*Bridge Maintenance, Safety, Management, Digitalization and Sustainability –
Jensen, Frangopol & Schmidt (eds)*

Resilience and sustainability assessment of a prestressed concrete viaduct

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ABSTRACT: The paper explores Greece's Polyfytos viaduct, the nation's second-longest bridge spanning 1,372 meters, renowned also for providing access to key power plants in South-East Europe. A resilience analysis of different retrofitting scenarios was conducted, including both transitability and structural capacity aspects, employing visual inspections, digital data collection, and advanced modeling techniques. The viaduct, conceptualized by Prof Riccardo Morandi and built in 1972-1975, displays typical degradation seen in prestressed and reinforced concrete bridges. Unlike previous research focused solely on retrofitting with LCA and LCC assessments, this study integrates resilience assessment, marking a pioneering holistic approach to viaducts refurbishment.

1 INTRODUCTION

1.1 *Summary*

Over the last five decades, the balanced cantilever method has become increasingly popular in constructing bridges with medium spans, typically ranging between 100 to 200 meters (Concrete Bridge Development Group, 2017). However, issues related to long-term material effects such as concrete creep, steel tendon corrosion, and others have been noted since the 1990s, resulting in excessive vertical deflections (Bažant and Chern 1984, Bažant and Kim 1991, Bažant and Panula 1980). These problems have led to instances of bridge deterioration, even partial collapse, primarily exacerbated by heightened traffic loads up to 5-6 times the original ones (Morgese et al. 2020) and potential construction complications (Lucko and De La Garza 2003). Despite multiple research efforts (Gu et al. 2011, Wang and Fu 2015, Domaneschi et al. 2020), a comprehensive mechanism to predict and calculate these faults remains elusive.

The lack of a standardized solution suggests to propose an alternative approach, moving away from traditional on-site inspections and extensive sampling. This paper suggests formerly a method for evaluating vulnerable assets with uncertain structural integrity, where destructive testing or extensive sample collection is not feasible. Drawing on digitalization and monitoring trends in the construction sector, the recommended approach relies on computer analysis and innovative tools like drone-based photogrammetry (Varbla et al. 2021). Emphasizing cost-effectiveness and environmental friendliness, this method aligns with the growing popularity of laser scanning technology (Lõhmus et al. 2018), capable of providing detailed results within limited time frames (Witcher 2017).

DOI: 10.1201/9781003483755-309

Furthermore, this study serves as a complement to prior research that focused on assessing various retrofit solutions for this bridge type, particularly concerning environmental sustainability and cost impacts. It aims to evaluate these solutions by quantifying their resilience considering both transitability and structural capacity issues in the resilience computation. Therefore, the result is to promote a holistic approach to the reinforcement and maintenance of existing viaducts, considering not only the classical technical aspects of structural engineering but also environmental impact, cost, and resilience in identifying the most suitable solution. The Polyfytos Bridge in Western Macedonia, Greece, has been chosen as the case study for this multi-step research effort.

1.2 *The Polyfytos Bridge*

The Polyfytos Bridge, constructed in 1975 within the Municipality of Western Macedonia, Kozani, Greece, stretches over the artificial Polyfytos lake, playing a crucial role in connecting local and national road networks. One section of the bridge, spanning 260 meters between piers 22, 23, and 24 (Figure 1), was built using the balanced cantilever method, contributing to the bridge's overall length of 1372 meters. Recent inspections, carried out by multiple inspectors, including one of the authors of this paper, revealed excessive deflections at the free ends of the cantilevers, a common issue in aging bridges constructed using this method (Markogiannaki et al. 2022). Initial evaluations highlighted corrosion and localized concrete damage, raising significant concerns about the bridge's structural soundness. Consequently, traffic restrictions, such as weight limitations for heavy vehicles and reduced speed limits, were imposed to minimize dynamic impacts.

Typically, extensive material sampling, destructive testing, and vibration/loading assessments are utilized to evaluate material conditions. However, due to concerns about critical points on the deck's capacity, the owners did not authorize these methods (Markogiannaki et al. 2022). Furthermore, because of the bridge's importance in the bustling national road network (part of the E65 Central Greece Highway), conducting tests that could disrupt traffic necessitates considerable challenges.

Figure 1. The Polyfytos bridge and the three piers under evaluation.

