Integrated Structural Assessment and Rehabilitation of Six Urban Viaducts with Minimum Traffic Disruption: A Case Study from Belo Horizonte, Brazil

Applications and Implications for Aging Urban Infrastructure Management in the United States

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ABSTRACT

This paper presents the integrated structural assessment, risk-based prioritization, and rehabilitation of six urban viaducts located on Avenida Dom Pedro I in Belo Horizonte, Brazil — one of the highest-traffic arterials in a metropolitan area of approximately 6 million inhabitants. The project was commissioned by the Municipal Government of Belo Horizonte under Contract DJ 125/2022 (total value: BRL 17,402,235.09) and executed between 2021 and 2023 under the technical responsibility of the author. The six structures presented distinct and critical pathologies of varying complexity, requiring a differentiated set of structural interventions: controlled viaduct lifting (5 hydraulic jacks of 1,000 tf capacity each, elevation of 12 cm over 5 days) for installation of new bearing devices; internal prestressing of box girder sections executed through access manholes of only 60 × 60 cm; pressed-pile foundation reinforcement (presso-ancoragem) pre-loaded at 70 tf; and carbon fiber reinforced polymer (CFRP) application — both sheet and laminate systems. All six interventions were executed while maintaining traffic flow on the arterial through a planned overlapping construction sequencing strategy, with the sole exception of a five-day planned full closure required for the most complex structure. All structural analyses were performed using CSi Bridge v21.2.0 finite element software under Brazilian standards NBR 6118:2014, NBR 6122:2019, NBR 6187:2003, and NBR 7188:2013 — functionally equivalent to AASHTO LRFD specifications. The paper presents the decision-making methodology as a structured four-phase framework — Assessment, Prioritization, Rehabilitation, and Institutional Documentation (APRI) — and discusses its direct applicability to the American infrastructure context, where the ASCE (2021) reports more than 45,000 structurally deficient bridges and the Infrastructure Investment and Jobs Act of 2021 has allocated USD 40 billion for bridge rehabilitation.

Keywords: *bridge rehabilitation; urban viaducts; carbon fiber reinforced polymer (CFRP); pressed-pile foundation; viaduct lifting; internal prestressing; traffic management; structural assessment; infrastructure prioritization; APRI Framework.*

1. INTRODUCTION

Urban bridges and viaducts are among the most critical elements of metropolitan infrastructure. They directly condition the movement of people and goods across dense urban environments, and their structural deterioration carries consequences that are simultaneously human, economic, and political. Yet across both developing and developed nations, urban bridge stocks age faster than they are rehabilitated — a gap driven not only by funding constraints, but by the absence of structured, replicable methodologies for systematic assessment, risk-based prioritization, and low-impact intervention.

In the United States, this challenge has reached a level of national policy urgency. The American Society of Civil Engineers (ASCE) 2021 Infrastructure Report Card assigns a C- grade to the nation's bridges, with more than 45,000 structures — approximately 7.5% of the national inventory — classified as structurally deficient. The Federal Highway Administration (FHWA) estimates that the accumulated maintenance backlog for bridges alone exceeds USD 125 billion. The collapse of the Francis Scott Key Bridge in Baltimore in March 2024 underscored, at tragic cost, the systemic risks embedded in deferred structural intervention.

The Infrastructure Investment and Jobs Act of 2021 responded to this crisis with an unprecedented USD 40 billion allocation specifically for bridge rehabilitation — the largest such federal investment in American history. Yet the availability of funding does not automatically resolve the underlying methodological challenge: how to systematically assess large numbers of structures, prioritize interventions objectively within constrained budgets, select solutions that minimize disruption to dense urban traffic, and document the process in a manner that generates replicable institutional knowledge.

This paper addresses that methodological challenge through a field-validated case study. Between 2021 and 2023, the author led — under individual technical responsibility (Anotação de Responsabilidade Técnica, CREA-MG No. 183345/D, the Brazilian equivalent of the American Professional Engineer stamp) — the complete structural rehabilitation of six urban viaducts on Avenida Dom Pedro I in Belo Horizonte, the capital of Minas Gerais state, Brazil. The project was commissioned by the Municipal Government of Belo Horizonte and required engineering solutions of significant technical complexity: lifting an entire viaduct with five 1,000-ton hydraulic jacks; executing internal prestressing through 60 × 60 cm access manholes; reinforcing foundations without interrupting traffic on a major urban arterial; and coordinating six simultaneous construction fronts on the same avenue using an overlapping sequencing strategy that maintained traffic flow throughout the 24-month intervention period.

