Cause-and-effect study of the structural failure of the historic complex of the St. Anna's Church in Warsaw

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Abstract. Repairs of historic buildings require the selection of such the design solutions to achieve the intended effects while ensuring the effectiveness of these repairs. This is particularly important in case of the structural failures of these facilities. Most of the conservation recommendations for renovations of cultural heritage buildings and monuments in Poland concern the preservation of the original building material, construction as well as the shape and appearance of the repaired facility [1]. The basic tasks for the designer who specifies the scope, methods and technology of the repair works is to ensure the building's safety of use and safety of its users while maintaining the conservation recommendations. The technical failure of the observation tower of the St. Anna's Church, which took place after a relatively short period of time from the major overhaul of this facility, is presented in this paper. The scope of expert and design works as well as the scope for the contractor of the repair works, that are necessary to select the proper technological solutions for this case, are given. The diagnostics of the building carried out by the authors of the article allowed to properly determine the degree of damage. This ensured the suitable selection of the design solution and further replacement of the damaged cornice of the supporting structure of this historic church.

1 Introduction

During the post-war construction of the W-Z Route, a deep excavation was not properly secured. As a result of these negligence, the walls and vaults of the historic St. Anna's Church have cracked to the level of the foundations. In addition, there was a slow slip of the apse and part of the presbytery of this Church. Probably the walls of the detached building of the observation tower of this church, especially from the north-east side, were damaged then. In 1949, prof. W. Zenczykowski carried out soil stabilization works using the prof. Cebertowicz method. The soil in the vicinity of the historic church complex was reinforced with reinforced concrete pillars and electroosmosis. Various construction works have been carried out on the façades of the tower since then. The scope of carried-out works rarely has included conservation work. The long-term impact of the low bearing soil of the slope as well as the vibrations caused by the WZ route traffic made it necessary to carry out a renovation in 1993

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on the façades of the building, including repairs of plasters, stucco and applying new paint coatings. Despite the reinforcing of the supporting structure of the church and the foundation soil stabilization in 1949, the so-called micro-displacements were observed, resulting from the overlap of the traffic vibrations and landslip tendencies inside the escarpment. This resulted in a repeated net of permanent damage in the same parts of the walls after subsequent renovations of the façade. The width of their openings was from 0.01 mm (hairline cracks) to 5 mm (cracking). Thus, an important significance, especially for the proper state of preservation of the historic post-Bernardine complex, which includes a detached tower building, had unfinished issues regarding unstable statics of the facility. The foundation of these buildings was disturbed due to the construction of the WZ route tunnel and the resulting transport vibrations. During the preliminary tests and conservation works conducted in 1992-1994, the resonance of the traffic caused vibrations was observed in the upper floors of the façade of both buildings - the church and the tower. The formation of damage - scratches and cracks is caused by the difference of physical properties of built-in construction materials resulting not only from different values of linear expansion coefficients, but also from variable resonance imbalances of transport vibrations transmitted by an unstabilized soil [4].

2 Scope of the construction and the conservation works in 2001

The expertise of the analysed facility carried out in February 2001 by the representatives of the Military University of Technology shows that the accumulation of cracks refers to the façades of the buildings parallel to the axis of the roadway with heavy traffic [4]. As a consequence of the abovementioned technological errors and micro displacements, the delamination of plastering occurs and its falling off.

A significant part of the details hanged on iron dowels (e.g. rosettes) and fixed (e.g. decorated corbels under the cornice) was being loose and cracked at the beginning of renovation works. In addition, distinct cracks, moisture of the entire cornice section as well as the presence of very weak bricks could be observed in the damaged cornice of the tower in this facility. As a consequence, it posed very serious hazard to the participants of the pedestrian traffic, which is very heavy under the walls of the tower.

In 2001, a number of conservation works were carried out. Their main aim was to renovate the façade of the tower crowned with a superstructure in the form of columns (pillars) covered with a dome - the so-called 'gloriette'. The scope of the carried out construction works included the following tasks:

- the removal of blistered, sagged plaster coatings and efflorescence on plasters,
- the cleaning of the façade and the removal of the secondary paint coatings from walls and stucco details, including disinfection of the walls;
- the repair of plasters and maintenance of stucco details,
- the applying new renovation plasters and façade colouring;
- conservation of the stone architectural details.

