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ASSESSMENT OF STRENGTHENING TECHNIQUES FOR PRESTRESSED REINFORCED CONCRETE BRIDGES: A COMPARATIVE ANALYSIS

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Abstract

Many existing Italian bridges were built between the 1950s and 1970s, employing Prestressed Reinforced Concrete (PRC) technology with post-tensioned cables. These structures are currently vulnerable due to reaching their end of life. For these reasons, the Italian Guidelines for the classification and risk management, safety assessment, and monitoring of existing bridges prescribe a specific evaluation framework for PRC beams with post-tensioned cables. This framework involves firstly a defect evaluation process and subsequently more accurate structural assessments, aimed at identifying structural deficiencies, particularly with regard to gravity loads. In most cases, the results of such structural assessments indicate the necessity of strengthening interventions to restore safety levels and enhance the durability of the structures. Given the extensive distribution of PRC bridges in the Italian infrastructure network, the need for structural interventions becomes a critical aspect. Based on these considerations, in order to provide useful insights for engineering practice, a state-of-the-art review of the available strengthening techniques is conducted, distinguishing between traditional methods and more advanced methods. By focusing initially on the most commonly used techniques, their main advantages and disadvantages can be compared, and their applicability and relative costs qualitatively estimated. Finally, through detailed analyses of PRC beams from a case study bridge, these strengthening techniques can be quantitatively compared, considering various aspects: (i) performance improvement; (ii) the impact in terms of additional weight, allowing the effective performance improvement evaluation; (iii) the intervention costs. In this way, each technique can be objectively evaluated based on purely structural parameters, as well as its applicability and costs, optimizing the intervention approach.

Keywords: Prestressed Reinforced Concrete bridge girders, Structural assessment, Strengthening interventions, Durability.

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1 INTRODUCTION

The majority of existing bridges in Italy were built between the 1950s and 1970s [1]. With few exceptions, no significant maintenance interventions have been carried out on these structures over decades of service. Additionally, simply supported decks made of post-tensioned prestressed concrete girders have been widely used over time, a technology highly susceptible to deterioration. In fact, the primary cause of load-bearing capacity reduction in this type of bridge is the ongoing corrosion of post-tensioning cables, which is difficult to detect from the outside [2].

In addition to design approaches that have not adequately considered durability-related aspects, construction defects are often present, such as voids within the grout injections between the duct and the cables [3]. Furthermore, the increase in traffic loads and the geometric and functional modifications undergone by infrastructures over the years highlight the urgency of addressing the safety of these structures. The vulnerability of existing bridges is evidenced by the numerous collapses that have occurred over the past decades with a disturbingly regular frequency [4].

In this context, the Guidelines for the classification and risk management, safety assessment, and monitoring of existing bridges [5] have been issued as a multi-level and multidisciplinary tool. Its structure emphasizes the various levels of detail that can be achieved in assessing the current condition of a bridge and the different factors that may affect its operability and safety. Through the approach provided by these Guidelines, it is possible to pass from the inventory of structures to the definition of an attention class, based on which, in specific cases, a safety assessment is carried out. This assessment helps determine which bridges require repair and/or strengthening interventions [6].

Based on these aspects, this article focuses on static strengthening techniques for post-tensioned prestressed concrete girders in viaducts with grid deck structures. First, a brief state-of-the-art review of available techniques, both well-established and advanced, is presented. Subsequently, a preliminary qualitative comparison is carried out to assess their main advantages and disadvantages. Finally, for specific techniques, structural strengthening solutions have been designed, calculating interventions aimed at achieving the same increase in flexural capacity as a prestressed concrete girder from a grid-deck bridge built in 1966 [7].

Thus, for each designed intervention, the added weight was evaluated, allowing for the definition of structural efficiency in terms of the net increase in load-bearing capacity. Finally, each design was supplemented with an assessment of the required operations and a corresponding cost estimation. This approach enables the definition of a synthetic cost index, providing insight into the practical feasibility of one technique compared to another. The goal was to offer useful and practical tools to compare not only the performance but also the efficiency and cost of the various strengthening techniques available for prestressed concrete girders.

2 RETROFITTING MEASURES FOR PRESTRESSED REINFORCED CONCRETE BRIDGES

An overview of available techniques for rehabilitating and/or strengthening prestressed concrete bridge girders has been provided. The following subsections outline the characteristics of various intervention techniques, highlighting their advantages, disadvantages, and performance aspects. To offer a broader perspective on the operational phases required for the implementation, it is important to note that each of the techniques described must be preceded by preliminary actions, including the removal of the damage cause, mitigation of steel corrosion, and restoration of deteriorated concrete where necessary, as detailed in [8].

