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STUDY AND RENOVATION OF HISTORICAL MASONRY ARCH BRIDGE

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Abstract. The aim of this research was the investigation of the properties of clay brick masonry arch bridge materials with a purpose of finding the best methods for reconstruction and renovation of the structure. The restoration, reconstruction and upgrading of historical heritage bridges require a careful investigation of materials and causes of damages. In many cases, the use of incorrect composition of joint mortar and clayed brick may lead to unfavourable result. It is important to ensure the natural water migration in historic masonry as it should not be interrupted after restoration or reconstruction measures performed. As an example the results of investigations and upgrading of historical clayed brick masonry bridge over the Venta River in Kuldiga town in Latvia had been analyzed. During the long lifetime and pro-active maintenance polity, the bridge had a lot of damages that could affect its further service life. For geometrical data collection laser scanning method was used that ensures sufficiently accurate data for reconstruction design, as well as the information for architectural investigation. Three-dimensional scanning of the heritage structure using 3D laser scanners allows the further transformation of information into the surface mesh model. This paper presents results of the investigation, and design of restoration and reconstruction works.

Keywords: masonry arch, bridge, brick, mortar, material investigation, reconstruction.

1. Introduction

The clay bricks had been known even since the 12^{th} century. Their use for bridge structures actually started only in the 19^{th} century. In a very short period (from the middle until the end of the 19^{th} century) major part of them had been built. Since the bridge building from clay bricks occurs in Europe in the relatively short period, today in many countries investigations regarding the restoration of old brick masonry structures have been carried out, also investigations of brick clay, methods of determination of load carrying capacity and restoration methods are among them, see Gattesco *et al.* (2012), Jurina *et al.* (2012), Krizek *et al.* (2012).

The mechanical behaviour of ancient masonry made during the nineteen century with bricks along with lime mortar have been investigated by Domède *et al.* (2009) where mechanical behaviour of masonry up to collapse of solid bricks had been experimentally obtained. The methods of experimental identification of behaviours of old masonry bridges were found in Brencich and Sabia (2008), Brencich and Francesco (2004), Maldonado *et al.* (2012), Mammino *et al.* (2006), Perret *et al.* (2002), Rafiee *et al.* (2013) and Aggelakopoulou *et al.* (2011).

During the time, the clay brick masonry deteriorated and lost its initial properties, therefore restoration and conservation of the existing clay bricks turned out to be the top priority task. Prior to performing restoration of the historical and cultural heritage it is crucial to carry out a careful investigation of composition of brick material, to determine its chemical and mechanical properties, and to give the prognosis of remaining service life. It is important because during restoration the old bricks require to be strengthened or covered by contemporary cover layers that would neither alter nor impose any damage on the existing brick masonry. The new materials for restoration and repair must have high resistance and stability against environmental actions; however, in many cases they can disarrange the inner environment of masonry: moisture migration, transport mechanisms of gas, liquid and ions and other processes, thereby they can deteriorate or even completely destroy the rehabilitated structure.

2. Historical overview

The first stone bridges as fortress elements in Latvia appeared near the middle age castles, whereas the building of massive stone and brick bridges commenced in Latvia only in the 18–19 centuries. The multi arch masonry bridge over the Venta River in Kuldiga (Fig. 1) belongs to this type of bridges. The bridge was built in 1874 and belongs to the longest clay brick masonry highway bridges

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in Eastern Europe. The bridge is an important headstone of technical development, and it is an essential part of the Civil Engineering Heritage in the Eastern Europe.

During the site investigation in 1871 it was decided that the most feasible route is opposite the city centre where the river was narrow with good ground conditions for shallow foundations – 2.1–2.4 m high dolomite layer. Regarding the static scheme it was decided to build clayed brick masonry arches based on stone masonry peers and abutments (Ritter 1877). The use of clay bricks and stone masonry was based on economic reasons; while the surrounding of Kuldiga town is rich in natural stones and raw materials for production of clay bricks and mortar.

According to the design the bridge consists of seven spans, each arched span is 17.03 m long. Total length of the bridge is 165.85 m (Fig. 2). The width of arch is 10.67 m (Fig. 3).

