Structural and Technological Aspects of the Historical Floors Replacement

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Abstract. The article presents structural and technological problems resulting from the use of historical floors in the process of planned renovation and modernisation. In the three-storey building, built at the end of the nineteenth century, there was significant damage caused by warfare. At the stage of post-war reconstruction, some structural elements were adapted to new functions. Structural walls, made of ceramic bricks, were suitable for further use, without the necessity of additional reinforcement. Damaged fragments of the floors were reconstructed. Due to the elevation of the street level, the rebuilt ceiling above the ground floor was weighted with a 600 mm layer of brick debris or crushed brick. In an additional layer, water-supply systems were located. In the following years, the building was superstructured by one storey. Structural walls made of ceramic bricks were covered with channel plates. After several decades of usage, the user decided to change the function of the rooms, which involved transferring additional loads to existing structural elements, i.e., floors, walls and masonry spot footing. As a result of the research, calculations and consultations with the conservator, it was recommended to strengthen the existing channel floor. After additional tests involving the trial loading of floors, they were qualified for modernization without the necessity of additional reinforcements. During demolition works aimed at replacing the elements of sanitary installations, significant damage to steel beams, which were the supporting structure of floors above the ground floor, was identified. As a result, all works were stopped and the concept of using existing floors was abandoned. On the debris layer, used as a formwork, a newly designed beam-and-slab floor was made, and then the stone vaults and the debris-ceramsite filling were demolished and utilized. At the request of the conservator, fragments of destroyed steel beams were left as a so-called "witness" of the history of the building. The authors of the abstract draw attention to the significant problem associated with the use of several hundred-year-old structural elements in the processes of modernization of objects. In the analysed case, conducting meticulous calculations and tests consisting of a trial loading of a degraded structure did not result in obtaining the results qualifying the structure for replacement. At the stage of construction works, the potential danger was identified. This leads to the conclusion that the process of modernization of historical buildings must be carried out under the constant supervision of construction designers and architects.

1. Introduction
Each stage of renovation, restructuring, or modernisation of a historical building should be preceded by preparation of detailed design documentation. In order to eliminate the possibility of failure or catastrophe, continuous cooperation of designers in the architectural and construction fields is required, starting from the inventory stage, through design and supervision stage, and may only be concluded
after placing the modernised object into service, [1, 2]. The most important criterion of a properly carried out modernisation is safety of the modernisation contractors and future users of the building.

![Figure 1. Overview and architectural details of a 19th century university building](image)

Suitability of historical substance used as structural bearing elements depends on designer’s decisions. However, the so-called “rule of limited trust” should always be applied, since it is impossible to identify all hidden faults of the structure, [3, 4, 5].

An example of a historical building which underwent modernisation is shown in Figure 1. The building was erected at the turn of the 20th century. It consisted of five four-story wings with basements and void attic. During the post-war reconstruction, the internal part of the building was superstructured by another floor. The ground floor of the building was located ca. 1 m below the current ground level. Currently, the building is used in accordance with its initial intention, i.e., as a didactic-laboratory university object.

2. Historical structural solutions identification

The 19th century building, covered with a hip roof, was created as a traditional masonry structure. The building is situated on spread foundation of solid ceramic bricks with cement mortar, [6]. Foundation sinking below the basement floor level varies from 650 mm to 950 mm. Spread was built directly on the ground, without any moisture protection, horizontal or vertical insulation. In the situating area under the foundation, dusty sand and sandy dust, clay and loam, as well as medium and coarse sand, were present. Ground water stabilized at the level of 0.6 m-1.0 m below the basement floor level.

Structural walls of various thickness (from 600 mm to 1100 mm including plaster) were made of solid ceramic bricks with cement mortar and plastered with lime lining. The used bricks had the following dimensions: 270 mm x 130 mm x 70 mm. Headers over the holes were made as flat Klein ones from rolled steel beams, and locally as arches of ceramic bricks with cement mortar.