The methodology applied is presented as a structured four-phase framework — the APRI Framework (Assessment, Prioritization, Rehabilitation, and Institutional Documentation) — designed to be replicable in different contexts, including American municipalities managing aging bridge inventories under operational and budgetary constraints.

2. PROJECT OVERVIEW

2.1 Context and Location

The six viaducts subject to this intervention are located along Avenida Dom Pedro I, a major urban arterial in Belo Horizonte, Brazil — a metropolitan area of approximately 6 million inhabitants and one of the largest cities in Latin America. The avenue carries high volumes of vehicular and pedestrian traffic daily, making any structural intervention logistically complex and economically sensitive with respect to traffic disruption.

The structures were built between the 1970s and 1990s and had not undergone structural rehabilitation since their original construction. A preceding structural verification study identified critical pathologies across all six structures requiring urgent intervention under Brazilian standard NBR 6122:2019.

The intervention was contracted by the Municipal Government of Belo Horizonte under Contract DJ 125/2022, with a total value of BRL 17,402,235.09. All structural analyses were performed using CSi Bridge v21.2.0 finite element modeling software. Design criteria followed Brazilian technical standards NBR 6118:2014 (reinforced concrete), NBR 6122:2019 (foundations), NBR 6187:2003 (bridge design and construction), and NBR 7188:2013 (moving loads), supplemented by Eurocode provisions and DER-MG recommendations where Brazilian standards were silent.

2.2 Viaduct Inventory and Complexity Classification

Table 1 presents the six viaducts, their assigned complexity classification, primary pathologies identified in the diagnostic phase, and the principal rehabilitation interventions applied. The classification reflects the technical complexity of the engineering solutions required — not the magnitude of physical deterioration observed.

Table 1 — Viaduct inventory: complexity classification and rehabilitation interventions

Viaduct	Complexity	Primary Pathologies (with key quantitative data)	Primary Interventions
Oscar Niemeyer	Critical	Foundation bearing capacity exceeded (P2: 76.87 tf < 110 tf limit; P3B: 77.32 tf < 83 tf limit); insufficient bearing devices at	Controlled viaduct lifting: 5 hydraulic jacks × 1,000 tf each (total 5,000 tf), elevation +12 cm, 5-day full closure; installation of new

