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REMAINS OF URBAN HERITAGE DEFENCE STRUCTURES – CONSERVATION, MONITORING AND USE

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Abstract. *Heritage masonry defence structures, which have survived to the present day, are typically used for purposes other than those originally envisaged by their builders. This is especially so in the case of the various elements of defensive walls, which have been adapted for use for residential, public service or storage purposes. Long periods of such use impacts the durability of these structures. Durability is closely related to improper maintenance of a building, changes in the type and value of external loading (including dynamic loading coming from, e.g., intensive street traffic), repair and "modernisation" work based on materials with mechanical, thermal and moisture parameters significantly different from the materials originally used. At the time of their construction, masonry defence structures were built of materials not susceptible to environmental pollution, which is nowadays an ever-present in town centres in most regions of the world.*

For the purposes of discussing the problem presented above, the paper focuses on examples of masonry defence structures, which are the remains of medieval and later defence walls located in a number of towns and cities in Poland and characterised by an unsatisfactory technical conditions.

The paper presents methods of repair, conservation and strengthening of heritage masonry defence walls which are used today and which are consistent with prevailing conservation doctrine. Methods for monitoring technical conditions are discussed. All the actions discussed are aimed at maintaining durability and utility of structures for future generations.

1 INTRODUCTION

Defence fortifications or their fragments (defence walls) were built to protect towns and their residents or sites of military importance, from potential enemy attacks. The first fortifications date back to ancient times, however the most prolific building dates from the Middle Ages. The fundamental assumption was that defensive walls would not only be resistant to environmental elements but also to military action aimed at purposeful destruction, employing military equipment. That is why the structures built were massive, durable and able to withstand various types of loading, even extraordinary loading. The authors of the paper set out to verify if the defence structures were really characterised by all these features.

Undoubtedly, defence walls constitute an element common to all fortifications, especially those constructed in the Middle Ages. Their basic function was to provide security to defence forces and everything what was located within the area enclosed by the walls. Over time the role of defence structures faded. By the 17th century, changes in military tactics and introduction of new types of weaponry rendered defence structures practically useless.

Historic masonry defence structures were constructed using a variety of technologies and materials [1]. For the purpose of this paper, the authors have introduced a classification of defence wall construction systems. The masonry materials used have been classified as: bricks, hewn stones and irregular stones. This classification is based on the surface geometry and texture of a building element. An additional distinction between single-layer and multi-layer walls enables description of the specific requirements for wall strengthening by means of in-filling, which translates into lower durability parameters [2].

2 ANALYSIS OF TECHNICAL CONDITION OF DEFENCE WALLS

This paper discusses the technical condition of defence structures located in southern Poland. Surviving fragments of defensive fortifications of the towns of Opole and Koźle are presented. These are not the only towns in this part of Poland where the remains of old defence structures can be found. Well preserved fragments of fortifications are located, among others, in Korzuchów, Bolesławiec, Dierżoniów, Kłodzko, Nysa or Paczków – known as the “Polish Carcassonne” as its defence walls are in excellent condition, having been well preserved.

The Opole fortifications (fig. 1, 2) were rebuilt and modernised several times in the period between the 13th and 18th centuries and represent an interesting example of the development of the practice of fortress construction in Poland. Walls were built of gothic ceramic bricks in a double-strecher bond (13th century) and single-strecher bond (14th century) with strongly fired tie-bricks. The external wall face consists of full ceramic bricks with lime mortar. The inside of the wall is filled with split lime stone, bound with lime mortar. The wall is 1.90 ÷ 2.25 m thick. Originally, the wall had a cladding of bricks in Polish (gothic) bond and Slavic/ Slavonic bond in places. It was originally 6 to 9 m high.

In Opole, a large fragment of the western part and a small part of the eastern part (near the upper castle) of the defence walls have been preserved to the present day. Heritage masonry defence structures, which have survived to the present day, are typically used for purposes other than those originally envisaged by their builders. This is especially so in the case of the various elements of defensive walls, which have been adapted for use for residential, public service or storage purposes. Long periods of such use impacts the durability of these structures. Durability is closely related to improper maintenance of a building, changes in the type and value of external loading (including dynamic loading coming from, e.g., intensive street traffic), repair and “modernisation” work based on materials with mechanical, thermal and moisture parameters significantly different from the materials originally used. The massive appearance of the walls can be misleading, as not all were built as monolithic structures of ceramic bricks, which at the time of building were difficult to obtain and expensive. Defence walls were often constructed as mixed multi-layer structures and comprised materials which are susceptible to contemporary environmental pollution. In the past, they marked out the boundaries of towns, today they are located in their very centres.

