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Reconstruction of the Right Ravelin Caponier of the Boyen Fortress in Giżycko – Conservation and Structural Analysis

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Abstract

The article presents the reconstruction project of the right ravelin caponier of the Boyen Fortress in Giżycko — a 19th-century Prussian fortification — with particular emphasis on conservation and structural aspects. In 2022, the structure suffered a major building failure (collapse of a wall and vaults), which necessitated comprehensive repair and restoration works. An analysis of the caponier's condition prior to the failure was carried out, and the causes of the collapse were identified. A conservation program was developed, including the stabilization and anastylosis (reconstruction from preserved original elements) of the historic structure. The design assumptions for the reconstruction are presented, along with an analysis of the materials used (bricks and mortar) and the structural and masonry solutions ensuring the durability and authenticity of the monument. A detailed numerical analysis using the Finite Element Method (FEM) was performed in Autodesk Robot Structural Analysis Professional, modeling the caponier's vaults and walls under permanent and service loads.

Keywords: Fortification Conservation, Masonry Vault Reconstruction, Structural Failure Analysis, Finite Element Modelling (FEM)

1. Introduction – Historical Outline of the Boyen Fortress and the Caponier

The Boyen Fortress in Giżycko (Feste Boyen) is one of the key examples of nineteenth-century military architecture in the former East Prussia [1][2][3]. Its construction began in 1843 at the initiative of King Frederick William IV and was completed after more than a decade, in 1855. The location on the narrow land isthmus between Lakes Kisajno and Niegocin was deliberate: it enabled control over major communication routes while providing natural protection against potential attackers. The entire fortification complex was designed as an irregular six-pointed star, characteristic of late bastion-type fortresses. The structure is surrounded by a dry moat and a Carnot wall extending over 2 km. Within an area of approximately 100 ha, a series of service buildings was erected—barracks, storage facilities, workshops, and granaries—forming a self-sufficient military organism capable of supporting a garrison of 3,000–4,000 soldiers. The system of six bastions was named after the motto and given names of General Hermann von Boyen: Leopold, Ludwig, Hermann, and Schwert (Sword), Recht (Law), and Licht (Light) [2][4]. Within the fortifications, four gates were constructed: the Giżycko Gate, Kętrzyn Gate, Powder Gate, and Water Gate, along with advanced

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outworks—ravelins that protected the approaches to the fortress. Integral to these outworks were caponiers enabling flanking fire along the moat [3][4]. The ravelin caponier was a typical fortification structure: a low, massive building with vaulted interiors, positioned at the base of the ravelin and equipped with a system of embrasures and firing chambers. In 1854–1855, two such structures were built—at the ravelins of the Kętrzyn Gate (Front III) and the Powder Gate (Front IV). The right ravelin caponier of Front III—the subject of the present study—was built of fired brick on a rectangular plan. Its interior featured segmental and cross vaults, while the exterior walls were equipped with rifle embrasures enabling defence of the moat. Evidence suggests that in its original form the caponier was equipped with two firing levels. At the end of the nineteenth century, during a modernization campaign triggered by the development of rifled artillery, parts of the structure were reinforced by adding additional concrete or reinforced-concrete layers above the vaults to increase resistance to shelling. Material and iconographic analyses indicate that the caponier discussed here may also have received such an additional protective layer, affecting both its durability and its dead load. During the First World War, the Boyen Fortress was not a direct target of military operations; instead, it served as a logistical base and observation point during the Tannenberg campaign. After 1918, it lost its military significance; some buildings were adapted for use as a military hospital and offices of intelligence services. After the Second World War, the complex was taken over by the Polish Army and later used by civilian enterprises, which contributed to the degradation of many structures. Since 1975, the Boyen Fortress has been listed as a protected monument, and systematic conservation efforts have been underway since the 1990s. Today, the site combines museum, educational, and cultural functions, remaining one of the most important elements of the military heritage of the Masurian region.