1.3 *Digital technologies toward bridge inspection*

A proposed method for digital damage assessment is introduced, employing sophisticated computational tools adaptable to diverse structural assets. While several monitoring systems utilizing sensor technology have been recommended in previous studies (Li et al. 2022, Zhou et al. 2021), none have achieved universal optimization due to varying levels of accuracy. The proposed innovative approach aims to minimize intrusion, time, cost, and environmental impact.

The suggested process starts with a report on the necessity for on-site inspections. High-tech surveying tools, such as drone-based photogrammetry, provide valuable data on deflections, rotations, and visible cracks without requiring physical access to the structure (Li et al. 2022). These measurements generate deflection curves for mathematical comparison with other datasets. Additionally, information sourced from design reports and literature complements this analysis, contributing to an advanced structural model.

Acknowledging existing knowledge gaps (Bažant and Jirásek 2018), the advanced model considers potential factors such as creep and shrinkage observed in similar structures.

Scenario-based analyses explore the impact of various parameters on the structure. By comparing the deflection curves from these scenarios with measured results, potential causes are identified, guiding further investigation without providing definitive conclusions.

While this approach may not offer conclusive findings, it provides engineers and asset stakeholders with reliable information, offering a digitally streamlined, cost-effective, time-efficient, and environmentally friendly solution with minimal structural intervention.

1.4 *Some remarks on corrosion issues*

The corrosion of tendons in prestressed concrete bridges poses a significant threat to their structural integrity, as seen in incidents such as the catastrophic failure of the Ynys-y-Gwas bridge in the UK in 1985 (Podolny 1992). Even early in a bridge's lifespan, events like the replacement of post-tensioned tendons in Florida's Mid-Bay bridge after eight years due to corrosion-related concerns emphasize the importance of this issue (Hartt and Venugopalan 2002).

This study primarily focuses on corrosion as the primary cause of the investigated bridge's deterioration, largely disregarding potential additional failure mechanisms such as scouring or spalling of the reinforced concrete. Exposure to moisture makes the exposed interface of a strand highly vulnerable to corrosion-induced damage. The concept of "localized corrosion" raises significant concerns as it could lead to substantial reductions in the strand's cross-section, resulting in severe decreases in its tension capacity. Variations may exist within a strut, with differences between corroded and uncorroded wires in the same section and corroded and uncorroded segments along its length (Bartolozzi et al. 2022, De Gaetano et al. 2020).

2 BRIDGE CONDITION

A more detailed description of the bridge, focusing on the segment examined in this research (piers #22, #23, #24 with cantilever and precast beams connected by half-joints), is presented in the study by Domaneschi et al. (2023), along with the utilization of prestressed concrete technique in construction. Additionally, specifics regarding geometry, constituent materials, conducted analyses, and degradation assessment are provided.

According to Domaneschi et al. (2023), an in-depth detailing of the current state of the bridge is presented utilizing a point cloud. This visualization offers insights into particular aspects of both the cantilever and the half-joint of the bridge.

The report also addresses the deflection of the most critical cantilever, noting a significant variance between the expected and measured elevations. The measured position reveals a considerable discrepancy, measuring 133mm and 207mm lower than the anticipated elevation.

These differences specifically highlight downward displacements at the tip or end of the most critical cantilever. Such considerable deviations from the expected positions may indicate potential structural concerns within this specific component of the bridge. Further investigation and analysis are crucial to determine the underlying causes and implement necessary measures to maintain the bridge's structural integrity and safety.

3 FRAMEWORK FOR THE ASSESSMENT

The comprehensive approach involves assessing the structure's condition, proposing various technical solutions, evaluating costs, analyzing environmental effects, and gauging resilience against diverse challenges. The ultimate selection of the retrofitting solution integrates these aspects, ensuring a balance between structural improvement, economic viability, sustainability, and long-term resilience. This framework aims to guide decision-making and implementation, aiming for a safer, more durable, and environmentally conscious infrastructure.

4 PRELIMINARY BRIDGE RETROFITTING MEASURE

The initial design for retrofitting the analyzed piers aims to improve the structural performance and safety of the bridge in accordance with standard regulations. As discussed earlier, significant damage to the bridge is primarily attributed to inadequate maintenance, potential issues during construction, increased traffic, high loads during service, and exposure to harsh environmental conditions. The critical reduction in prestressing stress at the cantilever supports severely impacts the bridge's functionality. Thus, two viable retrofitting scenarios have been identified to restore its original functionality (Domaneschi et al. 2023).