		TR1 (load ≈ 200 tf); deficient reinforcement at abutments E2/E3 and cross-beam TR3; post-reinforcement safety factor ~1.05	bearing devices at TR1; pressed-pile reinforcement (Dywidag Ø 31.75 mm, fy ≈ 950 MPa, pre-load ~70 tf) at P1/P2/P3B; CFRP sheets (1–3 layers) at TR3, E2, E3; execution sequence: tie rods → piles → CFRP
João Samaha (Casasanta)	High	Longitudinal box girders with insufficient reinforcement in positive moment zones (sections 2–5) and negative moment zone (section 7); combined flexure-torsion demand on bottom slab exceeding existing reinforcement capacity (deficit up to 22.45 cm^2/m); access to box girder interior restricted to two 60×60 cm manholes only	Internal box girder prestressing: 4 cables × 15 greased strands, Ø 15.2 mm, steel 190RB, prestress force P = 294 tf; CFRP laminates (MC CarbonFiber Lamella, e = 1.4 mm, w = 100 mm, E = 160,000 MPa): 2 layers × 10 laminates on internal face; CFRP sheets (300 g/m^2, e = 0.166 mm): 2–3 layers × 300 mm on internal bottom slab face; all installation executed through 60×60 cm manholes without traffic interruption
Monte Castelo	High	Foundation piles P1/P2 with safety factors below NBR 6122 (actual load 171 tf vs. max. 152 tf permitted; safety coefficient 1.68 < normative 1.89); insufficient shear reinforcement in cross-beams TR2/TR3 (diagonal cracking observed); deficient reinforcement in abutment walls E1/E2	Pressed-pile reinforcement: 4 micro-piles per pier block (ø 150 mm), pre-loaded 70 tf (0.78 × 90 tf capacity); post-reinforcement P1 load: 133.02 tf; P2 load: 128.79 tf (both within 152 tf limit); CFRP sheets TR2/TR3: 3 layers at 50 cm spacing, U-anchored; CFRP laminates at E1/E2; all executed under live traffic
Barragem da Pampulha	Moderate-High	Prestressed T-girder structure (VL.01–VL.05); mid-span diaphragms with insufficient bracing reinforcement (7.5 cm^2); support diaphragms inadequate for jacking during bearing replacement; bearing seat confinement (banquetas 40×70 cm) deficient; critical girder VL.01 with insufficient shear reinforcement at initial sections	New RC corbels cast onto support diaphragms (As1: 2 loops ø25 mm; As2: 2×3 loops ø10 mm) for bearing replacement jacking at 71 tf; CFRP sheets (300 g/m^2, 2 layers × 25 cm, spaced 35 cm) on VL.01 ends over 280 cm from each support; CFRP laminate confinement wrapping on bearing seats (E = 160 GPa, ffu = 27,200 kgf/cm^2); all executed under live traffic
Gil Nogueira	Moderate	Pile cap blocks BL1/BL2 with insufficient shear reinforcement (flexible behavior, a/d > 1); cross-beams TR1/TR4 with insufficient flexural reinforcement following neoprene bearing replacement; external box girder longarinas at section 29 with shear deficit (Vrd = 249,050 kgf < Vsd = 303,100 kgf; deficit: 54,050 kgf)	Pile cap geometry restoration via concentric ring (r = 1.95 m, t = 85 cm) to restore rigid behavior (a/d < 1); CFRP sheets (300 g/m^2, 3 layers) on TR1/TR4 top and bottom faces; CFRP laminates (MC CarbonFiber Lamella 160/2800, 2 layers × 10 cm, spaced 15 cm) on both faces of longarinas at sections S28–S30
Montese	Moderate	Abutment wall E1 with insufficient vertical reinforcement (existing 6.25 cm^2/m vs. required 12.75 cm^2/m); abutment wall E2 with horizontal reinforcement deficiency (existing 3.33 cm^2/m vs. required 4.42 cm^2/m); cross-beams TR2/TR3 with shear reinforcement deficiency around inspection holes	CFRP sheets (MC CarbonFiber Sheet, 300 g/m^2): ~2 layers at E1 vertical face; 1 layer at E2 horizontal zone; 3 layers × 50 cm wide at TR2/TR3, spaced ~56 cm, U-anchored; horizontal CFRP (2×25 cm) above and below inspection holes; all executed under live traffic

3. THE APRI FRAMEWORK — METHODOLOGY APPLIED

The approach applied across the six viaducts follows a structured four-phase decision-making process developed by the author through progressive experience in urban infrastructure projects of increasing complexity. Each phase produces concrete, documented outputs that serve as inputs for the subsequent phase and as permanent institutional records.

3.1 Phase 1 — Data-Driven Structural Diagnosis

Each of the six viaducts was assessed individually through systematic technical inspection of all structural elements: piers, longitudinal girders, cross-beams (transversinas), abutment walls (encontros), foundations, expansion joints, and bearing devices. Inspection combined visual survey with photographic documentation, identification and severity classification of each pathology, and finite element structural modeling in CSi Bridge v21.2.0 to quantify load demands against normative capacity under multiple load combinations.

Load combinations applied followed NBR 7188:2013 (Class 45 moving loads), including dead loads, live loads, braking forces, wind (longitudinal and transverse), temperature, and centrifugal forces. Partial safety factors followed NBR 6118:2014 (concrete: $\gamma c = 1.4$; reinforcement: $\gamma s = 1.15$).

The diagnostic process produced individual technical reports per structure, each documenting: specific pathologies and their root causes, structural elements affected, safety coefficients obtained against normative requirements, and estimated residual service life. This individualized documentation is the foundational output of Phase 1 and the basis for all subsequent decisions.

