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Limitations of Highly Skewed Bridges > 45 degrees

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Abstract

Highly skewed bridges are defined by the Queensland Department of Transport and Main Roads (TMR) as bridges whose decks have a skew of 45° or greater to the abutment. The structural behaviour of bridges with high skew angles are more complex than bridges with no or low skew angles. High skews can lead to additional stresses or displacements that may potentially affect a bridge's performance, increase maintenance demand or shorten the asset operational life. TMR, in partnership with the National Transport Research Organisation (NTRO), undertook a project to consolidate current literature, Australian and international design codes, industry best practices and stakeholder learnings relevant to the design, construction and management of highly skewed bridges.

The project scope included a literature review, a review of TMR's Bridge Information System (BIS) data, a desktop assessment of bridge inspection records, stakeholder consultation with road agencies and precasters, and site inspections of four highly skewed bridges.

The outcome of this research yielded recommendations and industry best practices which address the skew-specific considerations for bridges in the design, construction and maintenance phases. The project found that, when correctly managed, highly skewed bridges typically have an operational life comparable to that of bridges with low or no skew.

Keywords: Bridge, Skew, High skew, Asset management

1. Introduction

Paper Layout

This paper is structured around the lifecycle phases of a bridge, providing a comprehensive view of how high skew impacts each stage from planning to decommissioning. The sections include:

1. Introduction: Overview of the project objectives and scope, and the unique characteristics of highly skewed bridges.
2. Bridge Phases: Detailed exploration of each phase - planning, analysis, fabrication, construction and operation - with a focus on skew-related challenges.
3. Recommendations and Best Practices: Summarised findings and recommendations.

This phased approach ensures a clear delineation of challenges and solutions, providing a roadmap for addressing the complexities of highly skewed bridges throughout their lifecycle.

Project Scope and Objectives

Highly skewed bridges, defined by the Queensland Department of Transport and Main Roads (TMR) as bridges with skew angles exceeding 45°, present unique challenges in design, construction and maintenance. This project, titled 'Limitations of Highly Skewed Bridges', was instigated to consolidate the current knowledge relating to high skew. Such knowledge will inform road agencies of the design, construction and maintenance risks associated with highly skewed bridges and may provide an opportunity to innovate and challenge skew restrictions.

The project's scope included:

1. a literature review of standards, guidelines and research related to highly skewed bridges
2. an analysis of TMR's Bridge Information System (BIS) data, focusing on bridges with skew angles greater than 45°
3. a desktop assessment of Level 2 inspection reports to identify recurring defects and maintenance issues
4. stakeholder engagement with road agencies and precasters to understand constraints, risks, constructability, maintainability and feasibility of highly skewed bridges
5. field inspections of four highly skewed bridges to document relevant findings.

The overarching objective was to consolidate existing knowledge and provide guidance for the design, construction and maintenance of highly skewed bridges, ensuring that these structures achieve a lifespan comparable to their non-skewed counterparts.

Overview of Highly Skewed Bridges

Highly skewed bridges differ fundamentally from non-skewed and low-skewed structures due to their geometric alignment, which significantly influences their structural behaviour. Skewed bridges exhibit unique load paths, which run diagonally between obtuse corners. This results in altered internal reaction forces, rotational movements and increased susceptibility to cracking and other defects.

The following structural and performance impacts are discussed in this paper:

- Load path variations: Load paths deviate diagonally, causing higher bending moments and torsion near obtuse corners, while acute corners may experience uplift.
- Displacements and deformations: Skew geometry can impact deformations due to thermal expansion, creep and shrinkage, often leading to diagonal displacements.
- Common defects include:
  - acute corner cracking due to thermal and shrinkage stresses
  - rotational misalignments and bearing damage
  - lateral movement and misalignment at supports.

The fabrication and construction of components for highly skewed bridges present unique challenges that require careful consideration and, in some cases, adaptive techniques to address potential issues. These challenges include:

- Precaster challenges: Acute angles in girders and beams complicate reinforcement placement and increase the risk of spalling damage.
- Construction issues: High skew angles demand specialised construction techniques, such as saw-toothed arrangements for girder placement, to accommodate non-uniform geometry.

These complexities underline the importance of considering skew angles early in the planning and design phases to mitigate risks and optimise resource allocation.

Bridge Phases

Bridges undergo a lifecycle that spans from initial planning to eventual decommissioning. Each phase presents distinct challenges, particularly for highly skewed bridges, where geometric complexities introduce additional considerations. This paper divides the lifecycle into five key phases: planning, analysis and design, component fabrication, construction, and operation/management.

2. Skew Bridge Planning

The planning phase plays a fundamental role in mitigating challenges associated with highly skewed bridges and should focus on exploring alternatives to minimise or eliminate the need for skewed structures wherever possible. The planning stage can aim to avoid high skew through alternative alignments, longer girders or wider bridges where practical. These strategies reduce the need for complex design adaptations and minimise maintenance demands that result from skew.

The stakeholder consultation provided the following key considerations for highly skewed bridges during the planning stage:

- Site constraints should be carefully assessed before selecting a high skew angle because it introduces additional considerations throughout the bridge's design, construction, operation and maintenance.
- Bridge type selection is important because the angle at which high skew-related issues arise can vary. Super T-girder bridges and integral bridges have additional challenges resulting from higher skew angles. Super T-girder bridges encounter defects during precasting and introduce construction limitations, such as increased torsional instability during lifting and complex bearing alignment. Integral bridges are prone to plan rotation due to thermally induced forces, which trigger passive resistance at the abutments and increase the horizontal loads on piled foundations.
- The effects of skew must be analysed carefully during the design process, particularly as typical Australian bridge design codes do not make reference to key skew-related considerations.

3. Skew Bridge Analysis and Design

Australian and International Standards, Guidelines and Literature

Guidance on highly skewed bridges varies significantly across jurisdictions. A review of various publications was undertaken to summarise the current guidance for the design, construction, operation and maintenance of skew bridges. The publications analysed were from Standards Australia, Austroads, Australian and New Zealand state road agencies, and American Association of State Highway and Transportation Officials (AASHTO). The publications largely caution designers about the adverse effects of skew and emphasise the need for additional consideration when designing for skew, particularly in elements such as bearings, joints, restraints, girders and decks.

The following sections outline the specifics of the information provided in these documents concerning skew bridges. The aim is to highlight the guidance they provide, the challenges they identify and their proposed solutions during the design, construction and operation of skew bridges.