2.1 Steel jacketing ("Beton Plaqué")

The technique of steel jacketing is widely used for local strengthening of prestressed concrete girders in existing bridges, particularly for highway overpasses to restore damage caused by vehicle impacts. This technique involves the installation of a steel jacket that is bonded to the lateral and bottom surfaces of the prestressed concrete girder using mechanical anchors and high-strength epoxy resins, ensuring a perfect bond between the new and existing materials. As a result, a composite steel-concrete section is effectively created, leading to an increase in both the flexural and shear capacity of the girder. Several studies in the literature [9] present experimental tests on reinforced concrete beams strengthened with steel plates, demonstrating significant increases in flexural strength.

2.2 Reinforced concrete jacketing

Similar to the previous technique, this method involves the creation of a localized reinforced concrete jacket on the lower bulb of the prestressed concrete girders. It is a widely used technique in engineering practice because it can be easily implemented by removing deteriorated sections in the lower bulb and then positioning new reinforcing bars and constructing formwork for the new concrete pour. Special attention must be given to defining the geometry of the jacket, ensuring that the thickness is sufficient to accommodate the longitudinal reinforcement and provide proper coverage. As a traditional technique, it enhances the flexural capacity, stiffness, and ultimate deformation of the treated girder. Since it is applied only to the lower bulb, the intervention does not affect the shear capacity of the girder.

2.3 Application of composite materials (FRP)

Fibre Reinforced Polymers (FRP) are materials known for their highly advantageous strength-to-weight ratio (which facilitates handling and application), high fatigue resistance, and low susceptibility to corrosion [10]. In the case of bridge girders, the versatility of FRPs allows for interventions that limit cracking and increase both flexural and shear capacities, depending on the fibres' arrangement. Additionally, these materials can be integrated with other intervention techniques. One of the drawbacks of using these materials is failure due to delamination, which prevents the full utilization of the high strength of the fibres, leading to brittle failure [11]. It has been shown in [12] that the application of CFRP plates on prestressed concrete bridge girders leads to increases in flexural capacity ranging from 28% to 37%. Experimental studies in [13] confirm that the flexural capacity of a prestressed concrete girder can be increased to 70% while maintaining its ductility by adding transverse "U"-shaped CFRP reinforcements in addition to longitudinal ones. In [14], various studies from the literature on shear strengthening of reinforced concrete and prestressed reinforced concrete beams using fibre-reinforced materials were reviewed. The authors specifically highlighted that strengthening is particularly effective for bridge beams designed with outdated rules and poor or degraded materials.

2.4 External post-tension technique

A widely used and well-established technique in engineering practice, the post-tensioning subjects the prestressed concrete girder to an additional state of stress, which increases its flexural and shear capacity, reduces the existing cracking and limits the deformations induced by loads [15, 16]. Typically, post-tensioning is carried out using closely spaced tendons that are anchored to the girder at the ends through appropriate anchorage plates, and to the lateral and bottom surfaces using deviators that allow the geometry specified in the design to be achieved.

According to studies conducted in [7, 12], the application of post-tensioning leads to an increase in the flexural capacity of prestressed concrete beams by approximately 40-50%.

In [17], a comprehensive analysis of the main advantages and disadvantages of the technique was presented. Among the advantages, we certainly find the ability to install the cables with minimal disruption to traffic; the increase in both flexural and shear capacity of the girder, with minimal increases in permanent load; and the possibility of re-tensioning and replacing cables. Some limitations in its application, however, may include the presence of on-site materials with poor characteristics, which may not be able to absorb the additional prestressing forces; the increase in shear capacity of the original girder is not easily assessable without conservative modelling; and finally, the technique rarely allows for an increase in the girder's ductility due to the high strength of the used cables.

3 PERFORMANCE COMPARATIVE ANALYSIS

3.1 Design of equivalent flexural strengthening interventions

In order to quantitatively compare the performance of the most commonly used intervention techniques in engineering practice (steel jacketing, reinforced concrete jacketing and external post-tensioning), based on a prestressed reinforced concrete beam with post-tensioned cables from a case study bridge built during the 1960s, interventions were designed to be equivalent in terms of increasing the flexural strength.

