WARSAW UNIVERSITY OF TECHNOLOGY | Index 351733 | DOI: 10.24425/ace.2025.156162
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
ARCHIVES OF CIVIL ENGINEERING
POLISH ACADEMY OF SCIENCES | ISSN 1230-2945 | Vol. LXXI | ISSUE 4 | 2025

pp. 155–167

Research paper

Reconstruction of the road bridge on Monte Cassino Avenue in Koszalin

Piotr Łaziński[1], Stefan Pradelok[2], Marcin Jasiński[3], Jolanta Borucka-Lipska[4]

Abstract: This article presents the process of rebuilding the bridge on Monte Cassino Avenue in Koszalin, Poland. The deterioration of the pre-cast concrete beams resulted in a decrease in the load-bearing capacity. On this basis, the decision was made to demolish and build a new structure, taking into account existing foundations and strengthening them with additional pre-cast concrete piles. However, during demolition works, the northern structure of the bridge collapsed uncontrollably. After a reanalysis of the technology and taking into account additional safety requirements, the demolition works were renewed. Due to collapse and its possible negative impact on existing piles, design changes related to the location of the pier axes were introduced. The load tests conducted on the rebuilt bridge allowed the finite element (FE) model to be verified by determining and comparing the response of the structure to static and dynamic load. The verified model, as an element of a digital twin, can be used in facility management throughout the life cycle of the structure, minimising the risk of failures of strategic elements of critical infrastructure in the future.

Keywords: bridge, condition assessment, demolition, load test, reconstruction

[1]PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: piotr.lazinski@polsl.pl, ORCID: 0000-0002-6752-0460
[2]PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: stefan.pradelok@polsl.pl, ORCID: 0000-0003-1902-1269
[3]PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: marcin.jasinski@polsl.pl, ORCID: 0000-0002-7137-0813
[4]PhD., Eng., West Pomeranian University of Technology in Szczecin, Faculty of Civil and Environmental Engineering, al. Piastów 50a, 70-311, Szczecin, Poland, e-mail: jolanta.borucka@zut.edu.pl, ORCID: 0000-0002-5647-2993

1. Introduction

Bridge structures constitute a crucial component of the transportation infrastructure. Because they are exposed to direct environmental impacts, including pollution, varying weather conditions, dynamic loads, vibrations, diversity of actions, and fatigue loads, they require special care, both in the selection of structural solutions and over the entire service lifespan – from the construction to the operation stages. These findings arise from the analysis of the most recent bridge damage and failures by Çiftçioğlu and Naser [1]. Similar studies were also conducted in the United States [2, 3], or India [4]. The most prevalent causes of bridge failures include, specifically, hydraulic hazards [5, 6], such as scour, floods, and overtopping, collisions with piers and spans, overloads, and design or construction errors [7]. Although failures can occur during construction, for example [8], the vast majority of them are related to the operational stage. According to Lee et al. [9], it accounts for 97% of all incidents involved. The important factor here is the extended lifespan of a bridge, during which the characteristics of the materials and structural elements gradually deteriorate [10]. This causes a decrease in durability, deterioration, and corrosion.

In fact, there are no fully effective and reliable techniques for eradicating or protecting against adverse environmental factors that can cause damage to bridge structures, particularly those that contribute to their diminished durability. Therefore, most measures for this purpose consist of monitoring the condition of the structure and corrective actions based on administrative decisions necessary to ensure the safety of people and wealth. They include regular inspections and structural monitoring [11]. Detected faults and irregularities can also be assessed in an in-depth analysis taking into account the identified damage supplemented by laboratory tests of materials or entire elements [12]. The data collected consistently over the years should then be used by the administration responsible for maintaining the transport infrastructure to develop an appropriate asset management strategy [13]. Proposals and implementations in this area are presented, among others, by Kim et al. [14] and Natali et al. [15]. In further research, these data can be used to build predictive models responsible for estimating the durability of a bridge in the long term, thus facilitating management activities [16–18].

This paper presents a case of a road bridge in a pre-failure condition identified during inspection, confirmed by expert opinions and detailed analysis, resulting in the immediate closure of traffic. In place, a new structure was designed and constructed, preceded by the demolition of the existing bridge and an assessment of the possibility of reusing existing piling foundations. The new bridge is described in detail with the results of the static and dynamic load tests.

2. Overview and condition of the old bridge

2.1. Superstructure

The old bridge on Monte Cassino Avenue in Koszalin, before rebuilding, consisted of two parallel structures of ten simply supported spans made of post-tensioned concrete WBS beams. Their effective lengths were: $22.0 + 3 \times 21.8$ m $+ 2 \times 22.0$ m $+ 3 \times 21.8$ m $+ 22.0$ m (Fig. 1).