2. Existing Condition Prior to the Failure and Causes of the 2022 Structural Collapse

Condition prior to the failure:

Before the 2022 collapse, the right ravelin caponier of the Boyen Fortress was in a state of partial ruin and long-term neglect. Due to the absence of systematic conservation and protective works—typical for many Polish fortifications [5][6]—the structure was exposed to progressive deterioration caused by environmental factors [7] (rainwater infiltration, freeze–thaw cycles) and loads for which it had never been designed.

The July 2022 collapse:

In mid-2022 a sudden structural failure occurred. During the night of 18–19 July 2022, near the Kętrzyn Gate, a significant volume of soil slid downward, causing a section of the road running above the caponier to subside. As a consequence, the front façade of the semi-ravelin caponier collapsed together with fragments of its vaults (Fig. 1).

Fig. 1. Condition of the right ravelin caponier immediately after the collapse (19 July 2022).

Causes of the failure:

Determining the precise causes required technical investigations (including geotechnical studies) and expert assessments. However, initial observations already indicated a long-term accumulation of adverse factors. The most probable direct cause was overloading of the structure due to the passage of a heavy vehicle (a lorry) along the road situated above the caponier. A clear tyre mark of a large vehicle was visible at the edge of the resulting landslide, suggesting that the weight and vibrations associated with the vehicle's movement could have triggered instability in the already weakened structure [5][6].

It is important to emphasise that the caponier had never been designed to carry high-tonnage vehicular loads; in the nineteenth century, such structures were intended to bear only a layer of earth and pedestrian or horse traffic. Another significant contributing factor was prolonged neglect: the lack of maintenance and repair works led to degradation of mortar joints and portions of the brickwork, as well as the development of deep fissures [6][7]. Rainwater infiltrated through these discontinuities, softening the soil and reducing the adhesion between the earth fill and the vaults. Repeated freeze–thaw cycles exerted further destructive effects on the masonry. Finally, original structural vulnerabilities may also have played a role—historical damage (e.g. from attempted demolition or the action of tree roots) could have reduced the caponier's load-bearing capacity.

3. Conservation Programme

The project adopts the principle of minimal intervention in the historic fabric [8][9]. This means that all surviving elements of the caponier predating the collapse—such as intact sections of walls and vaults—will be secured and incorporated into the reconstructed structure. These components will undergo conservation treatment, including cleaning, desalination, and the strengthening of cracked zones through injections using specialist grouts (e.g., microcement- or trass-based), formulated to match the properties of the original lime mortar.

All solid bricks retrieved from the debris will be examined for suitability. Undamaged historic bricks will be used for anastylosis—that is, for reconstructing the wall using as much original material as possible [10][11]. Historically significant but weakened bricks that cannot bear substantial loads may be incorporated into the face (decorative) layers of the reconstructed wall to preserve the original appearance of the elevation. Material shortages—initially estimated at several dozen percent of the wall volume—will be supplemented with contemporary brick selected to match the nineteenth-century regional brickwork in dimensions, colour, and texture [12][13]. New bricks will be introduced primarily in less exposed areas, while recovered historic bricks are intended for the visible façades to maintain the structure's historical character.

Regarding mortar, the programme recommends the use of traditional lime–sand mortars (optionally with trass or a small addition of Portland cement—up to 10–15%—to improve strength and weather resistance). Analysis of the original mortar sampled from the caponier joints indicates that it was a lime mortar with clay and finely crushed brick aggregate (known locally as *ciężarówka*), characterised by relatively low mechanical strength but high porosity and vapour permeability. The new mortar will be formulated so that its physico-chemical parameters (elastic modulus, vapour permeability, colour) closely resemble those of the original [13][14], ensuring compatibility and uniform performance of the masonry. Likewise, the pointing mortar for the face layer will be tinted to match the historical shade (light grey/beige).

4. Design Assumptions, Materials, and Structural–Masonry Solutions

The reconstruction design for the caponier assumes a faithful geometric reproduction of the original structure while introducing subtle structural improvements that are invisible or barely perceptible to the observer, yet significantly enhance safety and durability [10][11][15]. The key design aspects are outlined below.