- Scenario #1: Demolition and reconstruction involve demolishing the current continuous deck, comprising six tapered box girder cantilevers and three girder bridges, while retaining the existing piers. Reconstruction maintains the same structural configuration, materials, and behaviors due to the widespread use of the bridge's design.
- Scenario #2: Local interventions and replacement of the girder bridge sections incorporate installing external prestressing cables to restore proper compression stresses in the six cantilevers, enhancing the bridge's functionality. Additionally, it considers replacing three girder bridges with steel box girder sections to prevent cable corrosion. This solution results in improved slenderness and reduced load on the cantilevers.

For Scenario #1, the interventions include:

a) Disassembling the defective balanced cantilever segment of the deck and the reinforced concrete girder bridge using non-explosive agents that rely on chemical action instead of explosive charges.
b) Recreating the original structural design of the bridge by reconstructing the decks. Calculations for construction expenses cover both the concrete deck and steel reinforcement, encompassing the steel reinforcement within the deck and the necessary attachments to secure the new cantilever to the existing piers' head.
c) Installing elastomeric bearings at the cantilever's extremity.
d) Introducing expansion joints at the girder bridge deck level to prevent thermal constraints or damage to the traffic pavement.
e) Building the road surface, incorporating layers such as surfacing layers, an asphalt bond coat, protective layers, epoxy bonding, waterproofing, and a reinforced concrete deck.
f) Installing all requisite functional amenities, including road signs, safety barriers, and others

For Scenario #2, the interventions involve:

a) Removing only the Gerber bridge sections using a controlled approach.
b) Installing a steel box deck designed to minimize overall weight. This encompasses procedures related to creating the reinforced concrete slab utilizing the predalles system.
c) Employing hot-dip galvanization on all steel surfaces of the deck to apply a passivating treatment.
d) Substituting girder deck bearings with the FPS system to prevent any slippage between the deck and its supports.
e) Introducing expansion joints at the girder bridge deck level to avert thermal impacts or harm to the traffic pavement.
f) Constructing the road surface, which includes surfacing layers, an asphalt bond coat, protective layers, epoxy bonding, waterproofing, and a reinforced concrete deck.
g) Implementing all necessary functional amenities such as road signs, safety barriers, etc.
h) Introducing an external prestressing system by adding four cables along each cantilever to reinstate the original deflection. The design considerations involve utilizing cables of the same section as those depicted in the technical drawings and introducing compression stress to prevent any cracking.

5 EFFECTS OF THE RETROFITTING MEASURES

5.1 *Costs*

The financial assessments for each scenario were conducted utilizing the price catalogs provided by ANAS (2022) from Italy, with the exception of the evaluation for the cost of the prestressing system, where the authors adopted the parametric cost outlined in Devitofranceschi (2018). Acknowledging potential variations in price lists across countries, the analysis primarily focused on comparing diverse retrofitting scenarios, noting that within the European community, discrepancies, while existent, are not considered significant.

For comparative purposes, a specific segment of the bridge was selected, encompassing all operations within an economic framework (one pier coupled with its associated cantilevers and one Gerber beam). The projected cost estimates for each scenario were derived from this slice, simplifying the extrapolation of the comprehensive intervention expenses. Table 1 provides a comprehensive overview of each intervention to facilitate the assessment of the total cost for individual scenarios. Ultimately, the final costs for each scenario clarify the higher financial impact associated with the first one (Domaneschi et al., 2023).

Table 1. Costs for each scenario.

Scenario #1 Phase	[k€]	Scenario #2 Phase	[k€]
(a)	80	(a)	25
(b)	2000	(b)	1100
(c)	11.2	(c)	9.5
(d)	13.5	(d)	11.2
(e)	106	(e)	13.5
(f)	133	(f)	76
		(g)	53
		(h)	35

5.2 *Environmental quality*

A Life Cycle Assessment (LCA) analysis, in parallel with the prior cost analysis, has been carried out for a comparative evaluation between the two scenarios and comprehend their collective environmental potential (Domaneschi et al., 2023). The selected functional unit for comparative assessment and benchmarking is the bridge's individual surface area (km² bridge). The analysis has predominantly centered on the Global Warming Potential impact category (GWP 100ys, CML 2001 calculated in ton CO_2 eq.), utilizing environmental data developed from GENERIS® software (Fraunhofer 2023). These data stem from available product-specific information (Environmental Product Declarations, EPD) and average datasets for common construction materials (Federal Ministry for Housing, Urban Development and Building 2023). For products lacking specific environmental information, like expansion joints and bridge support systems, average datasets have been employed for initial environmental assessments. For example, both bearing systems has been modelled as a double steel plate and an elastomeric intermediate element.