The overall width of a single structure was 11.5 m, comprising a clear width of 7.0 m for a one-way road, in addition to two sidewalks of 2.75 m and 1.75 m width. Each superstructure had five beams spaced at 2.5 m and a 21 cm thick concrete slab. At the piers, the beams were braced with reinforced concrete crossbeams, approximately 0.3 m wide. The middle piers were designed as two columns of circular cross-section and 1.2 m diameter. According to the original documentation, the structures were supported on Franki deep foundation piles.

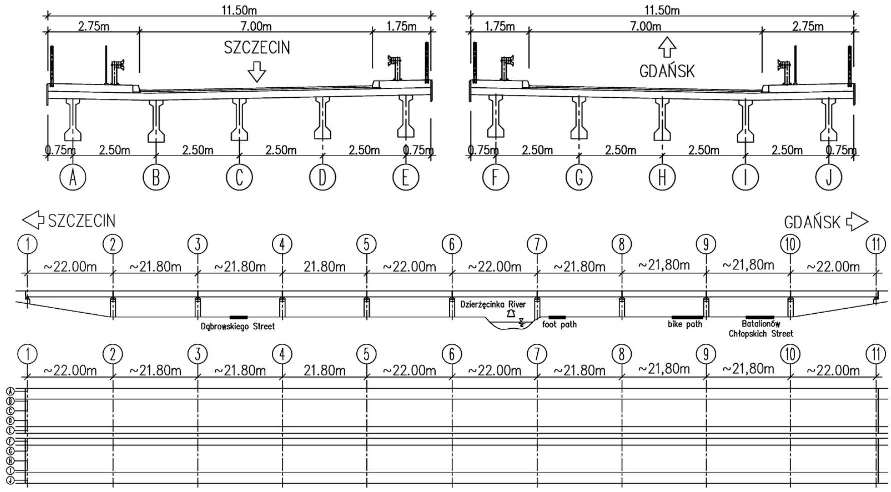


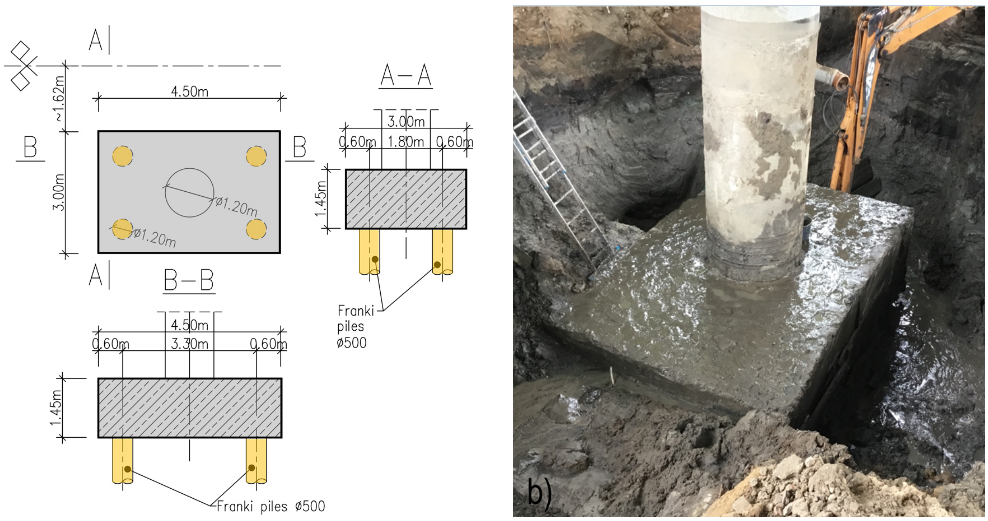
Fig. 1. Cross-section and side view of the old bridge

In 2020, an expert opinion was prepared to assess the current state of the structure, which confirmed its poor condition. On-site inspection combined with material tests, as well as static and strength analyses, showed a high risk of failure or collapse. The deterioration of pre-cast beams with a large number of inclined cracks near the anchor zones of the tendons (Fig. 2) exposed a reduced load-bearing shear capacity and indicated a prefailure condition. The damage found was a direct result of the yield strength exceedances in the stirrups and excluded the possibility of repair. Taking into account the above, the decision was made to close traffic and rebuild the bridge structure.

Fig. 2. Web cracks and damage to the pier zones of the WBS beams

2.2. Piers and foundation

In 2021, the ability of the deep foundation to be reused for the new bridge was checked. The study consisted of a geological survey, static load tests on bridge spans to measure the settlement of the piers, and exposure of the pile caps for visual inspection and condition assessment. According to the archived documentation, the structure was based on Franki piles. Each of the existing pile foundations consisted of a cap with dimensions of 3.0 m × 4.5 m × 1.45 m and four piles of 0.50 m diameter (Fig. 3a), reinforced with Ø14 plain-surface bars every 10 cm and Ø6 spiral reinforcement of 10 cm pitch. The foundation level of the existing piles was confirmed by sounding surveys conducted and exposing the pile caps (Fig. 3b).