Figure 1: Western side Opole defence walls – the northern fragment next to a tower.

Figure 2: Western side Opole defence walls – the southern fragment.

The multi-layer wall structure is presented in fig. 3, 4. Despite a number of efforts to investigate the interior of the structure with non-destructive methods, a more detailed analysis was possible only after an eastern part of the wall face collapsed in March 2012. A heterogeneous wall with a minimal bonding can be observed. The assumption is that the external wall face was made of bricks, serving as retaining structures for securing loose lime stones from spilling out of the wall. The wall has a significant number of cracks and fissures with damp along its whole length. The cause is changing atmospheric conditions which impact the wall surface and penetrate into the interior of the structure in different ways at different times of the year, leading also to problems with foundations. Even tiny leaks which appear in places where pointing is missing or in brick fissures can cause significant cracks and structural damage resulting from biological corrosion of the external materials and wall filling, as well as from water freezing inside the cracks.

Today, the wall is not a monolithic structure. It consists of three separate vertical parts, i.e. two external leaves and an in-filled (rubble) core. Wall surfaces are made of ceramic bricks with lime mortar, with new brick fragments (resulting from more recent repair work) laid with contemporary modified mortars. The core of the wall is made of lime stone bound with lime mortar. The mortar has lost its binding properties across much of the core surface, with the result that the core material acts as a typical filler, just as in the case of containers filled with loose material which generate not insignificant horizontal pressure on vertical wall surfaces, which are ½ a brick in thickness. An important factor which determines wall stability and safety is its fragility and the vertical loading value, which in a situation where there is no bonding of rigid building elements exceeds all limitations of wall building standards, including prevailing standards [3]. Moreover, not one of the external leaves has kept its vertical form. Concave wall deformations range between 4÷22 cm along the height of the structure.

The fortifications of the castle in Koźle (fig. 5), which were analysed, differ from the example described above in that they were constructed as a whole with bricks with lime mortar and stone foundations (fig. 6). Their technical condition is also very bad for reasons similar to those of the Opole case. The oldest fragments of the Opole Piasts' castle in Koźle date back to the first half of the 14th century. The castle was located on the left bank of the Oder river, on a man-made embankment which reached a height of 4 m in places. The stronghold was built on a quadrangle plan with three corners cut to give an impression of slightly rounded walls. A square tower protruding from the wall line was built in the fourth (south-east) corner. The walls were surrounded by a moat. The gate to the castle was located in the eastern wall next to the tower. A tower comprising residential quarters was placed in the middle of the main bailey. The castle had also an outer bailey. In the 16th century the castle was rebuilt. A new residential building was added and a tall bastille in the south-western corner. The outer bailey was rebuilt in the subsequent century and a whole southern wing was added to the castle. A new gate leading to the courtyard through the southern wing was built in the 19th century. After 1743, the Prussians established a big fortress comprising the castle and the town in Koźle. In 1915 more architectural changes were introduced. The castle was destroyed during the World War Two. Only fragments of the perimeter walls, tower foundations and the remains of two castle wings have survived to the present day.

Figure 3: Eastern part of the wall and its damaged 8 m long section.

Figure 4: Detail of damaged defence wall.

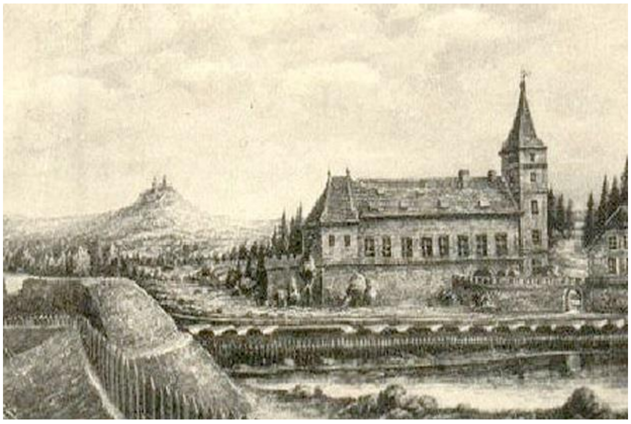

Figure 5: Kędzierzyn-Koźle castle – a 19th century drawing. [4].

