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Arch Bridge Construction Methodology: Lesson Learned from Failure Study

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Abstract

Bridges are vital components of national infrastructure, driving economic development by connecting regions, enhancing transportation efficiency, and facilitating trade. Among various types, arch bridges offer a superior solution for long spans, providing maximal navigational clearance due to their minimal girder depth, yet making no compromise on structural integrity or aesthetic quality. However, their construction presents significant challenges, primarily due to the need for carefully sequenced execution and the reliance on temporary works to ensure structural stability before completion. This study highlights several failure case studies and construction challenges, including those from Bangladesh, to illustrate the critical role of construction staging and temporary support systems. These failures underscore the consequences of inadequate planning, under-designed temporary structures, and insufficient attention to construction-phase behavior. Based on these insights, a systematic methodology for sequencing temporary works and arch bridge construction have been proposed which is further validated through a case study of a recently constructed arch bridge. The objective is to mitigate construction-stage risks and enhance overall structural reliability. The findings reinforce that the success of arch bridge projects relies not only on sound engineering design but equally on the precision, discipline, and integrity of on-site execution.

Keywords
Arch Bridge Construction, Construction Sequencing, Temporary Works, Bridge Engineering, Case Studies.

1. Introduction
Bridges are indispensable assets in national infrastructure, acting as vital links in transportation networks that drive economic growth, regional integration, and social development. By reducing travel time and improving connectivity between isolated or economically significant regions, bridges contribute directly to the movement of people, goods,

and services (Islam et al., 2023). As infrastructure demands evolve, engineers must not only meet structural performance criteria but also respond to site-specific constraints, environmental considerations, and architectural expectations (Khan et al., 2015a).

Among the many bridge typologies, arch bridges hold a unique position in both engineering and architectural history. They are frequently selected for long-span applications across deep valleys, wide rivers, and challenging terrain where the use of intermediate support is either impractical or detrimental such as over navigation channels, active fault zones, or environmentally sensitive areas. The inherent form of an arch efficiently carries compressive forces, allowing for slender and elegant structures that minimize vertical clearance obstructions and offer aesthetic appeal, especially in urban or scenic contexts (Nettleton & Torkelson, 1977).

However, the construction of arch bridges is inherently more complex than that of girder bridges. The unique load transfer mechanism of arch bridges necessitates precise temporary works and staged construction techniques (Au et al., 2003). The removal process may involve form travelers, stay cables, temporary towers, or even floating support systems all of which must be carefully sequenced and engineered to maintain global stability throughout each stage. Inadequate planning or poor execution during any construction phase can lead to disproportionate stress, deformation, or even catastrophic collapse (Tazowar & Siddique, 2022).

This study examines the construction methodologies of concrete tied-arch bridges, focusing on the role of sequential temporary works and the lessons learned from documented failures. Based on international standards or codes academic research, and practical case studies, the paper proposes a framework for construction planning that prioritizes safety, structural stability, and execution of reliability (*AASHTO LRFD Bridge Design Specifications*, 2007; ACI Committee 347, 2014). By aligning temporary work sequencing, final design intent and construction reality, the study aims to support more resilient bridge delivery especially in high-risk or resource-limited contexts.

2. Case Studies

Despite advances in design codes and construction technology, several arch and cable-supported bridges have experienced critical failures. Most of these failure occurred during construction and due to inadequate planning, flawed temporary work, or neglect of lifecycle responsibilities. This section highlights five case studies across the globe and one from Bangladesh, each offering valuable insights into the consequences of disregarding construction-stage behavior and structural integrity (Figure 1).

2.1 Sandö Bridge, Sweden (1939)

The Sandö Bridge was one of the earliest and most ambitious concrete arch bridges of its time. During construction, the timber falsework used to support the 264 m arch span collapsed under the weight of freshly poured concrete. Investigations revealed that the falsework lacked sufficient lateral bracing, and the stiffness of nailed plank connections had been overestimated (Åesson, 2014). The accident occurred on August 31, 1939, claiming the lives of 18 workers. Although overshadowed by the outbreak of World War II the next day, the disaster prompted a critical reevaluation of temporary works design in the field of bridge engineering. The bridge was later rebuilt with a more robust scaffold system supporting the arch throughout its entire length.