The case study bridge is described in detail in [7] in terms of geometry, material characteristics, and quantities of both ordinary reinforcement and prestressing used within the investigated beam. Therefore, through analytical evaluations [18], validated by detailed nonlinear finite element analysis, it was possible to assess the flexural capacity of the beam, considering a static scheme of a beam simply supported at the ends. Given the flexural capacity in as-built conditions, which is equal to M_{rd}^0 = 15318 kNm, it is possible to design each considered intervention technique to increase the beam's strength by 25% [19], with a tolerance of ±3%.

Below, the phases of the design for each of the intervention techniques are summarized in a simplified manner, with the aim of highlighting the main parameters of the design process. It is worth noting that no intervention design has been carried out for the technique based on the application of composite materials, due to the difficulties in reaching the set flexural capacity enhancement, related to the brittle delamination failure mechanism characteristic of these solutions, as well as the high cost associated with their implementation.

Regarding the steel jacketing technique, the goal of the design was to evaluate the optimal combination of plate thickness and steel grade capable of providing the desired increase in bending resistance. By iteratively varying the jacket thickness from 3 mm to 10 mm and the steel grade from S235 to S355 [20], simplified analytical evaluations were carried out. The final choice was a jacket with a thickness of 3.5 mm and the use of S355 CorTen steel (Figure 1). This made it possible to achieve an increase in bending resistance in line with the set objective ($\Delta M/M_{rd}^0$ = 28%), while minimizing the additional load due to the weight of the intervention (Δg_1 = 1.3 kN/m).

The design of the intervention through reinforced concrete jacketing of the lower bulb of the beam involves evaluating the flexural capacity of the new beam section, which is obtained by adding the lower bulb jacket to the original section, thus considering the perfect bond between the existing and new materials [21]. It was chosen to use C40/50 concrete and B450C steel [20]. In the study of possible configurations, it was found that the main challenges lie in determining an appropriate number of reinforcement bars with the required clearances and cover thicknesses, while also aiming to minimize the final volume of the intervention. Specifically, it was determined that a distribution of twenty-six bars of 26 mm of diameter results in a flexural resistance increase of approximately 25% (Figure 2). This approach leads to a significant increase in the resistant section area, with a corresponding increase in self-weight (Δg_1) of approximately 4 kN/m.

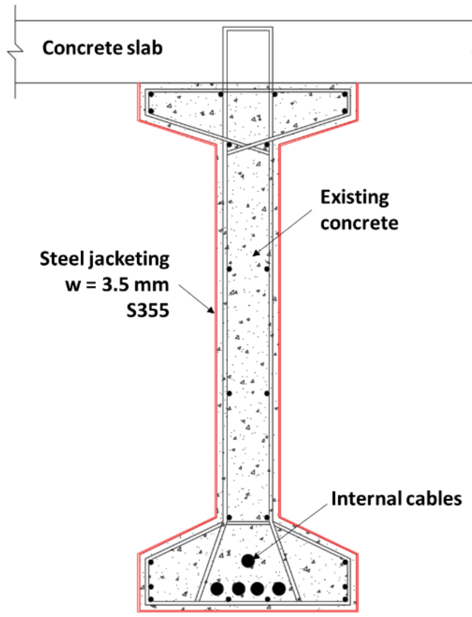

Figure 1: Strengthened configuration of the cross-section of the case-study prestressed reinforced concrete girder through steel jacketing.

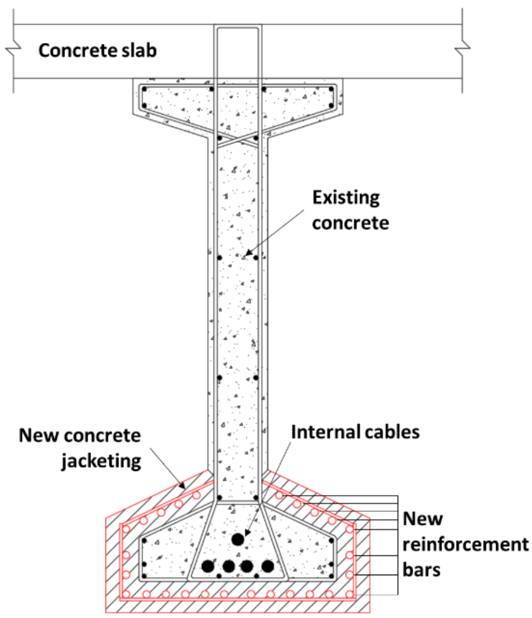

Figure 2: Strengthened configuration of the cross-section of the case-study prestressed reinforced concrete girder through reinforced concrete jacketing.

