International Monorail Association

# Guideline for Expansion Joints (Finger Joints) in Monorail Guideway Systems

First Edition, September 2026

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INTERNATIONAL MONORAIL ASSOCIATION

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Expansion Joint Working Group

# Guideline for Expansion Joints (Finger Joints) in Monorail Guideway Systems

# Disclaimer

International Monorail Association (IMA)

'Guideline for Expansion Joints (Finger Joints) in Monorail Guideway Systems'

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This document has been prepared by the International Monorail Association (IMA) Expansion Joint Working Group. It represents a consensus of current industry knowledge and best practice as understood by the working group members at the time of publication.

This guideline is intended to serve as a reference document for the design, procurement, and evaluation of expansion joints in monorail guideway systems. It does not supersede applicable national or international standards, regulations, or project-specific contractual requirements.

The IMA and its working group members make no warranty, express or implied, regarding the accuracy or completeness of the information contained herein. Users are responsible for verifying the applicability of this guideline to their specific project conditions.

The IMA Executive Council, September 2026

# Revision History

| Version | Date | Author(s) | Description of Changes |
|---|---|---|---|
| 1.0 | September 2026 | IMA Executive Council | First published edition. |

# Foreword

Expansion joints are critical components of monorail guideway systems. They accommodate differential thermal, creep, shrinkage, and dynamic movements between adjacent guideway structures while preserving the geometric continuity of the running and guidance surfaces required for safe, comfortable, and durable vehicle passage. In straddle-type monorail systems, the expansion joint is not merely a structural gap; it is a fatigue-critical mechanical interface subjected to repeated vertical, lateral, braking, and environmental demands throughout the service life of the line.

Despite their importance, no unified international guideline has existed to date covering the full lifecycle of monorail expansion joints, from typology and design through manufacturing, installation, bolt tightening, tolerance control, maintenance, and repair. This guideline consolidates working-group consensus, international standards references, and lessons learned from operating projects, with particular attention to load distribution, fatigue performance, corrosion protection, installation alignment, bolt preload reliability, and maintainability.

The IMA Expansion Joint Working Group was established to address this gap. This guideline consolidates the working group's recommendations across the following chapters:

- Chapter 1 — Joint Typology (this document)
- Chapter 2 — Design (this document)
- Chapter 3 — Manufacturing and Quality Assurance
- Chapter 4 — Installation
- Chapter 5 — Bolt Tightening
- Chapter 6 — Installation Tolerances
- Chapter 7 — Maintenance

**Normative Requirements and Informative Guidance**

This guideline has been developed to serve a broad audience that includes designers, manufacturers, procurement authorities, contractors, operators, maintainers, and other stakeholders involved in monorail guideway systems. Accordingly, the document contains both normative requirements and informative guidance. The normative requirements establish the technical provisions considered necessary to achieve the intended level of safety, performance, durability, and interoperability. Informative guidance is provided to explain the background, rationale, industry practices, and operational experience that led to those requirements.

The International Monorail Association recognizes that future editions may further refine the distinction between normative and informative content as industry experience is gained and comments are received from users of the guideline.

The Working Group encourages feedback from practitioners, owners, operators, manufacturers, and authorities to support the continued evolution of the document and its eventual progression toward a more formalized standards framework where appropriate.

## Interpretation of Notes, Recommendations, and Lessons Learned, Interpretation of Requirement Language

To improve usability and accessibility, the Working Group has supplemented the technical requirements of this guideline with Notes, Recommendations, and Lessons Learned. These informational boxes are intended to provide context, practical experience, and explanatory material that may assist readers in understanding the technical provisions.

**Notes** provide clarification, background information, references to related sections, or explanatory observations intended to aid interpretation of the guideline.

**Recommendations** describe practices that the Working Group believes represent sound engineering judgment or good industry practice. Unless explicitly stated using mandatory language such as shall or shall not, recommendations are advisory in nature and should be evaluated in the context of project-specific requirements.

**Lessons Learned** capture knowledge derived from previous projects, operational experience, field observations, and industry practice. Their purpose is to highlight recurring issues, common causes of failure, successful mitigation strategies, and considerations that may not be evident from technical requirements alone. Lessons Learned are included to help readers benefit from accumulated industry experience and to support informed engineering decision-making.

These informational elements are intended to make the guideline more user-friendly and educational while preserving the technical integrity of the document. Unless they contain explicit mandatory language, they should be interpreted as informative guidance rather than independent compliance requirements.

## Interpretation of Requirement Language

The term shall indicates a mandatory requirement of this guideline. The term should indicates a recommended practice. The term may indicates a permitted option. Notes, Recommendations, and Lessons Learned are provided for informational purposes unless they explicitly contain mandatory language.

The working group acknowledges the contributions of industry experience from projects in United States, Japan, Brazil, China, Thailand, Egypt, Mexico and other countries, which have informed the content of these guidelines.

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# Executive Summary

Expansion joints are among the most mechanically demanding components of a monorail guideway system. Every vehicle passage loads them in multiple directions simultaneously, every joint on every guideway, for decades without replacement. Yet until now, no unified industry guidelines have existed for their design, manufacture, installation, or maintenance. This document is the first attempt by the International Monorail Association to fill that gap, drawing on operational experience from projects in Brazil, China, Thailand, Egypt, Mexico, the United States, and Japan.

The guideline is organized in seven chapters, each addressed to a distinct phase of the joint lifecycle. Together they form a continuous chain of requirements from initial classification through end-of-life maintenance. It is the intent that the reader responsible for any single phase (design engineer, manufacturer, contractor, or operator) finds that chapter directly actionable, while the broader document provides the context needed to understand how each phase depends on the others.

**Chapter 1-Joint Typology**, establishes a unified classification framework for monorail expansion joints. Joints are classified by three independent criteria: movement capacity (standard up to 200 mm, large movement, and depot style), structural configuration (cantilever, simply supported, and nosing), and finger plate location (top/superior and side/lateral). This multi-axis classification provides a common vocabulary for the industry and supports clear specification and procurement.

**Chapter 2-Design** defines the essential design requirements for finger joints. Key topics include the definition of tire footprint and contact geometry, load models incorporating vertical and braking forces, fatigue assessment methodology, and corrosion protection systems. This document incorporates guidance from the AASHTO LRFD Bridge Design Specifications (Section 14) to provide an internationally recognized quantitative baseline for gap width limits, minimum finger overlap, braking force coefficients, and dynamic load allowance, adapted throughout to the monorail context. The chapter emphasizes realistic operational loading rather than simplified static assumptions. Surface texturing of finger plates is recommended to reduce skid risk. Corrosion protection requirements address hot-dip galvanizing, thread tolerance adjustments for galvanized fasteners, aluminum anodizing, and the specific problem of running-surface abrasion removing protective coatings, soft polymer coatings are explicitly excluded from running surfaces.