(a) (b)

Fig. 3. Geometry of existing foundations (a) and the exposure of a pile cap (b)

Before the work on the site, on August 20, 2021, static load tests were carried out on the bridge (Fig. 4). The aim of the tests was to confirm the elastic behaviour of the existing foundation, hence maintaining its safety margin in load-bearing capacity. Fourteen load schemes were used, designed to obtain maximum reactions on the piers. The maximum settlement measured during the load test did not exceed 0.70 mm, so they were much lower than the allowed value of 5 mm. The permanent settlement, remaining after unloading, is neglectable and reached up to 0.15 mm. The differential settlement, measured in relation to the adjacent piers, did not exceed 0.70 mm and was much lower than the maximum value allowed of 10 mm. Taking into account the results of the load tests, it was confirmed that the existing foundation could be reused in the new structure.

Fig. 4. Settlement of the piers during a static load test on the old bridge

3. Design and construction of the new bridge

3.1. Overview

The new bridge was designed as a slab-and-girder structure in the form of an eight-span continuous beam with a middle frame in the shape of an arch that supports the spans over the river (Fig. 5). The existing deep foundation was planned to be reused, allowing the placement of the piers to remain unchanged. The structure was shortened by two end spans (one on each side), so the new abutments would be located on the foundations of the existing middle piers. The frame consists of two reinforced concrete arches on each side of the bridge, together with a central steel arch. The length of the arches is 50.0 m in the. The lengths of the approach spans range from 21.7 to 21.9 m. The CB-type pre-cast beams made of steel and concrete were used for the superstructure.

The load-bearing capacity of the existing piles was insufficient in each of the analysed piers. It was necessary to strengthen the foundations as proposed in Fig. 6. The original pile caps were joined and extended. The load-bearing capacity was improved by adding new pre-cast concrete driven piles.

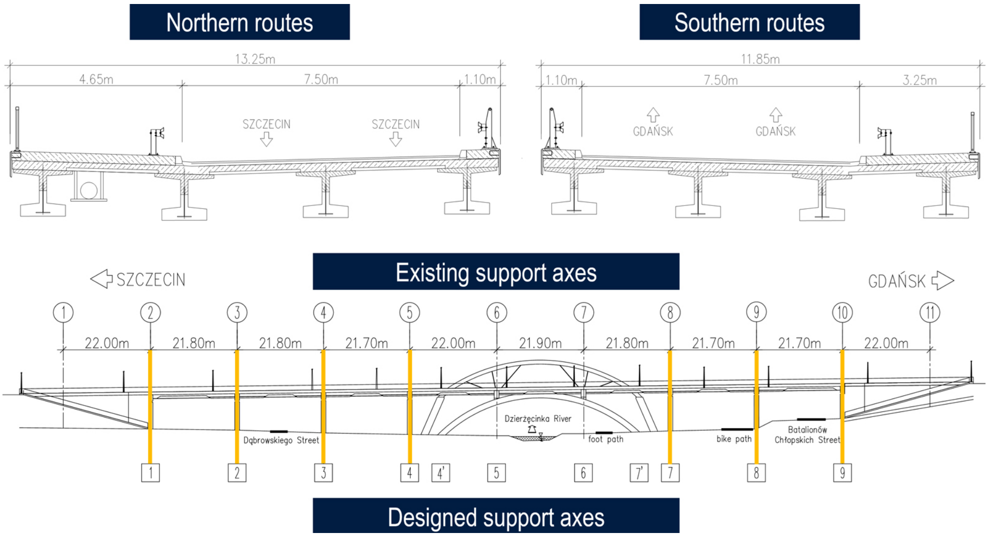


Fig. 5. Cross-section and side view of the new bridge

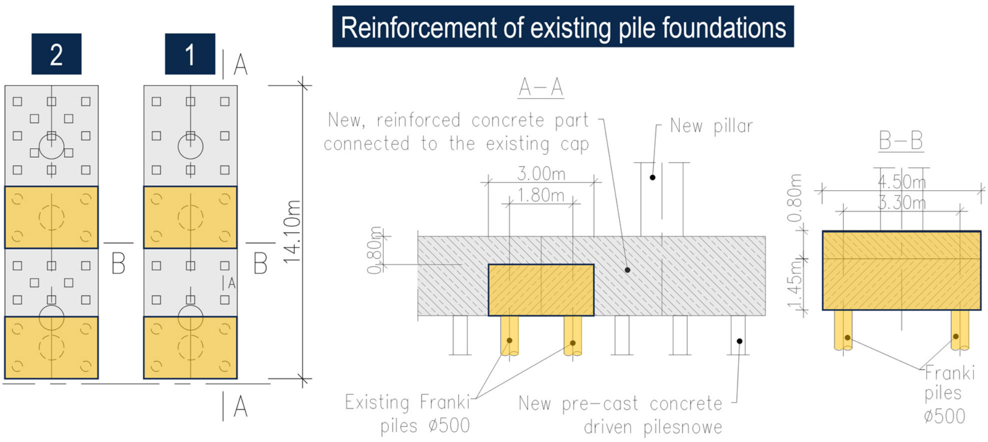


Fig. 6. Reinforcement of existing pile foundations with pre-cast concrete driven piles

