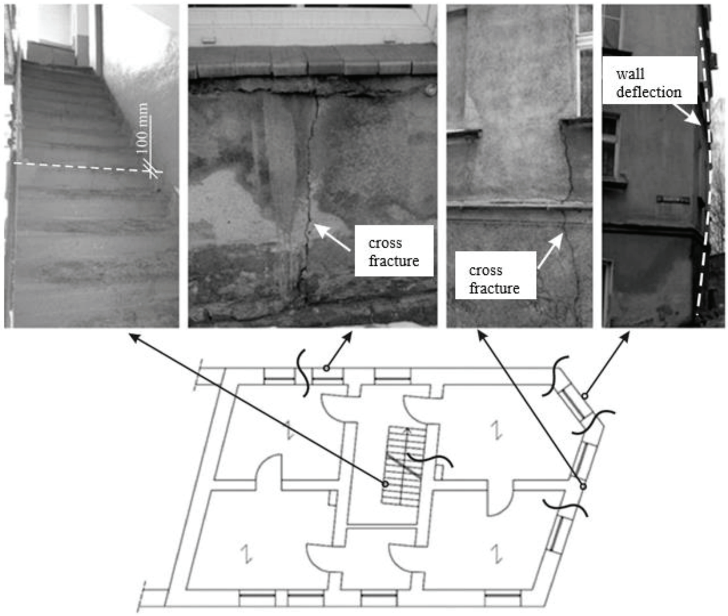


Fig. 3. Sketch of the second floor of the analysed brick masonry building, with photos documenting the cracks of masonry walls and deformation of the stone stairs that run from the ground floor to the first floor.

Figure 4 shows a bent and supported heavily corroded I-beam in the ceiling above the basement, while Figure 5 presents an exemplary view of the heavily damp ground floor walls, which are covered with salt efflorescence and mould fungi.

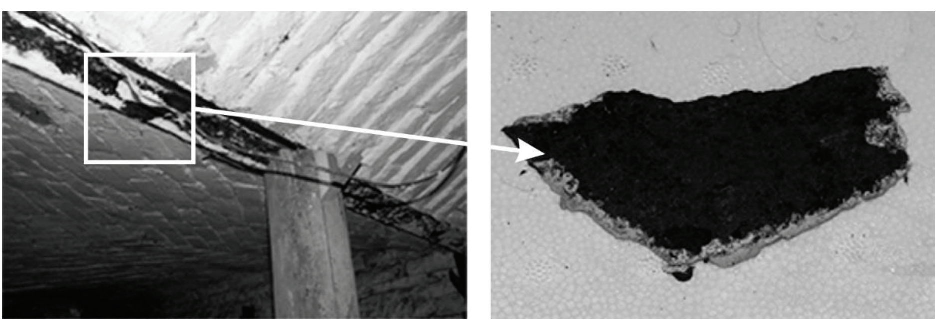


Fig. 4. View of a highly corroded steel beam in the ceiling above the basement.

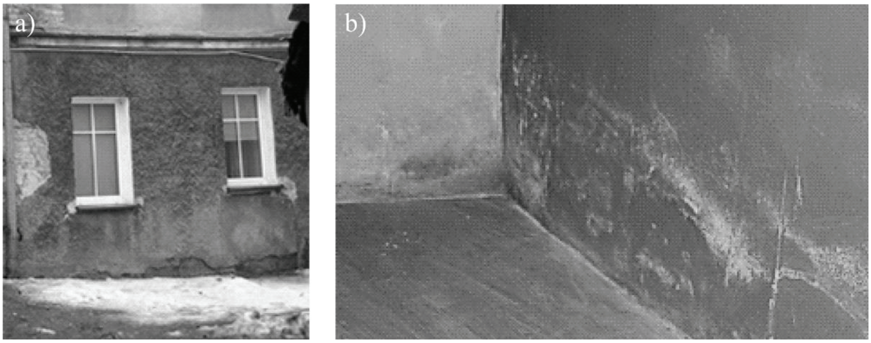


Fig. 5. View of the damp walls of the ground floor covered with salt efflorescence and mould fungi: a) from the outside; b) from the inside.