**Chapter 3-Manufacturing and Quality Assurance** sets out the production requirements for manufacturers operating under an Assessment and Verification of Constancy of Performance (AVCP) System 1 framework, consistent with the European EAD documents for expansion joints. Requirements cover material certification and traceability, welding procedures and qualification to EN 1090 or AWS D1.1/D1.2 as applicable, dimensional inspection at each production stage, corrosion protection application and verification, and Factory Acceptance Testing. Material-specific test requirements are defined for each component class: elastomers, structural steel, aluminum, fasteners, and welded dowels, with test methods and minimum frequencies drawn from the relevant ISO, EN, and DIN standards. An independent notified body or assessor is required to verify constancy of performance and to issue and maintain the Declaration of Performance.

**Chapter 4-Installation,** presents the joint as what it is in practice: a high-precision mechanical interface installed within a civil construction program, where every phase of work either preserves or permanently compromises the geometric conditions that govern joint performance. The chapter defines a five-phase installation sequence, preparation, base plate integration, closure pour, finger plate assembly, and torque-angle finalization, with the quality objective of each phase stated explicitly. Two lessons from operational projects run through the chapter. First, voids beneath the base plate caused by insufficient closure pour consolidation are one of the most common and most consequential installation defect, and they are invisible after concrete placement: the design must provide for vibration access, and the contractor must verify consolidation before the pour is accepted. Second, expansion joint components are heavier than they appear and require dedicated lifting and positioning equipment to achieve the sub-millimeter alignment tolerances that separate a good installation from one that will cause problems for the life of the line.

**Chapter 5-Bolt Tightening,** addresses another of the most common cause of in-service expansion joint problems: loss of bolt preload. Anchor connections with cut or reused threads are treated separately. Section 5.4 sets out two methods for this case, calibrated wrench with arbitration-torque verification or torque-angle curve monitoring, with the choice between them left to the fabricator or engineer of record, conditioned on a project-specific tightening study per Section 2.8. The chapter compares North American practice (Skidmore-Wilhelm field verification) with the European prequalification approach and provides complementary recommendations including torque mark application for in-service monitoring and sealant application to bolt recesses for corrosion protection.

**Chapter 6-Installation Tolerances,** identifies the 1.5 mm vertical deviation limit as the governing geometric acceptance criterion for the running surface interface. This is not an arbitrary figure: a level difference of 2 mm between adjacent beam ends is sufficient to transfer the entire tire contact load to a single finger, multiplying the design stress range and severely reducing fatigue life. The chapter places prevention before remediation; survey monitoring during base plate installation costs a fraction of the field adjustments required to correct an out-of-tolerance joint after the concrete has hardened.

**Chapter 7-Maintenance** provides a structured framework for keeping joints performing as designed throughout their service life. The maintenance program begins at approximately 1,000 operational cycles after revenue service commencement, with a bolt preload verification inspection comparing residual torque against original installation records. Recurring activities include visual checks for plate wear, corrosion, and concrete cracking; bolt marking verification; and seal integrity inspection. A structured checklist covering visual, bolt, seal, and structural interface conditions is provided for field use. The chapter also documents lessons learned from previous projects, one of the most important being that incorrect base plate alignment during installation is a leading cause of expansion joint problems across the global monorail fleet, and that early detection of installation deficiencies, before concrete strength is reached, eliminates a category of remediation that is otherwise extremely costly.

The working group notes that this document represents the current state of consensus within the IMA membership at the time of publication.

## Editorial Note – Originality and Attribution

This document has been reviewed for unintentional reproduction of third-party text. No verbatim copying from AASHTO LRFD, EAD 120109-00-0107, or any other referenced standard has been identified. All technical content is expressed in original working-group language, with referenced standards cited by name and clause number for the reader's orientation.

Design principles derived from AASHTO LRFD Bridge Design Specifications, 10th Edition, 2024 (Section 14) are incorporated in Section 2 and Table 2. These are adaptations and interpretations for monorail context, not reproductions of AASHTO text. The AASHTO LRFD Specifications are a copyrighted publication of the American Association of State Highway and Transportation Officials (AASHTO); working group members are advised to consult the current edition directly for normative requirements in road-bridge contexts.

Fatigue methodology referenced from EN 1993-1-9 (Eurocode 3) and EAD 120109-00-0107 is similarly summarized in original language.

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# Glossary and Abbreviations

| Acronym | Explanation/Definition |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| ASTM | American Society for Testing and Materials (today: ASTM International) |
| AVCP | Assessment and Verification of Constancy of Performance |
| AWS | American Welding Society |
| DIN | Deutsches Institut für Normung (German Institute for Standardization) |
| CAFL | Constant-Amplitude Fatigue Limit |
| EN | European Standard (German: Europäische Norm) |
| EAD | European Assessment Document |
| EPDM | Ethylene Propylene Diene Monomer |
| EXC3 | Execution Class 3 according to EN 1090 (Performance Class for Steel and Aluminum Structures) |
| FAT | Factory Acceptance Test |
| FPC | Factory Production Control |
| IMA | International Monorail Association |
| ISO | International Organization for Standardization |
| LRFD | Load and Resistance Factor Design |
| NDT | Non-Destructive Testing |
| MT | Magnetic Particle Testing |
| UT | Ultrasonic Testing |
| VDI | Association of German Engineers |
| VT | Visual Testing |
| QA | Quality Assurance |

# 1 Joint Typology

## 1.1 Scope and Purpose

This chapter establishes a unified classification framework for expansion joints used in monorail guideway systems. The purpose of this classification is to provide a common vocabulary for designers, manufacturers, procurement authorities, and operators, and to enable clear specification of joint requirements across the full spectrum of monorail applications.

Expansion joints in monorail guideways serve a fundamentally different role from expansion joints in conventional road or railway bridges. The monorail beam acts simultaneously as a structural element, a running surface, and a guidance surface. Accordingly, the expansion joint shall maintain geometric continuity, load transfer capability, and surface quality across all three faces of the beam section — top, left lateral, and right lateral — throughout the full range of thermal, creep, shrinkage and dynamic movements.

## 1.2 Applicable Standards

The classification framework in this chapter is independent of any single national standard. Designers shall verify the applicability of the following references to their specific project jurisdiction:

- Project-specific vehicle interface specifications (tire footprint, wheel loads, braking forces)
- EAD 120109-00-0107 — Nosing expansion joints for road bridges (European Assessment Document; referenced for fatigue methodology applicability to monorail finger joints)
- AASHTO LRFD Bridge Design Specifications, 10th Edition — Section 14: Joints and Bearings
- ISO 9223:2012, Corrosion of metals and alloys — Corrosivity of atmospheres — Classification, determination and estimation
- ISO 14713-1:2017, Zinc coatings — Guidelines and recommendations for the protection against corrosion of iron and steel in structures

**NOTE:** A dedicated monorail-specific expansion joint standard does not currently exist. This guideline is intended to inform **future** standardization efforts.

## 1.3 Classification by Movement Capacity

### 1.3.1 Standard Joints — Up to 200 mm Total Movement

Standard finger joints are designed to accommodate thermal expansion, concrete creep and shrinkage due to prestress shortening movements, and dynamic movements up to a total of 200 mm (combined opening and closing relative to the set position). This category covers the large majority of mainline monorail joints. The finger plate geometry, overlap length, and base plate dimensions are all governed by the movement range.