Regarding the external post-tensioning technique, the design of the intervention is based on determining the correct geometry of the high-strength harmonic steel cables, their proper dimensions, and the tension to which they should be subjected. Given the geometry of the beam and the position of the transverse beams, it is possible to define the path of the external cables and, once the desired resistance increase is established, calculate the necessary reinforcement quantity through static considerations. By arranging two cables, one on each side of the beam, anchored at the ends and to the deviators located at the transverse beam locations (Figure 3), an initial tension value of T^0 = 1200 kN was calculated. This calculated value was then appropriately increased as suggested in [22], resulting in a value of $T^0+\Delta T \approx$ 1500 kN. Ultimately, using commercial catalogues, the selection consisted of two cables made with nine strands of 15.7 mm diameter, which, when subjected to the previously calculated tension, provide the desired flexural resistance increase. As presented, this intervention increases self-weight (Δg_1) by approximately 0.40 kN/m.

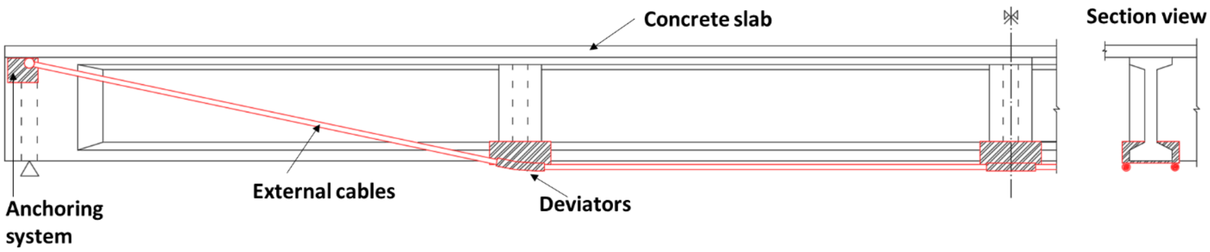

Figure 3: Strengthened configuration of the cross-section of the case-study prestressed reinforced concrete girder through external post-tensioned cables.

3.2 Assessment of the structural efficiency of strengthening interventions

Based on the design calculations described in the previous section, a performance comparison can be carried out by evaluating, for each of the considered techniques, the increase in the flexural capacity of the beam, net of the increase in self-weight (ΔM^n). To this end, the equivalent flexural load (q_{eq}) is introduced with reference to the midspan section's ultimate bending moment (M_{rd}). For a simply supported beam, these two quantities are related by the well-known equation (1).

$$M_{rd} = \frac{q_{eq} \cdot L^2}{8} \tag{1}$$

The equivalent flexural load has been evaluated for the beam in its as-built condition (q_{eq}^0) and in the various strengthened configurations (q_{eq}^r), filtering out the latter from the increase in self-weight (Δg_1) to obtain the net equivalent flexural load ($q_{eq}^{r,n}$). Considering the linear relationship between loads and the maximum bending moment, the net increase in the ultimate bending moment (I_{rf}^n) can be assessed using equation (2).

$$I_{rf}^n = \frac{\Delta M^n}{M_{rd}^0} = \frac{q_{eq}^{r,n}}{q_{eq}^0} - 1 \tag{2}$$

In this way, it is possible to provide a measure of the efficiency of each intervention through a synthetic index ($\eta = \Delta M^n/\Delta M$), defined as the ratio between the net increase in ultimate bending moment and the total increase in flexural capacity (not filtered from the load increments Δg_1). Table 1 presents a summary of the previously calculated results for each of the considered strengthening techniques.

As shown in Table 1, from a structural point of view, the external post-tensioning technique proves to be the most efficient, exhibiting an η value of 98.8%, compared to 96.2% and 86.4% for the steel jacketing and reinforced concrete jacketing techniques, respectively. On the other hand, reinforced concrete jacketing is the least efficient technique, as also evidenced by the significant increase in self-weight, amounting to 4.14 kN/m.

Technique	M_{rd} [kNm]	$I_{rf} = \Delta M/M_{rd}^{0}$ [%]	Δg_1 [kN/m]	q_{eq}^{r} [kN/m]	$q_{eq}^{r,n}$ [kN/m]	$I_{rf}^{n} = \Delta M^{n}/M_{rd}^{0}$ [%]	$\eta = \Delta M^{n}/\Delta M$ [%]
Steel jacketing	19689	28.5	1.30	153.8	152.5	27.4	96.2
Reinforced concrete jacketing	19201	25.3	4.14	150.0	145.9	21.9	86.4
External post-tension	19610	28.0	0.40	153.2	152.8	27.7	98.8

Table 1: Performance comparison of strengthening techniques in terms of flexural capacity increase, net increase and structural efficiency.

