The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 9.1
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.9.1

Forgotten and suffering structures – detailed inspection and finite element analysis of two railroad masonry arches in Poland

B. Sobczyk, J. Chróścielewski, M. Miśkiewicz,
Ł. Pyrzowski and K. Wilde

Department of Mechanics of Materials and Structures, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland

Abstract

The problems of structural response and load capacity estimation of two existing masonry arch railroad bridges located in Szczecin in Poland are described in this paper. The main properties and results of detailed inspection of the structures are shown. Computational models that were created in finite element method environment in order to recreate the behaviour of the bridges under typical loading conditions and estimate their load carrying capacities are presented. The outcomes of several linear and nonlinear static analyses that were conducted for this purpose are discussed. What is more the results of finite element analyses are reviewed against the inspected bridge condition and final conclusions are formulated on that basis.

Keywords: masonry arch, railroad bridge, masonry damage, FEA, linear and nonlinear static analyses

1 Introduction

Masonry arch bridges are still in service, although their age often exceeds 100 years (see Reccia et al [1]). The bridges are found in different countries around the globe. They are often in poor condition. They suffer from loss of bricks, loss of mortar joints, efflorescence, cracks of masonry walls and piers, excessive deformations of arch barrels or spandrel walls, etc. (see Modena et al [2]). Although, the structures are often severely damaged, surprisingly, many of them are located along main railroad lines. High durability of masonry, its relatively high strength in conjunction with the structural shape of arch allow them to carry high traffic loads, even though their condition is very poor. In view of that masonry arch bridges seem to be forgotten by local railroad administrators. The maintenance of masonry bridges is often inappropriate and many of the brick arches require immediate repair works (see for example Grillanda et al [3] and Beben et al [4]).

Approach to the analysis of masonry arch bridges is another important issue. The actual traffic load schemes are combined of loads with higher intensities than the ones used when the arch bridges were designed and constructed. Existing and new railway lines as well as the locomotives and railroad carriages have to be classified and categorized. Thus, appropriate estimation of the behaviour and load-bearing capacity of masonry arches under actual loads is being an important problem. This approach to the analysis has not been appropriately standardized, mainly due to the complex structure of brickwork that in general is unreinforced and does not carry tension. Although some guidelines for designers are available, like [5] or [6], researchers are still looking for new accurate and more efficient ones see for example (see Milani and Lourenço [7], Orbán and Gutermann [8] or Panian and Yazdani [9]). Therefore, research in this field is desirable.

This paper is focused on the aspects that have been discussed above. Structural response and load capacity estimation problems of two existing masonry arch railroad bridges are described. Both were constructed at the turn of the XIX and XX centuries and are located in Szczecin (Poland) over Fabryczna and Wilcza Streets, as shown in Figure 1. They are currently in poor condition and were carrying traffic until 2017.


a) b)

Figure 1: The analysed bridges: a) over the Fabryczna street, b) over the Wilcza street.

2 Methods

The literature study in the field of masonry arches response analysis (check the articles published by Researchers in [1][2][3][4][7][8][9]) reveals that it is a complicated and nontrivial task and generally each masonry bridge requires a careful and individual approach. That is because the whole bridge superstructure is built of many different elements as: unreinforced masonry arch, spandrel walls, backing, backfill, ballast, which interact with each other and can have various dimensions, shapes and properties (see the work done by Researchers in [10][11][12][13]).

Archival technical documentation was analysed and detailed inspection was done at first for the bridges. Some drawings depicting the geometrical properties of the studied arches are shown in Figure 2 to Figure 5. The bridge over the Wilcza street is not a typical one. The middle arch with constant thickness was built in 1896. Then it was rebuilt in 1940 (spandrel walls were partially disassembled) and two adjacent external arches with varying thickness were constructed. The three arches are separated with expansion joints. Both bridges are in poor condition (see Figure 6 and Figure 7 for the intrados damage) and require immediate repair works.