Figure 6: Kędzierzyn-Koźle castle – view of defence walls, beginning of the 20th century.

The wall has had no protection against moisture from both surface and ground waters for a long time. The ground water table is located around 20 cm below the level of the foundations but in so called "wet periods" it can rise by approximately 1 m above the level measured during the analysis. That is why it is not possible to rule out the impact of ground waters on the structure. Due to the fact that the walls are more than 2 m thick, there are problems with access to all their surfaces and so it is not possible to ensure continuity of horizontal and vertical damp-proofing which potentially could be introduced in the future. For this reason, the recommendation was to introduce a perimeter drainage system for collecting water and channelling it outside the area so that it no longer impacts the walls. Another recommendation involved adding a layer to separate filtration in- fill from the wall which would allow freer evaporation of moisture from the structure. This could be a layer of damp-proofing membrane with studs fixed to the surface of the wall put into place prior to in-filling drainage channels with filtration gravel. Only the membrane studs should be pressed against the side surface of the wall and the membrane must not be visible from the outside. A necessary safety precaution during this type of specialist work involves limiting the extent of the wall exposed to 2.0 ÷ 2.5 m, as there is a danger that the exposed structure may lose its stability. The minimum distance between exposures (to the open air) should be at least 1.5 times the length of the exposure, i.e. it should be no less than 3 m long.

The (drainage system) solution described above can prove inefficient when there is a temporary rise of the ground water table, but such situations are not frequent. The walls will be drying out over the long term as the amount of water infiltrating from the surrounding area to reach them will be reduced. At the same time, this solution enables evaporation of water, which has accumulated inside the wall. The special character of the building, the technology used in its construction and its heritage value all translate into difficulties in using injection diaphragms (horizontal and vertical) in connection with other water-proofing methods for securing the structure from incoming water. Such interventions do not guarantee effective protection of the building due to variations in ground level around the structure and the impact of other building in the vicinity. They would also be very expensive.

3 MATERIAL ANALYSIS

Highly advanced corrosion of bricks and mortar prompted sampling of masonry elements for laboratory analysis aimed at determining brick absorbability, their actual moisture, wall compression strength and salt content.

The tests conducted determined that the weight absorbability (n_w) for bricks from the Koźle stronghold ranged between 13.87 ÷ 18.52 % (average value was 16.27 %), and their porosity p_o ranged between 32.10 ÷ 38.00 % (average of 35.22 %). Measurements conducted with an ultrasound hygrometer indicated mass moisture U_m at a level of 16 ÷ 18 % and the wall was classified as wet (according to classification presented in tab. 1).

Tab. 1. Classification of masonry elements according to moisture level

Mass moisture U_m	Classification
Less than 3%	Wall with acceptable moisture level
3% - 5%	Wall with raised moisture level
5% - 8%	Wall with medium moisture level
8% - 12%	Wall with high moisture level
More than 12%	Wet wall

Another reliable indicator of masonry stability and durability is its resistance to compression. The defence walls investigated are massive structures, but represent structures which are technically worn-out and must contend with not just their own dead load but also a number of additional external loadings, including street traffic and buildings that have been placed on top of them. The type and size of additional loading varies for different wall sections. Brick compression tests indicate considerable variations in strength of wall samples, which range from around 3 up to 12 MPa. The average parameter value of 5 MPa was taken to be representative of brick strength. The technical condition of mortar also varied considerably. Some fragments of the wall had no pointing left whatsoever, whereas other fragments had lime mortar pointing with gaps in-filled with cement. Taking into account the original condition of mortar, a strength classification was adopted at a level of 0.8 MPa, with some fragments measuring 0.0 MPa.