In order to determine the causes of the numerous cracks in the walls of the brick masonry building, it was decided to carry out a soil test. For this purpose, an excavation in the vicinity of the foundation was made, which confirmed that the building has no foundation benches, and that the basement walls are laid directly on the rock ground beneath the building. In the opencast excavation under the basement, groundwater was found in marl rock at a level similar to the floor level.

An interview with residents showed that the water level in the basement is higher than the floor level after rainfall, and that the first cracks in the walls of the brick masonry building appeared several years ago, after the existing perimeter drain around the building ceased to operate as a result of breaking its continuity during the construction works conducted in its vicinity. It was concluded that the reason for the uneven settlement of the walls, and therefore the cause of their cracking, may be the loosening of the rock due to the gradual dissolution of the calcium carbonate ($CaCO_3$) that is in it, and also due to dynamic vibrations caused by traffic.

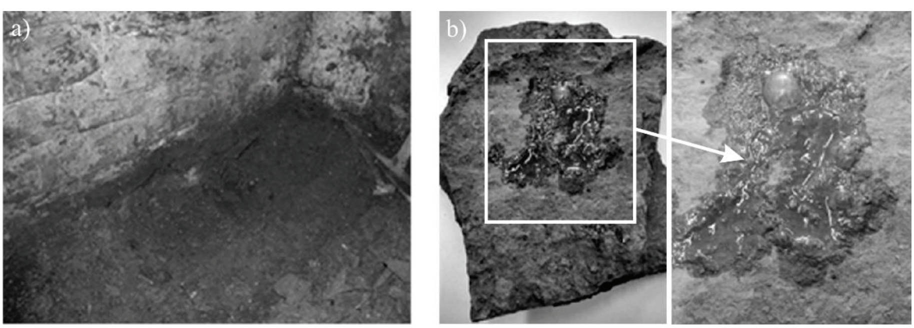


Fig. 6. View of: a) exposure of foundations, b) samples of marl rock taken from the excavation, which react when in contact with hydrochloric acid by producing foam.

Laboratory tests showed that the ground under the brick masonry building is mudstone with a high marl content. This was also confirmed by tests with the use of hydrochloric acid. Figure 6 shows the foundations that were uncovered in the basement in the corner of the outer walls, a view of the rock sample taken for laboratory testing, and the reaction of the mudstone to contact with hydrochloric acid (foam).

3.2. MOISTURE CONTENT AND SALINITY TESTS ON BRICK WALLS

Tests were carried out in order to determine the degree and causes of the strong dampness and salinity of the building's walls. Due to the poor technical condition of the walls and the lack of conservation restrictions, it was possible to carry out moisture tests using the destructive gravimetric method. However, it was decided to also use two non-destructive methods in the research, dielectric (Gann Hydromette Uni 2 meter) and resistance (Gann Hydromette RTU 600 meter) [26-28] in order to determine for each of them the exact correlative dependencies between the unitless X indications of the meters and the mass moisture content U_m of the wall, as described in [28]. These dependencies, which are shown in Figure 7, can be used by other researchers who deal with brick masonry buildings from a similar period, especially historic ones, in which the interference in the historical tissue is very limited due to restoration restrictions.

a) b)

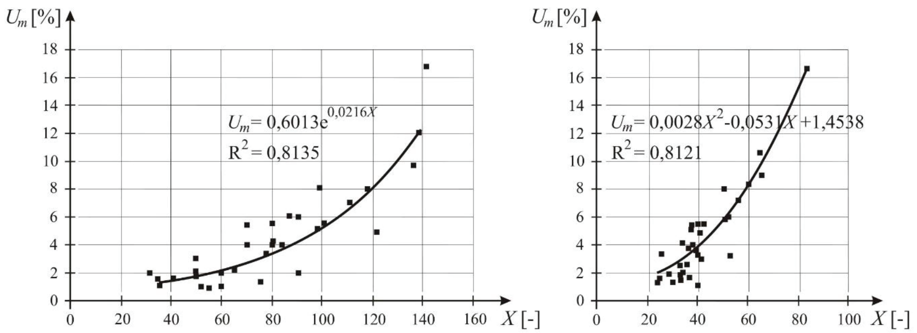


Fig. 7. Correlational relationship between the indications X of the meter and the mass moisture content U_m of the masonry wall: a) for the dielectric meter; b) for the resistance meter.