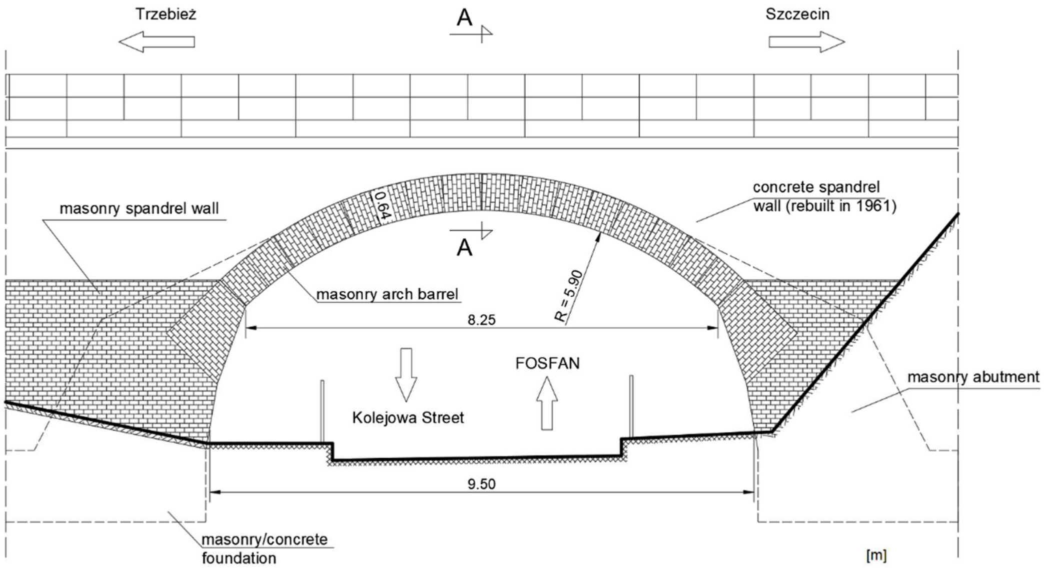


Figure 2: Fabryczna street bridge – side view.

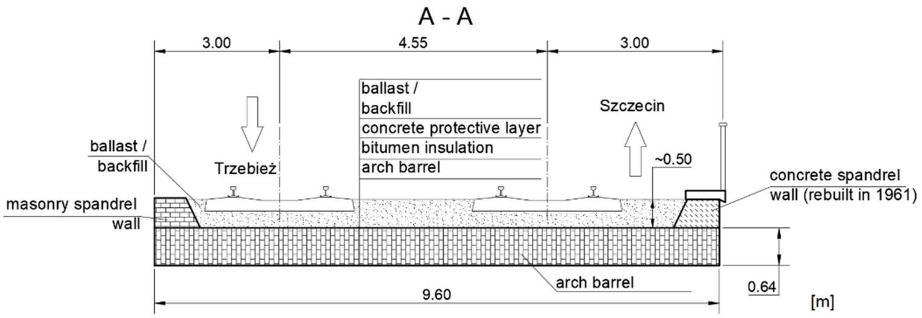


Figure 3: Fabryczna street bridge – cross section.