1. Foundations and bearing conditions:

The collapsed caponier was founded directly on native soil (clayey sands) or on a shallow foundation made of fieldstone bonded with mortar. Once the remnants of the original foundations were uncovered, partial loosening and displacement were observed. The design includes strengthening the foundation through underpinning with low-pressure injections (introducing a lime–cement mixture into the soil beneath the foundation) and the installation of additional reinforced-concrete footings at critical points [13][14][16]. Along the newly constructed section of the wall, the foundation will be supplemented with a concealed concrete strip footing shaped to the geometry of the structure (fully hidden below ground level and within the wall's footprint). This footing will be clad externally with fieldstone to visually reconstruct the original stone foundation while distributing loads from the new wall over a larger soil area.

2. Reconstruction of vaults:

The reconstruction of the segmental vaults will follow traditional methods using full formwork supported by scaffolding. The vaults will be built of solid brick (similar to the original—approximately 25 × 12 × 6.5 cm) laid in staggered bonding, with a thickness matching the historical one (about one brick = ~25–27 cm) [13][17]. The mortar will be a lime-based mix with a small Portland cement addition (strength class approx. M5–M10) to enhance the mechanical performance of the new vault.

A key structural solution is the introduction of a thin, concealed reinforced-concrete or composite layer above the reconstructed vault, acting as hidden structural reinforcement. A reinforced-concrete slab ~6–8 cm thick will be placed above the vault (embedded in the soil backfill) and connected to it with mechanical anchors, functioning as a composite structural system. This slab will act as an external hidden keystone, taking on part of the earth load and distributing it more uniformly onto the vault [18][19][20]. Historically, similar techniques were already used in the fortress at the end of the nineteenth century—for example, the caponier of the Giżycko Gate was reinforced with an added concrete layer—confirming the validity of this conservation–engineering approach, provided that the layer does not alter the interior's appearance. In the present design, the reinforced-concrete layer will be fully concealed by the soil backfill, leaving the brick vault visible from below.

3. Walls and façades:

The reconstruction of the caponier's exterior wall (the front elevation facing the moat) will follow the original alignment as determined from geodetic documentation and surviving fragments. The wall, approximately 90 cm thick (3.5 bricks), will be erected in traditional multi-leaf masonry with proper interlocking. In the internal (non-visible) parts of the wall, new solid bricks with a minimum strength of 15 MPa may be used, while the visible face will incorporate reclaimed historic bricks and new stylised bricks, as previously described.

An important invisible improvement will be the use of stainless-steel wall ties. At defined intervals (e.g., every three courses or roughly every metre of wall length), flat stainless-steel strips or helical bars will be inserted into horizontal joints to connect the external face with the internal core of the wall. This will increase monolithic behaviour and improve anchorage to surviving historic wall sections, which will likewise be stitched and strengthened using such ties [14][19]. These elements will be visually imperceptible from either side but will substantially enhance structural cohesion. Additional chemical anchors (composite or stainless steel) ~1 m long will be installed at the corners, bonded into drilled holes to integrate new masonry segments with the existing side walls of the caponier.

The gun embrasures and elevation details will be reconstructed according to iconographic sources and analogies from the symmetrically located counterpart, or according to the conservator's guidance. Preserved steel grilles from the embrasures will be cleaned and reinstalled.

4. Waterproofing and drainage:

Protecting the structure from water ingress is one of the most critical issues [7][22]. Historically, caponiers lacked modern waterproofing; instead, they relied on thick layers of earth and clay covering the vaults and on moat drainage systems. Due to documented leakage and mortar erosion, the design introduces discreet waterproofing atop the reconstructed vaults. Beneath the reinforcing concrete layer, a waterproof membrane (e.g., polymer–bitumen sheet or EPDM membrane) will be installed to protect the masonry from rainwater infiltration. This membrane will be turned up and connected to a linear drainage system at the foot of the embankment.

Around the caponier, at the interface with the terrain, French drains (gravel trenches with perforated drain pipes) will collect groundwater and channel it into the moat. Additionally, historical drainage outlets or gargoyles on the front elevation (facing the moat) will be restored to carry surface and roof water away from the caponier. These measures will minimise moisture exposure—crucial for preserving both the new and historic masonry.