Roofs over the basements were made as brick vaults of 130 mm thickness supported by steel 1200 beams or rail beams (Figure 2). Vault elevation (arch arrow) equalled 170-280mm. Filling over vaults of thickness of ca. 600 mm was made of brick debris, locally exchanged for ceramsite. The vaults were plastered, and the floor beams’ lower feet were secured with paint coating.
Figure 2. Different types of floors: a) brick vault, b) ceramic floor, c) wooden floor

During post-war reconstruction, the vault over the basement was recreated as a reinforced board 120 mm thick supported by steel I240 I-beams or as a Klein-type ceiling supported by I200 I-beams. The ceiling span was within the range of 3.50 – 5.50 m.

3. Modernisation chronology
The three-storey building, built at the end of the nineteenth century, housed didactic rooms of a university. As a result of warfare, it was severely damaged. At the stage of post-war reconstruction, some structural elements were adapted to new functions. Structural walls made of ceramic bricks were suitable for further use without the necessity of additional reinforcement. Damaged fragments of the floors were reconstructed using material obtained from demolition of the neighbouring buildings. Due to the elevation of the street level, the rebuilt ceiling above the ground floor was weighed with a 600-mm layer of brick debris or ceramsite. In an additional layer, water-supply and gas systems were located. In the following years, the building was superstructured by one floor. Structural walls made of ceramic bricks were covered with channel plates.

After several decades of usage, the user decided to change the function of certain rooms, with intention to change them into laboratories. Consequently, additional loads needed to be transferred to existing structural elements, i.e., floors, walls, and masonry spot footing.

As a result of the research, calculations and consultations with the conservator, it was recommended to strengthen the existing channel floor. After additional tests involving the trial loading of floors, they were qualified for the modernization without the necessity of additional reinforcements.

4. Current material parameters tests. Structure state assessment.
Structure elements usability assessment in the modernisation planning process was preceded by series of tests, the objective of which was to determine current physical and strength parameters of the historical materials. On the basis of laboratory tests, the following parameters were determined (among others): yield limit of steel out of which majority of structural beams are made (ca. 140 MPa), cement mortar strength (1-1.5 MPa), bricks strength (12-19 MPa). As a consequence of the experiments, moments of inertia of beams, which were not identified in the available documentation, were determined, [7, 8].

During an in situ inventory works, the following faults were noted [9]:
- vast damp areas of vaults over basements, caused by active leaks from the water supply system;
- Klein vaults reinforcements corrosion, locally leading to complete loss of band iron in binding of the brick plates;
- Klein vaults steel beams flanges and webs surface pitting corrosion, locally resulting in loss of flange or web fragments (Figure 3);
- advanced corrosive processes of lower reinforcements of plates and binding joists;
- brick and Klein vaults cement mortar bindings carbonisation processes and bricks chemical corrosion.
The conducted calculations and analyses including actual cross-sections and strength parameters of the historical materials led to the following conclusions:

- ceilings should carry, besides their own weight, a useful load of 3.5 kN/m²;
- bearing ultimate limit state conditions of Klein floor beams, weakened by the corrosion losses, were exceeded by 131-191%;
- bearing ultimate limit state conditions of vaults beams were fulfilled, despite local weakening caused by pitting corrosion losses.

The basic cause of identified internal dampness were leaks from the water supply system, but also penetration of rainwater into ceiling layers and permanent dampness of external basement walls and plaster linings, which caused excessive, reaching nearly 100%, air humidity in rooms located below the ground level.

Despite analytic confirmation of correct vaults bearing capacity, due to safety concerns, selected rooms underwent tests consisting of trial loading of historical ceilings, structured from extremely varied layer systems. Mechanical strain gauges of 0.01 mm preciseness were used for measurement purposes, as well as laser leveller with millimetre scale. Concrete blocks, stored on the square of the renewed building, were used as loading. Received deformation results did not reach half of ultimate values, determined by current standards [10], despite 40% loading of the examined structures. After the unloading stage, ceilings structure deformation reached low negative values, i.e., the ceiling remained over the initial level.

**Figure 3.** Substantial faults of steel beams supporting brick vaults

On the basis of conducted visual examination, NDT, strength tests, and calculative analyses, general technical state of the building was determined to be satisfactory in regards to the planned modernisation, [10, 11, 12], with an exception of Klein ceilings over the basement, the state of which was assessed as presenting risk for the building users and qualified for reconstruction or replacement with a reinforced structure, [13].