Australian Standard AS 5100

Australian Standard AS 5100 *Bridge Design* (Standards Australia[1]) is the principal bridge design standard in Australia. However, it provides minimal advice for the design of highly skewed bridges. The main references to skew appear in AS 5100.4, which addresses the design of bearings and deck joints. The considerations for skew include:

- AS 5100.4, Section 6: Requires the designer to assess variations of bearing loads across piers, abutments and bridge movements in skew bridges.
- AS 5100.4, Sections 9 and 19: Require the designer to consider transverse movements and rotation of the deck when setting the alignment of bearings and deck joints and designing for deck movements.

Austroads Guide to Bridge Technology

The Austroads *Guide to Bridge Technology* identifies high skew as angles exceeding 20°. References to skew bridges are presented in the following sections:

- Part 3, Section 14.2.8 (Austroads 2018[2]): Discusses the design and selection of restraints, bearings and deck joints for skew bridges.
- Part 4, Section 5.10 (Austroads 2018[3]): Focuses on adverse effects such as non-uniform load distribution; flexural behaviour of the deck; distributed loads at bearings and the propensity for large skew bridges to rotate.
- Part 4, Section 8.4.6 (Austroads 2018[3]): Addresses the issues associated with skewed abutments and explains that deflections occur normal to the abutment, resulting in a skewed abutment's stiffness along its front face being less than the stiffness along the bridge's centreline.

TMR Standards

TMR[4] defines extreme skews as angles greater than 45° and provides requirements for such bridges. The key sections of the guideline pertaining to highly skewed bridges are:

- Section 4.9.2.3: Details reinforcement for deck units cast at skews of 45° but installed at actual bridge angles.
- Section 3.2.3.2: Requires 'specific approval from the Director (Planning and Delivery) for bridges with extreme skews (over 45°)'.
- Section 4.9.2.3: Requires the ends of deck units in extreme skew to be cast with a skew of 45° but be installed at the actual angle of the bridge. Ligatures are required to be fanned at the ends to transition to the perpendicular. Sharp corners are required to be truncated.
- Section 4.9.2.4: Lists requirements for voids in prestressed concrete deck units. It states that skewed voids are required for skewed deck units.
- Section 4.9.4.5: Sets a requirement for concrete through and Super T-girders to be cast at a maximum skew of 45°. For bridges with a higher skew, the units can be placed at the high skew angle but must still cast at an angle of 45°.
- Annexure S01 (TMR[5]) and S02 (TMR[6]): Offers guidance on modelling skewed deck units for Tier 1 assessments, including grillage/frame models.

TfNSW Standards

The review of Transport for NSW (TfNSW) publications on highly skewed bridges included key requirements from engineering manuals and technical directions.

Roads and Maritime Services[7] (RMS), Section 11, has the following requirements:

- Skews > 35° require approval from the Director Bridges and Structures.
- Skews > 25° require linear elastic stress analysis of the deck slab to evaluate effects like transverse/longitudinal bending and differential shrinkage.
- Designers are advised to pay special attention to controlling bridge deck cracking within specification limits.

Road Transport Authority[8] (RTA) notes the following skew limitations for integral bridges:

- For bridge lengths ≤ 50 m, the maximum skew angle is 30°.
- For bridge lengths > 50 m but ≤ 70 m, the maximum skew angle is 20°.

These publications highlight that TfNSW imposes stricter requirements for Super T-girder bridges with skews > 25° and integral bridges with skews > 20°.

Other Australian and New Zealand Road Agencies

This section provides a review of publications from a number of road agencies, including the Victorian Department of Transport and Planning (DTP, formerly VicRoads), Main Roads Western Australia (MRWA), Department for Infrastructure and Transport South Australia (DIT SA) and New Zealand Transport Agency Waka Kotahi (NZTA).

- DIT SA[9] stipulates that ‘bridges with a skew angle of 35° or greater must have special consideration given to the detailing at the ends of the beams’ for bridges with Super T-beams.
- MRWA[10] restricts the skew in bridges with precast prestressed concrete trough beams to 30°.
- MRWA[11] provides guidance on developing three-dimensional models for skewed bridges. It recommends aligning the model elements with the reinforcement in the actual structure to accurately reflect the load distribution. It also suggests using finite element plate or shell element models over grillage models for heavily skewed bridges, as they typically yield better results.
- Victorian DoT[12] warns of ‘severe damage’ in many precast u-slab bridges due to induced torsional loads which the units were not explicitly designed for.
- NZTA[13] classifies bridges into four categories with varying levels of approval requirements. The design of bridges with a skew greater than 25° requires a Preliminary Structure Options Report to provide reasoning for why the skew angle was selected. Bridges with skew greater than 45° are categorised as complex structures, requiring the most onerous level of input into the options and design reports.
- Wood et al.[14] cites a recommendation from US practice, suggesting to limit the use of integral abutments for bridges with skew less than 30°. This is to minimise the magnitude and lateral eccentricity of potential longitudinal forces on the abutment.

These publications collectively reinforce the complexities associated with the design, construction and maintenance of skew bridges.

US Standards

AASHTO[15] provides detailed provisions for skewed bridges, including:

- Section 4.6.2.2.2: This section provides an approximate method of analysis for beam-slab bridges. Reduction factors are provided for the live load distribution for moments in longitudinal beams. This reduction factor is limited to bridges with a skew of less than 60° and where the difference between skew angles of two adjacent lines of support does not exceed 10°.
- Section 4.6.2.2.3c: This section provides correction factors for the uneven distribution of shear across interior and exterior girders as well as reduction factors for calculating longitudinal bending moments in girders on skewed bridges up to a skew limit of 60°.
- Section 6.7.2 Dead Load Camber (steel structures): This section states that in order for the girder webs of straight skewed I-girder bridges to end up theoretically plumb at the bearings under either the steel or full dead load condition, the cross-frames or diaphragms must be detailed for that condition in order to introduce the necessary twist into the girders during the erection.
- Section 6.7.4.2 I-section members (steel structures): This clause states that where support lines are skewed more than 20° from normal, intermediate diaphragms or cross-frames shall be normal to the girders and may be placed in continuous or discontinuous lines. In addition, the clause requires that where discontinuous intermediate diaphragm or cross-frame lines are employed normal to the girders in the vicinity of a support line, a skewed or normal diaphragm or cross-frame should match with each bearing that resists lateral force.
- Section C6.10.1 I-section Flexural Members (steel structures): This section warns of flange lateral bending in bridges with skew greater than 20°. It also recommends an examination of cross-frame or diaphragm forces in all bridges with skew angles exceeding 20°.
- Section 9.7.1.3 Skewed Decks: This section requires primary reinforcement to be placed perpendicular to the main supporting components in bridges with skew of 25° and higher.