On the arches the brick parapets are placed, 1.33 m wide sidewalks and 7.00 m wide carriageway. 28.6 cm long bricks have been used for masonry. The depth of arch has changed gradually from six bricks height on piers to five brick height in arch middle section. The arch has circumference form with radius R = 11.80 m. The inside surface of side walls was covered with lime mortar. In lowest points of arches water drainage pipes were placed. Waterproofing of arches was made from two layers of cement mortar, since the asphalt or analogous material was difficult to obtain. The bricks and binder for mortar were chosen after careful tests in labs of Riga Polytechnicum. The bridge was opened for traffic on 2 November 1874.

During World War I, the German troupes blew up two arches at the right riverside. After the war the temporary truss type structures were built over the demolished arches. The rebuilding of blown-up spans was performed in 1926. The both destroyed brick arch structures were rebuilt from cast-in-place reinforced concrete, the side wall structures were rebuilt from precast reinforced concrete elements, railings were rebuilt from clayed bricks which are visually similar to the old ones. The facade was painted in brick red colour in order to preserve the historical look of the bridge. Nevertheless, during the long lifetime the bridge had a lot of damages that influence its further service life.

3. Inspection

Historically, the bridge consists of two parts – the initial part of 133 years old and the restored part of 81 year old. Consequently, it is possible to analyze "old" and "new" parts separately, since different materials are used. The bridge inspection which was carried out already in 1926 discovered serious problems in waterproofing and water drainage. In the archival pictures the signs of water filtration can be clearly seen with mineral undermine in both facades, as well as on the arch surfaces.

Careful inspection and assessment of the structure and masonry materials was carried out in 2006 prior to the commencement of restoration works and upgrading design. The objective of the inspection and assessment of structure was to provide the designers with the appraisal and understanding of the present condition of the structure and future structural performance, i.e. the extent and degree of deterioration, and its causes, the relevance of such findings to the safety and service life of the structure and intervention possibilities.

3.1. Laser scanning

Masonry bridges are civil engineering structures that usually have a complex geometry. This complexity determines that the usage of measurement devices traditionally applied in heritage documentation were not feasible. In recent years, designers and consulting engineers have identified laser scanning technology as a favourable alternative for bridge geometric data collection and documentation (Armesto *et al.* 2010; Lubowiecka *et al.* 2011). Laser scanners collect thousands of 3D points per second and achieve mm-level accuracy for every single point. With laser scanned data the bridge engineer create 3D bridge models for any further analysis required.

Fig. 1. Side view of the bridge before reconstruction

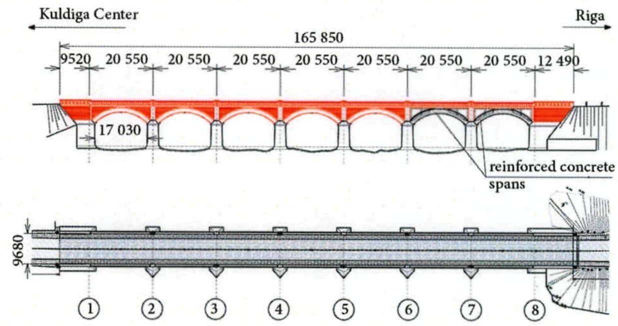

Fig. 2. Elevation and plan of the bridge

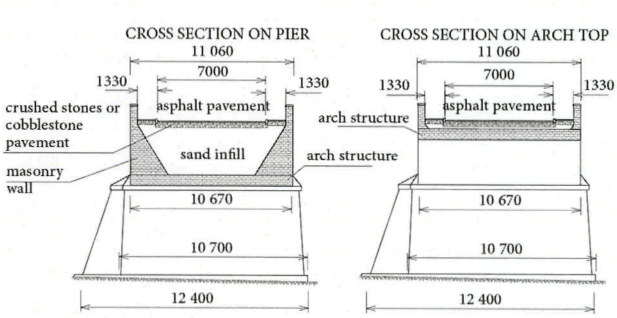

Fig. 3. Characteristics of the cross sections on the pier and on arch top before reconstruction

Since the original drawing did not survive until the present day, 3D laser scanning was used as a cost-effective method for producing as-constructed drawings. While traditional survey methods required either the installation of extensive access platforms or specialist roped access, the laser scanning surveying has the ability to safely and remotely acquire information without direct contact.