### 5. Reinforcement works conception

It was decided to exchange Klein vaults for monolithic beam-and-slab floor in stages, taking into account that the walls’ effective length increases with ceilings deconstruction. As a consequence, the deconstructed ceilings had to be supported during construction works with steel stretcher bars preventing moving or bending of the walls towards middle of the room. Existing walls, in which niches for beam supports were made, had to be reinforced with rims.
The floors were qualified as subject to the modernization without the necessity of additional reinforcements. During demolition works aimed at replacing depressurised elements of sanitary installations, several dozen centimetres of filling were removed. After the brick debris and ceramsite removal, microcracks appearing on the lower parts of the historical vaults were noted.

![Temporary supports of endangered floors and vaults](image)

**Figure 4.** Temporary supports of endangered floors and vaults

The vaults in the area of the conducted works were immediately supported (Figure 4), and after deconstruction of vault fragments, faults in the form of considerable web corrosion loss of I-beams through their whole length (Figure 3) were determined. As a result, all works were stopped and the concept of using existing floors was abandoned. On the debris layer, used as a formwork, a newly designed beam-and-slab floor was made, and then the stone vaults and the debris-ceramsite filling were demolished and utilized (Figure 5). At the request of the preservationist, fragments of destroyed steel beams were left as a so-called "witness" of the history of the building.

![Concept of the damaged vaults reconstruction](image)

**Figure 5.** Concept of the damaged vaults reconstruction: a) historical vault cross-section, b) reconstruction stage, c) newly designed RC floor

### 6. Ceiling beams effort and deformation verification

Due to identification of state of risk of ceiling structure, additional statistics and strength calculations were conducted, [14]. Brick floor bearing beam was modelled using Ansys Workbench software. Total length of an I-beam of 200 mm height assumed in the model equalled 3.89 m, while other dimensions were determined via a series of experiments. Joint support was realised through adding fragments of 50mm length on both ends of the beam. Beam end fragments were made of flexible material, thus no plastic deformation in them was identified. Additionally, they do not disturb the results through support
yielding due to local pressure. On the basis of strength tests, yield point of steel out of which the beam equalling 140 MPa was determined. Support is applied on the bottom flange edge. Moreover, movement in the direction perpendicular to the web, which corresponds to the actual structure of the vault, was blocked. In the case of not using the blockade, the beam becomes yielding, which leads to lack of results in the software. Weakening caused by corrosion within the beam were designed as irregular shapes. Three areas of thinness of 0.5 mm thickness each were applied to the web, and three areas of thinness of 0.8 mm thickness each were applied to the flanges. Numerical calculations are presented in a graphic form in Figure 6.

![Figure 6](image)

**Figure 6.** Graphical results of numerical calculations

The corroded beams were compared to openwork elements in the article. Justification of correct ceiling bearing capacity, despite considerable beam damage in the form of corrosion loss, may be the fact of ceiling protection from local equilibrium loss due to reinforcement with brick vault elements on both sides.

7. Results and discussion

In the analysed case, conducting meticulous calculations and tests consisting of a trial loading of the degraded structure did not result in obtaining the results qualifying the structure for replacement, [15]. Only at the stage of the construction works, the potential danger of corrosion loss on considerable beam surface on the whole web width was identified.

Utilising the structure in the described state would inevitably result in a delayed, unsignalled catastrophe. Collapse of vault fragment could have resulted in gas explosion caused by depressurisation of the gas, wiring of which was located in the debris layer [16]. As a consequence of faults, accidentally discovered by a specialist renovation company, the ceilings were eliminated as potential bearing elements.

A selection of contractor must not be dictated merely by the lowest price of the services. The investor needs to formulate detailed criteria which will allow to identify risks occurring during historical building modernisation and to select a contractor providing technical personnel of appropriate experience and qualifications [17, 18, 19, 20].