The brick external and internal walls of the ground floor were subjected to the tests. Measurements were taken in eight measuring places, in each place at four heights above floor/ground level, as shown at Figure 8. In total, for each of methods 32 measurements were obtained.

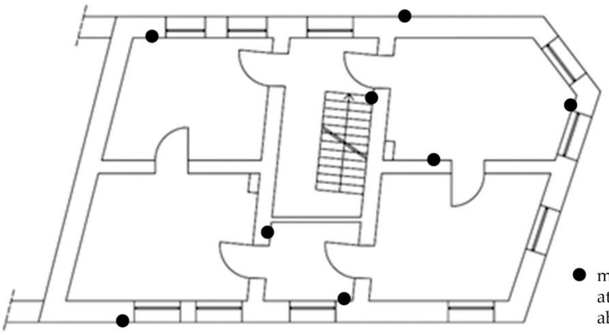


Fig. 8. The location of measuring places of the mass moisture content U_m of the masonry walls

The average values of the moisture content in the subsurface zone, determined at heights of 20 cm, 50 cm, 100 cm and 150 cm above the floor level, were equal to 6.40% (SD = 3,50), 4.70% (SD = 2,38), 3.50% (SD = 0,55) and 2.60% (SD = 1,11) respectively for the internal walls, and for the external walls they were equal to 10.20% (SD = 3,37), 6.80% (SD = 1,33), 3.80% (SD = 0,64) and 2.35% (SD = 0,59), respectively. This state is illustrated in Figure 9. Table 1 presents the classification of the moisture content adopted from literature [29-31], and the determined degree of dampness of particular batches of the tested walls. The measurement results clearly show that the building's walls are excessively damp up to a height of about 130 cm above floor level.

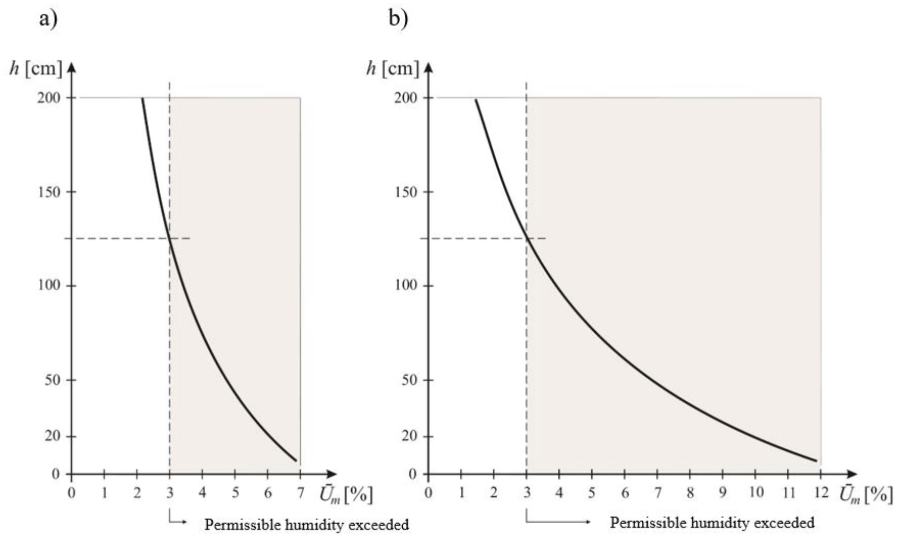


Fig. 9. Averaged mass moisture content distributions $\bar{U}_m$ in the masonry walls of the ground floor: a) at the height of the internal walls, obtained using the dielectric method; b) at the height of the outer walls, obtained using the resistance method.

Tab. 1. The degree of dampness of particular batches of the tested walls in relation to the classification of the moisture content in brick walls adopted in literature [29-31].