Tab. 2. Salt content levels in brick samples

Sample no	chlorides	sulphates	nitrates	nitrites	pH
	[%]	[%]	[%]	[%]	[-]
1	0.685	< 0.200	0.500	-	6.0
2	0.118	0.250	0.050	-	6.0

Salt content levels determined in brick fragments presented in tab. 2 significantly exceed acceptable levels as shown in tab. 3 in accordance with [5][6], and impact the technical condition of the walls.

Tab. 3. Acceptable levels of salt content in masonry elements

Salinity level	chlorides	sulphates	nitrates
	[%]	[%]	[%]
low	< 0.03	< 0.10	< 0.05
medium	0.03 ÷ 0.10	0.10 ÷ 0.25	0.05 ÷ 0.15
high	> 0.10	> 0.25	> 0.15

Test results for brick samples relating to weight absorbability and porosity indicate high potential for water accumulation (from precipitation, capillary rise from the ground, surface waters etc.) which has a direct and indirect impact on the masonry elements from which samples were taken.

The primary source of moisture in the defence walls is water penetrating vertical external wall surfaces above ground level, as well as surfaces adjacent and below ground level. This was demonstrated through mass moisture measurements conducted for the band of wall near to ground level. Excessive moisture of the wall is due to an absence of any type of water or damp-proofing. Groundwater penetrates inside the wall through external surfaces as well as those through those below ground and is "transported" upwards by capillary rise. Aside from water, capillary processes transport salts dissolved in the water. As water evaporates on wall surfaces, salt concentration increases and is deposited in brick spaces. This results in surface and deep-seated crystallisation of salts. Increasing volume of salt crystals generates tensile stresses inside brick fragments and as a consequence affects whole inside of the wall. The height to which water rises due to capillary action depends on several factors, such as *inter alia*: diameter and structure of capillaries, temperature of the wall and its surroundings, relative air humidity, salinity level of the wall, potential for water evaporation through vertical external and internal wall surfaces.

In masonry walls with no damp-proofing course, the height of capillary rise can be limited by reducing or eliminating the stream of water reaching the wall and enabling intense water evaporation through vertical wall surfaces. Salt crystallisation both inside and at the surface of the wall which always accompanies such processes has a very negative and destructive influence on masonry. Another significant danger for damp walls is related to periods of low temperatures, when water accumulated in brick and mortar spaces freezes and destroys their internal structure.

4 STABILITY CALCULATIONS

Results of material analysis and static and strength calculations for the wall structures investigated indicate unequivocally that there is a high probability of successive localised wall damage which may result in a collapse of the whole structure.

Verifying calculations indicate that despite many defects, both walls are capable of withstanding safely the loading bearing pressure to which they are subjected on account of their massive scale. Unfortunately the technical condition of bricks is so bad that it is possible to break them by hand. Their compression strength was estimated at 5 MPa, which is equivalent of the strength of the lowest class of ceramic bricks (hollow bricks) used for building partition walls. Verifying calculations were conducted in accordance with the standard [3]. The wall surface layers, which are now separating from the core indicate that the bonds between individual layers of the wall have been lost and need to be restored.

5 METHODS FOR CONSERVATION AND STRENGTHENING

The most favourable situation in applying strengthening systems is when there are brick walls with an even surface and a texture which allows adaption of surfaces. Hewn stones are relatively regular (depending on the quality of work and level of advancement of historic tools used) but their texture on the outward facing wall may be a source of problems during strengthening and structural work. The strengthening elements introduced (bands or surface plates) on uneven surfaces will additionally have to bear localised stress concentrations. Stone walls comprising an irregular arrangement of elements, consisting of pebbles or split stones, require more complex interventions. The way elements are arranged in the wall limits significantly the options for selecting the most appropriate strengthening method.

Materials which have been used traditionally to strengthen masonry structures include steel, concrete, lime and cement mortars. Each of these materials has specific characteristics which define the stability behaviour of the given form after strengthening.