8. Conclusion

The authors of the article draw attention to a significant problem associated with the use of several hundred-year-old structural elements in the processes of modernization of objects. The described example of a historical building renovation implies the necessity of thorough analysis of using historical substance as structural element. The process of modernization of historical buildings must be carried out under the constant supervision of construction designers and architects.
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References
[1] J. Krentowski, T. Chyży, P. Dunaj, “Sudden collapse of a 19th-century masonry structure during its renovation process”, Engineering Failure Analysis vol. 82, pp. 540-553, 2017.
[2] O. Bergamoa, G. Campioneb, C. Cucchiarab, G. Russoa, “Structural behavior of the old masonry bridge in the Gulf of Castellammare”, Engineering Failure Analysis, pp. 188-198, 2016.
[3] P. Foraboschi, A. Vanin, “Experimental investigation on bricks from historical Venetian buildings subjected to moisture and salt crystallization”, Engineering Failure Analysis, pp. 185-203, 2014.
[4] P. Matysek, T. Stryszewska, S. Kańka, “Experimental research of masonry compressive strength in the Auschwitz II - Birkenau former death camp buildings”, Engineering Failure Analysis, pp. 263-274, 2016.
[5] K. Shahata, T. Zayed, “Integrated Risk-Assessment Framework for Municipal Infrastructure”, Constr Eng Manage, 2016.
[6] D. Liberatorea, N. Masinib, L. Sorrentinoa, V. Racina, M. Sileob, O. AlShawaa, L. Frezzaa, “Static penetration test for historical masonry mortar”, Constr Eng Manage, pp. 810-822, 2016.
[7] AA. Adeleke, JK. Odusole, “Evaluation of the Mechanical Properties of Reinforcing Steel Bars from Collapsed Building Sites”, J Fail Anal Preven, pp. 737-743, 2013.
[8] J. Krentowski, P. Knysz, “Evaluation Aspects of Building Structures Reconstructed After a Failure or Catastrophe”, IOP Conference Series: Materials Science and Engineering, vol. 245, 2017.
[9] J. Douglas, B. Ransom, “Understanding building failures”, 4th ed. New York: Routledge, 2007.
[10] CEN European Committee of Standardization, “Eurocode6: Design of Masonry Structures (ENV 1996-1-1)”, 2004.
[11] CEN European Committee of Standardization, “Eurocode3: Design of steel structures (EN 1993-4-2)”, 2007.
[12] CEN European Committee of Standardization, “Eurocode3: Design of steel structures (EN 1993-3-1)”, 2008.
[13] S. Navaratnarajah, U. Rumeshkumar, “Effect of moisture condition on mechanical behavior of low strength brick masonry”, Journal of Building Engineering, pp. 23-31, 2018.
[14] S. Saloustros, L. Pelà, P. Roca, J. Portal, “Numerical analysis of structural damage in the church of the Poblet Monastery”, Eng Fail Anal, pp. 41-61, 2015.
[15] R. Szembrzyński, “The use of BIM technology in the process of analyzing the increased effort of structural elements”, Procedia Engineering vol. 172, 2017.
[16] T. Chyży, M. Mackiewicz, “Simplified function of indoor gas explosion in residential buildings”, Fire Safety Journal vol. 87, pp. 1-9, 2017.
[17] S. Hwang, M. Park, H. Lee, S. Lee, “Hybrid Simulation Framework for Immediate Facility Restoration Planning after a Catastrophic Disaster”, J Constr Eng Manage, 2016.
[18] E. Radziszewska-Zielina, G. Sładowski, “Supporting the Selection of a Variant of the Adaptation of a Historical Building with the Use of Fuzzy Modelling and Structural Analysis”, Journal of Cultural Heritage vol. 26, pp. 53-63, 2017.
[19] E. Radziszewska-Zielina, G. Sładowski, M. Sibielak, “Planning the reconstruction of a historic building by using a fuzzy stochastic network”, Automation in Construction vol. 84, pp. 242-257, 2017.
[20] J. Hulimka, J. Kubica, M. Kałuza, I. Galman, “Prefabricated RM facade panels - search for the safe solution”, IOP Conference Series: Materials Science and Engineering, vol. 245, pp. 1-11, 2017.