In practice, most installed mainline joints operate within a movement range significantly below 200 mm as shown in the figures below. However, the 200 mm threshold represents the boundary above which standard finger plate proportions are no longer adequate and a redesign or modular approach is required.

Hitachi — Tokyo Monorail, 1964

*Note: The side fingers have been removed.*

ALWEG — Seattle Monorail

Hitachi — Tama Toshi Monorail, 2000

Alstom — Bangkok Monorails, 2024

Puzhen Alstom — Wuhu

Alstom — Cairo Monorails, 2026

Alstom — Line 15 São Paulo, 2016

BYD — Line 17 São Paulo, 2026

*Figure 1: Samples of expansion joints in operating projects*

(Source: IMA members technical visits)

### 1.3.2 Large Movement Joints — Exceeding 200 mm Total Movement

Large movement joints are required where thermal, seismic, or differential settlement demands exceed 200 mm. These joints typically employ modular finger plate assemblies, multiple interleaved plates, or hybrid steel-elastomer systems. Design of large movement joints requires specific analysis of finger plate stiffness, overlap at minimum opening, and load distribution across the finger array.

Large movement joints are most encountered at locations where long beam runs terminate against a fixed structure. Their design shall be project-specific and subject to individual analysis and testing.

A sample of a Large Movement Joint for the 4th Panamá Canal Crossing Bridge is shown in Figure 2 below, courtesy of Metro Panamá:

Another example of a large movement expansion joint is in Daegu Monorail, connecting first a steel beam structure to a pair of iconic extradosed bridges (very shallow, externally deviating tendons) and then to concrete guideway beams over concrete deck, see Figure 3 below.

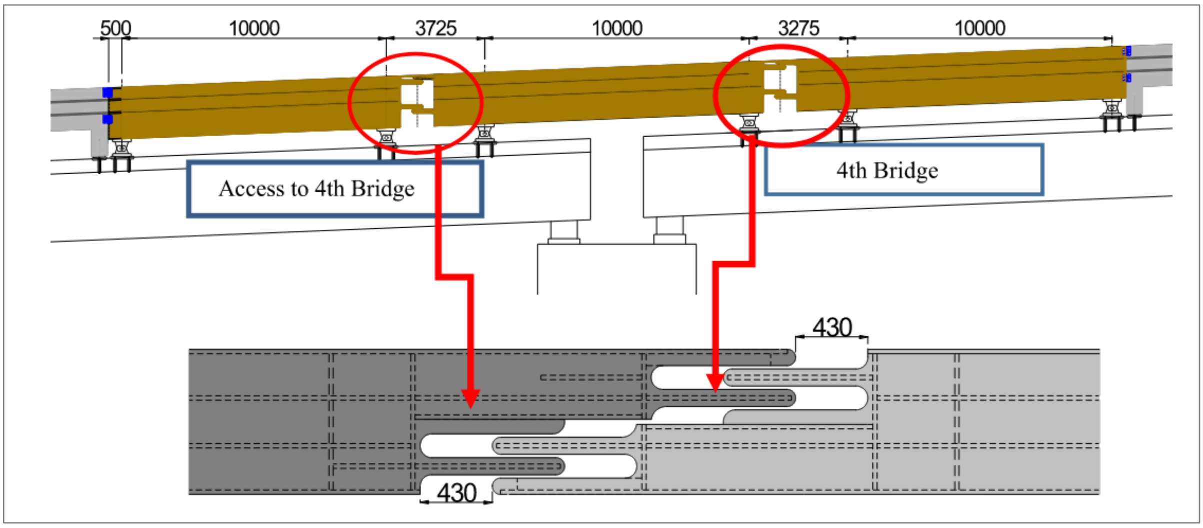



*Figure 2: Samples of large-movement expansion joints*

(Source: Metro de Panamá – Line 3 Tender Documents)

*Figure 3: Daegu monorail large span*

(Source: Naver maps street view & Google maps streetview, 2017)

### 1.3.3 Depot Style Joints

Depot style joints are used in maintenance facilities and low-speed trackwork areas where vehicle speeds do not exceed approximately 15 km/h and load cycles are limited. The reduced dynamic demand in depot environments permits the use of simpler joint types that would be inadequate for mainline service as shown in Figure 4.

Depot joints typically take a simple metal nosing joint, in which a galvanized steel or aluminum nosing plate is anchored to one beam end and bridges the gap without interlocking fingers.

Elastomeric compression seal can be added to the joints, in which a neoprene or EPDM seal element bridges the gap and prevents any debris or dust from accumulation within the joints.

If the joint has no simple metal nosing or elastomeric compression seal, there is a need to ensure dimensional tolerances at ends of beams and ensure that there is no damage over time on the running surfaces due to impact / wear from the load and guiding tires.

Depot joints are not subject to the fatigue requirements applicable to mainline finger joints, however, they shall be designed to accommodate the full thermal movement range at the joint location and to prevent water infiltration, debris, and dust into the gap.

Samples of depot expansion joints in operating projects follow:

Alstom — Depot, Line 15 São Paulo

Alstom — Depot, East of Nile Line, Cairo

Hitachi — Depot, Panama Line 3
(interface with switch)

Hitachi — Depot, Panama Line 3
(expansion joint detail)

Hitachi – Depot, Daegu Line 3

*Figure 4: Samples of depot expansion joints in operating projects*

(Source: Naver maps street view)

## 1.4 Classification by Structural Configuration

### 1.4.1 Cantilever Type

In the cantilever type, the finger plates are rigidly anchored to base plates at the beam ends or anchored to the concrete and extend as cantilevers across the expansion gap toward the opposing beam. The opposing beam has a similar configuration.

This is the most common configuration in straddle-type monorail systems. The principal structural action is bending of the individual fingers under vertical tire load, analogous to a cantilever beam. The critical cross-section is at the root of the finger, at the junction with the base plate. Fatigue assessment shall be carried out at this location.

Care shall be exercised in assessing whether the fingers will carry lateral loads due to the adjacent beams being able to displace laterally relative to each other. This condition can be addressed by using separate compatibility devices between the adjacent structures, or by mounting the beam ends over bearings that restrain differential lateral displacement.

The cantilever type is sensitive to the level difference between the two beam ends. A differential elevation of as little as ±2 mm can result in a single finger carrying the entire tire load, significantly increasing the stress range and accelerating fatigue damage. Installation tolerance requirements shall explicitly address this condition (see Chapter 6).

*Figure 5: Example of a cantilever finger plate*

(Source: Rodolfo Szmidke, 2026)

### 1.4.2 Simply Supported Type

In the simply supported type, both beam ends carry interdigitated finger plates such that each finger is supported at both its root (fixed to its own beam) and at its tip (resting on or engaging with the opposing plate). This creates a condition more analogous to a beam in bending than a cantilever, resulting in lower bending stresses at the root for a given load.

Simply supported types are rarely used in monorails, however this configuration can be used at high-load/displacement locations across the joint. They impose higher manufacturing precision requirements on the interdigitation geometry compared to cantilever designs.