Fig. 4. 3D model of the bridge generated from the Laser scanned data

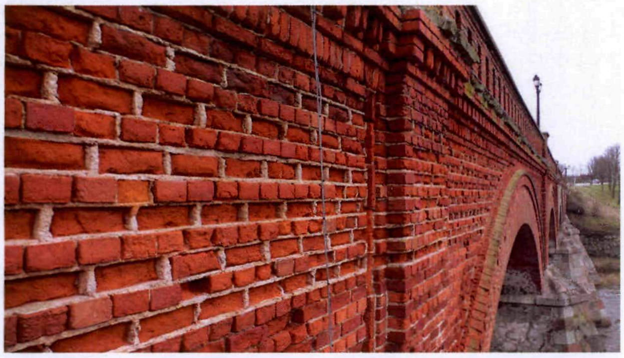

Fig. 5. Corroded and weathered bricks in wall surface from the upstream side

Fig. 6. Cracks and spalling in the reinforced concrete span surface

Fig. 7. A crack and falling out bricks around the water drainage pipes on pier 5

High speed pulse laser scanner Leica HDS 3000 was used for the measurement purposes. The data collection rate of this scanner is up to 4000 points per second. The accuracy of the positioning of a single point by using this scanner is about 4 mm at 50 m. Real accuracy was between 10 and 15 mm. Considering that the accuracy required by standards for most bridge geometric features are at a scale of several centimetres, the data density level of this scanner is expected to satisfy these requirements.

Based on obtained point cloud a 3D model was created using a CAD software package. Fig. 4 shows this 3D model. The obtained 3D point was attached to the National Geodetic System LKS-92 and the Baltic Sea Height System. That allowed getting the accurate dimensions and bench-marks of cross section (Fig. 5).

3.2. Side walls

Inspection of the side wall masonry (1–5 spans) showed that the brick surfaces had corroded (weathered) in approx 40% of the surface from upstream side, and in 20% from the upstream side (Fig. 5).

It was recognized that from upstream side (South side) the brick surface scaling dominated, but from downstream side (North side) the weathering of cladding mortar dominated. Due to water filtration the leached mineral material is visible on the wall's surfaces.

Inspection of the reinforced concrete side walls (span 6 and 7) showed that their technical condition is worse than that of the masonry sidewalls. It was recognized to have cracks in junction surfaces between precast wall elements and cast-in-place arched vault structure, partial plaster and concrete cracking and delamination (Fig. 6).

Obtained results showed that the recognized deterioration characteristics of side walls and sufficient compression strength of bricks allowed carrying out their restoration and reconstruction.

3.3. Arch

Similar to the side-walls, the arch surfaces are also divided into masonry vaults (1–5 spans) and reinforced concrete vaults (6 and 7 spans).

Inspection of masonry vault surfaces showed some minor brick surface deteriorations. In spans No. 2, 4 and 5 near piers around the water drainage pipes the damaged and falling out bricks were found in the area of 4 to 5 m^2 and up to 0.6 m depth. In the span No. 5 two 20 mm wide longitudinal cracks were found (Fig. 7).

These cracks had appeared obviously after the blow-up of two side spans during the World War I.

Inspection of the reinforced concrete vaults showed wide longitudinal cracks and honeycombing that uncovers reinforcement bars and leads to the reinforcement corrosion. The measured average concrete carbonation depth of 20 mm and the concrete cover layer thickness of less than

20 mm accelerate the development of reinforcement corrosion. Concrete strength was estimated as of class C12/15.

Obtained results showed that the recognized deterioration characteristics of arch structures, both brick and reinforced concrete, permitted carrying out their restoration and reconstruction.

3.4. Parapet and carriageway

The bridge has massive railing parapets made from clayed bricks and covered with dolomite cover plates. The parapet structures in the "old" part of the bridge preserved in good technical condition. The bricks have minor damages and the joints are in good condition. Occasionally, under damaged cover plates the damages in bricks are visible.