During the conservation works carried out at that time, the investor decided to renew flashings over the entire cornice of this tower. The existing flashings were replaced with new 0.6 mm thick copper sheets. The connections of each sheet were made to a double diamond shape. Planking above the cornices was proposed to increase the tightness. It was inserted into previously prepared gaps in the tower walls. However, this was done incorrectly because the cut resulted in the migration of rainwater into the masonry structure of the cornice. Moreover, rotten elements of the wooden structure of the soffit, constituting a soffit under the metal sheath, were replaced using lumber with a thickness of 32 mm. They were mounted on nails and impregnated with Intox S on both sides.

During the roofing works carried out in 2001, the problem of isolating a few centimetres of the wall between the terrace floor and the elements of planking over the cornice had also occurred. In order to ensure a homogeneous technological system, the same technology was used as in the repair of the insulation and the terrace floor. However, the applied rainwater drainage system did not work properly. The rainwater flowing down the gloriette pillars migrated in the bottom part into all the layers of the floor, then into the cornice. This resulted in the moisture damage of the terrace layers and the entire cornice. Increasing the weight of the cornice and cyclical changes of temperatures (cyclical freezing and thawing) were the direct causes of the structure failure that occurred on the night of 07 to 08 February 2004. It had been reported that the there was a sudden and unexpected detachment and collapse of about 4 m of the masonry cornice structure of the tower from Krakowskie Przedmieście street side.

3 Analysis of the causes of the structure failure and the proposal paquet of the repair works solutions

Repair of the damaged brick cornice with decorated corbels surrounding the building of the lookout tower of the St. Anna's Church had to be carried out in accordance with the restoration programme, which was developed by a conservator of the art works. This programme was approved by the voivodeship cultural heritage conservator. On its basis the investor obtained a permission for the execution of the construction works. The conservator also recommended a very detailed examination of the causes of cornice failure, the proposal for a change in the technology of its execution and diagnostics of the technical state of that element of the tower. A cornice in the so-called 'lightweight technology' was proposed with expansion joint damping the vibrations accumulating on the observation deck of the tower. Due to the fact that the repair programme recommended to investigate the causes for wetting the cornice structure, the local in-situ inspections were made of the following elements [4-8]:

- terrace floors (Fig. 1),
- fixing the wooden post of a gloriette balustrade (Fig. 2),
- checking the tightness of the flashing of the lower part of the gloriette (Fig. 3).

Fig. 1. Moisture of the terrace floor layers.

Fig. 2. Moisture in the fixing of the wooden post of a gloriette balustrade - the improper insulation of the wall, the terrace floor as well as the gloriette roof.

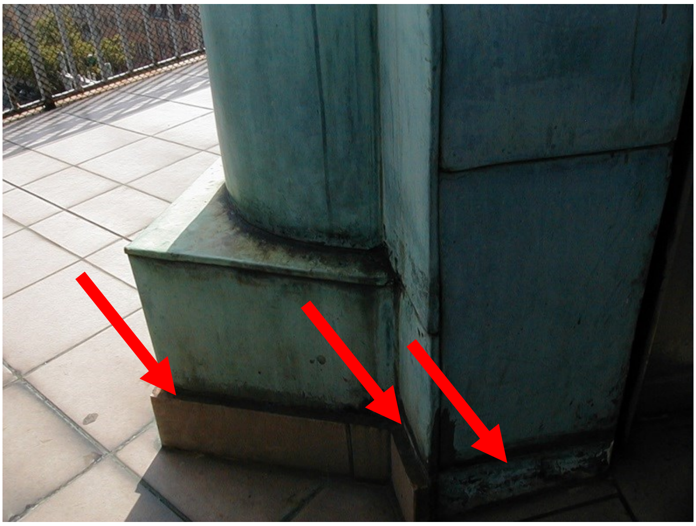

Fig. 3. Flashings of the lower part of the gloriette - visible rainwater leaks and the migration path of the rainwater to the terrace floor.

Particular emphasis was put on investigating and explaining the problem of rainwater migration under the floor of the observation deck. Based on the research, it was found that rainwater leakage, appeared as a result of [4]:

– improper drainage of the rainwater from gloriette flashing,
– incorrect attachment of the flashing around the tower terrace,
– incorrect sealing of the gloriette balustrade posts.