3.2 Phase 2 — Risk-Based Prioritization and Sequencing Strategy

With six structures presenting distinct pathologies and risk levels on the same arterial, a structured prioritization methodology was essential for two reasons: to determine the technical order of intervention urgency, and to design a construction sequencing strategy that would maintain traffic flow throughout the project.

Prioritization criteria included: structural risk level (safety coefficient deficiency relative to normative requirements), volume and type of traffic affected by each structure, estimated intervention duration, and operational complexity of the required solution. Based on this assessment, the Oscar Niemeyer viaduct was identified as most critical — the only structure requiring full traffic closure — followed by João Samaha and Monte Castelo.

Critically, the sequencing strategy was designed so that no more than two viaducts would be under active construction simultaneously, **and that the avenue would never be fully interrupted at multiple points at the same time.** This overlapping approach — beginning the second intervention before completing the first, and initiating the third upon completion of the first — maximized team efficiency and minimized the cumulative impact on urban mobility throughout the 24-month intervention period.

3.3 Phase 3 — Solution Selection with Minimum Operational Impact

The selection of rehabilitation solutions was governed by a principle that distinguished this project from conventional structural interventions: wherever technically feasible, solutions were required to be executable without interrupting traffic flow. This constraint drove the identification and application of specific technologies whose compatibility with traffic maintenance was verified in the structural modeling phase before adoption.

The primary technologies applied are described in detail in Section 4. Their selection was not arbitrary — each was chosen because finite element analysis demonstrated that its execution would not require shoring or temporary structural unloading that would necessitate traffic interruption. The sole exception was the Oscar Niemeyer viaduct, where the replacement of bearing devices physically required lifting the structure, making a five-day planned closure unavoidable.

3.4 Phase 4 — Systematic Documentation and Institutional Knowledge

All technical decisions, engineering justifications, structural calculations, and execution results were systematically documented in technical reports per structure, with the explicit objective of creating reusable reference material for future interventions on similar structures. This documentation practice — often neglected in conventional construction projects — transforms each completed project into an institutional asset rather than an isolated episode.

The complete case study is additionally documented in the author's published book, Engenharia Segura no Crescimento Urbano (Safe Engineering in Urban Growth), ISBN registered, available in Portuguese and English — which presents the six-viaduct project as a structured methodology applicable to urban infrastructure contexts beyond the original project location.

4. TECHNICAL INTERVENTIONS — KEY CASE STUDIES

4.1 Oscar Niemeyer Viaduct — Controlled Lifting, Foundation Reinforcement, and CFRP

The Oscar Niemeyer viaduct presented the most complex combination of structural pathologies of the six-viaduct project, requiring a precisely sequenced multi-technology intervention. Structural verification identified four concurrent deficiencies: foundation pile bearing capacity exceeded at piers P2 (actual load: 76.87 tf against a normative limit of 110 tf) and P3B (77.32 tf against an 83 tf limit); cross-beam TR1 carrying a load of approximately 200 tf with insufficient bearing device capacity; deficient reinforcement at abutments E2 and E3; and shear reinforcement deficiency in cross-beam TR3. The finite element model in CSi Bridge confirmed that post-reinforcement safety factors would reach approximately 1.05 — structurally compliant but with limited margin, making precise execution critical.

The intervention was executed in a technically mandated sequence: tie rods first, pressed piles second, CFRP reinforcement third. Foundation reinforcement was executed without traffic interruption through pressed-pile micro-piles (presso-ancoragem) with Dywidag Ø 31.75 mm anchors (steel fy ≈ 950 MPa), pre-loaded at approximately 70 tf per pile, which redistributed loads to within normative limits at P2 and P3B without conventional excavation.

Cross-beam TR1 — carrying an approximately 200 tf load with insufficient existing bearing device capacity — required the project's sole full traffic closure. The viaduct superstructure was lifted using five hydraulic jacks of 1,000 tf capacity each (total lifting force: 5,000 tf), elevating the structure by 12 cm over a five-day planned closure period. This controlled lifting operation created the clearance necessary to install two additional bearing devices per cross-section at TR1, restoring the required load distribution capacity. The five-day closure window was planned in advance and executed within that constraint.

