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Resilience Analysis of Different Retrofitting Solutions for a Prestressed Concrete Viaduct

M. Domaneschi[a*], R. Cucuzza[a], G.C. Marano[a], B. Chiaia[a], G.A. Ferro[a], V. Villa[a], S. Argyroudis[b], S. Mitoulis[c]

[a] *Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin – Italy*
[b] *Department of Civil and Environmental, Engineering, Brunel University London – United Kingdom*
[c] *Department of Civil Engineering, University of Birmingham, Birmingham – United Kingdom*

Abstract

This article introduces a resilience analysis conducted on Greece's prestressed Polyfytos viaduct. As the nation's second longest bridge, spanning 1,372 meters, it was conceptualized by Prof Riccardo Morandi and built between 1972 and 1975, marking it as an iconic structure at 48 years old. Notably, the bridge has strong interdependencies with key power plants, dams and solar pars in the region. Evaluating both risk and resilience, the study employed visual inspections and digital data collection methods. These methods involved a digital twin, offering current asset geometry and a dynamic model for advanced simulations; satellite imagery for ongoing updates on the structure's deformations and geometry; and advanced numerical modeling aimed at interpreting current deflections via back analysis. The bridge shows signs of degradation commonly found in reinforced concrete (RC) and prestressed RC (PRC) bridges, specifically concerning corroded tendons and concrete bonding. Prior research focused on evaluating various retrofitting approaches and their lifecycle impacts, whereas this study integrates the resilience assessment of such retrofit solutions. This contribution represents a new step in the direction of a holistic approach to identifying the appropriate retrofit of an existing viaduct aiming to inform decision-making about the benefits of different restoration investments.

Keywords: Bridge; Resilience; Costs; Sustainability; Holistic; Retrofit.

1. Introduction

Over the past 50 years, the balanced cantilever method in bridge construction has gained prominence for medium spans, around 100 to 200 meters (Concrete Bridge Development Group, 2017). Yet, long-term material effects like

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concrete creep, steel tendon corrosion, and more, causing excessive vertical deflections in cantilever ends, have been reported since the 90s (Bažant and Chern 1984; Bažant and Kim 1991; Bažant and Panula 1980). Instances of bridge deterioration and even partial collapse (Lu et al. 2017) stem from these issues, aggravated by increased traffic loads (Morgese et al. 2020) and potential construction problems (Lucko and De La Garza 2003). Despite efforts by multiple researchers (Gu et al. 2011; Wang and Fu 2015; Domaneschi et al. 2020), a comprehensive mechanism to calculate and predict these faults is lacking.

The absence of a standard solution led the authors to propose an alternative approach, diverging from traditional on-site inspections and extensive sampling. This paper offers an option for assessing fragile assets with uncertain structural integrity, where destructive testing or extensive sample collection is impractical. Leveraging digitalization and monitoring trends in the construction sector toward infrastructure resilience (Argyroudis et al. 2022), the suggested solution relies on computer analysis and innovative tools like drone-based photogrammetry (Varbla et al. 2021), prioritizing cost-effectiveness and eco-friendliness. Laser scanning technology's growing popularity (Lõhmus et al. 2018) and ability to provide detailed results in limited time frames (Witcher 2017) further supports this proposal.

Moreover, this study is also intended to be complementary to a previous study that focused on the impact of different retrofit solutions for this type of bridge, particularly in terms of environmental sustainability and cost. So it went to evaluate the different retrofit solutions by quantifying their resilience (Mitoulis et al. 2023).

The case study of the Polyfytos Bridge in Western Macedonia, Greece, has been selected for the development of this multi-step study.

1.1. The structure and traditional inspections

The Polyfytos bridge, constructed in 1975 in the Municipality of Western Macedonia, Kozani, Greece, spans the artificial Polyfytos lake, serving as a critical link in both local and national road networks. A segment of the bridge, extending 260 meters from piers 22, 23, and 24 (Fig.1), was constructed using the balanced cantilever method, contributing to the bridge's total length of 1372 meters. Recent inspections, conducted by multiple inspectors including one of this paper's authors, highlighted excessive deflections at the cantilevers' free ends, a common issue in aging balanced cantilever bridges (Markogiannaki et al. 2022). Preliminary assessments identified corrosion and local concrete damage, raising substantial concerns about the bridge's structural integrity. Consequently, traffic restrictions were implemented, including weight limitations for heavy vehicles and reduced speed limits to mitigate dynamic impacts.