5. Intended use after reconstruction:

Although the primary purpose is the rescue and stabilisation of the monument, the design anticipates the eventual adaptation of the caponier for exhibition or other educational–touristic functions. Accordingly, several elements facilitating future use have been incorporated: for example, concealed conduits for potential lighting installations will be prepared during reconstruction to avoid later cutting into historic finishes; and provisions have been made in the floor of one room for mounting a glazed display case presenting an in situ fragment of the original collapse debris as a commemorative exhibit [23][24][25]. All such interventions are planned to avoid structural weakening—e.g., installation conduits will be routed through mortar joints rather than through bricks, and only in sections where new bricks have been introduced.

5. Finite Element Analysis – Models in Autodesk Robot

An integral part of the design work was a detailed strength analysis of the reconstructed caponier using the Finite Element Method (FEM) [14][15][16]. Autodesk Robot Structural Analysis Professional 2022 was employed, enabling the modelling of masonry structures and the assessment of their behaviour under various loading conditions. The objectives of the analyses were to verify whether the proposed structural solutions (described above, e.g. the strengthening layer above the vaults, anchors) provide sufficient load-bearing capacity and safety, as well as to optimise these solutions. In addition, the FEM simulations were used to elucidate the mechanism of the previous failure: a model of the pre-collapse state was reconstructed in order to investigate which factors could have exceeded the capacity of the original structure (verification of the hypothesis regarding the influence of a heavy vehicle and water).

5.1. Geometric model

A 3D model of the right ravelin caponier was developed, including the segmental vaults, external walls, internal/partition walls and the adjacent embankment soil [15][16][17]. The model was created primarily with shell elements (plates/shells) for the vaults and walls—four-node shell elements with a mesh size of approximately 10–15 cm were adopted, which ensured good representation of the vault curvature. For the embankment soil, solid elements were used in order to account for the earth pressure acting on the vaults; however, for some simplified analyses the soil was modelled as an equivalent uniformly distributed surface load. The finite element mesh was locally refined in zones of expected stress concentration (e.g. near vault supports at the wall interfaces).

An isotropic nonlinear material model was assumed for the masonry, with parameters calibrated to represent solid brick masonry with mortar joints. The reinforced-concrete layer above the vault was represented by shell elements 6 cm thick with high stiffness parameters. For simplification, the anchoring elements were not modelled explicitly—their effect was introduced by increasing the local stiffness of the connections between the existing and new masonry (implemented through nodal kinematic constraints).

Two numerical models were developed for the calculations:

- a full model including the analysed wall (Fig. 2),
- a model with the damaged wall removed (Fig. 3).

The “no-wall” model demonstrates that the wall failure did not compromise the overall stability of the caponier. Consequently, it is not necessary to provide full temporary propping of the rooms adjacent to the analysed wall. The repair works can be carried out by shoring only the damaged, locally affected vault segments using telescopic props. Full, continuous centring of the vaults is not required.

5.2. Boundary conditions

The lower surfaces of the foundations and the wall segments resting on the soil were treated as elastically supported. For simplification, however, many sections of the lower wall edges were modelled as fixed supports—this yields conservative estimates of vault stresses, since less favourable support conditions would generate higher bending moments. A variant with pinned supports was also analysed to assess the sensitivity of the model. The interface between the reconstructed vaults and the existing masonry was modelled as continuous (monolithic), reflecting the post-reconstruction condition achieved through injection grouting and a reinforced-concrete ring beam.

5.3. Load cases

The following load cases were defined:

- **Self-weight** of the structure.
- **Historical self-stress condition** – a separate analysis considered the initial stresses from the nineteenth-century concrete layer (represented as a permanent load in the model).
- **Soil overburden** – earth fill of approx. 1.0–1.5 m above the vault.
- **Live loads:**
  (a) pedestrian/tourist traffic – uniform surface load corresponding to a group of visitors; (b) emergency vehicle load – modelled as a line load (single axle) or two concentrated forces simulating a heavy vehicle (this scenario was included only as an emergency robustness test, since vehicle access is ultimately to be prohibited).
- **Earth pressure** on the lateral walls, represented as lateral soil loads.
- **Thermal load** – a daily temperature gradient across the vault (e.g. +15°C from below in summer), analysed to evaluate potential cracking. Its influence proved minor and was excluded from primary combinations.