Following restoration of traffic, CFRP sheets (MC CarbonFiber Sheet, resistência 3,600 MPa, e = 0.166 mm, 1 to 3 layers depending on element demand) were applied to cross-beam TR3 and abutments E2 and E3 to address the remaining reinforcement deficiencies.

Technical significance: the Oscar Niemeyer intervention required the simultaneous management of four distinct structural deficiencies through three different technologies, executed in a precisely defined sequence. The combination of pressed-pile foundation reinforcement under live traffic, controlled superstructure lifting (5,000 tf total force, +12 cm), new bearing device installation, and CFRP reinforcement — all coordinated within a five-day planned closure for the most operationally sensitive phase — represents a level of multi-system engineering integration that is directly applicable to the complex, operationally constrained bridge rehabilitation challenges faced by American municipalities.

4.2 João Samaha Viaduct — Internal Prestressing Through Restricted Access

The João Samaha viaduct (formally Viaduto Casasanta) presented a structurally demanding combination of deficiencies in its box girder longitudinal elements. Structural verification identified insufficient reinforcement in the positive moment zones of end spans (sections 2 through 5) and in the negative moment zone at section 7, as well as combined flexure-torsion demand on the bottom slab exceeding existing reinforcement capacity by up to 22.45 cm²/m in the most critical sections. External CFRP reinforcement alone was insufficient — internal prestressing of the box girder was technically required.

Four prestressing cables were installed internally within the box girder, each comprising 15 greased strands of ø 15.2 mm (steel 190RB), with a prestressing force of P = 294 tf per cable. The cables introduce a compressive force that eliminates the need for additional slack reinforcement in the positive moment zones, in accordance with NBR 6118:2014 provisions for compression reduction. Reinforcement was executed between sections 0–1 and 6–10 of the first span, and their symmetric counterparts in the third span.

The critical engineering challenge was access: the interior of the box girder could only be reached through two inspection manholes of 60 × 60 cm — openings of 3,600 cm² each. All prestressing cables, anchorage components (Dywidag-type hardware), tensioning jacks, and construction personnel had to enter through these restricted openings. This required a purpose-developed construction methodology: equipment disassembly at the manhole, sequential introduction of components in the correct order, and reassembly inside the box girder in a confined, structurally critical environment with limited maneuvering space. The entire prestressing operation was executed without traffic interruption.

For negative moment zones at section 7, where prestressing alone was insufficient, CFRP laminates (MC CarbonFiber Lamella, e = 1.4 mm, w = 100 mm, E = 160,000 MPa) were installed in 2 layers of 10 laminates on the internal face of the upper slab. For bottom slab reinforcement against combined flexure and torsion — where the steel reinforcement deficit reached up to 9.85 cm²/m — MC CarbonFiber Sheet (300 g/m², e = 0.166 mm, f = 3,600 MPa) was applied internally in 2 to 3 layers of 300 mm width, also introduced through the 60 × 60 cm manholes.

Technical significance: the João Samaha intervention required the complete internal rehabilitation of a box girder section through openings of only 3,600 cm² — including installation of four prestressing cables at 294 tf each, CFRP laminates, and CFRP sheets — without any traffic interruption. The engineering challenge is not merely structural but logistical: every tool, every cable component, every CFRP roll, and every worker had to enter through a 60 × 60 cm opening. This type of constrained-access structural rehabilitation, executed under live traffic, is directly applicable to the thousands of aging box girder bridges in the American inventory that face similar access limitations.

4.3 Monte Castelo Viaduct — Foundation and Shear Reinforcement Under Live Traffic

The Monte Castelo viaduct presented three distinct categories of structural deficiency, each requiring a different intervention technology — all executed without traffic interruption. Structural verification identified: foundation bearing safety factors below NBR 6122 requirements at piers P1 and P2; insufficient shear reinforcement in cross-beams TR2 and TR3; and deficient reinforcement in abutment walls E1 and E2.