Typically, extensive sampling, destructive testing, and vibration/loading checks are employed to assess material conditions. However, due to concerns regarding the deck's capacity at critical points, these methods weren't authorized by the owners (Markogiannaki et al. 2022). Moreover, due to the bridge's significance in the busy national road network (part of the E65 Central Greece Highway), conducting tests that could disrupt traffic poses significant challenges.

1.2. The "digital" approach to inspection

In response, a digitalized damage assessment approach is proposed, utilizing advanced computational tools applicable to various structural assets. While various monitoring systems using sensor technology have been suggested (Li et al. 2022; Zhou et al. 2021), none have achieved universal optimality due to varying accuracy levels. Our innovative approach minimizes intrusion, time, cost, and environmental impact.

The proposed procedure begins with a fault report, determining the need for on-site inspections. High-tech surveying tools, such as drone-based photogrammetry, offer valuable data on deflections, rotations, and visible cracks without physical access to the structure (Li et al. 2022). These measurements create deflection curves for mathematical comparison with other data sets. Additionally, information from design reports and literature supplements this analysis, contributing to an advanced structural model.

Given existing knowledge gaps (Bažant and Jirásek 2018), an advanced model considers potential causes like creep and shrinkage observed in similar structures. Scenario-based analyses explore various parameters' effects on the structure. Comparing these scenarios' deflection curves to measured results identifies potential causes, guiding further investigation without providing absolute conclusions.

This approach, while not conclusive on its own, offers reliable information to engineers and the infrastructure operators, offering a digitally streamlined, cost and time efficient, and environmentally friendly solution with minimal structural interaction.

Fig. 1. General view of the Polyfytos lake and the bridge with the detail of Piers #22, #23, #24.

1.3. Corrosion as source of deterioration

The corrosion of tendons in prestressed concrete bridges is a critical factor threatening their structural integrity, evidenced by incidents like the catastrophic failure of the Ynys-y-Gwas bridge in the UK in 1985 (Podolny 1992). Even in the early stages of a bridge's life, instances like the replacement of post-tensioned tendons in Florida's Mid-Bay bridge after eight years of operation due to corrosion-related concerns highlight the significance of this issue (Hartt and Venugopalan 2002).

In this study, the focus has been primarily on corrosion as the main contributor to the investigated bridge's deterioration, largely overlooking potential additional failure mechanisms like scouring or spalling of the reinforced concrete. Moisture exposure renders the exposed interface of a strand particularly susceptible to corrosion-induced damages. The concept of "localized corrosion" poses a significant concern, as it could result in substantial reductions in the strand's cross-section, leading to severe decreases in its tension capacity. Within a strut, variations could exist between corroded and uncorroded wires in the same section, as well as corroded and uncorroded segments along its length.

2. The bridge description and the available data on its current condition

In Domaneschi et al. (2023) the bridge description with a focus on the part under evaluation in the present study (piers #22, #23, #24 with cantilever and precast beams connected by half-joints) is reported along with the construction technology adopted (prestressed concrete technique). Moreover, details on the geometry and the constitutive materials are also described, along with the performed analyses and the degradation assessment.

According to Domaneschi et al. (2023), an overview of the bridge's current condition is provided through a detailed depiction using a point cloud. This representation offers insights into specific aspects of the cantilever and the half-joint of the bridge.

The document also addresses the deflection of the most critical cantilever. It notes a notable difference between the expected elevation and the measured position. The measured position indicates a significant deviation, measuring 133mm and 207mm lower than the anticipated elevation.

These deviations specifically highlight downward displacements at the tip or end of the most critical cantilever. Such substantial deviations from the expected positions might indicate potential structural issues within this particular section of the bridge. Further investigation and analysis would be essential to determine the root causes and to implement necessary actions to maintain the bridge's structural integrity and safety.