It is crucial to note that in the LCA, functional amenities such as facilities, electrical and drainage systems, as well as safety barriers, have been intentionally omitted from the analysis.

Table 2. Environmental impact for each scenario.

Scenario #1 Phase	[ton CO_2 eq]	Scenario #2 Phase	[ton CO_2 eq]
(a)	171	(a)	54
(b)	165	(b)	189
(c)	30	(c)	3.8
(d)	385	(d)	30
(e)	23	(e)	385
(f)	out of scope	(f)	26
		(g)	out of scope
		(h)	out of scope
Total	778	Total	690
Ton CO_2 eq./km²	0.6	Ton CO_2 eq./km²	0.5

These elements have been deemed beyond the scope, as the primary focus was exclusively on the restoration scenarios themselves.

Parallel to the cost analysis, GWP calculations are tabulated and consolidated within interventions in Table 2. The ultimate environmental impact for each scenario emphasizes a reasonable similarity between them (Domaneschi et al., 2023).

6 RESILIENCE ASSESSMENT

6.1 *Transit capability*

This section discusses the functionality curves of the system for both retrofitting scenarios under consideration. While interventions encompass the entire viaduct, the primary focus of this work is on analyzing the three main piers from #22 to #24, which feature the largest spans consisting of cantilevers connected by Gerber beams. Expert bridge engineering specialists, involved in designing, executing, reinforcing, and rehabilitating similar bridge structures have been consulted to establish reasonable and realistic parameters for plotting functionality curves for each intervention type.

The initial phases, such as selecting the intervention designer, assessing technical-economic feasibility, finalizing executive designs, and administration, are estimated to take 6-8 months before the bridge closes for interventions. Safety concerns identified in inspections starting in 2020 have led to traffic limitations and reduced load intensity. This includes traffic restrictions, lowering vehicle weight limits to 500 kN and speed limits to 40 km/h.

Both scenarios aim to utilize existing piers and related foundational structures. Additionally, both scenarios account for the bridge's closure due to its single-carriageway design, preventing reconstruction partitioning.

Figure 2 illustrates the functionality curves for the proposed solutions, starting at time 0 when either the whole deck or Gerber beams only are demolished, resulting in a complete bridge closure. In Scenario #1, demolition using explosives is estimated to take around 10 days, while for Scenario #2, controlled demolition of the Gerber beams will take approximately 20 days.

For the solution involving deck replacement or a portion of it, it is assumed that before demolition starts, the replacement structure is prepared nearby for swift replacement. Specifically, installing the new deck is estimated to take 3 months for Solution #1. Scenario #2, involving new Gerber beams and external prestressing cables for the cantilevers, is estimated to take 5 months.

Upon construction completion, the estimated timeline for testing, processing (technical-administrative approval), and full bridge reopening is set at 90 days. Post this period, it is assumed that the bridge's transit capability will be restored to 100%. Resilience values for the different scenarios considering a maximum closure period of 360 days are tabulated in Table 3.

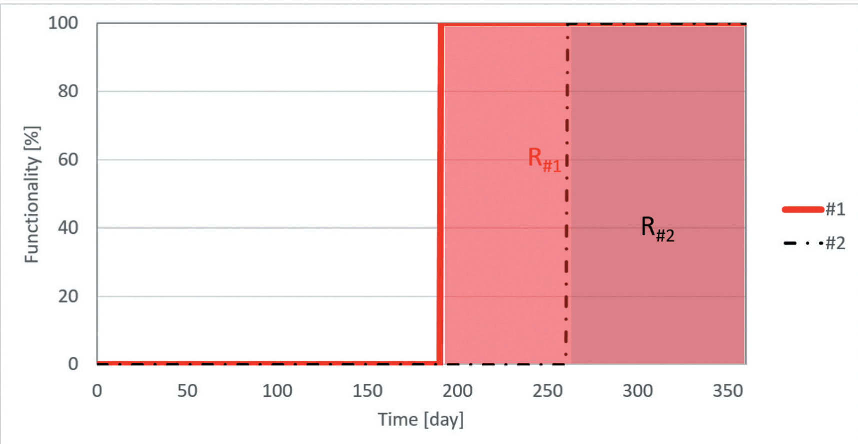

Figure 2. Functionality curves and resilience (transitability).