(a) (b)

(c) (d)

(e) (f)

Figure 1. Different arch bridge failure cases (a) Sandö Bridge, Sweden; (b) Qijiang Rainbow Bridge, China; (c) Dos Valires Bridge, Andorra; (d) Chirajara Bridge, Colombia; (e) Nanfang'ao Bridge, Taiwan; (f) Tangail Arch Bridge, Bangladesh

2.2 Qijiang Rainbow Bridge, China (1999)

The Qijiang Rainbow Bridge, a 140-meter reinforced concrete arch bridge in Chongqing, collapsed just three years after opening. The failure occurred in 1999 and killed 40 people. The investigation cited severe deficiencies in construction quality, including the use of substandard materials, poor workmanship, and lack of proper maintenance (He & Chen, 2014). The incident gained national attention and resulted in criminal prosecutions of engineers and public officials involved in the project (Ding, 2001). It highlighted how construction shortcuts such as improper curing, weak reinforcement anchorage, and lack of quality control can compromise even seemingly sound designs (Wu et al., 2018).

2.3 Dos Valires Bridge, Andorra (2009)

The Dos Valires Bridge, a twin-deck arch structure with partial cable-staying, collapsed on November 7, 2009, during the casting of its concrete deck. The temporary falsework supporting the formwork failed, sending wet concrete and several workers 15 meters into a valley below (Almeida, 2016). Five workers were killed and six were injured. Although an official cause was never conclusively published, reports suggest that misplacement of a traveling formwork segment may have triggered the collapse (Reina, 2009). This incident emphasizes the dangers of pouring concrete without a fully vetted and stable temporary support system.

2.4 Chirajara Bridge, Colombia (2018)

A catastrophic failure occurred during the construction of the Chirajara cable-stayed bridge on the Bogotá–Villavicencio highway. On January 15, 2018, one of the pylons (Tower B) failed mid-construction, causing the western half of the bridge to collapse and killing 10 workers (Georgakis et al., 2022). Forensic analysis later identified a critical design error: the strength contribution of a key diaphragm (transverse beam) in the tower was grossly overestimated, resulting in brittle failure under construction loads. The remaining tower was deemed unsafe and subsequently demolished. This case underlines the importance of independent design verification and close monitoring of temporary construction stages (Murphy et al., 2025).

2.5 Nanfang'ao Bridge, Taiwan (2019)

Nanfang'ao Bridge, a single-span steel tied-arch bridge over a fishing harbor, collapsed on October 1, 2019, 21 years after it opened. The failure began with the snapping of a corroded hanger cable, which caused a chain-reaction collapse as other cables failed in succession (Fan et al., 2025). A subsequent investigation found advanced corrosion in the hanger system, exacerbated by inadequate inspection and maintenance. The bridge lacked redundancy in its hanger configuration, relying on a single row of suspenders without backup systems. Six people were killed in the collapse, and the incident has since driven reforms in Taiwan's bridge inspection protocols, especially for coastal structures (Tseng et al., 2023).

2.6 Arch Bridge in Tangail, Bangladesh (2022)

In 2022, an under-construction concrete arch bridge in the Tangail district of Bangladesh collapsed, though fortunately without casualties. The failure was attributed to improper design of the temporary works and the use of unfit, low-cost materials like bamboo and untreated lumber in scaffolding. Additionally, no proper curing time was maintained before loading. While the collapse caused no injuries, it served as a wake-up call in the region and underscored the pressing need for adopting standard construction methodologies, even in low-budget infrastructure projects.

2.7 Lessons Learned from Case Studies

One of the most critical lessons is that falsework and scaffolding must be engineered with the same rigor as the permanent structure. Both the Sandö and Dos Valires bridge collapses demonstrate that inadequately braced or poorly designed temporary supports can trigger catastrophic failure during concrete casting. Temporary structures should undergo full structural analysis, including three-dimensional stability checks, and be designed with redundancy in mind (*AASHTO LRFD Bridge Design Specifications*, 2007). Neglecting these elements can compromise even the most carefully planned construction operations.

Another lesson centers on the need for designs to fully account for construction-stage loading. The collapse of the Chirajara Bridge highlights that even structurally sound final designs can fail if temporary load paths are not evaluated correctly. In this case, a misjudgment in the behavior of a critical transverse beam under temporary conditions led to brittle failure. This underscores the necessity for independent design reviews and staged analysis particularly for hybrid or non-redundant systems to ensure all phases of construction are structurally stable.