- Section 9.7.2.5 Reinforcement Requirements: This section requires that for bridges with a skew angle greater than 25°, the specified reinforcement in both directions is to be doubled in the end zones of the deck.

Okumus et al.[16] included a comparison of publications from 17 US state Department of Transportations (DoT)s with the AASHTO *LRFD Bridge Design Specification*. It found that there was alignment between the agencies, with minor differences where state DoTs took a more conservative approach to design calculations than the AASHTO standard.

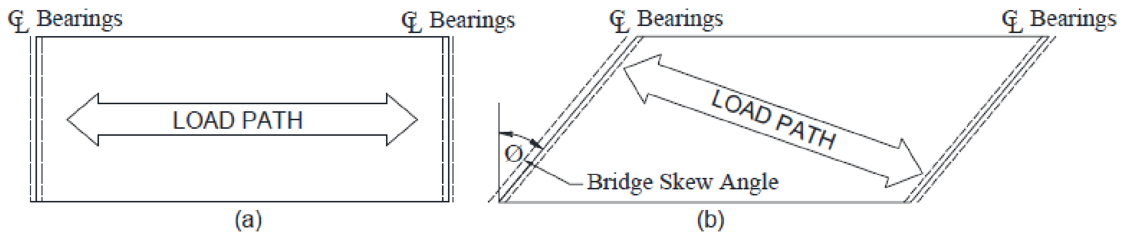
Load Paths and Structural Mechanisms

Unlike straight bridges, where load paths are generally uniform, skewed bridges exhibit diagonal load transfer patterns that affect bending moments, shear forces, torsion and displacements. Understanding the influence of skew on structural behaviour is essential for optimising bridge performance and ensuring safety. This section explores the implications of skew on load paths, deformation, bending moments, torsion and shear forces, emphasising how these factors vary with the degree of skew and structural configurations.

Load Path and Structural Behaviour

Highly skewed bridges perform differently to non-skew bridges. As shown in Figure 1, the load path in skewed bridges runs diagonally between the two obtuse corners, which is the smallest direct distance between supports (Okumus et al.[16]). As a result, highly skewed bridges experience altered internal reaction forces, rotational movement of the superstructure and deck cracking. The skew angle affects the behaviour of the structure in several ways, leading to changes in superstructure bending moments, changes in shear force reactions, the development of torsion and hogging moments at span ends, and displacement due to deck formations.

Figure 1: Load paths in straight and skewed bridge decks



Source: Reprinted with permission Okumus et al.[16], ' Load paths in (a) non-skewed and (b) skewed bridges', p. 4, copyright by authors, Wisconsin DoT, WI.

The effects of the altered load path are identified in (Hambly[17]):

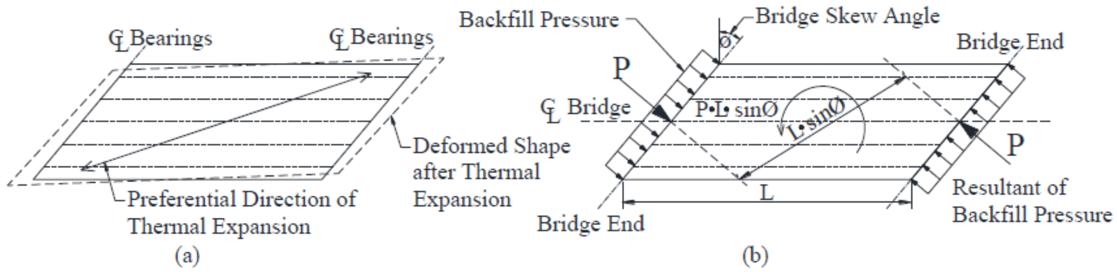
- variations in the direction of the maximum bending moment across the bridge width
- hogging moments near obtuse corners
- torsion of the deck
- higher reactions and shear forces near obtuse corners
- lowered reactions and possible uplift in acute corners.

The magnitude of these effects depends on factors such as the skew angle, the ratio of width to span, the superstructure type and support conditions.

Deformation and Displacement

Skewed bridges undergo unique deformations due to factors such as thermal expansion, concrete creep and shrinkage, and interaction with the abutments. These deformations cause the bridge deck to deform diagonally, which leads to lateral and longitudinal displacements. This is because the longest distance along the deck is diagonal between the acute angles, as shown in Figure 2. When superstructure movement is unrestricted, the bridge may rotate further towards the acute corners in a counterclockwise direction (Burke[18]; Okumus et al.[16]; Diaz Arancibia et al.[19]).

Figure 2: Displacements in skewed bridges



Source: Reprinted with permission Okumus et al.[16], '(a) Thermal expansion, and (b) backfill reactions due to thermal expansion ', p. 5, copyright by authors, Wisconsin DoT, WI.

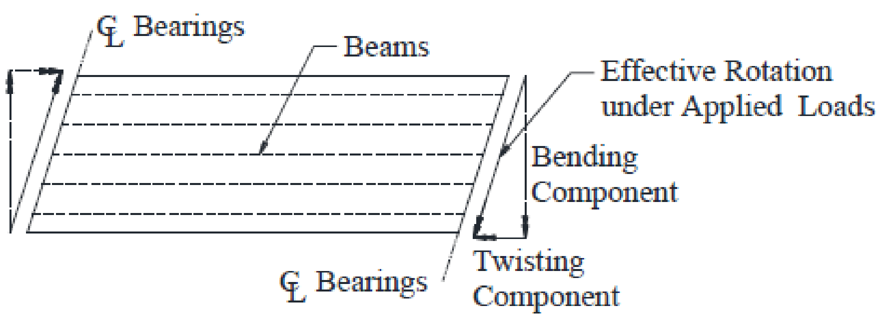
Altered Bending Moments

In skewed bridges, the bending moments in the superstructure follow the altered load path running between the obtuse corners. This causes the transverse bending moment to increase with the skew angle. For reinforced concrete (RC) and prestressed concrete (PSC) slab bridges, the transverse and longitudinal bending moments were found to vary with the skew angle. Compared to bridges with no skew, the maximum longitudinal bending moment due to wheel loads was found to decrease by up to 35% for bridges with skew angles of 60°. This was compensated for by an increase in the maximum transverse bending moment, which was shown to increase by up to 75% (Mallikarjun & Siddesh Kumar[20]). A similar behaviour can be seen in composite bridges, where the longitudinal bending moments decrease due to the reduced longitudinal component through the superstructure (Ebeido & Kennedy[21]).