4 COSTS COMPARATIVE ANALYSIS

In order to compare the costs associated with each of the analysed strengthening techniques, a cost estimation was carried out based on the design calculations from the previous section, adopting simplified assumptions. Specifically, cost items related to common and preliminary operational phases applicable to any intervention, such as the possible removal of deteriorated concrete, passivation of existing reinforcement, and volumetric restoration of removed concrete, were excluded from the computation. Additionally, a simplifying assumption was made regarding the equality of costs for scaffolding, platform rentals, and/or "by bridge" systems, as well as all auxiliary equipment required to access the beams under intervention. The cost estimates were performed based on the updated price list issued by the Italian transportation infrastructure authority, ANAS [23]. When not directly derived from design calculations, the estimated quantities were determined based on practical rules and previous cost assessments of similar interventions.

The computed costs were normalized with respect to the beam length, equal to 32 m, obtaining the cost per linear meter (C_L). Finally, a synthetic cost index (C_e) was calculated, as defined by equation (3).

$$C_e = \frac{C_L}{I_{rf}^{n} \cdot 100} \tag{3}$$

This index allows for the evaluation, for each strengthening technique, of the cost required to increase the flexural resistance by a unit percentage per linear meter of the beam. The results of these assessments are summarized in Table 2.

Technique	C [€/beam]	$C_L = C/L$ [€/m]	C_e [€/m·%]
Steel jacketing	29000	910	33
Reinforced concrete jacketing	21300	670	31
External post-tension	8000	250	9

Table 2: Comparison of intervention costs.

Table 2 clearly shows that the external post-tensioning intervention, in addition to being more efficient statically, is also more cost-effective. Therefore, it represents an excellent design solution in contexts where it is necessary to intervene on the entire beam while ensuring significant increases in flexural resistance. The more traditional techniques of steel and reinforced concrete jacketing of the lower bulb have costs that are quite comparable, although the latter is slightly more economical. Therefore, both techniques can represent a valid alternative when local repairs and restoration of limited portions of the beam are required.

5 CONCLUSIONS

The purpose of this article was to analyse and compare strengthening techniques for prestressed reinforced concrete bridge girders with post-tensioned cables. The review of the state-of-the-art allowed for an initial qualitative comparison, based on which the most common and established techniques were selected, such as steel jacketing, reinforced concrete jacketing of the lower bulb and external post-tensioning. Subsequently, interventions were designed to achieve the same flexural strength increase of a PRC beam from a case study bridge. The design of these interventions allowed for a comparison of the performance and efficiency of various techniques, as well as a cost assessment. According to the findings, external post-tensioning, being a statically active technique, has superior efficiency compared to the others, as the additional load applied is negligible compared to the strength increase achieved. From a static perspective, steel and reinforced concrete jacketing, although with limited efficiency, allow for significant flexural strength increases. Regarding intervention costs, external post-tensioning is the most economical technique, while traditional steel jacketing and lower bulb reinforced concrete jacketing are competitive in contexts with limited financial resources and a lack of skilled labour capable of performing more complex interventions. These techniques represent a valid solution to local damage issues, such as repairing beams damaged by impacts. Ultimately, it is essential to consider several factors when selecting the most appropriate technique, including the application context, expected loads and available financial resources. Undoubtedly, combining conventional methods with innovative solutions can offer a valuable opportunity to optimize intervention effectiveness while ensuring both economic and environmental sustainability.

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REFERENCES

[1] M. Di Prisco, “Critical infrastructures in Italy: State of the art, case studies, rational approaches to select the intervention priorities,” in *fib Symposium 2019: Concrete-Innovations in Materials, Design and Structures*, International Federation for Structural Concrete., 2019, pp. 49–58.

[2] L. Bertolini, B. Elsener, E. Redaelli, and R. Polder, *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair: Second Edition*. 2013.

[3] B. Godart, “Pathology, appraisal, repair and management of old prestressed concrete beam and slab bridges,” *Structure and Infrastructure Engineering*, vol. 11, no. 4, 2015.