Steel is one of the most commonly used materials both for repairing and strengthening masonry structures. There are a number of methods which make use of the elastic character of the material, its high resistance to stretching and the easy application of strengthening elements. Traditional methods often use steel with elastic and ductile properties that possess an explicit ductility limit for stresses of 235 MPa. Innovations in using steel require raising tensile resistance from 1.0 GPa (*Helifix* type drill rods) to 3.2 GPa (flexible connectors *UHTSS – Ultra High Tensile Strength Steel*, which are applied in the following systems: SRP – *Steel Reinforced Polymer*, SRG – *Steel Reinforced Grout* or SWM – *Steel Wire Mesh*). Despite numerous advantages, due to a high Young's Modulus value, the application of steel solutions must take into account deformation limitations of strengthened structure when selecting strengthening technology.

Strengthening intervention using traditional concrete is achieved through application of additional coats (often in the form of reinforced concrete) or beams and pillars. The fastest way of covering a wall surface with a coat of reinforced concrete involves application of shotcrete. The current definition of shotcrete is as follows: "concrete or mortar pneumatically projected at high velocity onto a surface as a construction technique". An appropriate system of linkages must be developed to ensure a proper interaction between the original structure and the strengthening layer applied. One interesting solution involves joining the historic masonry wall with the reinforced concrete structure using a system of steel links (stirrups and hangers) glued to joints between masonry elements with epoxy adhesive. Spot-use of adhesive substances (based on polymers) is a solution which compares favourably with mineral-based application systems. However, strengthening heritage structures with concrete is hard to accept due to prevailing principles of conservation doctrine, as well as due to the physical properties of the materials involved. Use of concrete is totally unacceptable in situations where brick or stone structures are directly exposed to atmospheric elements, especially precipitation (which washes out of calcium carbonate).

Contemporary materials with a fibrous structure provide an alternative to traditional methods for strengthening architectural structures and can be used in cases where a significant increase of load-bearing capacity is necessary. Mechanical properties of the fibres used for strengthening with composite materials enable tensile levels and bending stresses to be reduced, and consequently, increasing the loading-bearing capability of structural elements. The primary feature in classification of composite materials relates to the type of fibre used. Special attention needs to be given to composites based on carbon, glass, aramid and basalt fibres. Their most important advantage is the highly positive relation between durability and mass, as well as ease of transportation and installation. These materials are available as straps (most popular), meshes with separated fibres, mats or rods. In the case of straps, rods and mats with a polymer matrix (thermoplastic and thermosetting resins) the name of the material comprises the name of the primary substance used (e.g. *Carbon/Glass/Aramid/Basalt Fibre Reinforced Polymer*). An example of a mesh based on carbon fibres with a mineral matrix is *FRCM (Fibre Reinforced Cementitious Matrix)*, [7], [8], [9], [10], [11].

An interesting solution is the use of natural composite materials such as jute, flax, hemp or broom. Biological materials are characterised by a low Young's Modulus value (18 – 21 GPa) and low tensile resistance (500 – 700 MPa), which ensures in most cases the required level of deformation capability coupled with an acceptable durability parameter. Natural composites are available as mats submerged in a mineral or polymer matrix. These materials are environment friendly both during the process of production and utilisation, which is an important factor.

Substances based on concrete paste cement free mortars with increased durability are often used for strengthening building structures. Concrete based substances constitute mineral matrices for fibrous composites for which polymer matrices should not be used due to the prevailing conditions (high temperature) or application methods (mechanical joints). Mineral matrices with appropriately selected constituent elements indicate physical properties (diffusion coefficient) similar to those of historic walls (especially those made of brick) which means that such matrices can be used for structural conservation of heritage buildings. They can be also used in an injected form which penetrates into the structure of the wall and bonds with it. Cement free mortars with increased durability are primarily used for changing joints in an existing masonry structure. The material due to its constituent parts (lack of cement, epoxy additives, mineral and silica hardeners) possesses ability to deform, which is coupled with high durability. Compression strength ranges between 20 and 90 MPa, [2].