The parapets rebuilt in 1926 are heavily damaged. Approx 40% of all bricks are cracked or disintegrated (Fig. 8). The main reason thereof is low freeze/thaw resistance of the bricks and incorrect cladding material selection (Fig. 9).

The railing parapets are covered by dolomite cover plates. During service life approx 50% of dolomite plates have disappeared and were subsequently replaced with cast in place concrete plate.

Originally, the carriageway had a cobblestone pavement, that later was covered by asphalt layer. Pavement had cracks and potholes.

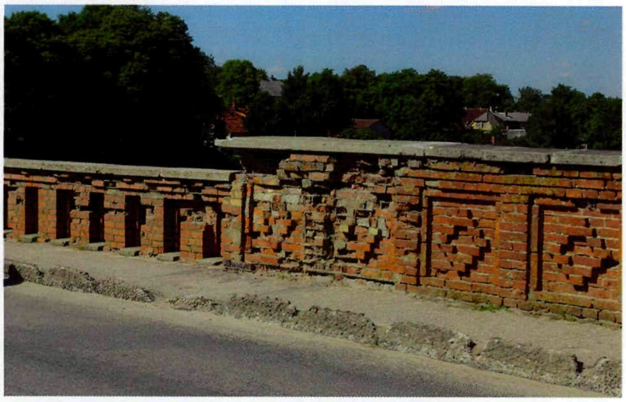

Fig. 8. Serious brick damages in the parapet structure

Fig. 9. Disintegrated bricks due to incorrect cladding material selection

Obtained results show that the bridge parapets could be restored to preserve the initial view, whereas the carriageway could be restored with cobblestone pavement.

4. Study of concrete, bricks and mortar

4.1. Investigation

Prior to commencing the restoration and reconstruction design, a careful chemical study of concrete, clay bricks and lime mortar properties was carried out.

For study purposes various bricks, concrete and mortar samples have been used, obtaining them in characteristic locations of the structure. The sample description is given in Table 1.

Chemical analysis was conducted according to *LVS EN 196-2 "Methods of Testing Cement - Part 2: Chemical Analysis of Cement", LVS EN 196-21 "Methods of Testing Cement - Determination of the Chloride, Carbon Dioxide and Alkali Content of Cement", LVS EN 623-2 "Advanced Technical Ceramics - Monolithic Ceramics - General and Textural Properties - Part 2: Determination of Density and Porosity"* requirements. Qualitative and quantitative chemical composition of salt pollution has been analyzed according to Teutonico (1988). Study results are shown in Table 2.

A grading composition of aggregates was analyzed after dissolving in 10% hydrochloric acid, elution, drying and bolting. Study results are shown in Table 3.

Table 4 shows the results of investigation of soluble salt saturation and carbonation (pH) level in samples.

The obtained results of chemical analysis showed that the actual soluble salt content in masonry is low. The results of carbonation analysis showed carbonation in concrete (pH 11–8.5). Detected content of MgO confirms the use of lime mortar in masonry.

In Table 5 the results of investigation of physical properties of the samples are shown. For investigation of

Table 1. Sample locations

No.	Sample material	Location	Production year
1	Clay brick	Parapet, span No. 7, downstream side	1926
2	Clay brick	Parapet, span No. 7, downstream side	1926
3	Concrete	Arch bottom, span No. 7	1926
4	Concrete	Side wall, span No.7	1926
5	Clay brick	Parapet, span No. 5, downstream side	1873
6	Lime mortar	Parapet, span No. 5, downstream side	1873
7	Clay brick	Parapet, span No. 5, downstream side	1873
8	Dolomite	Parapet, span No. 5, downstream side	1873