Foundation reinforcement was achieved through pressed-pile micro-piles (presso-ancoragem) — four piles per pier block (ø 150 mm), introduced through the existing foundation block and pre-loaded at 70 tf each using simultaneous hydraulic jacks. The pre-loading procedure, modeled in CSi Bridge with spring stiffness elements corresponding to each pile type, reduced the load on the original piles to within normative limits (maximum working load: 133.02 tf at P1; 128.79 tf at P2, against a normative maximum of 152 tf) without requiring any interruption of vehicular traffic above.

Shear reinforcement of cross-beams TR2 and TR3 was achieved through CFRP sheet application (MC CarbonFiber Sheet, 300 g/m², 3 layers at 50 cm spacing on both beam faces), anchored in U-configuration into the upper and lower slabs. Finite element analysis confirmed that the existing shear reinforcement was sufficient to carry permanent loads without temporary shoring — a critical verification that allowed CFRP application under live traffic.

Abutment wall reinforcement at E1 and E2 was executed with CFRP laminates applied to address vertical and horizontal reinforcement deficiencies identified in the diagnostic phase.

4.4 Barragem da Pampulha, Gil Nogueira, and Montese Viaducts

The three remaining viaducts — Barragem da Pampulha, Gil Nogueira, and Montese — presented moderate complexity pathologies that were addressed through targeted CFRP reinforcement, structural repairs, and in one case, new reinforced concrete elements. Each structure had distinct characteristics that required individual engineering solutions within the same diagnostic and documentation methodology.

The Barragem da Pampulha viaduct is structurally distinct from the others: it is a prestressed concrete structure with five T-girders (VL.01 to VL.05), making its structural analysis significantly more complex — involving combined shear-torsion interaction, fatigue coefficient verification, and prestress force contributions not present in conventional reinforced concrete box sections. The critical finding was that only the outermost girder (VL.01, adjacent to the existing viaduct) required CFRP reinforcement at its initial sections due to shear insufficiency — VL.02 through VL.04 passed verification without reinforcement. Additionally, the support diaphragms were found inadequate for jacking loads required during bearing replacement, necessitating the design and casting of new reinforced concrete corbels (71 tf capacity) onto the existing crossbeams. Bearing seat confinement (banquetas, 40×70 cm) was addressed through CFRP laminate wrapping, verified per ACI 318, achieving a confined compressive strength of 315 MPa.

The Gil Nogueira viaduct required intervention at three distinct locations. The central pile cap blocks (BL1 and BL2) had developed flexible block behavior ($a/d > 1$) due to insufficient shear reinforcement — a condition that was corrected by restoring rigid block geometry through a concentric concrete ring (radius 1.95 m, thickness 85 cm), bringing the blocks back to $a/d < 1$ and confirming that the existing reinforcement (797.50 cm^2) was adequate under the restored geometry. Cross-beams TR1 and TR4 required CFRP sheet reinforcement on both top and bottom faces following neoprene bearing replacement, which altered boundary conditions and generated higher bending moments than the original design had anticipated. External box girder longarinas at section 29 presented a quantified shear deficit of 54,050 kgf (V_{rd} = 249,050 kgf vs. V_{sd} = 303,100 kgf), addressed through MC CarbonFiber Lamella 160/2800 applied in 2 layers on both faces across sections S28–S30.

The Montese viaduct presented reinforcement deficiencies in both abutment walls and cross-beams. Abutment wall E1 had a vertical reinforcement area of 6.25 cm^2/m against a required 12.75 cm^2/m — a deficit of approximately 51% — addressed through approximately 2 layers of MC CarbonFiber Sheet (300 g/m^2). Abutment wall E2 presented a horizontal reinforcement deficit (existing 3.33 cm^2/m vs. required 4.42 cm^2/m), corrected with 1 layer of CFRP sheet. Cross-beams TR2 and TR3 required 3-layer CFRP sheet reinforcement around inspection holes, applied in U-configuration and anchored into top and bottom slabs — the same shear reinforcement approach validated in the Monte Castelo intervention.

Diagnostic significance: the diversity of pathologies across these three viaducts — prestressed girder shear in a T-beam structure, pile cap behavioral mode change, bearing seat confinement, and abutment wall reinforcement deficiencies — illustrates a core principle of the APRI Framework: that each structure in an urban bridge inventory requires individual diagnostic attention, even when located on the same arterial and built in the same era. Aggregate inspection approaches that treat multiple structures as a single category risk missing structure-specific deficiencies that, left unaddressed, can progress to safety-critical failure modes.

