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Life-time extension of masonry-arch bridges

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ABSTRACT: The present study reports on the management of masonry-arch bridges by the Swiss Railways. In Switzerland there is a large number of this type of bridge; they were constructed between 100 and 160 years ago. Since they are still extensively used and represent a backbone of the Swiss rail network, concepts for their preservation have been developed over the last 30 years. These concepts mainly consist of periodical conservation and maintenance work based on field status reports about the bridges.
These masonry-arch bridges exhibit different construction designs and they also differ in the combination of materials used. This results in a wide variability of disintegration patterns. The major causes for damage are wetting and freezing effects. The structural safety of the bridges is less critical because it significantly exceeds the operational requirements. In general, problems with structural safety result from progressive decay of masonry. The key measure for maintaining these bridges is protecting the masonry against wetting. For larger bridges, however, replacing the superstructure with concrete cantilevers is an established strategy not only for protection from wetting, but also for enlarging ramps relating to denser traffic. Such an intervention can ensure a long-term problem-free use of the bridges for decades. Over the past years, technical progress has made it possible to make thorough renovations while the bridges are in use. This has shown that renovating masonry-arch bridges, instead of replacing them, is of interest also from an economical point of view.

These bridges are heritage sites of 19th century industrialization, and landmarks in Swiss natural scenery. This aspect has to be considered when renovating masonry-arch bridges. Therefore striking a balance between technical and cultural needs is important when prolonging the life-time of masonry-arch bridges.

1 INTRODUCTION

The majority of the Swiss railway network existing today was built between 1850 and 1920; i.e. at a time when concrete did not yet dominate as a construction material. The construction technology commonly used at that time for building bridges and support structures was natural stone masonry, while many bridges for a time around 1860 were erected using a combination of natural stone masonry and riveted steel structures. When the railway lines were electrified around the turn of the century, a number of these bridges were replaced by masonry viaducts, with concrete coming to be used increasingly after 1900. The number of natural stone masonry bridges still existing today in the Swiss railway system is several hundred, not counting structures with a span of less than 4 meters. In many locations, the natural stone bridges have become an integral part of the developed and natural landscape, in addition to their significance for the traffic system. They are frequently located in densely populated areas, or they bridge deep valleys in locations crucial to the character of the landscape. In some instances, daily train frequencies lie around 600. Natural stone viaducts have increasingly become part of the protected body of historical structures. Contrary to other historical monuments, however, the unrestricted continued use of these bridges is a fundamental prerequisite for their preservation. In other words, there is usually a requirement that the structure must either fulfill its technical purpose with sufficient reliability, or it must be replaced. It is generally impossible to simply redirect a railway route just to save a structure that no longer meets the technical requirements. Consequently, it is in everyone's interest to repair and maintain the remaining natural stone viaducts in a manner that ensures their use for a long time to come.

From a usage point of view, today's technology requires wider beds. On the other hand, there is a desire to remove existing damage and to preserve the bridges in their original appearance and materials.

2 CONSTRUCTION METHODS AND MATERIALS

Most natural stone railway viaducts date back to the period from 1860 to 1915. During that relatively short time period, construction methods changed considerably. When the first railways lines were built around 1860, natural stone masonry was erected in true ashlar masonry, i.e., it was made of large cuboid stone blocks precisely dressed on all sides, some of which weighed over a metric tonne (Figure 1, left). The joints were less than 1 cm wide. This time-consuming and expensive construction method was soon abandoned. On railway lines built after 1870, the stone block sizes became increasingly smaller, they were dressed less precisely, and the joints were wider (Figure 1, right). True ashlar masonry with fine joints was used only very occasionally; e.g., for building pillars in rivers. From about 1900 on, lean concrete started to appear as masonry fill in pillars and abutments. From 1910 on, mixed-material structures made of concrete and natural stone or concrete block masonry were built. After 1930, the arched masonry bridge was practically completely superseded by armored concrete structures.
The stone used for construction was limestone, sandstone or conglomerates, as well as granite or gneiss. The stone was selected according to what was available in the region. Along the Jura Mountains, Jurassic limestone was used, on the Central Swiss Plateau and along the Prealps, primarily sandstones and occasionally conglomerates formed the building material. In the Alps, Alpine limestones as well as granites and gneisses were available.
The type of masonry mortar used also changed during the 1860 to 1915 time period. In the ashlar masonry of the first railway lines built around 1860, lime mortar was applied predominantly. From about 1870 on, hydraulic binding agents were used exclusively, with hydraulic limes and furnace slag cements prevailing. Around 1890, Portland cement-type binding agents started to appear. For railway lines built from 1900 on, mostly Portland cement was used, but this binding agent was applied sparingly. In some structures, only heavily loaded structural components were built using Portland cement mortars – for components with lesser loads, hydraulic lime was used.