Torsion and Negative Moments

High skew angles can induce torsion and negative moments at the bridge ends as the structure rotates around an axis parallel to the bridge supports. This is demonstrated in Figure 3 (Burke[18]; Okumus et al.[16]), emphasising the rotational behaviour and structural response at the bridge ends, which are subject to greater internal stresses.

Figure 3: Torsion and negative moments at bridge ends



Source: Reprinted with permission Okumus et al.[16], ' Effective rotation of girder ends', p. 5, copyright by authors, Wisconsin DoT, WI.

Shear Force Reactions

Shear forces at girder ends can increase at obtuse corners and decrease and possibly uplift at acute corners due to the abnormal load path (Ebeido & Kennedy[22]; Hambly[17]). The distribution of shear forces at the pier support is critical for 2-equal span and 2-unequal span continuous skew bridges. Shear forces increase at the exterior girders and decrease at the interior girders with increasing skew (Ebeido & Kennedy[23]).

Design Considerations for Mitigating Common Defects

Highly skewed bridges are prone to specific defects stemming from the unique structural behaviours introduced by their geometry. The lateral rotation caused by skew angles often results in issues such as misaligned bearings, damaged restraint systems and cracking in abutments and piers. These defects not only compromise the structural integrity of the bridge but also increase maintenance demands over time.

Addressing these challenges during the design stage can help mitigate their occurrence and lessen their impact. This section discusses the most common defects associated with highly skewed bridges, including diagonal cracking, spalling damage and issues with shear keys and bolts, while highlighting their causes and potential solutions.

Lateral Movement and Deck Cracking

Highly skewed bridges are often associated with defects such as lateral movement and deck cracking. The lateral rotation induced by the skew in the bridge deck can lead to defects such as rotated or misaligned bearings, damage to the restraint system, cracking in the abutment and pier, and misalignment of the wingwall and bridge parapets, as shown in Figure 4 (L) (Arancibia et al.[24]).

Specific Defects

In addition to the broad concerns relating to the lateral movement ensued, there are specific defects that should be considered during the design stage to minimise their impact upon occurring:

- Diagonal cracking: Diagonal cracks, commonly observed at the acute corners of concrete decks (Figure 4, R), are caused by thermal creep, shrinkage and loading stresses generated during concrete hydration. Live loading typically exacerbates these cracks (Fu et al.[25]).
- Spalling damage at acute corners: The skewed ends of precast ‘I’ beams are vulnerable to spalling damage during production at the bottom surface and at the apex of the end. The damage occurs when stress is transferred into the beam, and beam hogs upward, putting pressure on end corners, as shown in Figure 6 (Department of Planning, Transport and Infrastructure[26]).
- Fractured shear keys and loose bolts: Bridges constructed using older standards, such as the 1962 standard unit, may experience severe damage, particularly in skewed units due to induced torsional loads that were not accounted for in the original design. Inspectors are advised to watch for fractured shear keys and loose bolts (Department of Transport[12]).

Figure 4: Misalignment at kerb due to transverse movement (L), Corner cracking of skewed concrete bridge (R)

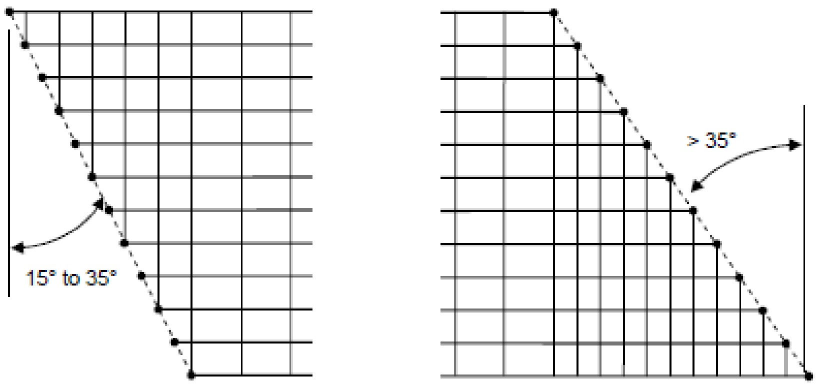
Source: (L) Provided by TMR, (R) Reprinted with permission Fu et al.[25], 'Corner cracking of skewed concrete deck', p. 10, copyright by authors, Wayne State University, MI.

Structural Modelling

The effects of skew highlight the need for refined structural modelling to represent the behaviour of highly skewed bridges. This section outlines approaches for selecting structural models for such bridges.

MRWA[11] notes the importance of using three-dimensional global models to accurately analyse skewed bridges, as they capture transverse load distribution and complex structural interactions. Grillage analysis, using a grid of beam elements, is effective for moderate skew angles. Hambly[17] recommends using orthogonal mesh for bridges with skew angles greater than 20 , while TMR[6] requires its use for skew angles greater than 15°. TMR[6] also requires the spacing of transverse members near supports to be reduced so that the transverse members intersect the longitudinal members at the supports as demonstrated in Figure 5. O'Brien et al.[27] discusses the inaccuracies related to grillage analyses, noting that adjacent transverse or longitudinal members that meet end-to-end at a node may not be equal, as torsional moments are present and contribute to the equilibrium at the node.

Figure 5 Layout of an orthogonal mesh for a skew deck – transverse members corresponding to alternate longitudinal members at left (15° < skew ≤ 35°) and all longitudinal members at right (skew > 35°)



Source: Reprinted with permission TMR[6], 'Layout of an orthogonal mesh for a skew deck – transverse members corresponding to alternate longitudinal members at left (15 < skew ≤ 35°) and all longitudinal members at right (skew > 35°). Typical reinforcement details for units with skew', p. 4, copyright by TMR, QLD.

For heavily skewed structures, plate or shell finite element analysis (FEA) models represent the structure more realistically, accounting for complex geometries and localised effects. Refinement of element mesh is required to balance computational efficiency with modelling accuracy. While grillage models are suitable for many cases, heavily skewed bridges benefit from FEA plate models, or a combination of both methods, to optimise analysis and design.