3.2. Demolition of the old structure

Several demolition technologies were considered taking into account the total length and type of the structure, including blasting and implosive methods, mechanical cutting along the joints of prefabricated beams, and crushing span by span using hydraulic machinery. One of the requirements was to maintain the continuity of road traffic under the bridge. On this basis, the demolition of successive spans was designed that provided excavators equipped with hydraulic breakers and concrete crushing shears. The operation started on pier no. 1 by demolition of the abutments and end spans on the northern and southern routes. Taking into account the static scheme of the bridge, the demolition technology required removal of the span preceded by removal of one of its supports that led the span to be tilted. I'n this state, one of the edges had to be lowered to the ground level and the other had to remain on the bearings. Following this assumption, the pier no. 2 of the northern structure was removed, and the second span leaned against the pier no. 3 (Fig. 7).

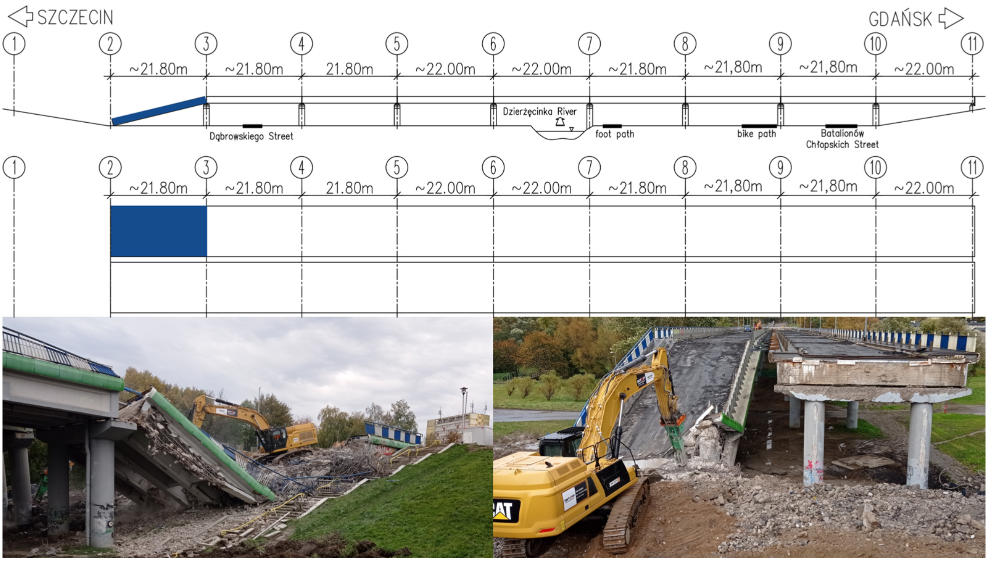


Fig. 7. Demolition works and the state right before the uncontrolled collapse

The mentioned state caused the top of the pier no. 3 to tilt out of the vertical direction by 30–50 cm. As a result, the continuation of demolition works caused an uncontrolled collapse of the support and successive parts of the northern structure (Fig. 8). On 21 October 2021, immediately after the collapse, demolition technology and security measures were reviewed. Road traffic under the bridge was closed to prevent third party access to the site. The investor indicated the need to immediately reassess the demolition technology and resume the works due to inclination of the pier no. 3 on the southern bridge and the risk of similar collapse.

On 27 October 2021, the technological design of the demolition works was revised. It was supplemented with additional security measures and protections under the southern bridge. However, the demolition technology itself did not change. The works were to proceed along the bridge starting from the outer side of the pier no. 2, using hydraulic breakers and concrete crushing shears, as before. Taking into account the works carried out so far, there was a high probability that the spans would collapse uncontrolled again as a result of the instability of the pier no. 3. However, changing the technology to an alternative method, e.g., implosion, would not increase the safety of the works. Considering the partial instability of the structure, it would pose a threat to people preparing the structures for demolition.