Long-term safety also depends on robust maintenance and system redundancy, as illustrated by the Nanfang'ao Bridge. The progressive collapse triggered by the failure of a corroded hanger cable revealed both the absence of adequate inspection regimes and a lack of redundant load paths. Regular inspection, proper detailing for corrosion protection, and the use of backup cable or hanger systems are non-negotiable requirements in modern arch bridge design, particularly in coastal or harsh environments.

The case of Qijiang Rainbow Bridge further emphasizes that construction quality control is critical from the foundation stage onward. Substandard materials, poor reinforcement placement, and lack of curing all contributed to its early failure. Quality assurance protocols must be strictly enforced at every stage from material selection and rebar installation to concrete testing and curing. Supervision must be continuous, and all site activities must align with the approved structural drawings and specifications.

Finally, the Tangail bridge incident in Bangladesh serves as a cautionary example of how improper sequencing and material misuse even on small-scale projects can result in failure. Project documentations often overlook the temporary work, and the design and implementation of temporary work are only on contractor's plan and capacity, unapproved substitutions, use of low-quality materials like untreated timber, and failure to follow curing protocols all weaken the structure long before it is operational. Proper methodology, as outlined in engineering standards and project specifications, must be followed regardless of project budget or scale.

Together, these cases reinforce that the success of arch bridge construction depends not only on good design but on disciplined execution, informed supervision, and a clear respect for construction-stage behavior. Temporary works are not optional add-ons; they are an integral part of the bridge system and must be treated as such to avoid repeating the costly lessons of the past.

3. Methodology of Construction

The methodology outlines the step-by-step construction methodology for the tied arch bridge, covering all major phases from substructure preparation to final formwork and scaffolding removal (Figure 2). Each step is organized sequentially to ensure structural integrity, alignment accuracy, and adherence to safety and quality standards throughout the erection process. The methodology integrates both standard engineering practices and project-specific requirements derived from design specifications, soil investigations, and site constraints.

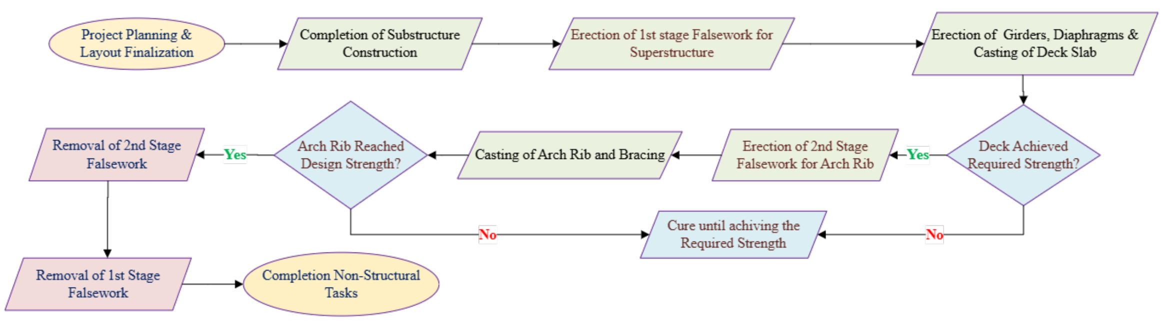

Figure 2. Flowchart showing the construction sequence

3.1 Substructure Construction

Substructure components, including piers and abutments, must be accurately referenced to the project's Temporary Benchmark (TBM). Since pile positioning governs global alignment, strict adherence to design coordinates is essential. Following installation, load and integrity tests are required to verify bearing capacity and structural soundness. Subsequent construction of pile caps and piers must incorporate continuous verification of alignment and Reduced Levels (RL) at every stage (Figure 3).