Table 2. Chemical composition of samples in % of mass

Elements	Sample No. 3 con-crete	Sample No. 4 con-crete	Sample No. 6 lime mor-tar	Sample No. 8 dolo-mite	Accu-racy (abs. error) ± %
Losses by heating:					
400 °C	9.11	8.08	7.90	3.32	0.5
1000 °C		13.24	12.54	38.50	0.5
Aggregate (sand)	41.41	41.90	60.50	4.62	0.5
SiO_2 instant	5.04	6.48	2.11	3.80	0.1
CaO	25.21	25.37	11.88	28.30	0.3
MgO	1.93	1.28	5.82	16.19	0.3
Al_2O_3	1.06	1.04	0.96	3.22	0.3
Fe_2O_3	1.88	1.10	1.15	0.88	0.1
Na_2O	0.45	0.96	0.46	0.47	0.1
K_2O	0.81	1.12	0.78	0.64	0.1
Total:	100.14	99.95	100.56	100.34	–
CaO/MgO	13.1	19.8	2.04	1.74	
Binder – sand ratio	1:1.2	1:12	1:2.7	–	–
Modulus of hydraulic $\frac{CaO + MgO}{SiO_2 + Al_2O_3 + Fe_2O_3}$	6.8	3.09	4.19	–	–
Binder	ce-ment	ce-ment	dolomite limestone		

Table 3. Recalculated aggregate composition in % of mass

Particle size, mm	Sample No. 3 concrete	Sample No. 4 concrete	Sample No. 6 lime mortar	Accuracy (abs. error) ± %
> 0.7	57.0	47.8	72.4	0.5
0.5–0.7	22.5	25.0	15.3	0.5
0.2–0.5	9.0	14.4	5.6	0.5
0.16–0.2	2.5	4.2	1.4	0.5
< 0.16	9.0	8.6	5.3	0.5
Total:	100.0	100.0	100.0	–

Table 4. Results of analysis of the salt saturation and pH level in samples

Sample No.	Elements CaO	MgO	Cl-	SO_3	pH
1 (clay brick)	0.23	–	0.15	–	–
2 (clay brick)	0.47	0.03	0.12	0.49	–
3 (concrete)	0.12	0.02	0.03	0.39	9.3
4 (concrete)	0.30	–	0.01	–	8.5
5 (clay brick)	0.07	1.49	0.05	–	–
6 (lime mortar)	0.08	0.49	0.17	–	8.25
7 (clay brick)	0.07	1.49	0.17	0.18	–
8 (dolomite)	0.26	0.1	0.07	–	–
Accuracy (abs. error) ± %	0.1	0.1	0.05	0.1	0.2

Table 5. Physical properties of the samples

Sample	Dry initial weight, g	Saturated mass in water, g	Saturated mass in air, g	Apparent density, g/cm³	Real density, g/cm³	Porosity, %	Volume of voids, cm³	Real volume, cm³	Apparent volume, cm³	Water absorp-tion, %
	M_1	M_2	M_3		$P_2 = \frac{M_1}{M_1 - M_2}$		$V_p = M_3 - M_1$	$V_r = M_1 - M_2$	$V_a = M_3 - M_2$	
1	234.03	142.9	274.94	1.77	2.57	31	40.91	91.13	132.04	16.45
2	133.91	80.5	153.60	1.83	2.51	27	19.69	53.41	73.1	13.18
3	271.28	164.2	287.66	2.20	2.53	13	16.38	107.08	123.46	5.31
4	36.87	22.1	39.27	2.14	2.50	14	2.40	14.77	17.17	6.35
5	101.60	62.1	117.74	1.83	2.57	29	16.14	39.5	55.64	14.00
7	353.83	209.2	401.69	1.84	2.45	25	47.86	144.63	192.49	12.50
8	170.68	108.2	188.28	2.13	2.73	22	17.60	62.48	80.08	9.03

compression strength of the "older" part masonry bricks the six samples were tested cut out from three bricks.

Brick compression strength test results are shown in Table 6.