Classification of the moisture content in brick walls according to [26-28]		Moisture content in the tested brick walls [present study]	
Mass moisture content U_m [%]	The degree of dampness	Internal walls	External walls
<3.0	wall with permissible moisture content	more than ~130 cm above the floor level	more than ~130 cm above the floor level
3.0–5.0	wall with increased moisture content	up to ~130 cm above the floor level	up to ~130 cm above the floor level
5.0–8.0	moderately damp wall	up to ~45 cm above the floor level	up to ~75 cm above the floor level
8.0–12.0	very damp wall	-	up to ~40 cm above the floor level
>12.0	wet wall	-	-

Qualitative and semi-quantitative tests of the type and concentration of salts showed that in the external and internal brick walls of the building there are mainly chlorides and nitrates, and to a lesser extent sulphates. Table 2 presents the average values of the concentration of individual salts in relation to the permissible concentration limits according to [32, 33].

Tab. 2. Average values of the concentration of individual salts in relation to the permissible concentration limits according to [32, 33].

Permissible salt concentration limits according to [32, 33]		Averaged values of salt concentration in the brick walls of the brick masonry building [present study]
chlorides	0.150%	0.211%
sulphates	0,500%	0,409%
nitrates	0,150%	0,205%

Despite the fact that the foundation walls of the brick masonry building are made of stone, it is not surprising that the concentration of chlorides is exceeded in most of the tested places of the brick walls. The building is located in the close vicinity of the road and pavement, which are sprinkled with salt in winter.

3.3. Analysis

One of the wooden beams in the bent ceiling above the first floor, and the bent steel I-beam in the sectional ceiling above the basement, were analysed. The cross-sections of these ceilings, a summary of their loads, and the results of calculations carried out for both beams are presented below.

Figure 2b shows cross-section of the wooden ceiling above the first floor. The beam rested on both sides on the walls, therefore a free-supported beam was adopted as the static diagram. The arrangement of layers in Figure 9 is presented on the basis of thickness measurements of individual layers in the ceiling. The volumetric weights of the materials in table 3 were adopted on the basis of standards [34, 35].

Tab. 3. Summary of loads per 1 m^2 of the wooden ceiling above the first floor.

Load	Characteristic value [kN/m^2]	γ_f [-]	Computational value [kN/m^2]
Wooden floor boards with a thickness of 0.22 m	0.21	1.35	0.29
Load-bearing beam with dimensions of 0.14 x 0.18 m 0.140 · 0.180 · 4.1 / 1.0	0.10	1.35	0.14
Joist with dimensions of 100 x 100 mm 0.10 · 0.10 · 4.1 / 1.0	0.04	1.35	0.06
Slag layer with a thickness of 0.05 m 12·0.05	0.60	1.35	0.81
Wooden boards with a thickness of 0.022 m	0.21	1.35	0.29
Wooden celling boards with a thickness of 0.022 m	0.21	1.35	0.29
Cement-lime plaster 0.015 m 0.015 · 19	0.29	1.35	0.40
Variable loads	2.00	1.50	3.00
Total:	1.66		5.28

Figure 2a shows cross-section of the segmental ceiling. The static scheme of the steel beam was assumed as a free-supported beam with a length of 5.14 m. The volumetric weights of the materials were adopted on the basis of standards [34, 35]. The arrangement of layers adopted in Figure 10 is presented on the basis of measurements of the thickness of the layers in the ceiling and the dimensions of its elements.

Tab. 4. Summary of loads per 1 m^2 of the segmental ceiling above the basement.

Loads	Characteristic value [kN/m^2]	γ_f [-]	Computational value [kN/m^2]	Characteristic value [kN/m]	Computational value [kN/m]
Brick layer 1.95·0.12·18	-	1.35	-	4.21	5.69
Expanded clay with a thickness of 0.15 m 0.364·8	-	1.35	-	2.91	3.93
Concrete 0.06 m 0.06·25	1.50	1.35	2.03	-	-
Boards on mud 0.022 m	0.23	1.35	0.32	-	-
IPN 240	-	1.35	-	0.37	0.50
Variable loads	2.00	1.5	3.00	-	-
Total	3.73		5,35	7.49	10.12

The analyzes were carried out in accordance with standards [36-38]. The results of the analyses for both beams are shown in Table 5: design value of effect of action E_d, design value of the resistance R_d, maximum deflection of the element w_{fin} and element deflection limit w_{ult}. They show that for the wooden ceiling beam the ultimate limit state was exceeded by 75.8% and the serviceability limit state by as much as 197.5%. In turn, the ultimate limit state for the steel beam was exceeded by 54.9%, and the serviceability limit state by 77.5%. These results show that the safety of the brick masonry building structure is not maintained.