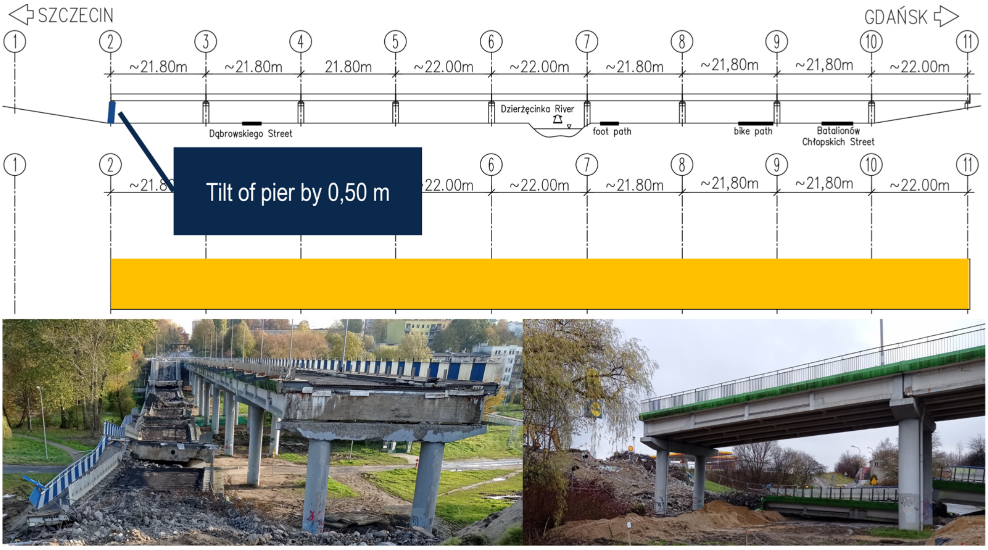


Fig. 8. The state after the uncontrolled collapse

The continuation of demolition works using the same technology was carefully analysed in the report. The acceptable level of risk was evaluated, taking into account the condition of the structure, the safety of people performing demolition works, as well as the impact on the environment and the closest infrastructure. To minimise the risk associated with the work and the choice of technology, the following conditions were determined:

– Setting a safe distance from the edges of the bridge for workers and machinery.
– Resignation from longitudinal cutting along the girders.
– Permanent closure of road traffic under the bridge, protection against unauthorised access by third parties and pedestrians.
– Protection of pavement, footpaths, and road infrastructure under the bridge with sand beds and mats that provide a physical barrier against falling debris and the dynamic impact in the event of uncontrolled collapse.
– Securing and monitoring of the gas network exposed to damage during demolition works.
– Monitoring of selected facilities and buildings in the closest vicinity.

The demolition works were continued taking into account all the requirements. The proposed technology was the only rational one that protected the people performing the works and the surrounding area, minimising the risks associated with the identified threats. In fact, there was no uncontrolled collapse of the southern bridge. This indicates the incidental nature of the construction failure caused by a structural defect of the per no. 3 of the northern structure that could not be predicted. The reason for the failure of the pier was identified as an excessive thickness of the cover concrete and the absence of the required reinforcement in the columns.