3. Considered retrofit options

Preliminary design for retrofitting the Piers under study is herein developed with the aim of enhancing the bridge's structural performance and safety in line with standard regulations. As previously discussed, the significant damage to the bridge primarily stems from inadequate maintenance strategies, potential issues during construction, increased traffic volume, high loads during its service life, and exposure to harsh environmental conditions. The critical reduction in prestressing stress at the cantilever supports is the main factor affecting the bridge's functionality. Consequently, two viable retrofitting scenarios have been identified to restore the bridge's original functionality (Domaneschi et al. 2023).

- Scenario #1: Demolition and reconstruction. This approach involves demolishing the existing continuous deck, which comprises six tapered box girder cantilevers and three girder bridges, while retaining the existing piers. The reconstruction phase assumes the conservation of the same structural configuration, materials, and behaviors, which is justifiable given the continued widespread use of the bridge's design.
- Scenario #2: Local interventions and replacement of the girder bridge sections (Gerber beams). This scenario incorporates the installation of external prestressing cables to reinstate proper compression stresses in the six cantilevers, thereby enhancing the overall functionality of the bridge. Additionally, consideration is given to replacing the three girder bridges with steel box girder sections to prevent corrosion in the prestressing cables. As demonstrated by the authors' assessments, this proposed solution results in improved slenderness and an overall reduction in the load carried by the cantilevers.

Once the retrofitting methods are identified, a comprehensive list of interventions for each scenario can be reported.

For Scenario #1, the activities considered are as follows:

a) Dismantling the defective balanced cantilever section of the deck and the reinforced concrete girder bridge using non-explosive agents with chemical action instead of explosive charges.

b) Restoring the original structural design of the bridge by reconstructing the decks. Construction costs for both the concrete deck and steel reinforcement have been computed. They encompass the steel reinforcement within the deck and the anchorages required to attach the new cantilever to the existing piers' head.

c) Installing elastomeric bearings at the end of the cantilever.

d) Incorporating expansion joints at the girder bridge deck level to prevent thermal constraints or damage to the traffic pavement.

e) Constructing the road pavement, including surfacing layers, asphalt bond coat, protective layers, epoxy bonding, waterproofing, and reinforced concrete deck.

f) Implementing all necessary functional facilities such as road signs, safety barriers, etc.

Conversely, for Scenario #2, the following activities have been considered:

a) Demolition of only the Gerber bridge sections using the same techniques as Scenario #1.

b) Installing a steel box deck designed with guidelines aimed at reducing total weight and ensuring a minimum height for easier maintenance. This involves operations related to the creation of the reinforced concrete slab using the predalles system.

c) Applying hot-dip galvanizing to all steel surfaces of the deck for passivating treatment.

d) Replacing girder deck bearings with the FPS system to prevent slippage between the deck and supports.

e) Adding expansion joints at the girder bridge deck level to prevent thermal effects or damage to the traffic pavement.

f) Constructing the road pavement with surfacing layers, asphalt bond coat, protective layers, epoxy bonding, waterproofing, and reinforced concrete deck.

g) Implementing all necessary functional facilities like road signs, safety barriers, etc.

h) Implementing an external prestressing system by adding four cables along each cantilever to restore the original deflection. Design considerations involve using cables of the same section as those in the technical drawings and introducing compression stress to prevent cracking.

4. Environmental and cost impacts of the retrofit options

The expenses related to each scenario have been assessed using the price lists provided by ANAS (2022) from Italy, except for the evaluation of the prestressing system cost, where the authors adopted the parametric cost detailed in Devitofranceschi (2018). While price lists might vary between countries, the analysis has been concentrated on comparing different retrofitting scenarios, noting that variations, though present within the European community, are not significant.

To facilitate a comparison between the two scenarios, a specific segment of the bridge has been considered, evaluating all operations from an economic perspective (one pier with the associated couple of cantilevers plus one Gerber beam). The calculated estimates for each scenario are based on this segment, allowing for easy derivation of the overall intervention cost. Table 1 and 2 summarize each intervention for the assessment of the total cost of each scenario. The final cost for each scenario highlight the higher impact of the first one (Domaneschi et al. 2023).

Table 1. Scenario #1, cost assessment.