Tab. 5. Summary of the analysis results for the floor beams.

Element	Ultimate limit state			Serviceability limit state		
	E_d [MPa]	R_d [MPa]	Exceeded by [%]	w_{fin} [mm]	w_{ult} [mm]	Exceeded by [%]
Beam of the wooden ceiling	23.8	13.5	75.8	77.7	26.1	197.5
Steel beam of the sectional ceiling above the basement	329.0	212.4	54.9	19.5	11.0	77.5

4. THE MOST IMPORTANT CAUSES OF POOR CONDITION OF THE BRICK MASONRY BUILDING

Based on the organoleptic tests, laboratory tests, non-destructive tests and analyses, the following causes that led to the poor condition of the brick masonry building were determined and formulated:

– non-performance for many years of periodic inspections and tests that are required by law,
– not carrying out the necessary renovations for several dozen years,
– not repairing the damaged perimeter drain around the building. This caused the groundwater table to rise above the foundation level for a long time, and in turn it weakened the soil that is made from the marble mudstone by leaching calcium carbonate ($CaCO_3$) from it. This contributed to uneven settlement of the building walls and their cracking, and also to a significant deviation regarding the level of the stone stair runs leaning on a cracked wall,
– many years of ignoring the progressive cracking of the building's walls and the bending of the ceilings, including the bending of the corrosive steel beam in the ceiling above the basement. As a consequence, the ultimate limit state of the wooden ceiling beams was exceeded by 75.8%, and the serviceability limit state by 197.5%. Moreover, the ultimate limit state of the steel beam was exceeded by 54.9%, and the serviceability limit state by 77.5%.

5. General recommendations to bring the building into technical condition guaranteeing safe use

In order to bring the building into technical condition guaranteeing safe use, it is necessary to undergo general renovation. The scope of renovation should include:

- replacement of all ceilings with new, massive ones. The ceiling on steel beams with reinforced concrete slab and expanded clay block is recommended in this case. Steel beams at the support points must be absolutely anchored to the walls and with each other and, moreover, connected with perpendicular stiffening steel ribs, so that the creation of rigid horizontal discs by individual floors. The gable walls should be anchored with such ceilings,
- lamping the steel structure of a bulging gable wall with perpendicular external and internal walls, at the level of the ceiling above the first and second floor,
- re-walling the entire internal wall with a chimney shaft and filling in the basement walls of mortar losses between stone elements using lime mortar similar to these used originally together with the replacement of rotten mortar to the depth that will be possible,
- analyse the structural behaviour of masonry walls with the special focus on the presence of in-plane damage (e. g. cross fracture as discussed in [39-41]), out-of-plane damage (e. g. wall deflection as discussed in [42-44]) and combined in-plane and out-of-plane damage of walls (for guidance's see for example here [45-47]),
- repair (stitching with steel rods placed in the wall joints) cracks occurring in external and internal walls,
- replacement of internal stairs with new reinforced concrete
- vertical insulation of foundation walls, unblocking the band drainage system that had functioned in the past, and the horizontal floor in the basement and on the ground floor in the basement,
- insulation of the external partitions in order to improve the thermal insulation of the building. It should be considered in the context of the requirements in the European standard [48],
- replacement of windows and doors with new wooden ones, windows should be equipped with air inlets ensuring air supply to the interior of the building
- recreation of all building finishes with the use of materials intended for use in historic buildings, characterized by, among others, low diffusion resistance.

These works should be preceded by making an inventory of the building for design purposes, and then by carrying out an appropriate construction design. At the design stage, the heating problem should be solved.