As with the cantilever type, care shall be exercised in assessing the transfer of lateral loads. The condition can be addressed by using separate compatibility devices between the adjacent structures, or by mounting beam ends over appropriately laterally constrained bearings.

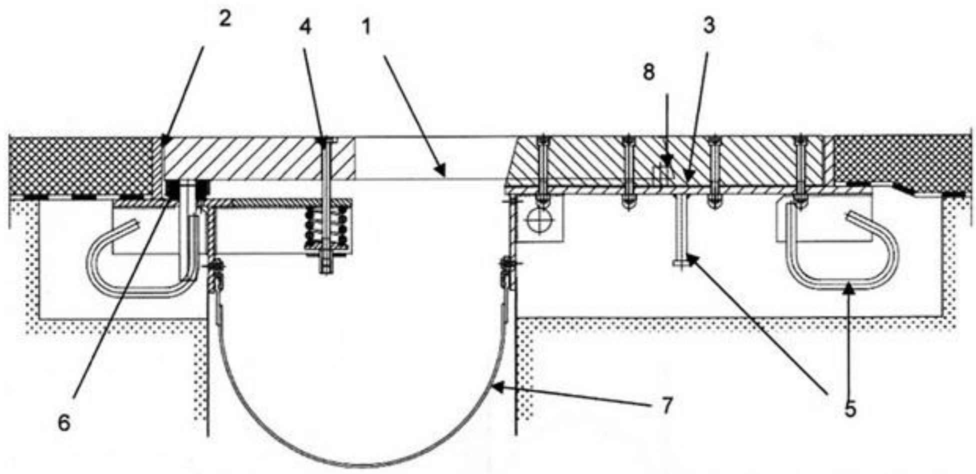



Figure 2: Example of supported expansion joint with fingers

Key for Figures 1 and 2:

| | |
|---|---|
| 1 | Sliding plate |
| 2 | Fixed support base |
| 3 | Sliding support base |
| 4 | Holding down device (flexible) of sliding plate |
| 5 | Anchorage system (dowels, anchor loops) |
| 6 | Rotational bearing |
| 7 | Gutter (devices for drainage system) |
| 8 | Sliding support |

*Figure 6: Sliding joint*

(Source: EAD 120112-00-0107)

### 1.4.3 Nosing Joint Type

Nosing joint type do not employ interlocking fingers. Instead, a continuous metal nosing profile, typically an extruded or rolled section, is anchored to the beam ends with a small air gap between them. The nosing provides protection for the precast concrete edges and assures dimensional control at the joint face, especially useful in cast-in-place depot beam applications. This type of joint does not transfer shear loads across the gap; shear continuity is provided by beam bearings, separate compatibility devices, or the underlying structure.

Nosing joints are limited to low-thermal movement, low-speed applications. They shall not be used on mainline track where vehicle speeds exceed 15 km/h or where the total movement range exceeds 30 - 50 mm, unless specific analysis demonstrates adequate performance of guidance wheels, run-flats, or other components in contact with the sides of the beams. Load tires, due to their larger contact patch, are less impacted by this joint type than guidance or stabilizing wheels.

## 1.5 Classification by Finger Plate Location

### 1.5.1 Top (Superior) Finger Plates

Top finger plates are mounted on the upper running surface of the guideway beam. They carry vertical tire loads from the drive and load-bearing wheels of the vehicle. The top plate is the primary structural element of the finger joint system and is subject to the highest fatigue demands and impact loads.

The surface of the top finger plate is in direct contact with the drive tires of the vehicle. It shall therefore provide adequate friction, resist abrasion from rubber tire contact, and maintain acceptable surface roughness throughout its service life. The use of surface texturing, such as longitudinal grooves, cross-hatching, or embossing, is recommended to reduce the risk of tire slippage during braking and acceleration (see Section 2.3.3) specially under extreme weather conditions, like rain or snow.

Top finger plates are present in all mainline joint configurations. Their geometry, including finger width, spacing, and overlap length, is determined by the movement demand and the tire contact footprint requirements.

### 1.5.2 Side (Lateral) Finger Plates

Side finger plates are mounted on the lateral faces of the guideway beam. In straddle-type monorail systems, the lateral faces carry the lateral guidance wheels and, in some systems, the stabilizing wheels. Side finger plates shall therefore maintain geometric continuity of the guidance surface across the joint.

Side finger plates operate in a different loading environment from top plates. While the primary loads are lateral (guidance forces) rather than vertical, braking forces are also partially transferred through the side guidance interface. The fatigue assessment for side plates shall account for the combined effect of lateral guidance forces and longitudinal braking forces.

Some monorail systems employ a protective skirt or side panel between the vehicle body and the guideway beam. In these systems, the side finger plate shall also maintain a seal-line with the skirt panel. This imposes additional requirements on the surface finish and dimensional tolerances of the side plate.

## 1.6 Summary Classification Table

Table 1 summarizes the classification framework described in this chapter.

*Table 1: Expansion Joint Classification Framework*

| Category | Type | Sub-type / Characteristic | Typical Application |
|---|---|---|---|
| **Movement-Based** | Minimum (Depot Style) | Low-speed, low-cycle; elastomeric seal or simple metal nosing | Depot and maintenance facility trackwork |
| | Standard | Up to 200 mm total movement | Typical mainline span joints |
| | Large Movement | Movement exceeding 200 mm; modular or multi-finger design | Long-span beams, high seismic zones, special switch areas |
| **Structural Configuration** | Cantilever | Finger plates cantilevered from one beam end; opposite end free | Most common mainline configuration |
| | Simply Supported | Finger plates supported at both beam ends; symmetric load distribution | High-load joints, switch zones |
| | Nosing Joint | Metal nosing profile covering the gap; no interlocking fingers; limited movement capacity | Low-movement applications, depot approaches |
| **Finger Location** | Top (Superior) | Covers the running surface; primary tire contact zone | Present in all mainline finger joint types |
| | Side (Lateral) | Covers the lateral guidance surface; lateral wheel and skirt contact zone | Present in straddle-type monorails with lateral guidance wheels |

**NOTE:** A joint installed on a mainline guideway will be classified across all three axes simultaneously. For example: 'Standard movement capacity / Cantilever style / Top and side finger plates' is a complete description applicable to most straddle monorail mainline joints.

# 2 Design

## 2.1 Scope and Purpose

This chapter defines the essential design requirements for finger joints used in monorail guideway systems. It covers the functional and geometric requirements of the joint, the load models to be used for structural design, quantitative design parameters adapted from the AASHTO LRFD Bridge Design Specifications, the fatigue assessment methodology, and the corrosion protection requirements.

This chapter applies primarily to mainline finger joints of the cantilever and simply supported types, covering both standard movement and large movement classifications. Depot style joints are subject to reduced requirements as noted in Section 1.3.3. Where project-specific requirements differ from those stated herein, the more stringent requirement shall govern.