Phase	[k€]
(a)	80
(b)	2000
(c)	11.2
(d)	13.5
(e)	106
(f)	133

Table 2. Scenario #2, cost assessment.

Phase	[k€]
(a)	25
(b)	1100
(c)	9.5
(d)	11.2
(e)	13.5
(f)	76
(g)	53
(h)	35

The primary objective of Life Cycle Assessment (LCA), as for the former cost analysis, has been to facilitate a comparison between the two scenarios and comprehend their collective environmental impact on the entire infrastructure, specifically the bridge (Domaneschi et al. 2023). The chosen functional unit for assessment has been the bridge unitary surface (km^2 bridge). The analysis primarily has been focused on the Global Warming Potential impact category (GWP 100ys, CML 2001), utilizing environmental data sourced from GENERIS® software (Fraunhofer 2023). The data have been derived from available product-specific (Environmental Product Declarations, EPD) and average generic construction materials' datasets (Federal Ministry for Housing, Urban Development and Building 2023). For products lacking environmental information, such as expansion joints and bridge support systems, average datasets have been used for a preliminary environmental evaluation. For instance, both bearing systems have been modeled as a double steel plate and an elastomeric intermediate element.

However, it's important to note that in the LCA, functional facilities, electrical systems, drainage systems, and safety barriers have been intentionally excluded from the analysis. These elements have been considered out of scope, as the primary focus has been solely on the restoration scenarios themselves.

Similar to cost analysis, GWP is computed and combined within interventions in tables 3 and 4. The final environmental impact for each scenario highlight a reasonable equivalence between them (Domaneschi et al. 2023).

Table 3. Scenario #3, GWP assessment.

Phase	[1000kg CO2eq]
(a)	170
(b)	164
(c)	30
(d)	385
(e)	3373
(f)	Out of scope

Table 4. Scenario #4, GWP assessment.

Phase	[1000kg CO2eq]
(a)	54
(b)	189
(c)	3.8
(d)	30
(e)	385
(f)	3350
(g)	Out of scope
(h)	Out of scope

5. Resilience assessment of the retrofit options

This section deals with the system functionality curves for both the recovery configurations considered. While interventions cover the entire viaduct, as anticipated, the primary focus is on analyzing the three main Piers from #22 to #24 characterized by the largest spans, consisting of cantilevers connected by Gerber beams. Professional bridge engineering specialists, involved in design, execution, reinforcement, and rehabilitation interventions of such type of bridge structures at the national and international levels, have been consulted to assume reasonable and realistic parameters, to plot functionality curves for each intervention type.

The preliminary stages, including selecting the intervention designer, technical-economic feasibility projects, final and executive designs, and administration, are estimated to take 6-8 months before the bridge closure for interventions. Traffic limitations and load intensity have been imposed due to safety concerns identified in inspections starting in 2020. This includes traffic restrictions, reducing vehicle weight limits to 500 kN and speed limits to 40 km/h.

Both scenarios aim to utilize existing piers and related foundational structures. Moreover, both scenarios consider the bridge closure due to the single-carriageway nature, impeding partitioning of reconstruction.

The functionality curves for the considered solutions are depicted in Figure 2, reporting the starting condition at time 0 when the deck or Gerber beams are demolished, leading to full bridge closure. In Scenarios #1, demolition is estimated to take around 10 days using explosives, whereas for Scenario #2, the controlled demolition of the Gerber beams will take longer, approximately 20 days.

Concerning the considered solution involving the replacement of the deck or a portion of it, it is assumed that before demolition begins, the replacement structure has been prepared nearby for swift replacement. Specifically, the installation of the new deck is assumed to take 3 months for solutions #1. Scenario #2, involving the installation of new Gerber beams and external prestressing cables for the cantilevers, is estimated to take 150 days.

Upon completion of the construction, the estimated timeline for testing, processing (technical-administrative approval), until the full reopening of the bridge, is set at 90 days. After this period, it is assumed that the bridge's transit capability will be restored to 100%. Considering a 360-day maximum closure period, resilience values for the different scenarios are tabulated in Table 5.