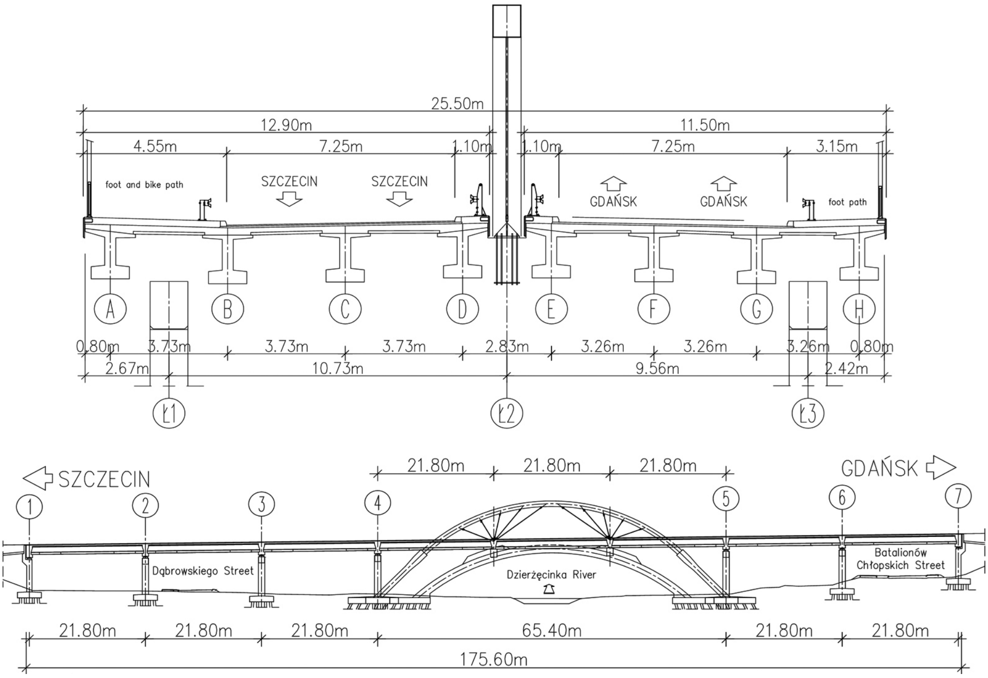
3.3. Overview of the new bridge

After the demolition of the existing structures, it was necessary to change the location of the piers. Due to uncertainty regarding the condition of the old foundations after the collapse of the northern structure and the related dynamic impact, the strengthening of the old pile caps was abandoned. The rebuilt bridge consists of the northern and southern superstructures, connected by common piers in all support axes and crossbeams in the main span. They were designed as a beam-slab continuous structure made of CB-type steel-and-concrete pre-cast beams. They are supported on the bearings on the abutments and most of the piers, except the main span over the river where an arch frame was designed (Fig. 9 and 10). The frame consists of three arch structures, in which the central arch was made of steel and the remaining two of reinforced concrete. The effective lengths between the support points are 21.80 m. In the main span, the central arch was connected to the piers no. 4 and 5 and its total length is 65.40 m. The lengths of the edge arches are 50.0 m. The river span deck is connected to the central arch by steel hangers and, at the same time, lies on the lower reinforced concrete arches and the crossbeams. The pre-cast beams, pre-cast slabs used as lost formwork between the girders, and reinforced concrete arches were made of C50/60 concrete. The bridge deck and crossbeams were made of C40/50 concrete. The main arch was made of S355 steel. The abutments, designed as massive concrete bodies, and the piers, designed as double-column of rectangular cross-section, were supported on the pre-cast concrete driven piles.

4. Load testing

In order to verify the model and assess the behaviour of the bridge under controlled static and dynamic load, acceptance tests were carried out on 28 June 2023. Five load schemes were provided, namely S1, S2, S3, S4, and S5. Dynamic tests included a vehicle driving in both directions up to a speed of 50 km/h and passing over an obstacle. A spatial grid model consisting of 1D and 2D shell elements was used for the design (Fig. 10). The geometric features of the prefabricated beams were assumed as composite. An orthotropic plate of actual thickness was placed on the grid, in which the stiffness in the longitudinal direction (x) was reduced. The stiffness in transverse direction remains unchanged. Displacement sensors, precise levelling, inductive sensors, and accelerometers were used for the measurements (Fig. 10).

The analysis of the structural response from the basic arch span schemes (Fig. 11) confirmed that the code requirements were met and that the developed Finite Element (FE) model is correct. The elastic deflections of the girders were similar to those calculated theoretically in the uncracked phase and amounted on average for the S2, S3, and S4 span schemes in the relevant cross-sections to 97%, 85% and 83% of their values, respectively. Such results indicate that the stiffness of the girders is similar to the values assumed in the model analysed in the



(a)

(b)

Fig. 9. Cross-section and side view of the rebuilt bridge in its final form (a) and the overview of the rebuilt bridge (b)

uncracked phase. The model adopted for dimensioning provides results on the safe side and thus the load-bearing capacity that was theoretically assumed is correct. Permanent deflections are within the range of 0% to 8% of total deflections and therefore meet the code condition of not exceeding the level of 20%. Additionally, the displacements of the arches were measured during the selected load schemes. The maximum value was 1.39 mm and was slightly lower than the calculated values after updating the model (1.43 mm). The tests confirmed that the stiffness of the arches was close to that assumed theoretically.

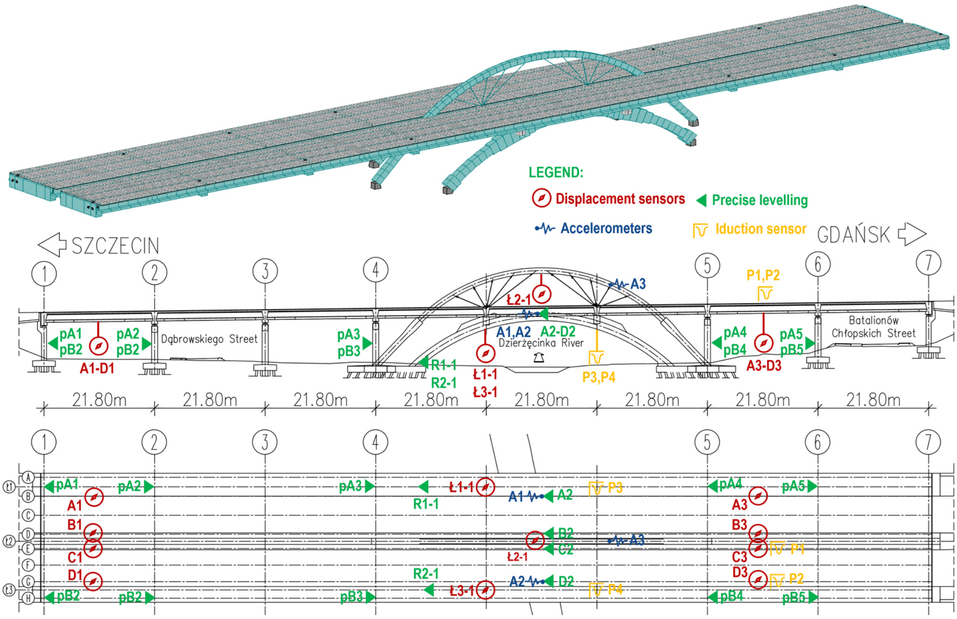


Fig. 10. The overview of the Finite Element (FE) model of the new bridge and location and labelling of the measurement points