## 2.2 Applicable Standards

The design requirements in this chapter draw on the following standards. Designers shall verify current editions and applicability to their project jurisdiction:

- EAD 120109-00-0107 — Nosing expansion joints for road bridges (European Assessment Document; referenced for fatigue methodology applicability to monorail finger joints
- EN 1993-1-9:2025 — Eurocode 3: Design of Steel Structures — Fatigue (structural steel fatigue)
- AASHTO LRFD Bridge Design Specifications, 10th Edition, 2024 — Section 14: Joints and Bearings (quantitative design parameters for gap width, overlap, braking load, and dynamic allowance; adapted for monorail application in Section 2.5)
- AASHTO LRFD Bridge Construction Specifications — for installation tolerances and construction staging
- ISO 12944 — Paints and Varnishes — Corrosion Protection of Steel Structures
- ISO 1461 — Hot Dip Galvanized Coatings on Iron and Steel Articles
- EN ISO 7599 / MIL-A-8625 — Anodizing of Aluminum (where aluminum components are used)
- VDI 2230 — Association of German Engineers — Systematic Calculation of High Duty Bolted Joints (for fastener design)
- EN 1090-2: Technical Requirements for Steel Structures.
- EN 1993-1-8 Design of steel structures Part 1-8 Design of joints
- New York State Department of Transportation (NYSDOT) Steel Construction Manual (SCM)
- Project-specific vehicle interface specification (tire loads, footprint, braking coefficients)

## 2.3 Functionality and Geometry

### 2.3.1 Tire Footprint Definition

The tire contact footprint is the primary input to the structural design of the finger plates. It determines the load distribution across individual fingers and governs the minimum finger width and spacing requirements. The tire footprint shall be defined for:

- The drive/load-bearing tire (top surface): contact patch dimensions under maximum static and dynamic wheel loads, including any load amplification factor applicable at the joint location.
- The lateral guidance tire (side surface): contact patch dimensions under maximum lateral guidance force, including the combined effect of curve negotiation and braking.

The tire footprint definition shall be obtained from the vehicle manufacturer or tire suppliers and shall reflect the worst-case combination of tire inflation pressure, wheel load, and contact surface stiffness. Assumed values shall be documented and submitted for review by the vehicle system integrator.

**Lessons Learned:** Experience from in-service monorail systems indicates that uniform distributed tire footprint assumptions are frequently underestimated during the design phase, resulting in higher-than-expected loads on individual fingers. A conservative approach, incorporating appropriate load factors, is strongly recommended.

### 2.3.2 Finger Geometry Requirements

The geometry of the finger plates — including finger width, spacing, overlap, and root radius — shall be determined from the following design inputs:

- Maximum total movement range (thermal + creep + prestress shortening, including effects of construction installation sequence and long-term concrete deformation).
- Minimum required overlap at maximum opening, sufficient to maintain load transfer and satisfy the minimum contact area by rolling stock supplier.
- Maximum gap width at minimum temperature, limited to prevent wheel or tire damage on gap crossing.
- Minimum root radius at the finger-to-base-plate junction, governed by fatigue classification requirements (see Section 2.6)
- Minimum transversal space between teeth, sufficient to allow the movement from different modulus of the structure when the train is riding.

The finger width and spacing shall be proportioned such that, for the worst credible load position within the tire footprint, no single finger is subjected to a load exceeding its individual design capacity. The design shall account for the possibility of uneven load distribution resulting from manufacturing tolerances and installation misalignment.

### 2.3.3 Surface Texturing

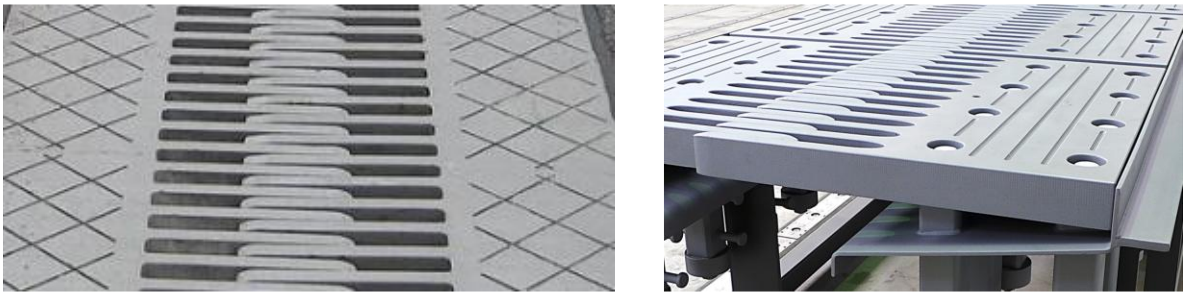
The upper surface of top finger plates and, where applicable, shall be textured to provide adequate friction for vehicle operation, particularly during braking and acceleration maneuvers at the joint location.

The following texturing approaches are considered appropriate:

- Longitudinal or transverse grooves or ribs machined or rolled into the finger plate surface, oriented parallel or perpendicular to the direction of travel. Note that grooves parallel to the direction of travel tend to channel water and may require complementary cross drainage.
- Cross-hatched or diamond-knurl patterns applied by machining or pressing.
- Embossed profiles produced during the rolling of the plate material.

Surface coatings alone, including paint, thermally sprayed zinc, or anodizing, shall not be relied upon as the primary means of achieving surface friction, as these coatings are subject to abrasion from tire contact and will degrade over time. The textured profile shall be formed in the base material without impacting the base material fatigue capacity or initiating cracking due to fabrication process.

Please note that current practice in most monorails has not provided this feature, however rolling stock suppliers are requesting to incorporate such a treatment in steel beams for switches or expansion joints to address sliding and skidding. Samples of these applications are shown below:



German Highway authority, A45, Wetzlar

*Figure 7: Samples of textured finger plates*

(Source: Maurer SE)

**Lessons Learned:** It is recommended that this essential characteristic only applies for expansion joints with flat running surfaces larger than 150 mm x 150 mm square and with surface textures less than ± 1,2 mm (possibly met by special design, e.g. checkered plate). This applies to the carriageway and footpath.

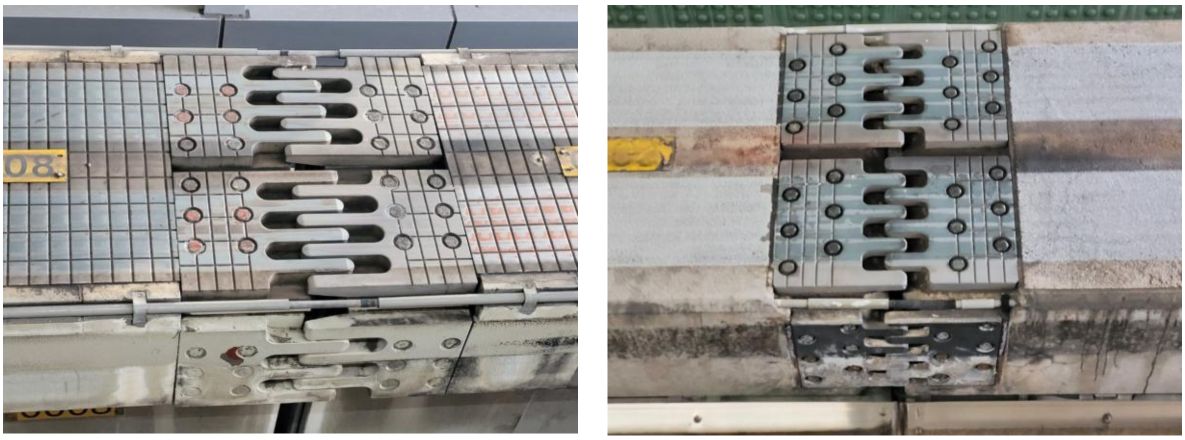


*Figure 8: Samples of textured monorail finger plates from Kitakyushu Monorail*

(Source: Rodolfo Szmidke, 2024)

**NOTE:** Soft coatings (polymer, e.g., rubber-based anti-slip coatings) are not suitable for use on finger plate running surfaces. Abrasion from tire contact will remove the coating rapidly, and residual coating debris may cause tire damage or joint contamination.