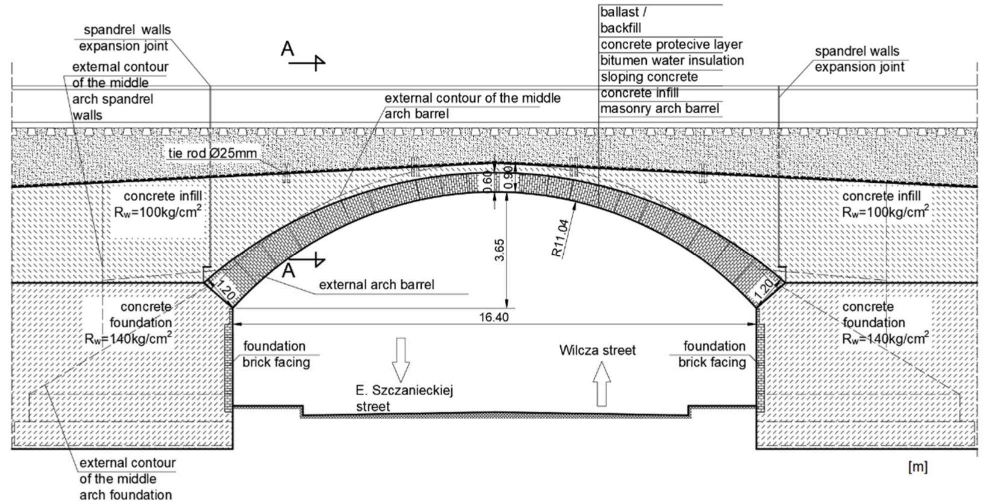


Figure 4: Wilcza street bridge – longitudinal section.

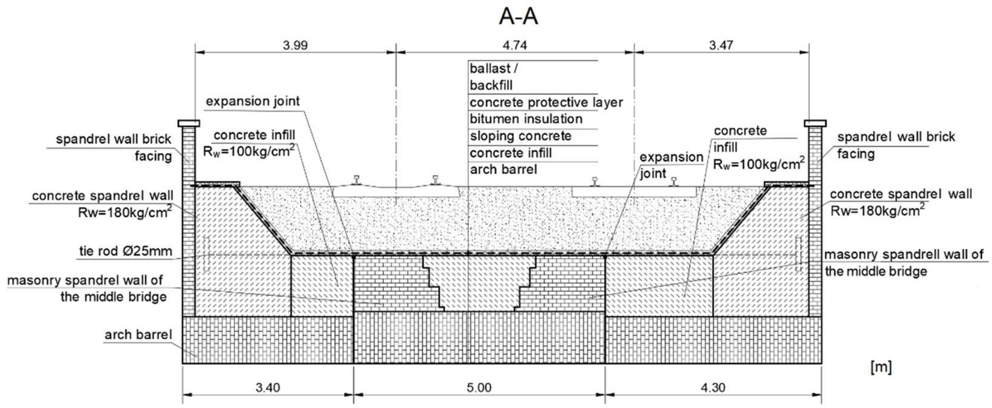


Figure 5: Wilcza street bridge – cross section.

Figure 6: Intrados damage of Fabryczna Street bridge.

Figure 7: Intrados damage of Wilcza Street bridge.

Computational models were created in the finite element method (FEM) environment in order to recreate the behaviour of the bridges under typical loading conditions (see [14]) and estimate their load carrying capacities. All the important load carrying structural members of the bridges were taken into account (see for example Figure 8).

Interaction between the backfill and the arch and spandrel walls was included in the form of a normal contact with separation and tangential friction. Isotropic and homogenous material law was assigned to describe response of the masonry walls. In the locations where, after preliminary calculations, tension was observed, simplified description of mortar joints cracking was introduced using a cohesive contact. Longitudinal translations are restrained at the sides of the model, whereas vertical motion is blocked at the bottommost surfaces of foundations. The whole model was built of 8-node brick incompatible C3D8I finite elements in the Abaqus code. Mesh convergence was checked using the h-refinement technique. Nonlinear static analyses were conducted to estimate the bridges response including contact (described above) and geometric nonlinearities. Such an approach to the analysis is efficient. It enables to solve the statics equations in a reasonable amount of time and the most important features of masonry behaviour descriptions are taken into account.

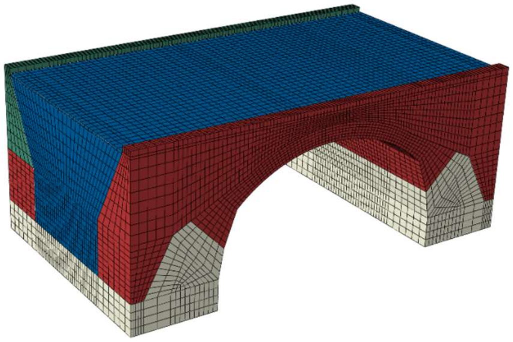


Figure 8: Computational FEM domain, Fabryczna street bridge: red – masonry walls, green – concrete spandrel wall, blue – backfill, white – foundations and abutments.