In the case of the defence walls investigated, it was concluded that repair of damaged fragments would not solve the problems with load-bearing capacity and stability of the structure as a whole. Consequently, a much wider scope of repair and strengthening work was recommended. The work conducted will not change the appearance of the walls or decreasing their historical and heritage value and attractiveness for tourists. Additional investigation of foundation sub-soil indicated that the walls had not been built on load-bearing sub-soil. The building structures were deemed to require full structural strengthening both at the level of their foundations and along their whole height and thickness. In the case of the Opole defence walls, an additional strengthening proposal was to introduce a palisade topped with a pile cap and cantilevers for supporting the whole wall structure in the bottom part (figs.7 - 11). Two leaves on the external wall face were joined together with transverse steel anchors, each one ending with ceramic supports made from original bricks (fig. 12, 13).

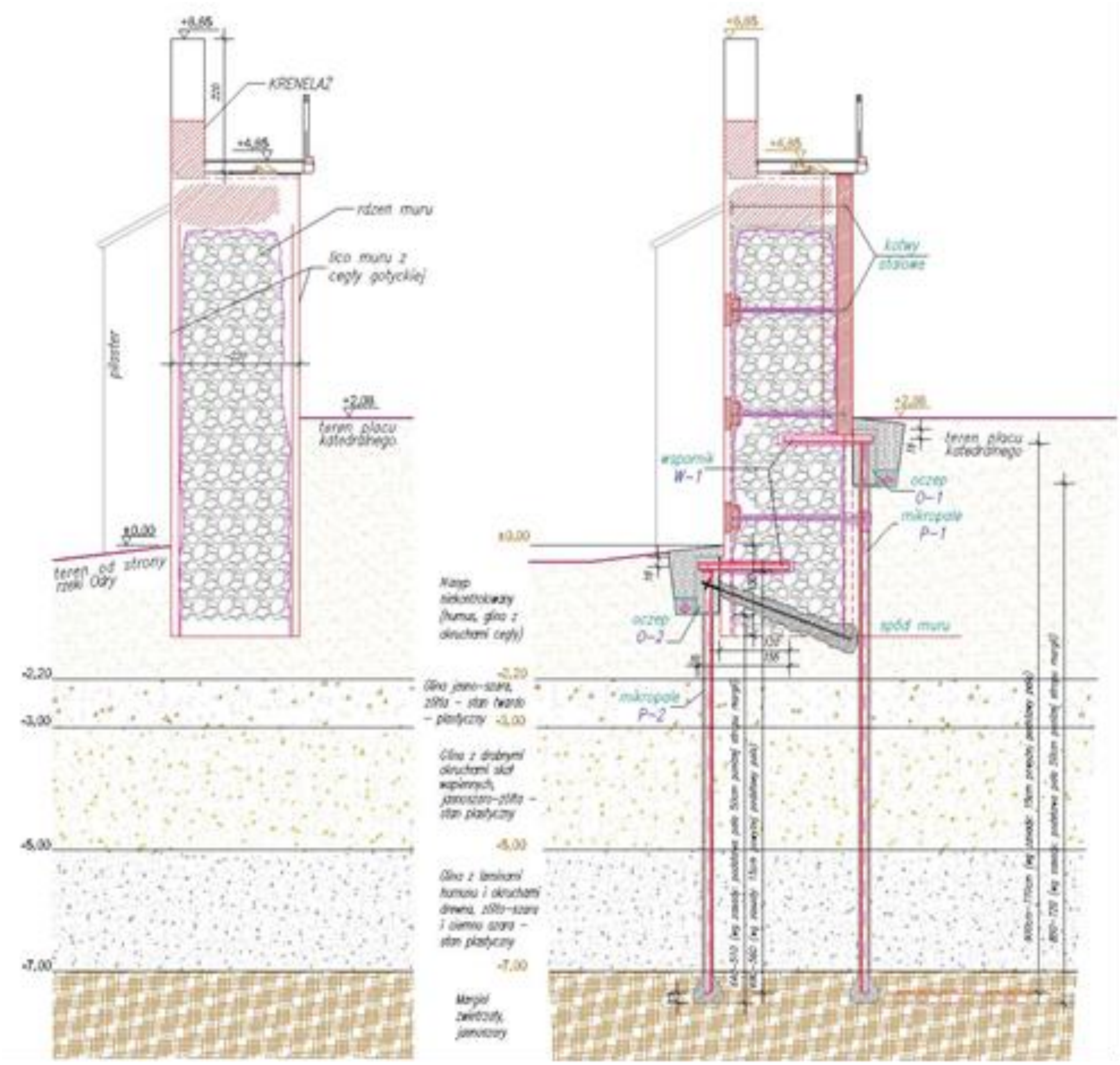

Figure 7: Wall cross-section before and after strengthening.