### 2.3.4 Friction Coefficients

One of the most important considerations between the bolts and the joint is the friction coefficients, because this has impact on the tightening process. The friction coefficient between the base head of the bolt and the plate, and the thread of the bolt and the thread of the anchor need to be specified.

## 2.4 Load Definitions

### 2.4.1 General Load Model

The structural design of finger joints shall be based on load models that realistically represent the vehicle-induced forces transmitted to the joint. A conservative load model can be adopted wherever project-specific load data is not available, or impact factors below 75% are not applied (see section 2.5.2 Dynamic Load Allowance). The load model shall include, as a minimum:

- Vertical axle load: maximum static axle load multiplied by a dynamic amplification factor applicable at the joint location. The dynamic amplification factor accounts for the vehicle speed, the joint gap width at the time of crossing, and any level difference between the two beam ends.
- Braking and traction forces: longitudinal forces arising from vehicle deceleration and acceleration. These forces shall be applied simultaneously with the vertical load. In the absence of project-specific data, a minimum braking force of 20% of the concurrent vertical wheel load shall be applied, consistent with in-service measurements of horizontal load ranges reported in the AASHTO LRFD literature for comparable expansion joint types.
- Lateral guidance forces: applicable to side finger plates. These shall include curve negotiation forces and any dynamic lateral load component.
- Other forces (e.g. water/frost, seismic, etc.): It is suggested to perform a project-specific risk analysis in order to cover all project-specific potential forces.

### 2.4.2 Uneven Load Distribution

The design shall explicitly address the condition of uneven load distribution among the fingers. Uneven distribution can arise from:

- Level differences between the two beam ends at the joint. A level difference of ±2 mm is sufficient to cause a single finger to carry the entire tire contact load for that pass. This condition is probable during the operational life of the joint due to differential creep, bearing settlement, and maintenance imprecision.

- Manufacturing tolerances in finger flatness and alignment.
- Differential thermal expansion of individual fingers.
- Debris accumulation in finger gaps, lifting individual fingers above the nominal surface plane.

The maximum design load for an individual finger shall assume that the full tire contact load for the relevant surface (top or side) may be carried by a single finger or a reduced number of fingers. A minimum load concentration factor shall be defined in the project specification and applied in the fatigue assessment.

**Recommendation:** Depending on the geometry of the fingers, designing an individual or a reduced number of fingers for 100% of the tire contact load is recommended as a conservative baseline. Where analysis demonstrates load sharing among multiple fingers with high confidence (e.g., through finite element analysis validated against test data), a reduced load concentration factor may be applied with appropriate justification.

### 2.4.3 Load Model for Fatigue Assessment

The load model for fatigue assessment shall reflect the full operational load spectrum, not merely the maximum design load. The fatigue load spectrum shall be defined in terms of:

- Number of vehicle passages per day (peak and off-peak operations), consider longer vehicles and headway between trains reduction, if any.
- Distribution of axle loads across the operational fleet (including light, normal, and fully loaded conditions).
- Speed distribution at the joint location, informing the dynamic amplification factor for each load level.
- Percentage of time the joint is at or near maximum opening, which governs the lever arm for cantilever bending.

Where a full operational load spectrum is not available, a simplified conservative spectrum shall be adopted. The simplified spectrum shall use the maximum design axle load for all cycles and shall assume the joint is at average opening for all cycles. This approach is conservative and may be relaxed where validated operational data is available.

**Lessons Learned:** Fatigue assessments should use the operational load spectrum, not just peak loads. If operational data is unavailable, use a conservative approach with 60% load for fatigue checks and fully open joint conditions for ultimate limit state verification.

## 2.5 AASHTO LRFD Reference Parameters — Adaptation to Monorail

The AASHTO LRFD Bridge Design Specifications, Section 14 (Joints and Bearings) contains the most widely referenced quantitative design criteria for finger plate joints in English-language practice. While AASHTO addresses road bridges rather than monorail systems, several of its provisions translate directly or with modest adaptation to the monorail context. The table below summarizes the most relevant AASHTO criteria and their adapted equivalents for this guideline.

Designers working on projects governed by US practice should apply AASHTO Section 14 directly. Designers working on projects in other jurisdictions may use the adapted criteria in Table 2 as a conservative baseline in the absence of more specific national or contractual requirements.

*Table 2: AASHTO LRFD Section 14 Reference Parameters and Monorail Adaptations*

| Design Criterion | AASHTO LRFD §14 (Road Bridges — Reference) | Adaptation for Monorail Finger Joints |
|---|---|---|
| **Gap width at max. movement** | Single gap on adjacent fingers:<br>≤ 50 mm for longitudinal opening > 200 mm, or<br>≤ 75 mm for longitudinal opening ≤ 200 mm, (AASHTO §14.5.3.2) | Maximum opening between adjacent fingers shall be checked at maximum thermal movement; monorail tire width governs; gap shall not exceed conservatively 50 mm (approx. 2 in.) in any direction movement joints unless the load is shared between adjacent opposite side finger plates. |
| **Minimum finger overlap** | Finger overlap ≥ 38 mm at max. movement, strength limit state (AASHTO §14.5.3.2) | Minimum overlap ≥ 38 mm (1.5 in.) at maximum movement shall be maintained to ensure load transfer and prevent tire drop |
| **Structural design basis** | Finger plates designed as cantilever members at strength limit state (AASHTO §14.5.3.4); differential settlement investigated | Finger plates designed as cantilever or simply supported members; level difference between beam ends shall be investigated (2 mm differential critical based on current practice, see § 2.4.2) |
| **Horizontal (braking) load** | Horizontal load range ≥ 20% of vertical wheel load range for fatigue; 20% peak for strength (AASHTO C14.5.6.9.4) | Minimum horizontal (braking/traction) load of 20% of concurrent vertical load adopted as baseline; project-specific braking coefficients shall supersede this where available |
| **Dynamic load allowance** | 75% dynamic load allowance for deck joints at fatigue limit state (AASHTO Table 3.6.2.1-1) | A dynamic amplification factor shall be applied; AASHTO's 75% (IM = 0.75) is adopted as an upper-bound reference for high-speed crossings; lower factors may be justified by vehicle-specific analysis |
| **Fatigue design approach** | Infinite-life fatigue (Fatigue I) is the standard; fatigue governs over strength for most expansion joint members (AASHTO C14.5.6.9.7a) | Infinite-life approach recommended (see §2.6.3); fatigue is the governing limit state; strength limit state shall also be verified at maximum gap opening |

| Design Criterion | AASHTO LRFD §14 (Road Bridges — Reference) | Adaptation for Monorail Finger Joints |
|---|---|---|
| **Differential settlement** | Differential settlement between sides of bridging plate shall be investigated; incompatible differential settlement requires different joint type (AASHTO §14.5.3.4) | Level difference between beam ends at joint shall be specified and monitored (see §2.4.2, Ch.6, and Ch. 7); design shall assume worst credible level difference for individual finger load |
| **Movement during construction** | Construction staging and closure pours used to manage prestress shortening (AASHTO §14.5.3.1) | Closure pour sequence and temporary plate tightening torque shall be defined to prevent premature overloading of anchor threads; final finger plate installation deferred until major dead loads are in place |