3 Results

In this chapter selected results of the static analyses under typical railway loads according to [14] are presented for both bridges. Preliminary calculations revealed that circumferential tensile stresses, for both structures, are greater than respective strengths in the springer and keystone zones, where the arches are fixed in the abutments, as shown for the Wilcza street bridge in Figure 9. Therefore, in later FEAs a contact interaction was defined in the vicinity of these zones, allowing simplified description of mortar joints cracking, to better represent the response of the system. This is quite typical for arches (see Kurrer [10] or Holzer and Vihelmann [12]), but still not yet included in European recommendations for masonry design ([6]).

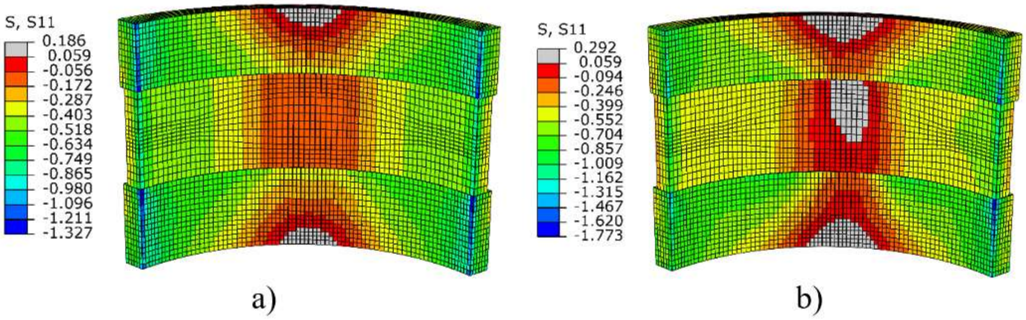


Figure 9: Circumferential stress in the Wilcza street arch barrels fixed in the abutments: a).under permanent loads; b) when traffic loads are added.

A further analysis of the Fabryczna street bridge indicates that even when cracking is allowed in the vicinity of the keystone, strong tension in circumferential directions is still observed (Figure 10) e.g. close to quarter spans under characteristic traffic loads which is even bigger when dynamic factors are included ([15]). Moreover, high longitudinal stresses are observed as well, as the bridge is wide (Figure 11).

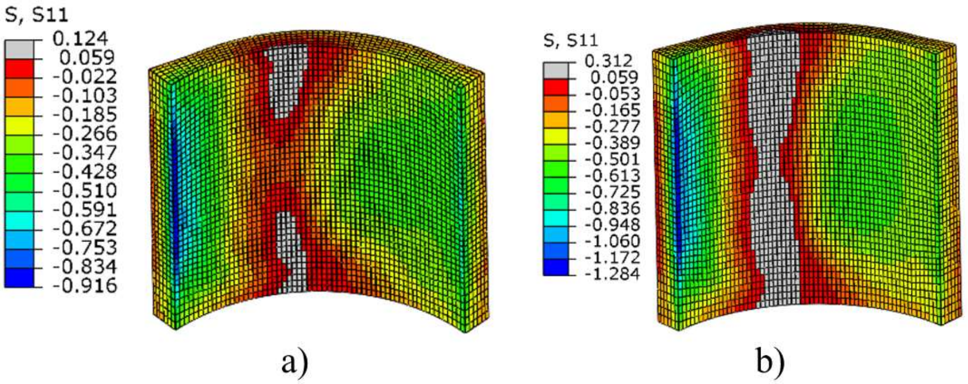
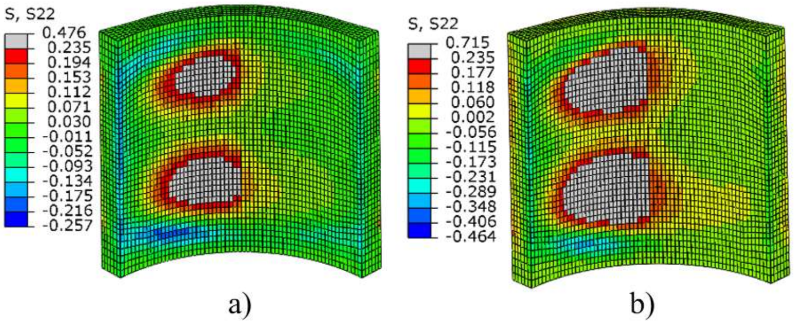