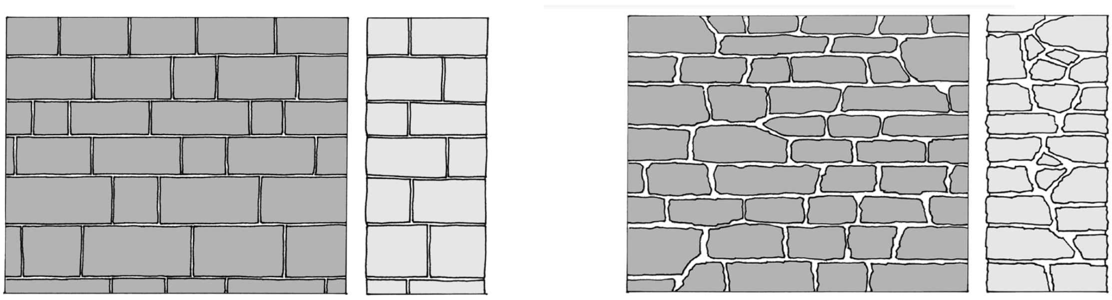

Figure 1: Ashlar masonry – Coursed masonry, elevations and sections

3 WEATHERING AND DAMAGE

Due to their already considerable age, railway bridges made of natural stone masonry are showing more or less obvious weathering symptoms. Here, a distinction must be made between superficial weathering, and deeper-reaching disintegration symptoms affecting structural strength. Table 1 provides an overview of the most frequent symptoms.

Table 1. Most frequent types of damage

Superficial weathering symptoms	Deeper-reaching disintegration symptoms affecting structural strength, and structural types of damage
Patina formation, crust formation, contamination by biofilms, mosses and lichens	Fracturing due to root expansion from increasingly woodier growth of shrubs and trees
Mortar in the joints detaching and falling out	Eluviation and abrasion of the masonry mortar, erosion of the masonry mortar
Superficial spalling on sandstones (depths of 5-40 mm)	Deep spalling of sandstones
Superficial crumbling decay; specific type of decay for certain lime and sandstone types.	Deeper-reaching crumbling decay for limestones (See Figure 2)
Sanding-off and flaking-off	Softening and separation of entire masonry stones due to the impact of wetness and freezing
Scaling-off and forming of fissures due to mortar being too hard	Forming of fissures in and between building parts, masonry deformations, chipping of the masonry
	Erosion and underwashing of masonry

Structural decay symptoms relevant to the load-bearing capacity of natural stone masonry railway bridges are primarily the result of strong wetting in conjunction with freezing. The reason is usually a lack of, or defective sealing. More comprehensive studies performed by the Swiss Federal Railways (SBB) have confirmed that it is not the age of railway bridges that is indicative of their condition but the question whether and how well a structure has been protected from wetting during its lifetime. Secondly, the severity of damage depends on the existing type of building materials and the construction method used. Sandstones and Jurassic limestones widely show deep-seated damage, while Alpine limestones, granites and gneisses – due to their high weathering resistance – hardly show any damage.

With regard to masonry mortar, the degree of damage also depends on its composition. Mortars based on hydrated lime (calcium hydroxide), hydraulic lime, or slag cement are usually sensitive to freezing when they are thoroughly wetted. Consequently, in arches that remain wet for long periods of time, the masonry mortar often becomes crumbly. The joints between the masonry crumble, and the softened masonry mortar sands off. This results in a decrease of the structurally relevant cross-section of the masonry.

In case of advanced decay symptoms in masonry mortar and/or masonry stones, structural damage may result over time, extending across individual building parts. As a consequence, deformations and massive formation of fissures can occur, and masonry stones may fall out. Thanks to the periodic inspections and the measures resulting from these, such damage is rare in railway bridges. A modest amount of fissures is, however, very often found on natural stone masonry bridges. They constitute a kind of a joint system allowing some movement within the structure that has resulted over time from temperature changes, load reversals, and differences in the level of rigidity. Their extent usually remains stable when the protection from wetting is intact.