A sample for the overlapping in the European Code is shown below:

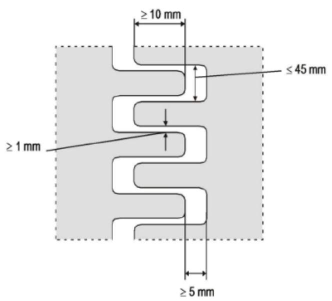



*Figure 9: Sample of overlapping fingers-European Code*

**NOTE:** AASHTO LRFD Section 14.5.3.4 states that finger plates and bridging plates should be designed as cantilever members at the strength limit state, and that differential settlement shall be investigated.
Both requirements apply directly to monorail finger joints and are incorporated without modification in Section 2.4.2 and Chapter 6 of this guideline.

### 2.5.1 Gap Width and Minimum Overlap

Based on AASHTO Section 14.5.3.2, the following geometric limits are conservatively adapted for monorail application:

- The maximum opening between adjacent fingers at any point along the joint shall not exceed 50 mm (approximately 2.0 in.) at the maximum movement condition defined by the applicable strength load combination, unless the load is shared between adjacent opposite side finger plates.

- The minimum finger overlap between adjacent fingers at maximum movement shall not be less than 38 mm (1.5 in.) at the strength limit state. This ensures load transfer continuity and prevents tire ingress into the gap.
- For joints where the total longitudinal opening is 200 mm or less, the 50 mm individual finger gap limit governs. For large-movement joints exceeding 200 mm, specific analysis of tire ingress risk at all gap positions shall be carried out.

**Lessons Learned:** AASHTO's original criteria are expressed in US customary units and were calibrated for road traffic including motorcycles and bicycles. For monorail systems, the tire contact geometry differs significantly from road vehicles. The 50 mm / 38 mm limits are adopted as conservative defaults; they may be modified by reference to the specific vehicle tire specification where the tire supplier confirms acceptable performance at greater gap widths.

### 2.5.2 Dynamic Load Allowance

AASHTO Table 3.6.2.1-1 specifies a dynamic load allowance (impact factor) of 75% for deck joints at the fatigue limit state, based on field measurements of modular bridge joint systems. This factor accounts for both downward amplification (approximately 32%) and upward rebound (approximately 31%), yielding a combined load range amplification.

For monorail finger joints, the applicable dynamic amplification factor depends on vehicle speed, the vehicle's suspension characteristics, and the gap width at the time of crossing. In the absence of vehicle-specific data, a dynamic amplification factor of 75% (IM = 0.75) shall be applied conservatively to the vertical wheel load for fatigue limit state assessment, consistent with AASHTO practice. Where the vehicle manufacturer provides validated dynamic response data at the specific joint gap, that data shall be used in place of the default value.

**NOTE:** AASHTO notes that the 75% dynamic load allowance is conservative for the strength limit state, where field measurements indicate the maximum downward amplification is approximately 32%. Designers may apply conservatively a reduced dynamic factor of 35% for strength limit state calculations where there is project-specific justification but shall retain the 75% factor for fatigue limit state design unless vehicle-specific dynamic analysis supports a lower value.

### 2.5.3 Construction Staging and Closure Pours

AASHTO Section 14.5.3.1 recommends construction staging to defer joint installation until major settlement and prestress-induced shortening have occurred. This principle applies directly to monorail guideway construction:

- The final finger plate assembly shall not be permanently installed until the structural system has reached the long-term deformation condition assumed in the joint gap setting calculation. Where construction programs preclude deferred installation, the gap shall be set to account for predicted future movement.

- Closure pours shall be designed to minimize the effect of prestress-induced shortening on the structure, and the corresponding joint lengthening at the time of final finger plate installation. The torque applied to temporary blind plate bolts during closure pours shall be defined by the manufacturer to avoid overloading the anchor threads (see Chapters 4 and 5).
- The joint installation width (gap at time of installation) shall be specified for a range of probable installation temperatures. An offset chart relating installation gap to installation temperature shall be included in the installation documentation.

## 2.6 Fatigue Design

### 2.6.1 Importance of Fatigue

Fatigue failure is the primary failure mode for steel finger joints or their components in mainline monorail service. A monorail vehicle crosses each joint at every passage, and a busy line may accumulate 200,000 to 500,000 vehicle passages per year. Over a design life of 30 to 50 years, this translates to 6 to 25 million load cycles per joint. Fatigue design is therefore not a secondary consideration but the governing design criterion.

This position is consistent with AASHTO practice: AASHTO Section C14.5.6.9.7a notes that for most structures requiring modular expansion joints, traffic volumes justify an infinite-life fatigue approach, and that the proportions of expansion joint members are typically governed by fatigue rather than strength.

### 2.6.2 Fatigue Assessment Methodology

Finger joints may be assessed for fatigue by one of two methods, consistent with the flexibility provided in EAD 120109-00-0107:

- Calculation-based assessment: The stress range at the critical cross-section (typically the finger root) is calculated under the design fatigue load and compared against the allowable stress range for the applicable detail category. The fatigue life in cycles is determined from the S-N curve (Wöhler curve) for the detail category.
- Testing-based assessment: Physical fatigue testing of a representative joint specimen is carried out under realistic loading conditions, including vertical load and braking force. The test demonstrates survival to the required number of cycles at the specified load level.

Both methods shall use a detail category consistent with the geometric and manufacturing quality of the finger-to-base-plate junction. The root radius, weld quality (where applicable), surface finish, and manufacturing tolerances all influence the detail category.

### 2.6.3 Fatigue Life Criteria — Discussion of Infinite Life Regime

A central question in the fatigue design of monorail finger joints is whether a finite-life or infinite-life approach is appropriate. The following positions are recognized within the working group:

- Non-welded, non-sharp-notch details, such as bolted finger plates with appropriate root radii and surface finish, may be assessed against the applicable Constant-Amplitude Fatigue Limit (CAFL) or endurance-limit concept at approximately 2 million cycles, where permitted by the governing standard and detail category.
- Welded or sharp-notch details, such as certain anchorage, base plate, or welded finger-to-base-plate connections, shall be assessed using the applicable CAFL for the relevant detail category. In the revised Eurocode 3, EN 1993-1-9, this is generally associated with a 5 million cycle limit for welded detail categories; AASHTO applies CAFL values by fatigue category, commonly in the range of approximately 4.4 to 6.4 million cycles for relevant welded details. Stress ranges below the applicable CAFL may be considered non-damaging for constant-amplitude loading, subject to the requirements of the selected code.