All sub-terrace layers have been soaked. Therefore, their weight has significantly increased and an additional load was applied on the supporting structure of the tower roof. The resulting load together with accelerated technical degradation of the structural elements were the primary causes of the element failure. In the next step, a decision was made to make a new waterproofing insulation with a flat roof of the tower building [4]. This design solution was in line with the recommendations indicated by the cultural heritage conservator, who clearly advised to take immediate actions to remove the cause of rainwater leakage into the masonry structure of the analysed building.

3.1 Repair works of the cornice

The technical condition of the tower walls under the cornice was characterized as bad. The visible cracks with width up to 3 mm were diagnosed. Built-in bricks were locally wet and were in a very poor technical condition. As a result of organoleptic macroscopic investigations, it was found that the tensile strength of these bricks was low. These bricks could be crushed in the hands under the very low pressure.

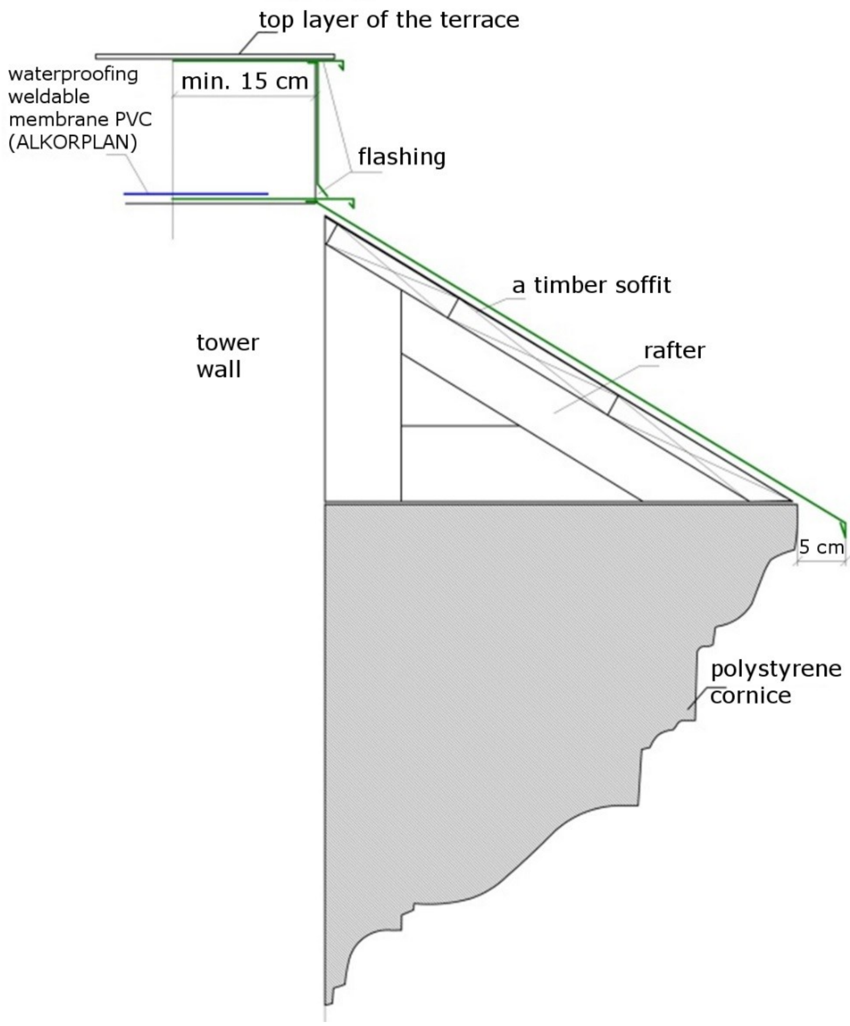

Fig. 4. Cross-section of the repaired cornice of the tower [4].

Due to the poor technical condition of the tower walls under the viewing terrace, the restoration of the cornice made of clinker brick would be a very difficult task. This would have required many steps and special treatments related to reinforcement of the weakened masonry foundation, soil, as well as the reconstruction of the complex system of cornice anchoring in the walls of the tower. The investor decided to renew flashing over the entire cornice of the tower together with the rotten wooden soffit elements.