Load combinations were generated in accordance with relevant standards. Particular attention was given to the pre-repair scenario (simulation of 2022 conditions): self-weight + soil + heavy vehicle on the road + water-saturated soil (approx. 20% increased density). This model was used to compare with the capacity of the original caponier and indicated that the resulting stresses exceeded the masonry strength, thus explaining the collapse. For the post-reconstruction model, deflections and stresses were verified to ensure sufficient safety margins.

5.4. Analysis results – post-reconstruction condition

The FEM results indicate that the reconstructed caponier exhibits satisfactory structural performance under the assumed loads.

- **Vault deflections:**
  Maximum vertical deflections of the vault under earth fill and live load were approximately 2–3 mm at mid-span—very small values, confirming the high stiffness of the system. This corresponds to the model with the reinforced-concrete layer. For comparison, the purely masonry model (without reinforcement) produced deflections of ~5 mm, still acceptable but showing that the reinforcement stiffens the vault by roughly 40%.
- **Masonry stresses:**
  Maximum compressive stresses occurred at the vault supports, reaching 40–50% of the characteristic compressive strength of the brick masonry—indicating a safe reserve (safety factor > 2). At the vault crown, compressive stresses were low (0.5–1.0 MPa). In the outer vault zones (near abutments), small tensile stresses (0.1–0.2 MPa) appeared due to asymmetric loading and soil pressure. However, these zones are effectively controlled by the strengthening layer, which carries tension, and by the concealed reinforcement. Consequently, no tensile capacity of the masonry was exceeded—in the reinforced model, tensile stresses in the brickwork were practically eliminated and transferred to the "substitute reinforcement elements" introduced in the model.
- **Wall stresses:**
  Compressive stresses in the caponier walls (from soil pressure and vault weight) reached a maximum of approximately 1.0 MPa at the base—well below permissible values for solid brick masonry.

Overall, the computations demonstrate that the strengthened and reconstructed structure possesses adequate stiffness, no critical overstress zones, and a robust safety margin under all design load combinations.

Reserve Capacity

Load-bearing capacity was verified according to both material strength criteria and ultimate limit states. In the serviceability limit state (SLS), deformations were small (deflections of 2–3 mm—insufficient to affect appearance or function). In terms of ultimate limit state (ULS), even combined loading (self-weight + soil + 5 kN/m² crowd load) generated maximum compressive stresses below allowable thresholds; thus, the wall and vault fulfilled the capacity requirements for both compression and shear. Notably, the bending-capacity analysis showed that the added reinforced-concrete layer or CFRP strips carry the bending moments generated by asymmetric loads, preventing cracking of the vault. The reinforced vault exhibited an internal force distribution similar to that of a plate, increasing structural redundancy—local overloads could be redistributed, a mechanism absent in the original arch-like behaviour.