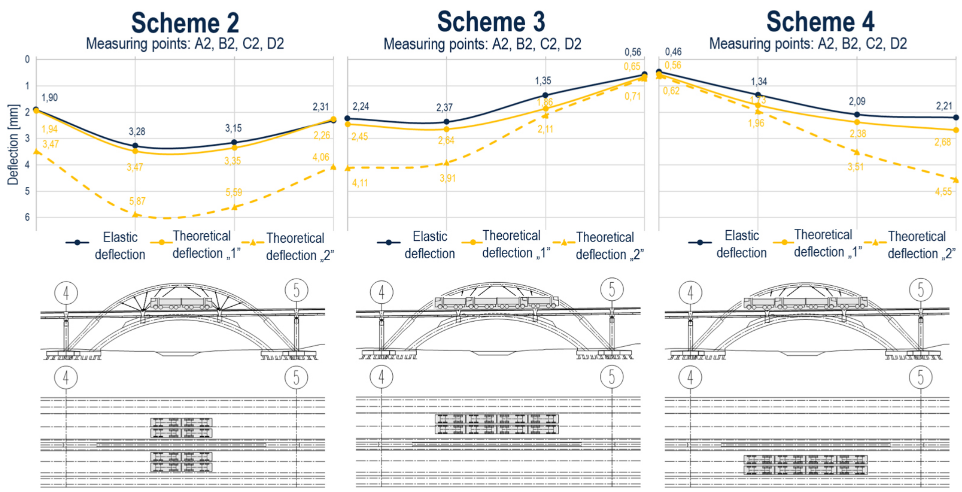


Fig. 11. Selected static load schemes and deflections, including theoretical and measured values

In general, results of the dynamic test were positive. The lowest natural frequency identified was 2.78 Hz, which was higher than the theoretically estimated of 2.34 Hz. The logarithmic decrement had a typical, moderately low value from 0.0221 to 0.1210. No tendency to beating was observed during the tests.

5. Summary

Reconstruction of existing bridge structures often requires preparation of additional demolition works. The choice of technology for such works depends on many factors. Typically, deteriorated structural elements that are subject to demolition pose a high risk related to the safety of the works. Identifying all these threats is very difficult. The example of the bridge failure in Koszalin indicates the necessity of risk analysis. However, to clearly assess these risks, reliable information is required regarding the existing structure, solutions and design assumptions, its history, and its current condition. All this information should be stored in bridge management systems, including digital databases, e.g., BIM models. It is necessary to realise that the basis of the BIM methodology is the building information. Perhaps in the future, BIM information models will be developed in the form of a digital twin concept, which will be used to collect, process, and share information about physical structures. This approach, combined with verified computational models, will provide tangible benefits in streamlining facility management processes throughout their life cycle, while minimising risks related to failures of strategic critical infrastructure systems, including bridge structures.

References

[1] A.Ö. Çiftçioğlu and M.Z. Naser, "Identifying and estimating causal effects of bridge failures from observational data", *Journal of Infrastructure Intelligence and Resilience*, vol. 3, no. 1, art. no. 100068, 2024, doi: 10.1016/j.iintel.2023.100068.

[2] W. Cook, P.J. Barr, and M.W. Halling, "Bridge Failure Rate", *Journal of Performance of Constructed Facilities*, vol. 29, no. 3, 2015, doi: 10.1061/(ASCE)CF.1943-5509.0000571.

[3] K. Wardhana and F.C. Hadipriono, "Analysis of Recent Bridge Failures in the United States", *Journal of Performance of Constructed Facilities*, vol. 17, no. 3, pp. 144–150, 2003, doi: 10.1061/(ASCE)0887-3828(2003)17:3(144).

[4] R.K. Garg, S. Chandra, and A. Kumar, "Analysis of bridge failures in India from 1977 to 2017", *Structure and Infrastructure Engineering*, vol. 18, no. 3, pp. 295–312, 2022, doi: 10.1080/15732479.2020.1832539.

[5] D. Wirkijowski and F.L. Moon, "Identifying Characteristics of Bridges Vulnerable to Hydraulic Hazards Using Bridge Failure Data", *Journal of Performance of Constructed Facilities*, vol. 34, no. 6, 2020, doi: 10.1061/(ASCE)CF.1943-5509.0001513.

[6] S. Qin, H. Wang, and Z. Luo, "Recent hydraulic bridge failures in China: review and discussion", *Revista de la construcción*, vol. 21, no. 2, pp. 193–203, 2022, doi: 10.7764/RDLC.21.2.193.

[7] G. Zhang, Y. Liu, J. Liu, S. Lan, and J. Yang, "Causes and statistical characteristics of bridge failures: A review", *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 9, no. 3, pp. 388–406, 2022, doi: 10.1016/j.jtte.2021.12.003.

[8] R. Adhikari, P. Jha, L. Bhatt, D. Thapa, D. Forcellini, and D. Gautam, "Failure Investigation of under Construction Prestressed Concrete Bridge in Chitwan, Nepal", *Infrastructures (Basel)*, vol. 7, no. 2, art. no. 14, 2022, doi: 10.3390/infrastructures7020014.