Figure 10: Circumferential stress in the Fabryczna street arch barrel: a) under permanent+characteristic traffic loads of C3 class; b) dynamic factors are added.

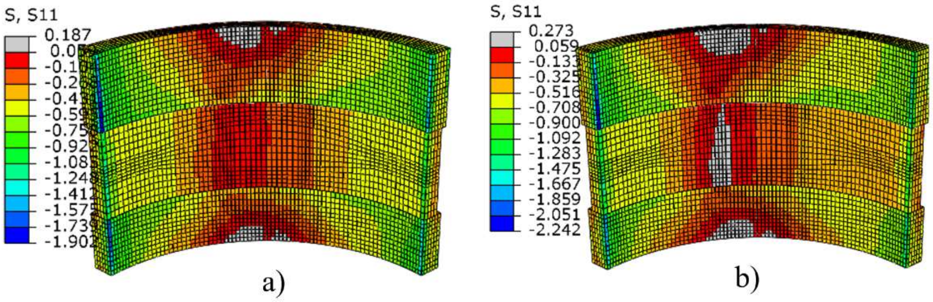


a) b)

Figure 11: Longitudinal stress in the Fabryczna street arch barrel: a) under permanent+characteristic traffic loads of C3 class; b) dynamic factors are added.

This state of strass could have contributed to the deterioration of the Fabryczna street masonry arch. The estimations of the bridge response are in accordance with the inspected damage, observed all over the intrados surface (refer to Figure 6). The bridge has not collapsed because the real masonry strengths are higher than the recommended ones (see Loo [11] and Ng et al [13], compare with [6]). What is more, the structure is located close to the railway station and the train speeds have been possibly low in this area, which resulted in minimalization of dynamic effects. Formally, according to the code [6] the bridge is not able to carry loads of C3 class.

Similar conclusion can be drawn for the Wilcza streets arches (Figure12). However, in this case only circumferential stresses are important, while the longitudinal ones are rather small. The highest circumferential stresses are mainly located close to the external sides of the external arch barrels, while the state of stress in the middle barrel is more favourable. This coincides with the inspected bridge condition.



a) b)

Figure 12: Circumferential stress in the Wilcza street arch barrels: a) under permanent+characteristic traffic loads of C3 class; b) dynamic factors are added.

4 Conclusions and Contributions

Masonry arches are very specific structures. Two historic, more than 100 years old masonry bridges in Poland were analysed in this paper.

The analysed bridges had been capable of resisting the tensile stresses for a long time. The tension had been carried without any negative symptoms, since the masonry elements have large margins of load carrying capacity, which is confirmed in many literature studies. As the years elapsed, the stiffness of the masonry decreased naturally, whereas the loads applied to the bridges increased. Thus, the initial cracks, appearing due to tensile stress, started to propagate, new ones developed and the bridges condition deteriorated. Moreover, the cracking process could have been accelerated, similarly as it is assumed in the shakedown processes, due to cyclic character of railway loads. Therefore, it is claimed that the damage, among others on the intrados of both bridges, could have been caused by the unfavourable state of stress revealed in the computational analyses, which coincides with the inspected damage.