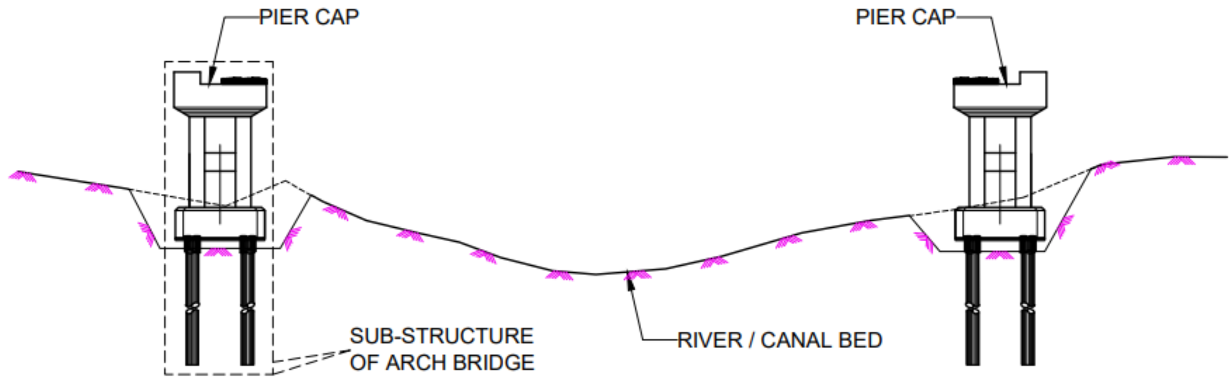

Figure 3. Substructure construction

3.2 Long Girder Cross Girder and Deck Casting

1st Stage Scaffolding Construction:

Based on the sub-soil investigation report, vertical loads (Dead Load, Live Load, Construction Load, etc.) and horizontal loads (Wind Load, Stream Pressure, Construction Load, etc.) the scaffolding arrangement must be designed and constructed with sufficient structural redundancy (Figure 4).

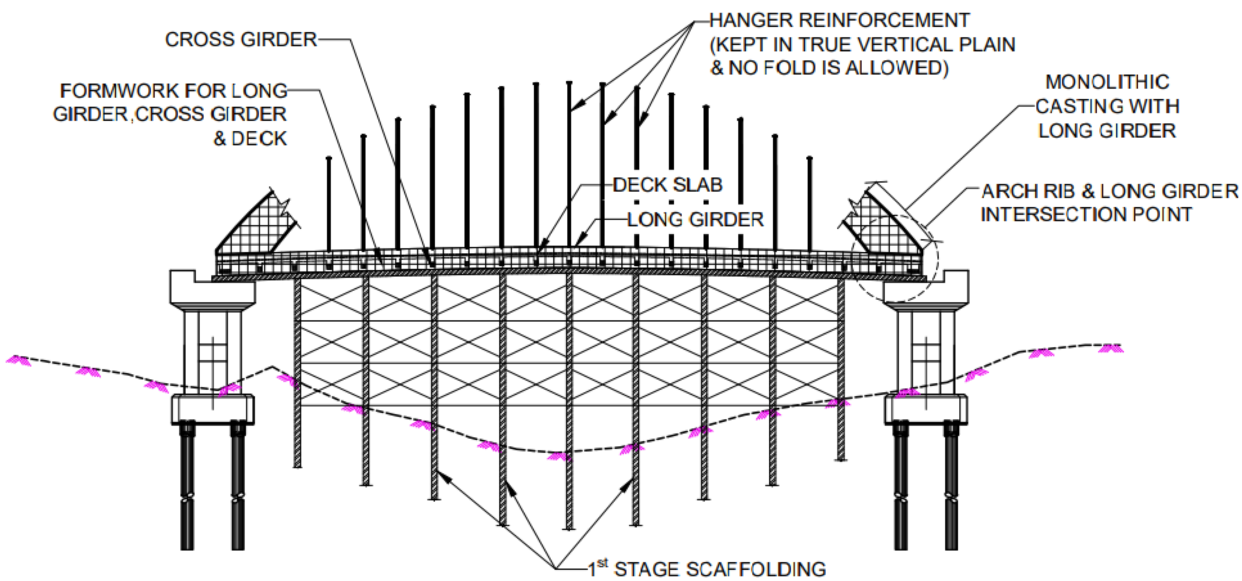

Figure 4. Long girder cross girder and deck casting

Long Girder Construction:

Following the erection of 1st stage scaffolding and bearing installation, formwork has to be prepared for the longitudinal girders, cross girders, and deck. Prestressing tendon profiles and anchorage layouts must strictly adhere to design specifications. Hanger reinforcement requires precise vertical alignment with support points; due to their tension-critical nature, splices or laps are precluded. The longitudinal girders, arch ribs, and deck are intended to be cast monolithically; however, construction joints in the deck may be permitted subject to prior approval.