Figure 2: Crumbling decay on Jurassic limestone

4 STRUCTURAL INVESTIGATIONS, STRENGTH OF MASONRY WORK

Structural investigations are usually triggered by remodeling projects of the operator, or observations of building inspectors. They are used to evaluate structural soundness, and to determine the need for repairs. A complete presentation of the systems and methods used for these investigations would exceed the space and time available here. They are performed based on the Swiss standard SIA 269/6 (2010), which can be used as a guideline in conjunction with the other applicable standards. Usually, the examinations are based on detailed on-site observations, probing and taking of samples, as well as building material analyses in the lab.

Central for assessing structural soundness is determining the strength of the masonry. For this purpose, Swiss standard SIA 266/2 (2010) provides a procedure for estimating, based on the type of masonry bond, the compressive strength of the rock, and additional parameters. Recent series of tests on masonry objects have shown that this procedure, at least when the masonry is intact, does not result in excessive compressive strength values for masonry. In quite a few cases, however, the impact on the strength of the masonry caused by damage from weathering and use is hard to assess. In cases of far-reaching crumbling decay in limestone masonry, for example, the resulting estimated reductions varied widely as compared to the as-new condition (Figure 2). In such cases, the last resort is to physically test masonry objects taken from the structure (Figure 3). In this actual case the result was that the compressive strength of the masonry had to be derated by about 60% in case of crumbling decay, as compared to equivalent masonry free of decay symptoms. Such tests are expensive, cannot be applied systematically and consequently, are only of an exemplary nature.
With regard to the repair measures, the structural investigation points out the extent of the damage, and allows determining its causes. The investigation provides a basis for deciding on the repair methods and the scope of the required measures.

Figure 3: Removal of masonry object for a compression test

5 RECOMMENDED MEASURES

For railway operators, the recommended measures are the key statement of any investigation. As a rule, an operator will provide technical and temporal parameters that must be taken into account when recommending measures. Almost without exception, maintaining railway operation while the measure is implemented is a prerequisite. Targeted residual use periods can be specified. Adjustments in the bed area required from a railway technology point of view, such as increasing the thickness of the ballast layer, or increasing the width of the bed, must be taken into account.

From the point of view of historic preservation, the request is for the structure to be maintained in a form that corresponds as closely as possible to the original. And the structure should be repaired using original materials, if possible.

In most cases, measures for strengthening the load-bearing structure are not required. Recent tests have confirmed that usually, sufficient load-bearing reserves exist (Grandjean 2009). Occasionally, strengthening measures on abutments are necessary on structures built with a combination of a steel framework and natural stone arches. In these, deficits with regard to the shear forces to be absorbed sometimes exist in the abutment area of the steel framework structures. In areas near flowing water, measures to protect against underwashing must be added occasionally. In individual cases, measures for stabilizing the subsoil can also be required.

In most cases, the measures recommended are limited to protection from wetting, and repairs of the masonry. Usually, replacing the entire sealing system must be recommended. The urgency of this measure depends on the current condition of the structure, and on the type of the existing building materials. Structures made of sandstone or Jurassic limestone should be protected as fast as possible since, for these types of rock, decay progresses relatively rapidly when they are constantly wet. For structures made of granite, gneiss, or hard Alpine limestones, an intact protection system from wetting should also be recommended since in these cases, it is particularly the mortar that can suffer severe damage. It is only in few cases that the combination of materials allows sealing to be postponed for any length of time; such as in more recent structures made of gneiss and a firm, wetting-resistant cement masonry mortar.

Lately, replacing the bridge superstructure with a concrete trough has taken hold as a repair method. As a positive side effect, the wider trough provides the bridge with a protective roof that has a wide overhang.

6 RENOVATION OF THE SUPERSTRUCTURE, TROUGH INSTALLATION

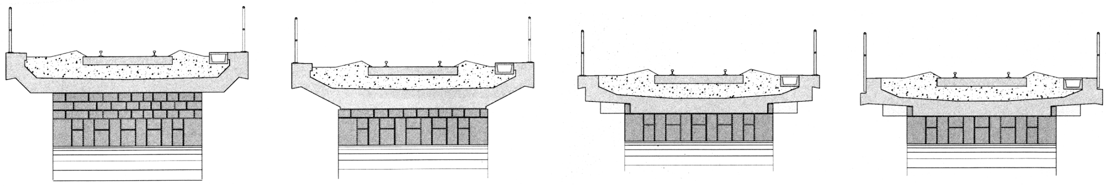

Figure 4: Trough variants (Fachstelle für Denkmalschutzfragen SBB)