The analyses show that from the formal point of view (see code [6]) the structures do not have sufficient load carrying capacity under typical loading conditions (C3 class, code [14]). It is worth to mention that the bridge design railway loads (see code [15]) are greater than the real ones. Therefore, even if the bridge is completely restored its load carrying properties are far from the actual design requirements, which also stems from the fact that the creep processes in masonry cannot be reversed.

Both bridges need structural modification, if the local administration wants to reopen them to traffic. These specific bridges definitely deserve restoration works, as they are part of the engineering history, which beautiful examples should be preserved.

Acknowledgements

The Abaqus calculations were carried out at the Academic Computer Centre in Gdansk.

References

[1] E. Reccia, G. Milani, A. Cecchi, A. Tralli, "Full 3D homogenization approach to investigate the behavior of masonry arch bridges: The Venice trans-lagoon railway bridge", Construction and Building Materials, 66, 567-586, 2014. doi: 10.1016/j.conbuildmat.2014.05.096

[2] C. Modena, G. Tecchio, C. Pellegrino, F. de Porto, M. Donà, P. Zampieri, M.A. Zanini, "Reinforced concrete and masonry arch bridges in seismic areas: typical deficiencies and retrofitting strategies", Structure and Infrastructure Engineering, 11, 415-442, 2015. doi: 10.1080/15732479.2014.951859

[3] N. Grillanda, G. Milani, S. Ghosh, B. Halani, M. Varma, "SHM of a severely cracked masonry arch bridge in India: Experimental campaign and adaptive NURBS limit analysis numerical investigation", Construction and Building Materials, 280, 122490, 2021. doi: 10.1016/j.conbuildmat.2021.122490

[4] D. Beben, J. Ukleja, T. Maleska, W. Anigacz, "Study on the Restoration of a Masonry Arch Viaduct: Numerical Analysis and Lab Tests", Materials, 13, 1846, 2020. doi: 10.3390/ma13081846

[5] UIC Code 778-3R. "Recommendations for the inspection, assessment and maintenance of masonry arch bridges", International Union of Railways, 1994.

[6] EN 1996-1-1 "Eurocode 6 - Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures", 2005.

[7] G. Milani, P.B. Lourenço, "3D non-linear behavior of masonry arch bridges", Computers and Structures, 110-111, 133-150, 2012. doi: 10.1016/j.compstruc.2012.07.008

[8] Z. Orbán, M. Gutermann, "Assessment of masonry arch railway bridges using non-destructive in-situ testing methods", Engineering Structures, 31, 2287-2298, 2009. doi: 10.1016/j.engstruct.2009.04.008

[9] R. Panian, M. Yazdani, "Estimation of the service load capacity of plain concrete arch bridges using a novel approach: Stress intensity factor", Structures, 27, 1521-1534, 2020. doi: 10.1016/j.istruc.2020.07.055

[10] K.E. Kurrer, "The History of the Theory of Structures. Searching for Equilibrium. 2nd edition", Wilhelm Ernst&Sohn, Berlin, Germany, 2018.

[11] Y. Loo, "Collapse Load Analysis of Masonry Arch Bridge", in "Arch Bridges", C. Melbourne, (Editor), Thomas Telford Publishing, London, United Kingdom, 167-174, 1995. doi: 10.1680/ab.20481.0017

[12] S.M. Holzer, K. Veihelmann, "Hinges in historic concrete and masonry arches", Proceedings of the Institution of Civil Engineers - Engineering History and Heritage, 168(2), 55-64, 2015. doi: 10.1680/ehah.14.00019

[13] K.H. Ng, C.A. Fairfield, A. Sibbalds, " Finite-Element Analysis of Masonry Arch Bridges", Proceedings of the Institution of Civil Engineers - Structures and Buildings, 134(2), 119-127, 1999. doi: 10.1680/istbu.1999.31378

[14] EN 15528:2008+A1:2012 Railway applications - Line categories for managing the interface between load limits of vehicles and infrastructure.

[15] EN 1991-2 "Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges", 2005.