3.3 Arch Rib and Top Bracing Casting

2nd Stage Scaffolding Construction:

A Tied Arch bridge is designed such that loads are initially transferred from the deck and cross girders to the tie beam and subsequently transmitted to the arch rib through hanger bars. Due to the combined action of the tie beam, hangers, and arch ribs, the tie beam acts primarily as a tensile member and is not designed to withstand the full flexural load of the deck and cross girders in isolation (without hangers and arch ribs). Consequently, premature removal of the 1st stage scaffolding before the load is transferred to the arch is likely to cause catastrophic failure of the tie beam, even if the concrete has reached its full design strength (f'_c). Therefore, the 1st stage scaffolding must be retained till the end of the construction. Once the longitudinal girder, cross girder, and deck achieve required strength, 2nd stage scaffolding is installed above the deck. Critical attention must be given to preventing excessive stress on the deck caused by this secondary shoring. Concurrently with the 2nd stage scaffolding, formwork for the arch rib and top bracing must be installed. Following formwork preparation, the hanger reinforcement and arch rib geometry must be positioned with precision according to design specifications to ensure proper alignment prior to casting (Figure 5).

Construction of Arch Rib and Top Bracing:

Hanger bars function as primary tension members and, typically composed of steel, are highly susceptible to corrosion. Beyond galvanization, grouting is the most effective method for corrosion mitigation. This process eliminates air voids within the steel duct or casing of the hangers. In order to prevent shrinkage and bleeding, the grout mix must incorporate appropriate admixtures. To avoid air entrapment, grout injection must proceed from the bottom of the hanger casing upwards. Grouting operations must be completed prior to the casting of the arch rib and top bracing.

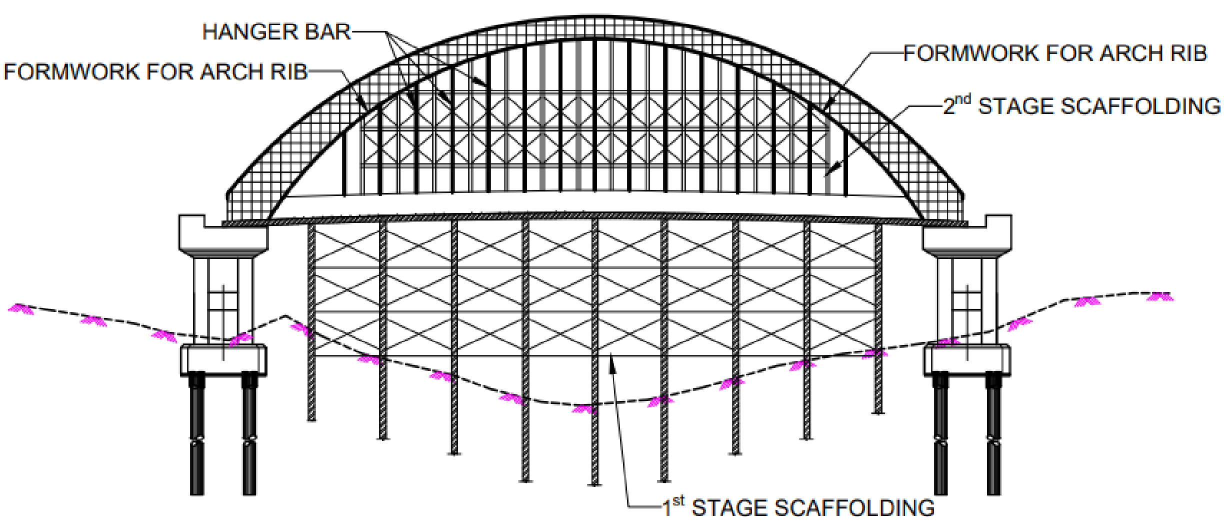

Figure 5. Arch rib and top bracing casting

3.4 Removal of Formwork and Scaffolding

The structural integrity of tied arch bridges during construction is governed by concrete strength acquisition and the sequence of scaffolding removal. Given the two stages support system, a critical challenge is defining a removal sequence that maintains structural safety and adheres to the anticipated design load path. Rigorous engineering analysis is required to justify this sequence. If the 1st stage scaffolding (deck support) is removed while the 2nd stage scaffolding (arch support) remains in place, the tie beam is forced to mobilize prematurely. In this scenario, the tie beam acts as a flexural member supporting the dead load of the arch rib transmitted through the remaining second-stage scaffolding. Since the tie beam is designed primarily for axial tension, it lacks the flexural capacity to withstand these loads, creating a high risk of excessive deflection and structural failure. Conversely, removing the 2nd stage scaffolding first activates the arch rib and hanger system. Subsequent removal of the 1st stage scaffolding then correctly transfers all the superstructure load to the arch, replicating the design load path. Furthermore, scaffolding removal for simply supported spans must be executed in a controlled manner, initiating from the mid-span and progressing symmetrically toward the supports (Figure 6).