6. Summary

The article presents the results of non-destructive tests and analyses for a brick masonry building from the 19th century, which has many irregularities that involve a lack of inspections and tests of its technical condition for many years, as well as a failure to carry out necessary repairs. This situation led to the building being in such a bad condition that it was necessary to move out its residents due to a threat to their life or health. The basic requirements for ensuring the safety of the structure and appropriate hygiene and health conditions were not met. The conducted organoleptic tests enabled the most significant building damage to be indicated, and its causes were determined on the basis of the results of non-destructive tests and analyses. The purpose of the article is to present the existing poor technical condition of the brick masonry building and to indicate its causes, as well as to highlight that a lack of appropriate maintenance can lead to a situation where the life or health of residents is endangered

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LIST OF FIGURES AND TABLES:

Fig. 1. View of: a) building location, b) facade with the main entrance to the building, c) gable wall of the building, d) facade from the yard

Rys. 1. Widok: a) lokalizacji budynku, b) fasady z głównym wejściem do budynku, c) ściany szczytowej budynku, d) fasady od strony dziedzińca

Fig. 2. Cross-section of: a) the segmental ceiling above the basement, b) the wooden ceiling above the first floor

Rys. 2. Przekrój: a) stropu odcinkowego nad piwnicą, b) stropu drewnianego nad pierwszym piętrem

Fig. 3. Sketch of the second floor of the analysed brick masonry building, with photos documenting the cracks of masonry walls and deformation of the stone stairs that run from the ground floor to the first floor.

Rys. 3. Szkic drugiego piętra analizowanego budynku z cegły murowanej, ze zdjęciami dokumentującymi pęknięcia ścian muru i deformację kamiennych schodów biegnących od parteru do pierwszego piętra.

Fig. 4. View of a highly corroded steel beam in the ceiling above the basement.

Rys. 4. Widok mocno skorodowanej stalowej belki w stropie nad piwnicą.

Fig. 5. View of the damp walls of the ground floor covered with salt efflorescence and mould fungi: a) from the outside; b) from the inside.

Rys. 5. Widok wilgotnych ścian parteru pokrytych wykwitami solnymi i grzybami pleśniowymi: a) z zewnątrz; b) od wewnątrz.

Fig. 6. View of: a) exposure of foundations, b) samples of marl rock taken from the excavation, which react when in contact with hydrochloric acid by producing foam.

Rys. 6. Widok: a) ekspozycji fundamentów, b) próbek skały margla pobranej z wyrobiska, które reagują w kontakcie z kwasem chlorowodorowym wytwarzając pianę.

Fig. 7. Correlational relationship between the indications X of the meter and the mass moisture content U_m of the masonry wall: a) for the dielectric meter; b) for the resistance meter.

Rys. 7. Zależność korelacyjna między wskazaniami X miernika a masową wilgotnością U_m ściany muru: a) dla miernika dielektrycznego; b) dla miernika rezystancji.

Fig. 8. The location of measuring places of the mass moisture content U_m of the masonry walls

Rys. 8. Lokalizacja miejsc pomiaru masy wilgotności wilgoci U_m ścian murowanych

Fig. 9. Averaged mass moisture content distributions U_m in the masonry walls of the ground floor: a) at the height of the internal walls, obtained using the dielectric method; b) at the height of the outer walls, obtained using the resistance method.

Ryc. 9. Uśrednione rozkłady zawartości wilgotności U_m w ścianach murowanych parteru: a) na wysokości ścian wewnętrznych, uzyskane metodą dielektryczną; b) na wysokości ścian zewnętrznych, uzyskane metodą oporności.

Tab. 1. The degree of dampness of particular batches of the tested walls in relation to the classification of the moisture content in brick walls adopted in literature [27-29].

Tab. 1. Stopień zawilgocenia poszczególnych partii badanych ścian w stosunku do przyjętej w literaturze klasyfikacji wilgotności w murach ceglanych [27–29].

Tab. 2. Average values of the concentration of individual salts in relation to the permissible concentration limits according to [30, 31].

Tab. 2. Średnie wartości stężenia poszczególnych soli w stosunku do dopuszczalnych granic stężenia zgodnie z [30, 31].

Tab. 3. Summary of loads per 1 m^2 of the wooden ceiling above the first floor.

Tab. 3. Podsumowanie obciążeń na 1 m^2 stropu drewnianego nad pierwszym piętrem.

Tab. 4. Summary of loads per 1 m^2 of the segmental ceiling above the basement.

Tab. 4. Podsumowanie obciążeń na 1 m^2 stropu odcinkowego nad piwnicą.

Tab. 5. Summary of the analysis results for the floor beams.

Tab. 5. Podsumowanie wyników analizy dla belek stropowych.

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