[4] L. Deng, W. Wang, and Y. Yu, “State-of-the-Art Review on the Causes and Mechanisms of Bridge Collapse,” *Journal of Performance of Constructed Facilities*, vol. 30, no. 2, 2016.

[5] Ministero delle Infrastrutture e dei Trasporti, *Linee Guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti*. Consiglio Superiore dei Lavori Pubblici, 2020.

[6] G. Santarsiero, A. Masi, V. Picciano, and A. Digrisolo, "The Italian guidelines on risk classification and management of bridges: Applications and remarks on large scale risk assessments," *Infrastructures (Basel)*, vol. 6, no. 8, Aug. 2021.

[7] G. Santarsiero, V. Picciano, A. Masi, and G. Ventura, "Retrofit of PRC bridges by external post-tension under different corrosion scenarios," in *Bridge maintenance, safety, management, digitalization and sustainability - Proceedings of the 12th international conference on bridge maintenance, safety and management, IABMAS 2024, 24-28 June 2024, Copenhagen, Denmark*, 2024, pp. 571–579.

[8] P. E. Pinto, P. Franchin, and A. Lupoi, "Linee guida e manuale applicativo per la valutazione della sicurezza sismica e il consolidamento dei ponti esistenti in c.a.," 2009.

[9] S. Aykac, I. Kalkan, B. Aykac, S. Karahan, and S. Kayar, "Strengthening and Repair of Reinforced Concrete Beams Using External Steel Plates," *Journal of Structural Engineering*, vol. 139, no. 6, 2013.

[10] CNR-DT 200 R1/2013, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures," *ACI committee 440*, 2008.

[11] L. Chen, X. Qiang, P. Sun, S. Zhang, and X. Jiang, "Experimental and theoretical study on flexural behavior of prestressed concrete beams strengthened by CFRP tendons with external unbonded retrofit system," *Journal of Building Engineering*, vol. 89, p. 109301, Jul. 2024.

[12] P. F. Takács and T. Kanstad, "Strengthening prestressed concrete beams with carbon fiber reinforced polymer plates," *NORDIC CONCRETE RESEARCH-PUBLICATIONS*, vol. 25, pp. 21–34, 2000.

[13] O. Rosenboom, T. K. Hassan, and S. Rizkalla, "Flexural behavior of aged prestressed concrete girders strengthened with various FRP systems," *Constr Build Mater*, vol. 21, no. 4, 2007.

[14] M. I. Ary and T. H. K. Kang, "Shear-strengthening of reinforced & prestressed concrete beams using FRP: Part I - Review of previous research," *Int J Concr Struct Mater*, vol. 6, no. 1, 2012.

[15] G. Santarsiero and V. Picciano, "Post-tension retrofitting of RC dapped-end beams: A numerical investigation," *Structural Concrete*, 2024.

[16] G. Santarsiero, V. Picciano, and A. Masi, "Structural rehabilitation of half-joints in RC bridges: a state-of-the-art review," *Structure and Infrastructure Engineering*, vol. 21, no. 2, pp. 227–250, Feb. 2025.

[17] A. F. Daly and I. W. Witarnawan, "Strengthening of bridges using external post- tensioning," in *2nd Conference of Eastern Asia Society for Transportation Studies*, 1997.

[18] P. Gelfi, "Verifica Cemento Armato Stato Limite Ultimo (VCA SLU).," 2006, *Programmi Gratuiti per l'Ingegneria Civile*.

[19] G. Santarsiero, P. Albanese, V. Picciano, G. Ventura, and A. Masi, "Level 3 Assessment of Highway Girder Deck Bridges according to the Italian Guidelines: Influence of Transverse Load Distribution," *Buildings*, vol. 13, no. 7, Jul. 2023.

[20] Ministero delle Infrastrutture e dei Trasporti, *Aggiornamento delle Norme tecniche per le costruzioni (NTC 18), DM 17 gennaio 2018*. 2018.

[21] Ministero delle infrastrutture e dei trasporti, *Circolare n. 7 del 21 Gennaio 2019, Istruzioni per l'applicazione dell'aggiornamento delle norme tecniche per le costruzioni*. 2019.

[22] R. J. G. MacGregor, M. E. Kreger, and J. E. Breen, "Strength and ductility of a three-span externally post-tensioned segmental box girder bridge model," in *American Concrete Institute, ACI Special Publication*, 1990.

[23] ANAS, "Listino prezzi 2024 - Nuove costruzione e Manutenzione programmata," 2024, *ANAS Direzione Tecnica, Italia*.