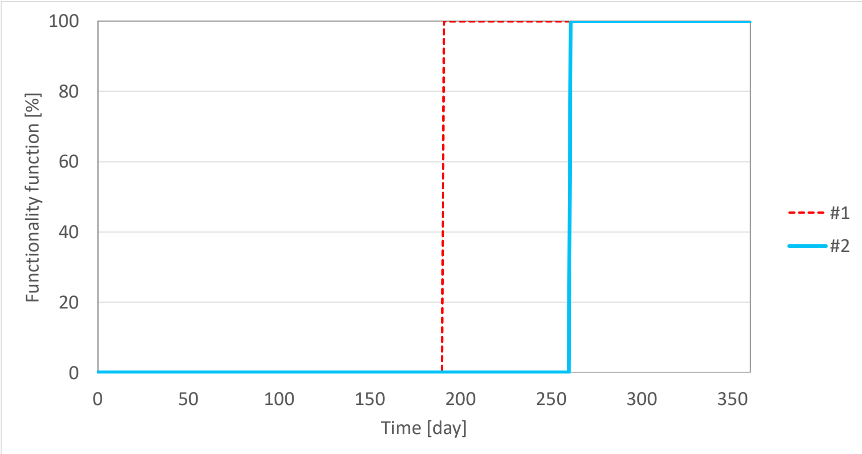

Fig. 2. Transitability: functionality curves.

Table 5. Resilience values computed through transitability.

Scenario	#1	#2
Resilience	0.47	0.28

Interesting to note is how resilience, in this case, has been calculated concerning the bridge's transit capability, without considering the structural capacity, which is, instead, partly independent and influenced by bureaucratic and administrative issues (e.g., bridge static testing for technical certification, administrative processes). Structural capacity gradually varies over time due to actions taken on the bridge (e.g., installation of external prestressing cables and new structural components) (Mitoulis et al. 2021). This variation occurs both in terms of the bridge's capacity degradation due to aging and other processes as corrosion or fatigue, and in terms of capacity restoration through maintenance, reinforcement, and restoration actions.

6. Conclusions

- This multi-step investigation assesses potential retrofits for addressing the deterioration of the Polyfytos bridge.
- The study utilizes cutting-edge surveying tools (laser-photogrammetry) with other analyses of the Polyfytos bridge.
- Different interventions have undergone evaluation concerning their costs and environmental sustainability. The present study is focused on the resilience assessment of the investigated interventions to be coupled to previous investigations for a holistic approach to the bridge retrofit.
- Initial findings revealed a comparable level of environmental sustainability but display a notable contrast in intervention costs, while the present study highlights interesting differences also in terms of resilience assessment.
- Despite being an initial study with a limited range of scenarios, it is apparent that there exists an anticipated disparity in intervention costs and resilience between the two types of restoration. Future developments aim to incorporate additional scenarios. Resilience computed with respect to structural capacity in contrast to transitability will be also considered. Long-term effectiveness of interventions will be also investigated as a critical parameter for the identification of the optimal solution.

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References

ANAS S.p.A. 2022. Price list for New Construction and scheduled maintenance (in Italian). https://www.stradeanas.it/it/elenco-prezzi

Argyroudis, SA, Mitoulis, SA, Chatzi, E, Baker, JW, Brilakis, I, Gkoumas, K, Vousdoukas, M, Hynes, W, Carluccio, S, Keou, O, Frangopol, DM, Linkov, I. 2022. Digital technologies can enhance climate resilience of critical infrastructure. Climate Risk Management 35, 100387.

Bažant, Z.P., Chern, J.C., 1984. Bayesian statistical prediction of concrete creep and shrinkage. ACI Journal 81(4), 319-330.

Bažant, Z.P., Panula, L., 1980. Creep Shrinkage Characterization for Prestressed Concrete Structures. J. of the Prestressed Concrete Institute 25, 86-122.

Bažant, Z.P., Kim, J.K., 1991. Improved prediction model for time-dependent deformations of concrete: Part 2 - basic creep. Mater. Struct. 24 (6).

Bažant, Z.P., Jirásek, M., 2018. Creep and Hygrothermal Effects in Concrete Structures. Solid Mechanics and Its Applications 225. Springer, Dordrecht.