FEA plate models have been extensively used in studies, such as:

- ‘Role of Skew on Bridge Performance’ (Diaz Arancibia et al.[19]) to review skew effects on load distribution and performance.
- *Design and Performance of Highly Skewed Deck Girder Bridges* (Okumus et al.[16]) to assess bridge end details on deck cracking behaviour.
- *Bridge Deck Corner Cracking on Skewed Structures* (Fu et al.[25]) to analyse corner cracking in skewed concrete bridges.
- ‘Structural Performance of Acute Corners on Skewed Bridge Decks’ (Mawson et al.[28]) to evaluate detailing for acute corners in skewed bridges.

4. Skew Bridge Component Fabrication

The fabrication of precast components for skew bridges presents unique challenges, particularly at high skew angles. Four concrete precast suppliers, including Con-Tec, ENCO Precast, Holcim (Australia), and Quickcell Technology Products, provided valuable insights into the manufacturing difficulties associated with highly skewed girders.

The restricted space in the acute corners often results in either insufficient or congested corner reinforcement. Insufficient reinforcement can lead to concrete spalling at the corners, which was the most common issue identified by precasters. This issue is typically caused by girder hogging, with skew putting pressure on the acute corners at transfer, and an example is shown in Figure 6 Spalling of acute corner in precast girder unit. On the other hand, if reinforcement is increased to reduce spalling, the acute corner may become congested, which increases the risk of honeycombing or insufficient compaction at the corners.

One precaster also noted that precast components decrease productivity as the preparation and process requires more time and skill to complete. This means that skewed precast girders are typically more expensive to manufacture than square units.

Figure 6 Spalling of acute corner in precast girder unit

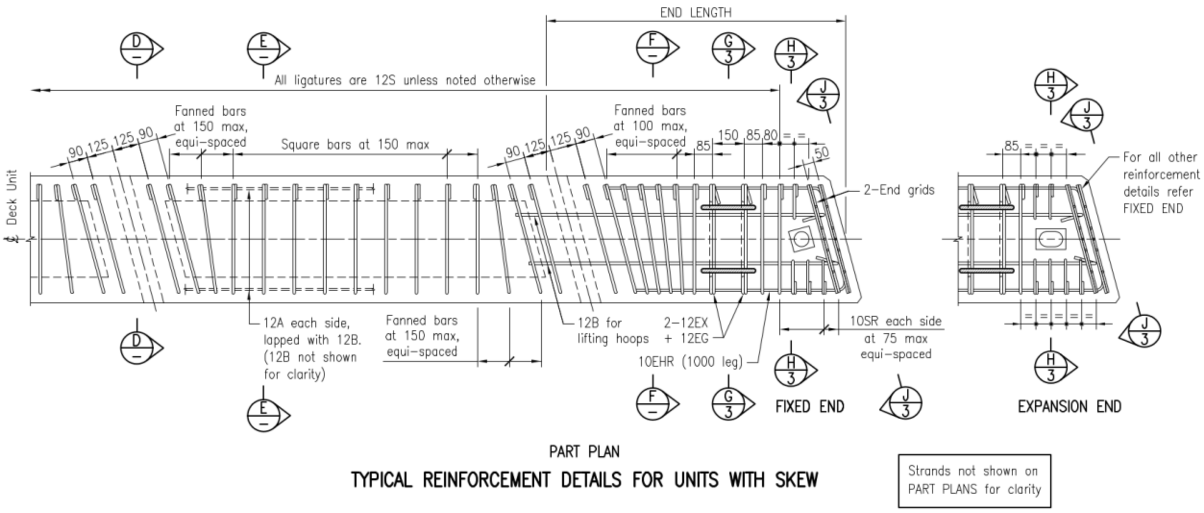
Note: Girder markings removed.

Source: Provided by TMR.

Stakeholder feedback indicated that skew defects typically start to occur at angles between 15 and 30°. Specifically, one supplier reported defects occurring at 15°, two suppliers observed defects at 20° and another supplier identified defects at 30°. To mitigate these issues, manufacturers follow standards such as Main Roads Technical Specifications (MRTS70 and MRTS73), with defect remediation requiring approval from the Administrator.

One suggestion to improve fabrication included moving the reinforcement transition from skewed to square further towards the middle of the girder than the current detailing practice shown in Figure 7. The cross bars further up the beam reportedly make reinforcement placement easier. This method has been done successfully previously, although it is noted that it slightly increases the amount of reinforcement required in the girder. It is also noted that any changes to the current standard detailing of TMR girders will require structural analysis and further stakeholder consultation.

Figure 7: Typical reinforcement details for units with skew



Source: Reprinted with permission TMR[29], 'Typical reinforcement details for units with skew', Standard Drawing No. 2059, copyright by TMR, QLD.

The precaster engagement revealed that skew angles introduce significant complications in the fabrication of precast elements, with spalling at acute corners being the primary defect. While defect remediation is possible using approved repair products, it is acknowledged that these defects are difficult to fully prevent without reducing the skew angle. The increased manufacturing cost and potential for defects should be carefully considered when specifying the skew angle for bridge projects.

5. Skew Bridge Construction

Construction of highly skewed bridges is inherently more time consuming and costly due to the precision required in girder placement and alignment, and it typically results in:

- A need for specialised techniques: Techniques such as saw-toothed arrangements are often employed for very highly skewed girders.
- Increased costs and time: The geometric complexity of skewed bridges often leads to longer construction timelines and higher costs compared to standard bridges.

Deck Corner Cracking

For concrete decks, acute corners are particularly susceptible to cracking. As outlined by Fu et al.[25], the primary causes include thermal and shrinkage loads during concrete hydration. Over time, vehicular live loading can exacerbate these cracks. Measures to reduce cracking include:

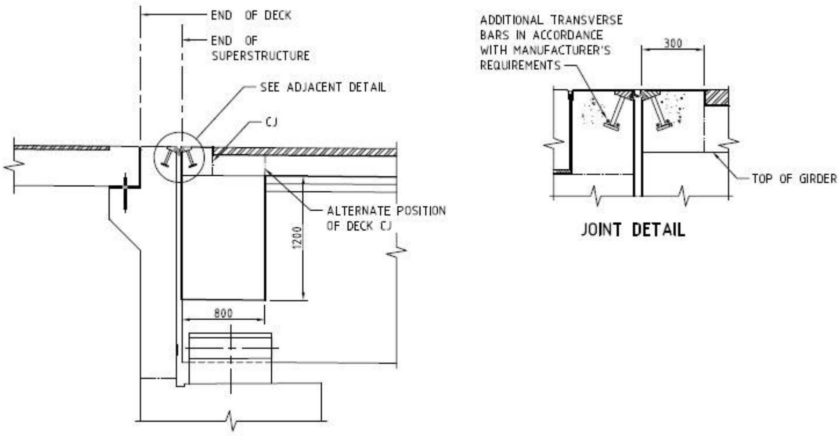
- reducing or relaxing restraint, such as modifying the deck configuration

- optimising concrete mix design to reduce heat generation and shrinkage
- increasing steel reinforcement in acute angle corners.