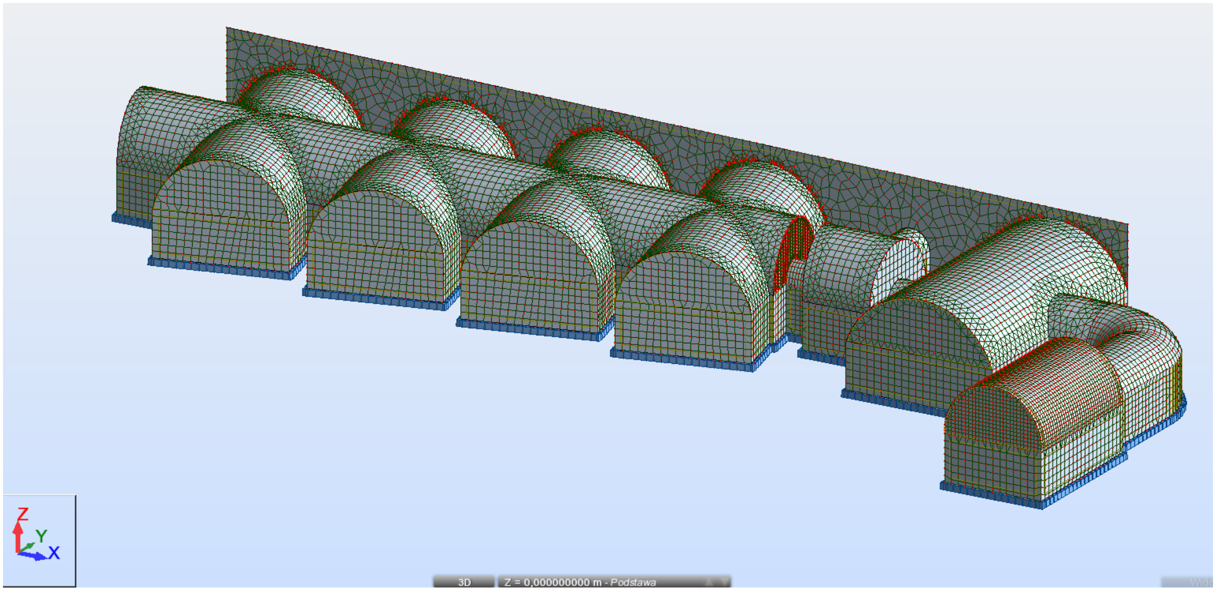

Fig. 2. Full numerical model of the caponier (with the wall) with the FEM mesh applied

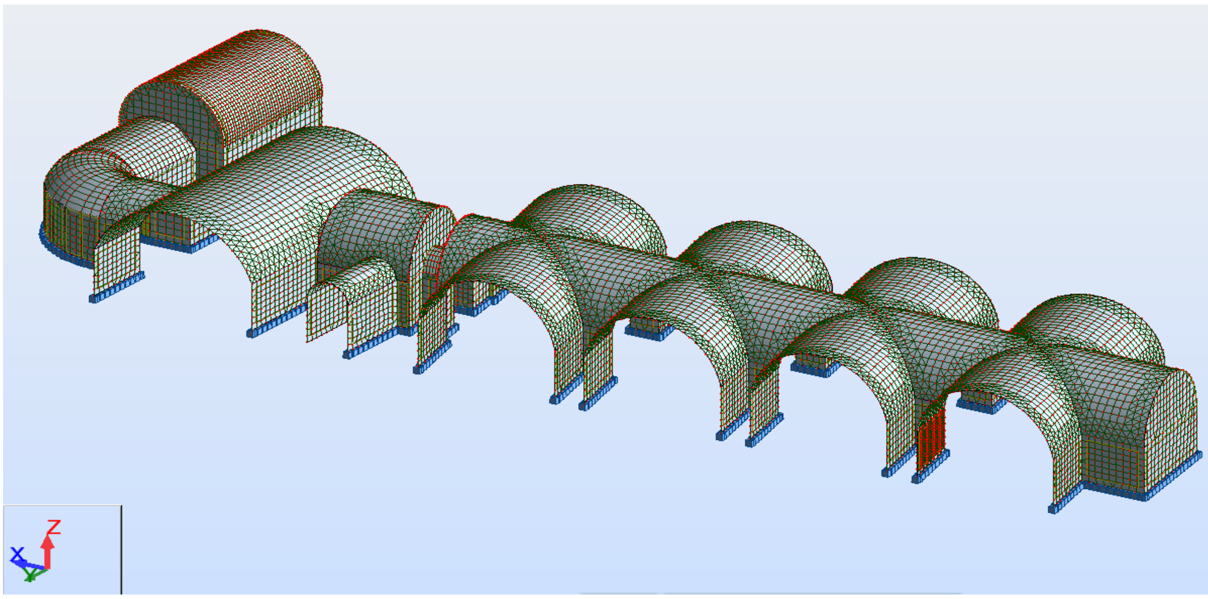

Fig. 3. Numerical model of the caponier with the damaged wall removed

Comparison with the pre-collapse condition:

To better understand the 2022 failure, the "original" model (without reinforcement, with the historic cross-section, loaded with a ~10-ton truck) was compared with the strengthened model. The analysis revealed compressive stresses of 3–4 MPa in critical regions, along with extensive tensile zones (up to 0.5 MPa) at the vault haunches. These values exceeded the tensile capacity of the mortar and the cohesion of the masonry, explaining the collapse mechanism: cracking at the supports, joint separation, loss of arch continuity, followed by sudden failure. In the new design, this behaviour cannot occur due to the reinforcement— even under a simulated heavy-vehicle load (50 kN per axle), the reconstructed model remained within safe limits. The concrete layer carried the majority of the bending moment, and stresses in the brickwork increased only slightly (to ~60% of allowable values) [19][20][21]. Although heavy traffic will ultimately be prohibited, this scenario confirmed that the structure retains a sufficient safety margin for unforeseen actions.

5.5. Interpretation of results and influence on design decisions

The FEM results were used iteratively to refine the design. For example, the initial concept assumed a 5 cm concrete layer; analysis showed improved performance with 8 cm (30% reduction in deflection and a twofold reduction in tensile stresses in the masonry). Consequently, the thickness was increased to 8 cm. The influence of anchor length was also assessed—anchors connecting old and new masonry with an embedded depth of 0.5 m proved sufficient; further increases did not affect the results, allowing minimisation of intervention in the historic walls. Modal (dynamic) analyses showed no significant vibration issues—the dominant natural frequency of the vault was approx. 15 Hz, well above typical excitation frequencies from footfall (2–4 Hz) or wind loads, ensuring that pedestrian-induced resonance will not occur.

The FEM analyses confirmed that the adopted strengthening measures provide full structural safety. All capacity criteria were met with reserve. This is essential, as conservation doctrine requires that a reconstructed monument not only appear authentic but also be safe for users. Literature emphasises the need for rigorous capacity assessment in such structures demonstrated for a brick arch bridge that FEM analysis (also using Autodesk Robot) is effective in verifying compression and shear capacity after strengthening. Our results similarly confirmed the efficacy of the proposed measures.

6. Conclusions – Integrating Heritage Conservation with Structural Requirements

The presented case study of the reconstruction of the right ravelin caponier of the Boyen Fortress demonstrates that effective cooperation between heritage-conservation specialists and structural engineers enables the preservation of a valuable defensive-architecture monument while meeting contemporary safety standards.

Priority of authenticity:

Thanks to consistent implementation of the conservation programme, a maximum amount of original material has been preserved. The use of anastylosis—reapplying historical bricks—and traditional materials (brick, lime mortar) ensures that the reconstructed parts integrate naturally with the historical fabric [8][9][10][27][28]. The caponier retains its sense of place despite being partly reconstructed. Differences between original and supplemented parts remain subtly legible, in line with conservation principles.

Durability and safety:

Introducing modern but concealed structural solutions—such as stainless-steel anchors, vault strengthening and waterproofing—provides safety levels required by current building standards without compromising the monument's character. Analyses showed that the structure has a substantial reserve capacity and resilience to potential extreme actions. Thus, a balance is achieved: originally, the caponier was designed for much lower loads, but with reinforcement it can safely meet new demands while retaining its historic appearance.

Importance of diagnostics and monitoring:

The 2022 collapse highlighted the need for regular monitoring of historic engineering structures. Nineteenth-century fortifications, long unused for their intended purpose, undergo gradual degradation that may manifest suddenly. A long-term monitoring programme (sensors, annual inspections) should be implemented for the Boyen Fortress to prevent future failures [26]. According to conservation guidelines, maintaining such structures must be a continuous process rather than a one-off intervention.

Synergy of conservation and engineering:

The project exemplifies good practice in which rescue works on a heritage structure respect both conservation principles and engineering requirements. Dialogue between conservators and engineers produced non-standard but optimal solutions: e.g., the concrete layer—typically discouraged by conservators—was accepted here because it is historically justified (late nineteenth-century reinforcements existed) and invisible, while significantly improving safety [11][13][17][19][24]. Conversely, engineers accepted that certain parameters (e.g., mortar composition, retention of mildly deformed wall fragments) were conservation-driven rather than structurally ideal. This mutual flexibility proved essential to the project's success.

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