[9] G.C. Lee, S.B. Mohan, C. Huang, and B.N. Fard, "A Study of U.S. Bridge Failures (1980-2012)", University at Buffalo, State University of New York, 2013.

[10] R. Al-Rashed, A. Abdelfatah, and S. Yehia, "Identifying the Factors Impacting Bridge Deterioration in the Gulf Cooperation Council", *Designs (Basel)*, vol. 7, no. 6, art. no. 126, 2023, doi: 10.3390/designs7060126.

[11] B. Torres, P. Poveda, S. Ivorra, and L. Estevan, "Long-term static and dynamic monitoring to failure scenarios assessment in steel truss railway bridges: A case study", *Engineering Failure Analysis*, vol. 152, art. no. 107435, 2023, doi: 10.1016/j.engfailanal.2023.107435.

[12] A. Benenato, B. Ferracuti, S. Imperatore, M. Kioumarsi, and S. Spagnuolo, "Experimental Test on Flexural Performance of Prestressed Concrete Beams Damaged by Corrosion", in *Materials Proceedings CMDWC 2021*. Basel Switzerland: MDPI, 2021, doi: 10.3390/CMDWC2021-09974.

[13] J.-S. Tan, K. Elbaz, Z.-F. Wang, J.S. Shen, and J. Chen, "Lessons Learnt from Bridge Collapse: A View of Sustainable Management", *Sustainability*, vol. 12, no. 3, art. no. 1205, 2020, doi: 10.3390/su12031205.

[14] K H. Kim, M.S. Nam, H.H. Hwang, and K.Y. Ann, "Prediction of Remaining Life for Bridge Decks Considering Deterioration Factors and Propose of Prioritization Process for Bridge Deck Maintenance", *Sustainability*, vol. 12, no. 24, art. no. 10625, 2020, doi: 10.3390/su122410625.

[15] A. Natali, A. Cosentino, F. Morelli, and W. Salvatore, "Multilevel Approach for Management of Existing Bridges: Critical Analysis and Application of the Italian Guidelines with the New Operating Instructions", *Infrastructures (Basel)*, vol. 8, no. 4, p. 70, 2023, doi: 10.3390/infrastructures8040070.

[16] G.P. Bu, J.H. Lee, H. Guan, Y.C. Loo, and M. Blumenstein, "Prediction of Long-Term Bridge Performance: Integrated Deterioration Approach with Case Studies", *Journal of Performance of Constructed Facilities*, vol. 29, no. 3, 2015, doi: 10.1061/(ASCE)CF.1943-5509.0000591.

[17] C. Wang, "Resistance Assessment of Service-Proven Aging Bridges Incorporating Deterioration-Load Dependency", *Infrastructures (Basel)*, vol. 5, no. 1, art. no. 10, 2020, doi: 10.3390/infrastructures5010010.

[18] M. Ilbeigi and M. Ebrahimi Meimand, "Statistical Forecasting of Bridge Deterioration Conditions", *Journal of Performance of Constructed Facilities*, vol. 34, no. 1, 2020, doi: 10.1061/(ASCE)CF.1943-5509.0001347.

Przebudowa wiaduktu drogowego w ciągu Alei Monte Cassino w Koszalinie

Słowa kluczowe: mosty, stan techniczny, przebudowa, technologia, badania, analizy

Streszczenie:

W artykule przedstawiono proces przebudowy wiaduktu drogowego w ciągu Alei Monte Cassino w Koszalinie. Degradacja belek prefabrykowanych spowodowała brak spełnienia wymaganej nośności. Na tej podstawie podjęto decyzję o rozbiórce i budowie nowej konstrukcji z uwzględnieniem istniejącego posadowienia w osiach filarów. Analiza wykazała możliwość wzmocnienia istniejących fundamentów palowych palami prefabrykowanymi. Podczas prac rozbiórkowych doszło do niekontrolowanego zawalenia się konstrukcji północnej wiaduktu. Po analizie technologii rozbiórki i uwzględnieniu dodatkowych wymagań, Wykonawca przystąpił do dalszych ich prac. W trakcie prowadzonych robót nie doszło do niekontrolowanego zawalenia się konstrukcji południowej. Po dokonaniu rozbiórki istniejących konstrukcji wprowadzono zmiany do projektu przebudowy związane z położeniem osi filarów. Przeprowadzone badania odbiorcze przebudowanego wiaduktu pozwoliły zweryfikować model MES z określeniem odpowiedzi przęseł w zakresie oddziaływań statycznych i dynamicznych. Zweryfikowany model obliczeniowy jako element cyfrowego bliźniaka może być stosowany w zarządzaniu obiektem w cyklu życia, minimalizując w przyszłości ryzyka związane z awariami strategicznego systemu infrastruktury krytycznej.

Received: 2025-05-27, Revised: 2025-06-17