Concrete Bridge Development Group, 2017. Development of prestressed concrete bridges. https://www.cbdg.org.uk/

Devitofranceschi, A., 2018. Repair of prestressed road viaducts: intervention techniques and cost-benefit analysis (in Italian). Italian Concrete Days-AICAP.

Domaneschi, M., Pellecchia, C., De Iuliis, E., Cimellaro, G.P., Morgese, M., Khalil, A.A., Ansari, F., 2020. Collapse analysis of the Polcevera Viaduct by the Applied Element Method. Engineering Structures 214, 110659.

Domaneschi M., Mitoulis S.A., Cucuzza R., Villa V., Di Bari R., Siva G., 2023. RESTORATION OF A LANDMARK BALANCED CANTILEVER BRIDGE CONSIDERING DIFFERENT RESILIENCE AND SUSTAINABILITY STRATEGIES. COMPDYN Proceedings. EDS: Papadrakakis M., Fragiadakis M. PUBLISHER: National Technical University of Athens.

Federal Ministry for Housing, 2023. Urban Development and Building. ÖKOBAUDAT. https://oekobaudat.de/

Fraunhofer, 2023. IBP GENERIS®. www.generis-solution.eu

Guo, T., Sause, R., Frangopol, D., Li, A., 2011. Time-Dependent Reliability of PSC Box-Girder Bridge Considering Creep, Shrinkage, and Corrosion. J. Bridge Eng. 16(1), 29-43.

Hartt, W.H., Venugopalan, S., 2002. Corrosion evaluation of post-tensioned tendons on the Mid Bay Bridge in Destin, Florida. Florida Department of Transportation Research Center. Report 33890.

Li, S., Wang, W., Lu, B., Du, X., Dong, M., Zhang, T., Bai, Z., 2023. Long-term structural health monitoring for bridge based on back propagation neural network and long and short-term memory. Structural Health Monitoring 22(4), 2325-2345.

Lõhmus, H., Ellmann, A., Märdla, S., Idnurm, S., 2018. Terrestrial laser scanning for the monitoring of bridge load tests – two case studies. Survey Review 50:360, 270-284.

Lu, N., Beer, M., Noori, M., Liu, Y., 2017. Lifetime Deflections of Long-Span Bridges under Dynamic and Growing Traffic Loads. J. Bridge Eng., 22(11), 04017086.

Lucko, G., de la Garza, J.M., 2003. Constructability Considerations for Balanced Cantilever Construction. Pract. Period. Struct. Des. Constr. 8(1), 47-56.

Markogiannaki, O., Hang, X., Chen, F., Mitoulis, S., Parcharidis, I., 2022. Monitoring of a landmark bridge using SAR interferometry coupled with engineering data and forensics. International Journal of Remote Sensing 43, 95-119.

Mitoulis, SA, Bompa, DV, Argyroudis, SA. 2023. Sustainability and climate resilience metrics and trade-offs in transport infrastructure asset recovery. Transportation Research Part D: Transport and Environment 121, 103800.

Mitoulis, S.A., Argyroudis, S., Loli, M., Imam, B. 2021. Restoration models for quantifying flood resilience of bridges. Engineering Structures 238, 112180

Morgese, M., Ansari, F., Domaneschi, M., Cimellaro, G.P., 2020. Post-collapse analysis of Morandi's Polcevera viaduct in Genoa Italy. Journal of Civil Structural Health Monitoring 10, 69–85.

Podolny, W., 1992. Corrosion of prestressing steels and its mitigation. PCI journal 37(5), 34-55.

Varbla, S., Artu, E., Raido, P., 2021. Centimetre-range deformations of built environment revealed by drone-based photogrammetry. Automation in Construction 128, 103787.

Wang, S., Fu, C.C., 2015. Simplification of Creep and Shrinkage Analysis of Segmental Bridges. J. Bridge Eng. 20(8), B6014001.

Witcher, T.R., 2017. From disaster to prevention: The silver bridge. Civil Engineering Magazine Archive 87(11), 44-47.

Zhou, J., Sun, Z., Wei, B., Zhang, L., Zeng, P., 2021. Deflection-based multilevel structural condition assessment of long-span prestressed concrete girder bridges using a connected pipe system. Measurement 169, 108352.