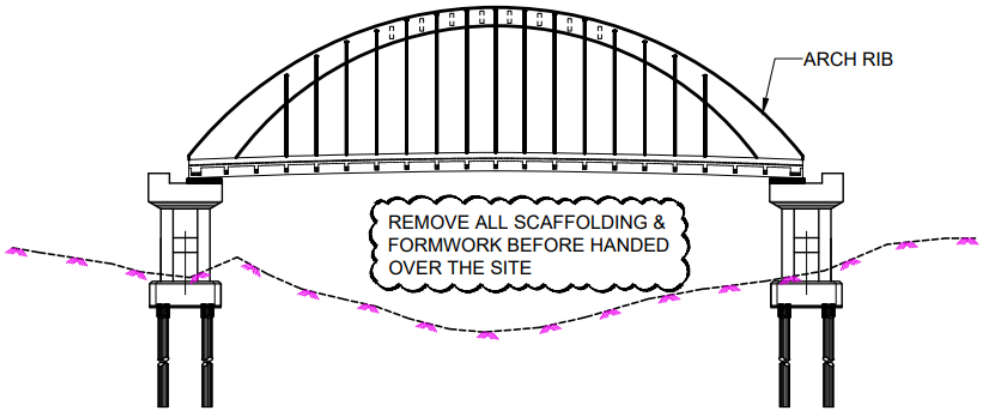

Figure 6. Removal of formwork and scaffolding

Successful Construction

To validate the understanding of arch load transfer mechanics and the lessons learned from previous failures, a 35-meter tied arch bridge was constructed at Shibchar Pourashava (Shibchar Upazila, Madaripur District) under the authority of the Local Government Engineering Department (LGED), Bangladesh. Completed in 2022, the project strictly adhered to the detailed construction methodology and scaffolding removal sequence outlined in this study (Mostafiz, 2022). Upon completion, the bridge was successfully commissioned for service, exhibiting no signs of structural distress or construction-related defects, thereby verifying the efficacy of the proposed methodology (Figure 7).

(a) 1st Stage Scaffolding

(b) Tie beam, cross girder and deck casting preparation

(c) 2nd stage scaffolding

(d) After removal, the bridge in service

Figure 7. Successful completion of arch bridge construction (Mostafiz, 2023)

4. Challenges and Construction Deficiencies in Bangladesh

While arch bridge construction follows a highly technical methodology requiring precise execution, the practical realities on the ground in Bangladesh often diverge from ideal practice. In many rural and semi-urban infrastructure projects, particularly those delivered under local contracting frameworks, several recurring challenges compromise the integrity and durability of the structures being built (Mostafiz, 2011; Tazowar & Islam, 2023).

One of the most critical issues is the improper sequencing of temporary work. In many cases, elements such as the deck, bracings, or even arch ribs are cast without ensuring the necessary curing time for substructure components like piles or pile caps. This practice introduces uncontrolled stress into partially completed systems, leading to structural instability . The situation is made worse when scaffolding is dismantled prematurely or without maintaining proper load paths, increasing the risk of collapse during construction stages.

Material selection and usage present another major concern. In several observed cases, low-cost and unfit materials such as untreated bamboo or makeshift timber are used for scaffolding and formwork (Tazowar et al., 2023). These materials often lack the required strength and consistency to support dynamic construction loads, particularly during concrete pouring. Even where steel formwork is available, its improper bracing or reuse without inspection contributes to failures. Concrete quality also suffers from reliance on manual mixing, non-standard aggregates, and a lack of control over water-cement ratios factors that significantly reduce the performance and durability of key structural elements.