5. CONSTRUCTION SEQUENCING — TRAFFIC MANAGEMENT STRATEGY

A defining characteristic of this project — and a central element of the APRI Framework — is the construction sequencing strategy designed to maintain traffic flow on a major urban arterial throughout a 24-month, six-structure rehabilitation program.

The strategy was built on three principles. First, no more than two viaducts would be under active construction at any given time. Second, a new intervention would begin before the preceding one was complete — creating controlled overlap that maximized team continuity and resource utilization. Third, the one unavoidable full closure (Oscar Niemeyer, five days) would be planned with sufficient advance notice and traffic diversion to minimize metropolitan impact.

This overlapping sequencing approach — initiating Viaduct 2 before completing Viaduct 1, then initiating Viaduct 3 upon completion of Viaduct 1, and so forth — is conceptually simple but operationally demanding. It requires precise scheduling of material deliveries, equipment movements, and labor allocation across multiple simultaneous fronts, and continuous monitoring to ensure that progress on each structure allows the planned handoff sequence to be maintained.

The result was the complete rehabilitation of all six structures — including a 12 cm controlled viaduct lift and internal box girder prestressing — with only five days of full traffic closure over the entire 24-month project duration. This outcome represents a measurable demonstration of the framework's core principle: that well-planned structural rehabilitation in dense urban environments can achieve complete technical objectives with minimal operational disruption.

6. KEY MATERIALS AND TECHNICAL SPECIFICATIONS

Table 2 — Primary materials and technical specifications applied across six viaducts

Material / System	Product / Type	Key Specifications	Application

CFRP Sheet	MC CarbonFiber Sheet	300 g/m²; t = 0.166 mm; E = 230,000 MPa; ftu = 3,600 MPa; εfu = 2.1%	Shear reinforcement (cross-beams, abutments); applied 2–3 layers at 50 cm spacing
CFRP Laminate	MC CarbonFiber Laminate	High-modulus unidirectional laminate	Flexural and axial reinforcement of walls, girders, and abutment faces
Pressed Piles	Presso-ancoragem	ø 150 mm; pre-load: 70 tf (0.78 × 90 tf capacity); steel Ø 1¼" DYWIDAG (fy = 950 MPa; fu = 1,050 MPa)	Foundation block reinforcement at P1/P2 (Oscar Niemeyer, Monte Castelo)
Prestressing Cable	Internal box girder	High-strength steel cables; installed through 60×60 cm manholes	Longitudinal girder reinforcement (João Samaha)
Bearing Devices	Structural neoprene/steel	New devices installed at Oscar Niemeyer after controlled lifting	Replacement of 2 insufficient devices; installation of 2 additional per cross-section
FEA Software	CSi Bridge v21.2.0	Finite element analysis; spring stiffness modeling for pile groups	Structural verification and dimensioning for all six viaducts

7. APPLICABILITY TO THE AMERICAN INFRASTRUCTURE CONTEXT

The methodology presented in this paper was developed and validated in the Brazilian urban infrastructure context. Its applicability to the United States is direct and substantive — not by analogy, but by the structural equivalence of the engineering problems, the technical compatibility of the solutions, and the documented gap in American bridge management practice that the APRI Framework addresses.

7.1 Structural Equivalence

The pathologies addressed in this project — foundation bearing capacity deficiency, insufficient shear and flexural reinforcement, bearing device degradation, and box girder structural deficiency — are identical in nature to those documented in structurally deficient American bridges. The solutions applied — CFRP reinforcement, pressed-pile foundation reinforcement, controlled lifting, and internal prestressing — are recognized and applied in American bridge engineering practice, regulated under ACI 440.2R (CFRP for concrete structures) and FHWA technical guidance documents.

The structural design standards applied (NBR 6118, NBR 6122, NBR 7188) are functionally equivalent to their American counterparts (ACI 318, AASHTO LRFD, AASHTO Standard Specifications) in their treatment of limit states, load factors, and material safety coefficients. The engineering principles are universal; the specific regulatory parameters are adapted in the APRI Framework's American version.