Firstly, the damaged cornice and all the flashings together with the timber soffit elements were removed. The surface of the wall in the place of the removed cornice was levelled by making the rending coat. Then the new plasters were applied. A crucial milestone of the works was the repair of the flashing of the gloriette to prevent further penetration of the rainwater into the floor of the terrace. All terrace layers had been removed to the level of the tower ceiling. The anchoring of the gloriette balustrade posts was then sealed. New terrace layers were laid on the ceiling with its existing slope. The waterproofing insulation in the form of a weldable, flexible membrane was tightly joined with the new column anchoring insulation (liquid foil) and rolled over for flashing - Fig. 4.

A new flashing of the cornice was carried out and based on a new support structure (timber soffit). Cornices and decorated corbels were made of hard Styrofoam, which was covered with a glass fibre mesh and then anchored with mechanical fasteners - Fig. 5. The last stage was the performance of a new flashing. Finally, the cornice was painted with a silicate façade paint in the colour of the existing façade.

a)  b) 

Fig. 5. New cornice of the observation tower, a) bottom view with visible holes for mechanical connectors, b) top view with flashing of the tower ceiling.

In order to calculate the necessary number of fasteners for fixing the cornice, the design load was determined by the wind pressure [4]. In these calculations, the height of the tower, the exposure coefficient and gusting were taken into account. The number of fasteners was designed not due to the tearing off, where two fasteners (M16 threaded bolt) were sufficient to transfer the load over the length of one tower wall, but due to the pressure surface. One wall should have 15 ÷ 16 connectors (M16 threaded bolt). Their layout has been designed in accordance with the scheme presented in Figure 6.

In turn, to calculate the number of fasteners used to attach the flashing structure to its formwork (wooden soffit), both climatic loads, i.e. wind pressure and snow load, as well as the design load due to the deadweight of the structure were taken into account. Using the 'Force Method', the maximum value of the reaction force acting on a single anchor bolt was calculated. Due to the tensile, the force value was 0.39 kN, whereas due to shearing 0.56 kN respectively. Similarly to the anchoring of the cornice, M16 screws [4] were used.

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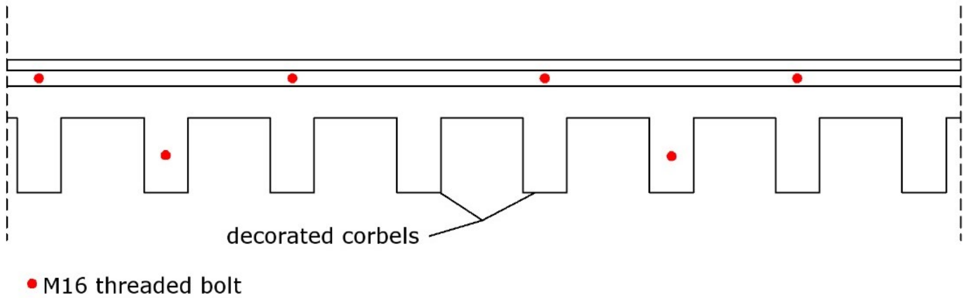

Fig. 6. Scheme of cornice anchoring on each façade with mechanical fasteners.

3.2 Repair works of the observation deck

Due to the fact that after the renovation in 2001, the leakage of rainwater was observed, the new drainage system was designed in order to avoid a similar structure failure in the future. A very crucial element of the repair works was to ensure the proper safety of the foundation of the gloriette pillars as well as the supporting structure of the bells. According to the technology approved by the investor, the repair of the observation deck was carried out after previous disassembly of all existing layers of the terrace. Firstly, the foundations of the balustrades around the terrace as well as the pillars of the gloriette were reinforced. This required the removal of the lower part of the flashing of gloriette pillars up to a height of approx. 30 cm along with the cutting of the timber soffit. The foundation reinforcement of the columns was made by using steel anchors (two by each pole) bolted to the roof of the tower [4]. In order to obtain continuity of waterproofing, the designer proposed the steel anchors of terrace columns to be protected by the airtight concrete and the liquid foil - Fig.7.

a)

b)

Fig. 6. Designed foundation for gloriette pillars, a) steel anchors, b) protection of the anchor with the airtight concrete.

Then, after levelling the surface of the supporting structure of the flat roof, new flashings were made and a new waterproofing of the terrace along with insulation of the roof of the tower. A cross-section of new terrace layers is shown in Fig. 4.