Despite these recommendations, current Australian guidelines lack specific provisions for additional steel reinforcement in skewed bridges. Observations from the construction of a highly skewed Super-T bridge in NSW in 2010 (Deck et al.[30]) suggest further measures, such as:

- Perform rigorous structural analysis including construction sequence and evaluating stress at acute corners.
- Increase longitudinal steel reinforcement.
- Use additional reinforcement mesh in acute corners.
- Adjust the location of the deck construction joint to line up with the inside face of the diaphragm; the section of deck over the diaphragm would be poured as one section with the expansion joint and reduce restraint from diaphragms (Apply appropriate curing practices to maintain moisture levels and control temperature, while ensuring adequate curing duration to prevent cracking.
- Figure 8).
- Apply appropriate curing practices to maintain moisture levels and control temperature, while ensuring adequate curing duration to prevent cracking.

Figure 8 Construction joint in deck slab to line up with inside face of diaphragm



Source: Reprinted with permission Deck et al.[30], 'Typical Detail for Infra 7a Diaphragm and Expansion Joint', p.10, copyright by authors.

The AASHTO[15] *LRFD Bridge Design Specifications* recommends additional reinforcement for concrete deck slabs designed using the 'empirical design process' to minimise cracking during construction. Section 9.7.2.5 requires four layers of isotropic reinforcement in all slabs designed with this method, with doubled reinforcement in both directions for skewed bridges (over 25°) in the end zone. This provision addresses crack control, as skewed beam-slab bridges are prone to torsional cracks due to differential deflections in the end zone (Ministry of Transportation[31]).

Fu et al.[25] conducted a cost-benefit analysis to evaluate the investment in additional steel reinforcement for skewed concrete bridges to reduce corner cracking. The analysis assumed a 15% increase in deck service life (6 years over a 40-year life). The cost of additional reinforcement, estimated from the AASHTO specifications, increased by US$17/m². With a net benefit ratio of 0.43, the analysis showed that adding steel reinforcement in the end zones of skewed bridges is cost-effective in minimising corner cracking.

Impact of Deck Restraints on Deck Cracking

Studies, including Okumus et al.[16], highlight that cracking can be mitigated by reducing deck restraint. However, design trade-offs must be considered as diaphragms and restrained bearings provide critical structural functions.

Steel Girder Bridges During Non-Composite Construction

High skew angles can also impact the construction of steel girder bridges. Non-composite loads can subject steel girders to differential deflections. If intermediate cross-frames are used during unpropped construction, the combination of high in-plane stiffness of the cross-frames and differential deflections can lead to torsion and flange lateral bending on the beams. This torsion and flange lateral bending has also been observed where skewed intermediate cross-frames are used. This can lead to beams being out-of-plumb during the concrete deck pour and can compromise the strength of the in situ concrete slab (Arancibia et al.[24]).

6. Skew Bridge Operation, Management and Decommissioning

The operation, management and decommissioning of skewed bridges present unique challenges that require careful consideration of various factors, including performance, maintenance requirements and inspection complexities. This section explores stakeholder feedback on operational issues, the impact of skew on bridge condition, common defects associated with highly skewed bridges and long-term performance issues, supported by both statistical analyses and field investigations.

Stakeholder consultations highlighted a broad range of operational challenges, including increased inspection complexities, consideration of the angle of expansion joints, observed defects and maintenance requirements.

Both MRWA and TfNSW identified that skewed expansion joints provide a suboptimal driving experience. The non-orthogonal geometry can cause the expansion joint to move in a non-uniform manner, leading to increased wear and misalignment. MRWA suggested a solution where the approach slab ends are squared off rather than left parallel to the abutments to provide a smoother driving experience. Generally, TfNSW uses strip seal joints on highly skewed bridges to manage this issue. If the bridge has a skew of less than 35° and improved bridge articulation is required, finger plate joints with cover plates may be considered.

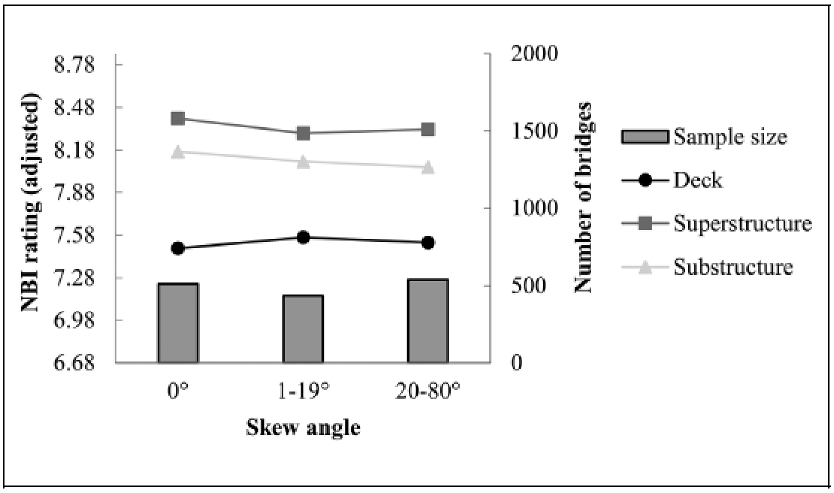
TfNSW also noted that abutments and piers must be designed to accommodate skewed loading conditions and provide adequate support and stability. Expansion joints must consider skew-induced movements while maintaining structural integrity and rideability. TfNSW also noted that the gap between girders and abutments may not be consistent at each girder end, and an in situ deck slab overhang may be required to suit the expansion joint installation and operation.

DTP provided commentary around the maintenance and aesthetics of highly skewed bridges. They noted that it may be more challenging to access and inspect highly skewed bridge components such as bearing and expansion joints, necessitating innovative inspection and maintenance strategies. They also mentioned that high skew angles can impact the visual appearance of bridges, requiring careful design integration with surroundings and urban environments.