Design adherence and verification are often neglected in local contexts. Construction crews frequently improvise on-site without consulting structural drawings or approved erection sequences. Temporary arrangements such as falsework, bracing, or hanger supports are altered or omitted to speed up progress or reduce costs. These unauthorized modifications, when not accounted for in the original design, can lead to catastrophic failure modes (Khan et al., 2015b). Moreover, geometric control during execution such as level setting, camber adjustments, and alignment of girders and arch ribs is rarely performed with precision instruments or qualified oversight. The shortage of site supervision is another persistent issue. Many projects proceed without the continuous presence of qualified civil engineers or trained bridge supervisors. As a result, critical construction activities like reinforcement placement, hanger anchorage, or formwork tightening are managed by unskilled labor without adequate guidance. In particular, poor bar placement, insufficient lap lengths, and inconsistent cover can undermine the structural capacity of arches and decks (Figure 8)

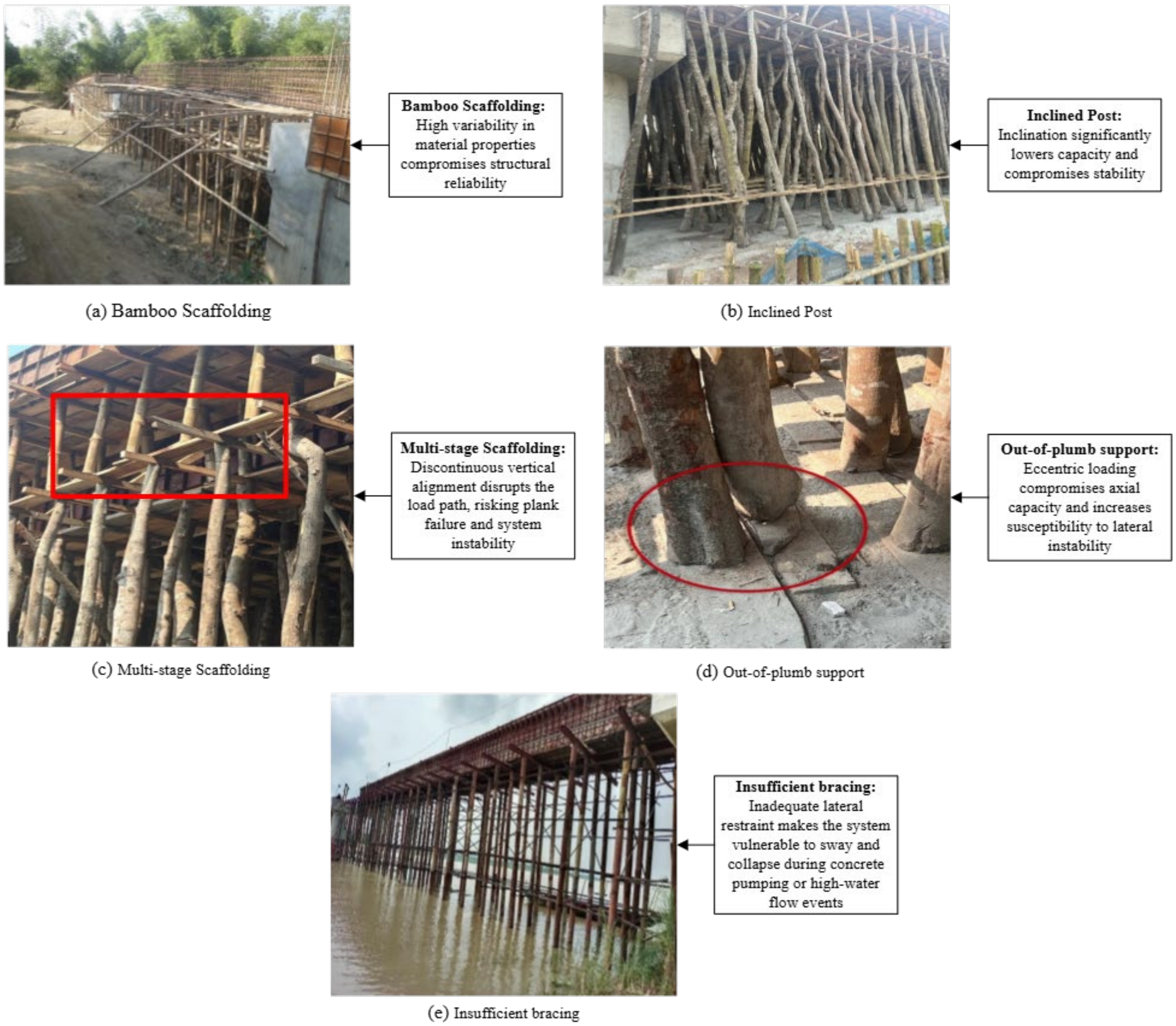

Figure 8. Scaffolding

Testing and quality control are often sacrificed due to budget or time pressures. Pile integrity tests (PIT), load testing, and even basic cube strength verification are either skipped or documented superficially. Monitoring tools like inclinometers, strain gauges, or level markers are rarely used in small to medium-scale bridge projects, leaving the structure's true behavior during staged construction unknown. Without these checks, issues such as differential settlement, excessive camber loss, or overstressed temporary supports may go undetected until failure occurs.