Installing a concrete trough will result in both a wider bed, and a new sealing carrier. Since the track level usually cannot be lifted, it will be necessary to remove the original cover elements, such as curbs and corbels, as well as the top one to three courses of the natural stone masonry. For this purpose, diamond cutting technology or diamond wire saws are used. The new trough is cast on location or built from prefab elements. Depending on the design expectations, old curbs and corbels will be integrated into the concrete structure, and parts of the natural stone masonry will be used to face the new structure (Figure 4). By selecting the trough profile accordingly, the new superstructure can be fashioned in such a way that a pleasantly harmonious match of old and new will result. The first concrete troughs were lacking in this regard. Other important aspects of appearance are the transitions to the surrounding terrain, the locations of the traction poles, the railing, the construction joints in the concrete, and the routing of the drainage pipes.

Performing this work requires complex logistics planning and work. Route closures must be kept to the required minimum. Today, structures on more important lines are usually restored using temporary bridges. Temporary bridges are primarily installed in night-time operation (Figure 5). But first, and also at night, the foundations for the temporary bridge must be erected on or at both ends of the bridge. The foundations are already provided with a seal so that the sealing level is completed when the temporary bridge is removed. Only in exceptional cases, on branch lines, longer interruptions of railway operations are possible so that the trough can be erected freely.
The construction method selected depends on the amount of space available and on the project engineer. Before the trough is installed, its subsurface must be leveled. For this purpose, lean concrete is usually used. The trough is poured on location, either in combination with concrete elements and concrete poured on-site, or only using concrete elements. Occasionally, troughs are built on assembly platforms erected parallel to the railway line, and then pushed onto the bridge in a concerted effort.

Figure 5: Installation of a temporary bridge above an exposed natural stone arch

7 REPAIRING THE MASONRY

Masonry repairs on railway bridges made of natural stone are performed by stone mason firms or contractors specializing in stonemasonry. The traditional work processes include cleaning, stone replacement, and joint repairs. In addition, on a case-by-case basis, injections and anchoring may be required.

Repair methods will be adapted to each individual case. The replacement material for the stone should be as similar as possible to the existing material. Great importance is placed on the appearance of the masonry surface. Joint grid, color, structure, and surface finish of the replacement areas are matched to those of the existing structure, regardless of whether natural stone, artificial stone or concrete plugs are used. The replacement materials (stones and mortar) are matched to the technical properties of the existing original materials. Crucial parameters include strength, modulus of elasticity, water absorption, as well as weathering resistance criteria.

On prominent visible surfaces, using artificial natural stone is preferred. On the undersides of arches, concrete plugs are often used, both for economical and technical reasons. A special challenge here is imitating and recreating the joint grid and the surface finish.

Joint and masonry mortars are matched, both esthetically and from the point of view of technical properties, to the existing work. The use of binding agents compatible with natural stone in the joint and masonry mortars is a mandatory requirement. Key with regard to visual appearance are both the position and the surface finish of the joints; i.e., whether a joint is recessed or raised, and whether it is smooth or not. As a rule, samples are created before work commences.

Interruptions in the masonry bond, such as fissures and visible deformations, are secured or removed using needles, anchors, as well as injections of binding agents. Injections are made by companies specializing in this technology. They require prior determinations regarding the porosity and shape of voids within the masonry, as well as control bores to ascertain that the work was successful.

8 CONCLUSIONS

The current state of experiences with natural stone railway bridges shows that these structures will be capable of fulfilling their function for a long time to come, even after over 100 years of use - thanks to their solid construction and their structurally good-natured behavior. An intact protection system from wetness is absolutely central for their continued preservation, and thus, their continued use. For the majority of the existing natural stone bridges, neglecting protection from wetting will slowly but surely result in irreversible damage to their masonry. In structures made of sandstone and of certain Jurassic limestones, such damage develops relatively fast. It can come to a point where repairs are technically barely possible anymore, and become economically absurd.

By installing concrete troughs including seals, the continued decay of these structures can be greatly slowed down. Periodic maintenance on the masonry is greatly reduced. From a technical point of view, cantilevered concrete troughs represent an ideal protective system. They allow a considerable extension of the residual lifespan of natural stone bridges, while taking into account the current requirements of railway technology. From an esthetic and historic preservation point of view, installing a concrete trough represents an essential intervention into the appearance of a bridge. This intervention can be optimized by means of adjustments in construction technology and architectural design. Since unrestricted use of the bridges is usually a condition for their preservation, this type of renovation represents an acceptable compromise even for historical preservation.

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