7.2 The Methodological Gap in American Practice

The United States possesses well-developed systems for bridge inspection and condition rating — notably the National Bridge Inspection Standards (NBIS) administered by FHWA, and the AASHTO bridge classification system. These systems are effective at generating inventory data and condition ratings at the individual structure level.

What is less systematically available is the layer of decision-making methodology that sits between condition data and executed intervention: how to prioritize among many deficient structures with limited budgets, how to design construction sequencing strategies that maintain traffic flow across multiple simultaneous interventions, and how to document the process in ways that generate replicable institutional knowledge. This gap is explicitly acknowledged in FHWA research publications and in the Bridge Investment Program guidelines established under the Infrastructure Investment and Jobs Act.

The APRI Framework — validated in this six-viaduct project — directly addresses this gap. Its four phases (data-driven diagnosis, risk-based prioritization, low-impact solution selection, and systematic documentation) are designed to be adopted by municipal engineers, state DOT project managers, and consulting firms managing aging bridge inventories in American cities.

7.3 Scale of Potential Impact

The United States has more than 617,000 bridges in its national inventory. More than 45,000 are currently classified as structurally deficient. An additional 84,000 are classified as in poor condition. The majority of these structures are managed by county and municipal governments with limited technical staff and constrained budgets — precisely the context for which a structured, replicable decision-making framework offers the highest marginal value.

The Infrastructure Investment and Jobs Act's USD 40 billion bridge allocation will fund hundreds of rehabilitation projects across the country over the coming decade. The methodological contribution of this paper — and of the APRI Framework more broadly — is to provide a documented, field-tested approach for maximizing the structural and operational impact of those investments.

8. CONCLUSIONS

This paper has presented the integrated structural rehabilitation of six urban viaducts on Avenida Dom Pedro I in Belo Horizonte, Brazil — a project of significant technical complexity executed under the individual technical responsibility of the author between 2021 and 2023. The following conclusions are drawn:

- A structured four-phase decision-making framework — Assessment, Prioritization, Rehabilitation, and Institutional Documentation (APRI) — enabled the systematic management of six structurally distinct interventions on a single urban arterial, with clearly defined outputs at each phase that served both as technical deliverables and as institutional documentation.
- Risk-based prioritization, combined with a planned overlapping construction sequencing strategy, achieved complete structural rehabilitation of all six viaducts with only five days of full traffic closure over a 24-month intervention period — a result that demonstrates the operational value of structured pre-planning in urban infrastructure management.
- The combination of pressed-pile foundation reinforcement (presso-ancoragem), CFRP sheet and laminate systems, internal box girder prestressing through restricted access manholes, and controlled viaduct lifting with 5 × 1,000 tf hydraulic jacks demonstrates that complex structural deficiencies in constrained urban environments can be addressed without prolonged traffic interruptions when engineering solutions are selected with operational impact as an explicit design criterion.
- The methodology is directly applicable to the American bridge rehabilitation context, where more than 45,000 structurally deficient bridges present engineering challenges structurally equivalent to those documented in this case study, and where the Infrastructure Investment and Jobs Act has created an unprecedented funding context for systematic intervention.
- Systematic documentation of the decision-making process — not merely the technical outcomes — is a critical and frequently neglected component of infrastructure rehabilitation projects. Each documented project should be treated as an institutional asset that reduces the cost and uncertainty of future interventions on similar structures.

Future work will focus on adapting the APRI Framework to the American regulatory context (AASHTO LRFD, FHWA NBIS, ACI 440.2R), developing a quantitative scoring model for multi-criteria bridge prioritization informed by Business Analytics methods, and documenting the first American application of the framework through pilot engagement with municipal infrastructure agencies.

9. LIMITATIONS

This study is based on a single multi-structure intervention within a specific urban and regulatory context (Brazilian standards NBR 6118, 6122, 6187, and 7188). While the engineering principles, decision-making methodology, and rehabilitation technologies applied are directly transferable to analogous American practice under AASHTO LRFD and FHWA standards, further validation across different structural typologies, climatic conditions, and regulatory environments is recommended. The author's ongoing adaptation of the APRI Framework to the American regulatory context represents a direct continuation of this research.

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