Figure 8: Infilling masonry in collapsed wall.

Figure 9: Drilling of holes and installing pile cantilevers.

Figure 10: Pile cap reinforcement.

Figure 11: Completed pile cap reinforcement with a drainage system protective layer.

Figure 12: Elements joining together external leaves – anchor arrangement.

Figure 13: Elements joining together external leaves – an anchor.

The wall fragment which had collapsed has been rebuilt. But instead of applying the original external half-brick thick leaf, a massive wall one brick thick was constructed and strengthened internally with pilasters. Internal steel anchors (made of stainless steel) have support elements at each end made from original bricks taken from the wall. The supports have been strengthened with Ruredil X MESH C10/M25 composite mesh glued with mineral mortar (fig. 9). An ending made of stainless steel to be linked directly to the bricks and in supporting joints was made of stainless steel (fig. 9). The strengthening system described above represents only one stage in protecting the damaged building structure from further degradation. Such structures have to be secured from atmospheric conditions, engineering appropriate inclination of flat surfaces to enable total extraction of water from precipitation and full hydrophobisation of surfaces penetrated by external moisture.

6 MONITORING

The term "monitoring" defines a system of techniques and methods measuring stability behaviour of a structure. There are various classifications of monitoring based on different criteria, e.g. the aim of monitoring, type of measurements (static, dynamic), character of tests (destructive, quasi-destructive and non-destructive tests), monitoring period etc. According to

[12], the most important monitoring technologies can be classified as assessing static or dynamic behaviour of a structure over a period of time. Joining these technologies into one hybrid system appears to be the most effective solution for tracking changes (also those resulting from delayed phenomena) with a focus on the geometry of a building and non-destructive testing of structural materials. Monitoring technologies for building geometry include: laser scanning, global positioning system (GPS), photogrametry and teledetection technologies. The scope and type of non-destructive testing is very wide and includes: thermography, georadar research, tomographic research and x-rays, flat-jack testing, ultrasonographic research and others.

In these situations, it is best to focus mainly on monitoring wall geometry. It is proposed that verification of stability behaviour is undertaken using 3D scanning as this is a fast and non-invasive method for monitoring building structures for the purposes of assessing the effectiveness of solutions adopted and identifying areas, which might require intervention for structural strengthening in the future. The digital information generated is also a valuable tool for heritage resource conservation. The models developed can be used in the future for assessing the stability behaviour of the structure and for identifying factors contributing to its destruction [13].

By repeating 3D scanning and superimposing scans on one another, it is possible to identify displacements and development of cracks. This provides an effective tool for monitoring structural behaviour without the need for physical intervention into building elements. The technology can be used also for registering degradation of surfaces with an accuracy at the level of millimetres, such as brick or stone wall surfaces.

Following realisation of a conservation intervention into the building structure, it is recommended that periodic scanning is undertaken to verify whether the process of deforming the defence wall structures has been arrested.

7 CONCLUSION

Despite appearances, not all defence structures are today heritage estates focused exclusively on tourism. Many have a functional role, which is quite different from that envisaged originally. As building structures, they were built to withstand large and dynamic loading, which can today be classified as out of the ordinary. If they survived destruction from military operations, which they were originally designed to withstand, they had to deal with impacts of atmospheric conditions, human destruction and time. The massive nature of a building structure is not always an indicator of high staying-power and permanence. Damage or total destruction can be caused be small distortions in the form of micro-cracks, fissures or cracks on fragments exposed to rain-water and also to groundwater. Every type of intervention into existing structures is significant, whether it be reconstruction, adaption for a different purpose, such as commercial use, or simply inappropriate management. The absence of conservation intervention or repairs leads to intensification of technical degradation. The examples of existing defence structure discussed in this paper indicate that such buildings still exist, but that their number and volume are decreasing. The lack of appropriate care contributes to their degradation or to loss of their heritage character as uncontrolled renovations proceed. In this way, they lose their authenticity.

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