Impact of Skew on Bridge Condition

While high bridge skew presents design and construction challenges, several studies have questioned the idea that skewed bridges perform worse than those with low or no skew. Diaz Arancibia et al.[19] analysed 1,486 bridges from the Wisconsin DoT’s database, comparing the condition ratings of deck, superstructure and substructure for varying skew levels. Contrary to common belief, skew did not significantly affect condition ratings in the National Bridge Inventory (NBI) (Figure 9).

Figure 9: Deck, superstructure and substructure NBI ratings for Wisconsin DoT bridges with no, mild and high skew



Source: Reprinted with permission Diaz Arancibia et al.[19], 'Deck, superstructure, and substructure National Bridge Inventory ratings for bridges with no, mild, and high skew', p.287, copyright by SAGE Publications.

Okumus et al.[16] performed field inspections on two pairs of bridges in Wisconsin with different skew levels (30° and 52° for prestressed concrete and steel girder bridges, respectively). The study found that highly skewed bridges had less cracking than their low skew counterparts, suggesting that skew is only one factor influencing bridge performance.

To explore whether this finding applies to TMR's bridge inventory, a desktop review was conducted on 131 bridges provided by TMR. The review utilised data from TMR's BIS and Level 2 inspection reports for bridges with skew angles greater than 30°. These bridges, constructed between 1930 and 2018, exhibit skew angles ranging from 30 to 65°. The primary objective of this review was to identify recurring defects associated with skew and assess any correlation with condition ratings.

The bridge data was analysed to determine if a correlation exists between skew angle and bridge condition rating. Several other bridge characteristics were analysed to provide further context and understand which bridge characteristics have the biggest impact on condition rating. The following bridge characteristics were used in the analysis:

- skew angle
- construction year
- bridge length
- maximum span length
- deck width
- number of spans.

The Pearson correlation matrix and t-test were employed to understand which bridge characteristics, if any, have a statistically significant correlation with the condition ratings in the provided dataset. The Pearson correlation coefficient, denoted as r, is a statistical measure that quantifies the strength and direction of the linear relationship between two continuous variables. It ranges from −1 to 1, with negative values indicating a negative linear relationship and positive values indicating a positive linear relationship.

The strength of positive (or negative) correlation is commonly categorised (Cohen[32]) as:

- weak correlation: r between 0.1 and 0.3 (or −0.1 and −0.3)
- moderate correlation: r between 0.3 and 0.5 (or −0.3 and −0.5)
- strong correlation: r greater than 0.5 (or less than −0.5).

Following this, the relationships between various bridge characteristics and the condition rating were tested for statistical significance using the t-test with a p-value of 0.05.

The correlations between condition rating and various bridge characteristics are shown in Table 1.

Table 1: Condition rating correlation to various bridge characteristics

Rank	Bridge characteristic	Correlation coefficient (r)	Correlation strength
1	Construction year	−0.34	Moderate
2	Max span length	−0.22	Weak
3	Skew angle	−0.17	Weak
4	Deck width	−0.16	Weak
5	Bridge length	−0.07	N/A
6	No. of spans	0.06	N/A

The relationship between skew angle and bridge condition rating was found to not be statistically significant with the Pearson test showing a weak negative correlation ($r = -0.17$). A statistically significant relationship was identified between construction year and condition rating, with a moderate negative correlation ($r = -0.345$). As bridges deteriorate over time, this result is expected. There was no statistically significant relationship identified between structure condition rating and other bridge characteristics.

These results show the complexity of bridge deterioration, which could not be accurately predicted from the selected individual characteristics. There are many factors that affect a bridge's condition rating such as its environment, design, construction, maintenance and operation history. Skew angle was not shown to have a statistically significant impact on TMR's bridge data for skew angles greater than 30°. To gain insights specific to skew, the provided BIS data and Level 2 inspection reports were further explored.

Common Defects

Inspection records for 47 bridges with skew angles greater than 45° were reviewed to identify defects that may be related to skew. The defects observed included superstructure movement (e.g. sheared restraint bolts), deck cracking and structural cracking in various components (e.g. abutments, headstocks). A review of the inspection reports identified 16 structures with defects that may be related to skew. Defects associated with superstructure movement were identified in 9 of these structures, which included damage to restraint bolts and restraint angles, differential movement at expansion joints and rotation of bearings. Transverse deck cracking was identified in 4 structures and cracking of deck units, headstocks, abutments, wingwalls and cross girders was identified in 6 structures.

The inspection reports were reviewed for defects that may reveal irregular load effects due to skew, such as:

- Superstructure movement: Evidence of superstructure movement through signs of misalignment or sheared lateral restraints (Figure 10 – Left).
- Deck cracking: Transverse cracking in the wearing surface, especially at acute corners (Figure 10 – Middle).
- Cracking: Indicators of structural stress and potential weakness (Figure 10 – Right).

Figure 10: Sheared restraint bolts (L), Deck cracking (M), Abutment cracking (R)

Source: Provided by TMR.

Following the desktop review of the Level 2 inspection reports, field investigations were carried out on four highly skewed bridges (see Table 2) showing defects that could be related to skew. The aim of the inspections was to attempt to correlate observed defects with the skew of the structures and assess whether skew might have an impact on their overall condition.

Table 2: Bridges selected for field investigations

Structure type	Structure name	Skew (°)	Curvature radius (m)	Condition state (CS)
Steel I-girder with RC slab	Water Creek	50	800	3
PSC I girder	Back Creek J Mcd Sharp Bridge	45	280	2
Steel I-girder with RC slab	Sandy Creek	45	None	3
PSC Deck units with RC infill	Innisplain Railway Overbridge	54	None	3

The key findings from these investigations are as follows:

1. Lateral rotation and displacement: Lateral rotation of the superstructure was clearly observed in the Water Creek Bridge and Back Creek J Mcd Sharp Bridge. Minor signs of rotation were also noted in the Sandy Creek Bridge and Innisplain Railway Overbridge. The literature indicates that lateral rotation of bridge superstructures towards the acute corners is a result of the differential thermal expansion in highly skewed bridges. However, the on-site observations were inconclusive:
   - Structure BIS ID 92: This skewed and curved structure exhibited lateral rotation towards its acute corners. However, testing of the sheared bolts revealed failure due to longitudinal movements of the superstructure parallel to the girders, not due to lateral rotation. It is recommended that superstructure lateral rotation be inspected and monitored during regular bridge inspections to provide valuable insights into the behaviour of the bridge over its operational life and to determine when intervention may be required.