Table 3. Resilience values computed through transit capability.

Scenario	#1	#2
Resilience	0.47	0.28

6.2 *Capacity*

It is interesting to analyze the problem of assumed interventions by considering structural capacity and its restoration instead of transit capability. Consequently, for capacity analysis, purely administrative aspects are neglected. Obviously, it is necessary to introduce some assumptions, for example, it is assumed the linear pattern of the recovery curves, which in real conditions are associated with high uncertainty, including pauses, accelerations, and so on.

Shows the trends of the capacity curves for the various assumed scenarios, while Table 4 reports the resilience values computed concerning capacity.

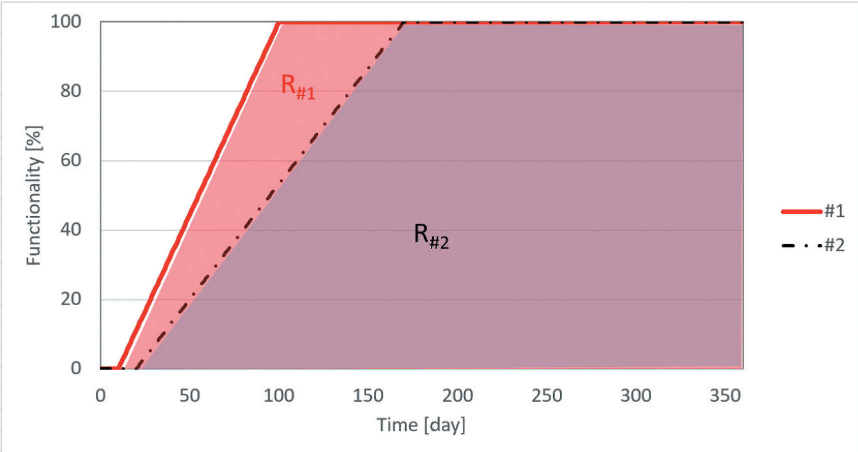

Figure 3. Functionality curves and resilience (capacity).

Table 4. Resilience values computed through capacity.

Scenario	#1	#2
Resilience	0.85	0.73

7 CONCLUSIVE REMARKS

This investigation assesses retrofit for the deteriorating Polyfytos Bridge using advanced surveying tools. A couple of different interventions are evaluated in terms of cost, sustainability, and resilience, aiming for a comprehensive (holistic) retrofit approach. Initial findings highlight cost disparities and interesting differences in resilience when transit capability is considered among interventions. On the other hand, the environmental impact, and the resilience values in terms of capacity results are reasonably equivalent.

Differences in resilience calculations, whether focused on transit capability instead of capacity, indicate how bureaucratic and administrative components might impact the process and, consequently, resilience by extending downtime. This underscores the significance of administrative efficiency in mitigating delays during retrofitting or maintenance processes for bridges. Streamlining bureaucratic procedures and administrative tasks can significantly minimize the downtime experienced during these critical infrastructure projects. Efficient administrative processes contribute to shorter project timelines, reducing disruptions to the bridge's functionality and overall resilience of transport infrastructure.

ACKNOWLEDGEMENTS

The research has received funding from the (i) ERC Grant ID: 101007595 of the project ADDOPTML, MSCA RISE 2020; (ii) EU HORIZON-MSCA-2021-SE-01 Grant No: 101086413, ReCharged. Stergios Mitoulis and Sotirios Argyroudis received funding from the UK Research and Innovation (UKRI) under the Horizon Europe funding guarantee (agreements No. EP/Y003586/1, EP/X037665/1), for the project 'ReCharged - Climate-aware Resilience for Sustainable Critical and interdependent Infrastructure Systems enhanced by emerging Digital Technologies' (Grant No: 101086413). Dr. Andrea Benincasa - Nemesis Engineering (Turin, Italy) is gratefully acknowledged for his support in the assessment of the intervention phases for the resilience curves computation.

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