Compounding these problems is the broader administrative environment, which often emphasizes rapid completion and cost savings over engineering integrity. Contractors working under fixed-budget, low-bid contracts are incentivized to minimize expenditures on materials, testing, and supervision. Technical vetting of construction methodology is sometimes limited to paperwork, with little enforcement at the site level. As a result, bridges that appear structurally sound on drawings may be compromised in practice due to execution shortcuts and overlooked safety measures.

In summary, while the design and engineering of arch bridges in Bangladesh may align with modern standards, execution on-site frequently suffers from weak planning, poor supervision, and cost-driven compromises. These challenges highlight the urgent need for stricter enforcement of construction protocols, capacity building in local bridge teams, and a cultural shift toward treating temporary works and staged construction with the same seriousness as the permanent structure.

5. Conclusion

In conclusion, arch bridges combine structural efficiency with aesthetic appeal, making them a preferred choice for long-span applications. However, their construction is inherently complex and demands precise methodology, robust temporary works, and disciplined execution. This paper has outlined the essential construction sequence and highlighted how failures often result not from poor design but from overlooked construction-stage behavior, non-engineered falsework, inadequate supervision, and substandard material practices. Case studies illustrate that even well-designed structures may collapse if temporary systems are improperly designed or implemented, or sequencing is violated. In countries like Bangladesh, these risks are amplified by resource limitations, unskilled labor, and pressure to cut costs, all of which can compromise safety. The findings emphasize that a successful arch bridge project depends equally on sound structural design, strict quality control, and adherence to approved construction procedures including the engineering design of all temporary works. Without these, failure can be repeated. The importance of research and development in shaping the future of construction practices for the construction industry.

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Biographies

Md Yeasin Mostafiz is a diligent PhD student, enrolled in the Department of Civil Engineering at the University of Texas at Arlington, where he is actively engaged in research under the guidance of Dr. Nur Yazdani with a strong penchant for structural engineering. Yeasin has amassed a wealth of practical experience during his career trajectory for more than a decade. The focus of his career is design and construction of bridges. His recent role as a Bridge Design Engineer at Local Government Engineering Department (LGED) of Bangladesh showcases his expertise in the field of bridge engineering. Prior to that, he served for two well reputed consulting firms in Bangladesh as well. Before joining UTA, Yeasin completed the detailed design of four bridges of around 300 m under the authority of LGED. He had designed around forty small bridges (less than 100 m long) under the authority of several government and semi-government agencies of Bangladesh. His extensive background and unwavering dedication to advancing the field of civil engineering render him an asset within both academic and professional spheres.

Manshib Tazowar is currently pursuing a Ph.D. in the Civil Engineering at the University of Texas at Arlington, where he is also a member of the Next-Gen Sustainable and Resilient Infrastructure Lab (NSRI Lab). He earned his bachelor's degree from Bangladesh University of Engineering and Technology (BUET), with his undergraduate research focusing on an innovative approach to enhancing the bond strength of Bamboo Reinforced Concrete using corrugation. After graduation, Manshib worked as a Research Assistant at the Bureau of Research, Testing, and Consultation (BRTC-BUET) more than a year, contributing to one of Bangladesh's mega projects, the BNS Submarine Base Project. In this role, he analyzed structural performance in high seismic and coastal environments under various loading conditions and prepared technical reports and presentations. His research interests lie in structural engineering, design and analysis and the integration of traditional materials into modern construction practices.

Dr. Ishtiaque Ahmed is a professor in the Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET). Dr. Ahmed is a commonwealth scholarship holder, who completed his Ph.D. in Civil Engineering at University of Sheffield, UK in 1992. He has over 30 years of experience in teaching, consultancy and professional work at many national and international levels. He has been marked as a successful leader of the consultation team in various mega projects namely Dhaka Chittagong Expressway, Chittagong Container Terminal (CCT), Patenga Container Terminal (PCT), Repair and Renovation of Jetty (NCT Jetty) and pavement designing of Zia International Airport. His research interest lies in Seismic design of structures, design for structural fire protection, repair and retrofitting of structural elements, engineering procurement and construct contracts for development projects.