- Structure BIS ID 145: Contrary to expectations, lateral rotation in this skewed and curved structure occurred towards the obtuse corners. This unexpected movement highlights the complexity added by the curvature, which might have influenced the behaviour.
- Structures BIS ID 169 and BIS ID 101: Both structures exhibited slight superstructure movements, but these could not be conclusively linked to skew. In the case of BIS ID 169, the direction of movement was unclear. For BIS ID 101, movement was observed at one corner in the opposite direction to what is typically expected in highly skewed bridges.

2. Implications of curvature and skew: The presence of curvature in two of the inspected structures (BIS ID 92 and BIS ID 145) adds complexity to the assessment of skew. Gupta and Kumar[33] highlighted the complex relationship between skew and curvature, which necessitates robust structural analysis to fully understand the response of individual bridges. The findings from these structures demonstrate that curvature can complicate skew-related issues, making it more challenging to predict structural behaviour.

These field investigations were limited by the small sample size and the unique characteristics of the individual bridges inspected. A larger dataset would provide a more comprehensive understanding of trends and allow for more accurate conclusions. To mitigate potential issues arising from skew and curvature, it is recommended that bridges undergo rigorous design analysis and careful monitoring during both the construction and maintenance phases.

Long-Term Performance Issues

Over time, skewed bridges may experience greater wear in specific components, necessitating targeted interventions.

DIT SA provided details of defects recorded on six bridges with skews ranging from 53 to 67° which are shown in Table 3. High skew angles may be a contributing factor to the following defects:

- Bridge 1 shows signs of rotational movement, with rotation in plan and extruding elastomeric bearing being observed.
- Bridge 2 may also have rotational movement, with the gap between the kerbs being closed by bridge rotation.
- Bridges 4 and 5 require further investigation to understand if the cracking/spalling of the abutment side walls was due to rotational effects.
- Bridge 6 defects may show that the skewed bridge joints are leading to vehicle bouncing which increases the dynamic loading on the structure.

Table 3: DIT SA defects in sample of highly skewed bridges

No.	Bridge type	Skew angle (degrees)	Defects
1	Two span simply supported with PSC I-girders	67	• Spalling of abutment under girder. • Rotation in plan and extruding of elastomeric bearings.
2	Single span simply supported with RC slab	62.25	• Spalling of kerbs at acute corners.
3	Three span continuous with PSC voided slab	60	• Downward creep deflection of acute corners of slab resulting in up to 30 mm height difference at joints. Hazard to pedestrians and cyclists. Addressed by raising joint nosings and re-levelling deck surfacing.

No.	Bridge type	Skew angle (degrees)	Defects
4	Three span continuous with steel I-girders	57	• Cracking/spalling of abutment side walls.
5	Three span simply supported with PSC plank girders	55	• Cracking/spalling of abutment side walls.
6	Six span simply supported in situ concrete T-girders	53	• Creep of concrete has caused girders to sag and high skew has resulted in vehicles bouncing irregularly, which increases dynamic loading. Bridge resurfaced with increased dead load being a trade-off to reduce dynamic loading.

Defect Monitoring and Inspection Strategies

DTP provided commentary around the maintenance and aesthetics of highly skewed bridges. They noted that it may be more challenging to access and inspect highly skewed bridge components such as bearing and expansion joints, necessitating innovative inspection and maintenance strategies. This was also witnessed during the field investigations where high skew angles limited the Under Bridge Inspection Unit from extending to its full length.

Recommendations and Best Practices

Summary of Key Findings

This section notes the major insights from the study, highlighting the primary challenges associated with highly skewed bridges and the critical areas requiring attention. The findings aim to inform industry stakeholders about the implications of skewed geometry on structural performance and management.

1. Highly skewed bridges present unique challenges in design, construction and maintenance due to altered load paths, increased torsion and abnormal reaction forces.
2. Acute corner cracking, bearing misalignments and uneven deformation are common defects that require targeted mitigation strategies.
3. Existing Australian standards provide limited guidance for skewed bridges, necessitating reliance on advanced modelling techniques like FEA.
4. Stakeholder engagement highlighted the need for enhanced construction practices and reinforced detailing to address skew-induced stresses effectively.

Implications for Industry Practice

To address the challenges identified, this section outlines practical measures for the industry. These recommendations focus on improving current practices, standards and maintenance approaches to better manage the unique demands of highly skewed bridges.

1. Design adaptations: Industry guidelines should incorporate specific provisions for skewed bridges, such as increased reinforcement in acute corners and improved recommendations for bearing and deck joint alignment.
2. Enhanced standards: Updates to AS 5100 and Austroads guidelines are critical to address gaps in skew-specific provisions and to align with international best practices.
3. Construction innovations: Practices such as optimising concrete mixes, adopting alternative reinforcement arrangements, such as those in Figure 7, and implementing efficient construction sequences should be prioritised.
4. Maintenance frameworks: Routine inspections and targeted maintenance strategies should focus

on areas prone to skew-induced defects, ensuring long-term structural integrity.

Future Research Directions

To address existing knowledge gaps, this section highlights key areas for further investigation. These research priorities aim to advance the understanding of skewed bridge behaviour and inform the development of more robust design and maintenance strategies.

1. Improving the accessibility of structural modelling: While advanced structural modelling techniques exist, their application in consulting environments remains limited due to staff knowledge, software complexity, computational demands and a lack of streamlined workflows. Future research should focus on developing user-friendly methodologies, improving integration and creating practical guidelines to bridge the gap between research-level modelling and industry application.
2. Impact of Skew on Seismic Performance: Future research should investigate how skew affects bridge performance during earthquakes, with a focus on developing mitigation strategies to prevent unseating and abutment pounding.
3. Field validation: Long-term monitoring of existing highly skewed bridges should be conducted to validate proposed recommendations and refine industry practices.

Conclusion

Highly skewed bridges present a series of interconnected challenges that affect every stage of their lifecycle. The unique geometry of these structures influences load paths, deformations and reactions, often leading to specific maintenance and operational concerns. This paper emphasises the importance of understanding these challenges to ensure that skewed bridges are planned, designed, constructed and maintained with proper consideration of their unique behaviours.

The findings highlight the necessity of proactive planning, careful design and collaborative stakeholder engagement to mitigate the risks associated with high skew. By incorporating detailed considerations for acute corners, bearings and reinforcement, and by refining construction and inspection practices, the industry can address these challenges effectively. Proper consideration and tailored solutions are key to achieving structural longevity and reliability in highly skewed bridges.

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