4.2. Analysis of results

Results of the investigation showed that in masonry in 1874 the porous clayed bricks and dolomite stones with dolomite lime mortar were used. Tests of physical features of stones showed that all historic bricks had a high level of porosity from 25% to 31% with water absorption from 12.55% to 16.45%, dolomite porosity reached 22% with water absorption 9.03%. Dolomite lime mortar contained coarse sand and gravel where 72.4% of particles are greater than 0.7 mm. The joint mortar contains aggregates with relatively coarse particles that guarantee the mortar's porosity and permit the right moisture migration in masonry. It means that dolomite is compatible with bricks and ensures the right breathing of the brick wall. Cement mortar used in renovation carried out in 1926 has only 57.0% and 47.8% of particles greater than 0.7 mm, while its porosity is lower by 13% to 14% with water absorption from 5.31% to 6.35% that disturbs the moisture migration in masonry and initiates disintegration of bricks.

It explains a better condition of the historical masonry compared to the masonry parts restored in 1926.

Chemical tests of salt saturation in bricks, reinforced concrete, dolomite elements and in the old lime and mortar indicate that the level of penetration of the soluble salt water is very low and does not correspond to the criteria of unsalted brick walls. The reason for that might have been Calcium Carbonate ($CaCO_3$) that usually appears on historic monuments due to water migration through bricks, undermining Calcium Hydroxide ($Ca(OH)_2$) out of grout and mortar. When the drying $CaCO_3$ carbonizes on the brick surface it creates insoluble $CaCO_3$ that can be cleaned by pressed water or sand jet, only thus increasing the brick corrosion because the natural protection layer is getting damaged. The pH level that was found in the reinforced concrete part is 8.5 and 9.3 thus showing signs of corrosion created by carbonization.

5. Reconstruction design

After careful inspection and material investigation, the structural analysis was carried out by 3D finite-element models. Obtained results showed that the load carrying capacity is sufficient for ordinary traffic loads indicated in traffic rules and allowed by authority without any restrictions on public roads.

The bridge peers and abutments are founded on dolomite base. There were no signs to indicate deformations. Therefore, the renovation of peers and abutments included only the reconstruction of missing surface stones or bricks and cladding material between them, as well injection of cracks.

To verify the technical condition of overarch surfaces, it was decided to dig out the sand infill. The surface of brick arches was in good condition, old waterproofing and protection layers were still partly there (Fig. 10).

Therefore, the most necessary tasks were to restore waterproofing and fill the overarch part with draining sand.

The surfaces of reinforced concrete arches have no large damages or cracks. The calculation showed that the load carrying capacity of the reinforced concrete arches was reasonably good. Therefore, it was planned to strengthen them with additional reinforced concrete arches placed over the existing (Fig. 11). New waterproofing layer

Table 6. Results of compression strength test of the bricks

Sample	Dimensions			Mass M, kg	Density ρ, kg/m^3	Compression strength, MPa
	x_m	y_m	z_m			
1	7.21	7.29	7.25	0.690	1811	6.7
2	7.12	7.20	7.28	0.700	1876	19.5
3	6.67	6.86	6.62	0.550	1816	18.0
4	6.14	6.57	6.69	0.498	1845	35.3
5	6.74	6.58	6.59	0.535	1831	32.1
6	6.60	6.53	6.63	0.546	1911	25.5
Mean value					1848	23.3
Standard deviation					39	10.7
Coefficient of variation, %					2.1	45.7

Fig. 10. Opened surfaces of brick arches showed remaining waterproofing and good technical condition

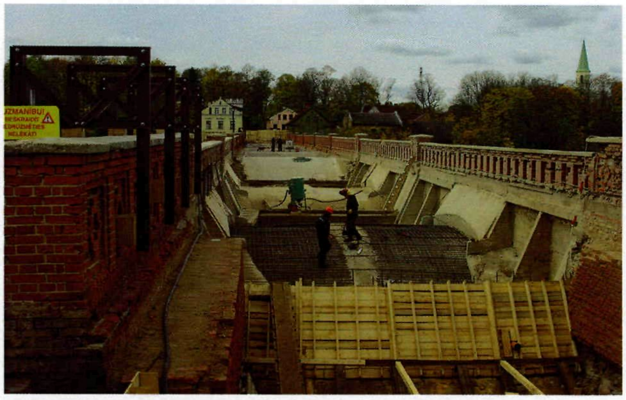

Fig. 11. Strengthening of the reinforced concrete arch span

was provided on the arches and inside parts of the walls. The design provided back-of draining sand between the side walls.