4 Discussion

Often, construction experts or specialists who develop the assessment or technical expertise of the moisture-caused damage in the construction elements of buildings draw their conclusions based on incomplete information about the supporting structure of the secondary elements of these objects. It sometimes happens that the proposed solutions to the problem of moisture are inadequate to the causes of damage and focus only on the historic aspect of the object [9]. In the analysed case, the structure failure occurred just after three years since the renovation of the flat roof of the tower building. The pre-existing (before the structure failure) problem of waterproofing the vertical wall fragment of the construction has been treated very superficially. The proposed solution enabled only to cut off the inflow of rainwater in the horizontal direction. This solution, combined with leaks in rainwater drainage, improper installation of the flashing around the entire tower terrace and leaky embedment of the gloriette balustrade posts, caused the entire structure to be wet as a result of water migration into the masonry construction elements.

After the building failure a series of organoleptic macroscopic examinations and local in-situ inspections of the terrace elements were carried out. This allowed a proper diagnosis, identification of the all cause-and-effect issues and study of the case. The proper assessment of the reasons for the emergence of rainwater in the layers of the terrace and in the cornices of the tower allowed in turn the selection of the most suitable technical solutions for solving the problem.

Described and presented in this paper case required a detailed assessment of both the technical condition of the masonry structure of the St. Anna's Church, its observation tower as well as the reasons for the structure failure [4]. The results of the carried-out macroscopic examination of the structure as well as the inspection of its elements allowed for the development of an state-of-the-art solution involving the conversion of a brick cornice into a cornice made of light materials.

The implementation of the new waterproofing insulation of the terraces of historic buildings is associated with great responsibility. Their improper design and construction can even lead to a structural failure, an example of which was the presented case of the tower of St. Anna's church in Warsaw. The proposed solution in the form of not only a tight floor, but also the insulation laid directly on the ceiling of the tower, allowed effective drainage of rainwater.

5 Conclusions

Conducting repairing and renovation works on historic buildings, constituting the cultural heritage of the country, is an extremely complex task. This applies to both regulations related to the protection of cultural heritage buildings and monuments, as well as technical issues related to interference in the structure and its individual elements. Particular attention should be paid to the strength parameters of built-in materials, the nature and behaviour of the structure and the possible impact of external factors that may arise [1, 9]. When carrying out repair works related to the implementation of an effective drainage system for terraces of historic buildings, it is necessary to take into account the necessity to remove all possible sources of water within the structure and its vicinity [10].

The proper diagnosis of the causes of moisture and their consequences for the structure behaviour, as well as the assessment of possible repair systems, enables the selection of the most suitable solution that will ensure the effectiveness of repairs over a very long period of time. This requires both the experience and the knowledge in this specific area of the civil engineering field. The reconstruction of the cornice structure in the analyzed case would involve the practical demolition of the entire upper part of the tower. The proposed solution has allowed not only to preserve the appearance and the original shape of the tower from before the structure failure but also enables to ensure the safety of the structure and its users.

References

1. R. Chmielewski, L. Kruszka, Case Stud. Constr. Mater., **3**, pp. 92-101 (2015)
2. L. Binda, A. Saisi, C. Tiraboschi, Constr. Build. Mater., **14(4)**, pp. 199-233 (2000)
3. B. Balduzzi, D. Mazza, D. Papis, Ch. Rossi, P.P. Rossi, *Structural Analysis of Historical Constructions* (New Delhi, 2006)
4. R. Chmielewski, L. Kruszka, *Expertises and technical opinions in the area of building construction* (WAT, 2005-2017) [in Polish]
5. Janowski Z., *Zasady diagnostyki konstrukcji murowych w pracy rzeczoznawcy budowlanego* (Kielce, 1996) [in Polish]
6. A. Saisia, C. Gentilea, A. Ruccolo, Procedia Eng., **199**, pp. 3356-3361 (2017)
7. G. Barluenga, F. Estirado, R. Undurraga, J.F. Conde, F. Agua, M.Á. Villegas, M. García-Heras, Constr. Build. Mater, **54**, pp. 39-46 (2014)
8. S. Churilov, *Experimental and Analytical Research of Strengthened Masonry* (Doctoral dissertation, University Ss. Cyril and Methodius, Skopje, 2012)
9. L. Kruszka, MATEC Web of Conferences, **174,** 03013 (2018)
10. R. Chmielewski, P. Muzolf, MATEC Web of Conferences, **174,** 03013 (2018)