Reinforced concrete cover slab, directly supported on arch top, was provided over draining sand (Fig. 12). The slab helps to not only increase some bearing capacity and load distribution, but the surfaces shape also assists in collecting and draining water from the deck. The slab will be a suitable base for cobblestone pavement.

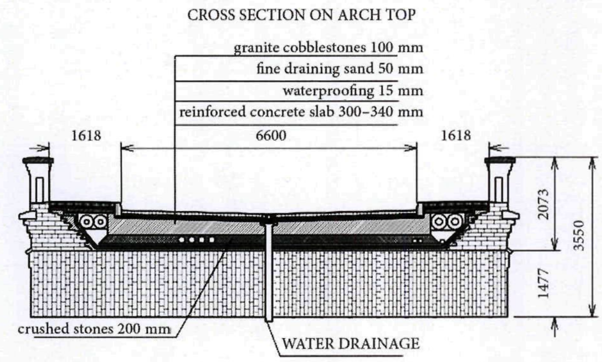

Fig. 12. Characteristic of the cross sections on the pier and on arch top

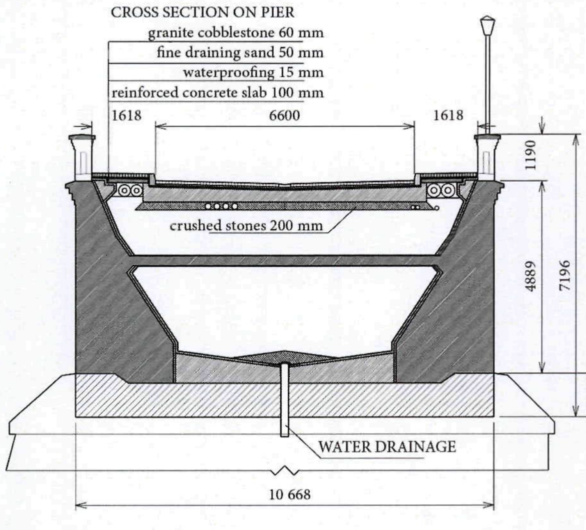

Fig. 13. View of the carriageway after reconstruction

Fig. 14. Side view of the bridge after reconstruction

Special requirement was worked out for renovation of the brick masonry parts. For conservation of disintegrated and mechanically weak brick surfaces special restoration mortar Funcosil Steinfestiger 100 was provided. The replacements of damaged bricks are allowed only with bricks of the same quality utilizing the cleaned old bricks from buildings of the same time or new bricks made according to the old mixing formulae. For cladding material the lime mortar was allowed with negligible 5–10% of cement additive. Such approach ensures the natural water migration in this historical masonry bridge, as well as protects the bearing structures from further development of deterioration.

Figs 13–14 show the bridge after reconstruction.

6. Conclusions

The intervention in this bridge showed the importance of analyzing the chemical and mechanical properties of clayed bricks and cladding materials. The durability of bricks and cladding materials is limited. Therefore, the products used for repair must be compatible with older parts and mortars. All historic bricks from 1874 showed a high level of porosity with good water absorption and the joint mortar with relatively coarse aggregates guarantees the mortar's porosity and permits the correct moisture migration in masonry. It means that dolomite is compatible with bricks and ensures the right breathing of the brick wall. On the other hand, the cement mortar that was used later during the renovation had lower porosity and accordingly lowered water absorption that disturbed the moisture migration in masonry and initiated disintegration of bricks. That explains a better condition of the historical masonry compared to the masonry parts restored in 1926. Chemical tests of salt saturation in bricks, dolomite elements and in the old lime mortar indicate that the level of penetration of the soluble salt water is very low and does not correspond to the criteria of unsalted brick walls.

The installation of a reinforced concrete slab on top of arch and infill material efficiently distributes the live load on side walls and arches and increases the load bearing capacity.

Laser scanning method allows obtaining accurate metric data and identifying structural pathologies in shape and dimensions, possible cracks or voids, etc. All this information can be used for a more accurate structural analysis.

The bridge was restored according to its initial historical view, and at the same time the bridge is open for traffic without any restriction.

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