The working group notes that the operational load spectrum of a monorail joint is variable-amplitude in nature, and that a conservative criterion for a safety-critical component with limited inspection access should be applied. For the purposes of this guideline, the fatigue design target shall reference the applicable CAFL under the governing EN or AASHTO detail category, rather than the mandated one fixed cycle value for all connections. This recognizes that non welded, non-sharp-notch details and welded or sharp notch details are treated differently under both code frameworks. Where the applicable CAFL target is not achievable with the selected detail category, a replacement strategy with defined inspection intervals shall be established.

**NOTE:** Projects may adopt different cycle thresholds subject to specific technical justification and agreement with the relevant authority.

### 2.6.4 Fatigue Testing Requirements

Where fatigue performance is demonstrated by testing (rather than calculation), the following minimum requirements shall apply:

- The test specimen shall replicate the actual joint geometry, material, surface finish, bolt installation, and galvanizing condition of the production joint.
- The applied load shall represent the worst-case single-finger or number of fingers loads as defined in Section 2.4.2, including a simultaneous braking force component consistent with Section 2.4.1. Simplified testing using vertical load only is not acceptable where braking forces contribute significantly to fatigue damage.
- The test shall be carried out at the maximum designed joint opening unless analysis demonstrates that the maximum stress range occurs at a different opening position.
- Crack initiation and propagation shall be monitored throughout the test. The test shall continue until either the specimen survives the required number of cycles without crack initiation or propagation, or until a defined failure criterion (typically a crack of specified length) is reached.

- Where bolted connections are included in the test specimen, the bolt assembly procedure shall replicate the field installation procedure exactly, including lubricant application, tightening sequence, and bolt grade.

### 2.6.5 Bolt Fatigue Considerations

The bolts securing the finger plates to the base plate are subject to fatigue loading due to the cyclic nature of the vehicle passage loads. Bolt fatigue is a distinct failure mode from finger plate fatigue and shall be assessed independently.

- Bolts in friction-type connections (clamped joints) experience significantly lower fatigue stress ranges than bolts in bearing-type connections, provided the clamping force is maintained throughout the service life. Loss of preload converts the connection from friction-type to bearing-type, dramatically increasing the fatigue stress range in the bolts.
- Maintenance procedures including bolt replacement shall be designed such that the replacement bolts can be installed and preloaded using the standard procedure. Bolts that have experienced yielding during initial installation shall be replaced, not re-tightened. See section 5.5
- The fatigue category of the bolt thread root under cyclic tension shall be assessed for the case of partial preload loss. The minimum preload required to maintain friction-type behavior under the design fatigue load shall be specified.
- Where the maintenance program requires periodic bolt replacement, the structural integrity of the anchor nut cut thread in the base plate tube shall be verified for the number of re-tightening cycles anticipated over the service life.

## 2.7 Corrosion Protection

### 2.7.1 General Requirements

All steel components of the finger joint system shall be protected against corrosion for the full design service life. The corrosion protection system shall be compatible with the operating environment of the joint, the surface finish requirements of the running surface, and the fatigue performance requirements of the joint components.

- The corrosion protection system shall be specified in terms of the corrosivity category of the environment, as defined in ISO 12944-2, for both the internal (concealed) and external (exposed) surfaces of the joint components.
- The selected system shall be compatible with the contact geometry of the joint in particular; the running surfaces shall not be coated with materials that reduce friction below the required level, or that will degrade under tire abrasion.
- The corrosion protection system shall not reduce the fatigue performance of the finger plates. Certain metalizing processes applied after fatigue-critical machining may introduce residual stresses; their effect shall be evaluated.

### 2.7.2 Hot-Dip Galvanizing of Steel Components

Hot-dip galvanizing in accordance with ISO 1461 is the most widely used corrosion protection system for steel finger joints in mainline monorail service. It provides robust, long-life protection and is compatible with the hot-and-humid operating environments typical of tropical monorail projects.

- All fasteners (bolts, nuts, washers) shall be galvanized in accordance with ISO 10684. The thread tolerance of bolts intended for use with galvanized threads shall be specified to account for the coating thickness, as prescribed in ISO 965-4 (tolerance class 6az for external threads) or ISO 965-5 (tolerance class 6AZ for internal threads). Failure to adjust thread tolerances results in galling and seizure during assembly, which can prevent attainment of the required preload.
- The running surfaces of finger plates (top surface and, where applicable, side surface) shall be assessed for the effect of galvanizing on surface roughness and friction. The zinc coating on running surfaces will be abraded by tire contact within the first years of service. The design shall not rely on the zinc coating for friction; surface texture shall be provided in the base material as specified in Section 2.3.3.
- Post-galvanizing machining of contact surfaces and fastener holes may be required to achieve dimensional tolerances. Where machining exposes bare steel, touch-up with a zinc-rich paint compatible with the galvanizing system shall be applied.

### 2.7.3 Aluminum Components — Anodizing

Where aluminum alloys are used for finger plates or associated components (for example, in systems where weight reduction or avoidance of galvanic corrosion are design drivers), anodizing in accordance with EN ISO 7599 is the standard surface treatment.

- The anodic coating thickness shall be specified in accordance with the corrosivity category of the operating environment. A minimum coating thickness of 20 micrometers (Class AA20 per EN ISO 7599) is recommended for outdoor exposed components in corrosive environments.
- Anodized surfaces used as running surfaces are subject to abrasion from tire contact. The residual friction and surface texture after abrasion of the anodized layer shall be assessed. The base material texture shall be designed to maintain adequate friction even after the anodized layer is removed.
- Galvanic coupling between aluminum components and steel base plates or fasteners shall be addressed in the design. Direct metal-to-metal contact between aluminum and steel shall be avoided in wet environments; non-conductive isolating layers or coatings shall be used at interfaces.

### 2.7.4 Abrasion Considerations

- Protective coatings of any kind (paint, zinc spray, anodizing, polymer coatings) shall not be the primary corrosion protection on running surfaces. Coatings on running surfaces will be abraded within weeks to months to years of service commencement. Corrosion resistance of running surfaces shall be provided by selection of a corrosion-resistant base material or by a robust bulk treatment such as hot-dip galvanizing.
- Soft polymer coatings intended to provide anti-slip performance on running surfaces are not suitable. Such coatings abrade rapidly under tire contact, generating debris that may contaminate the joint and potentially cause tire damage.
- The design service life of the corrosion protection system shall account for the reduced zinc layer thickness on running surfaces due to tire abrasion. Where inspection data from comparable in-service systems is not available, a conservative assumption of zinc depletion on running surfaces within 10 years of service shall be made, and the maintenance program shall include inspection of zinc layer condition.

**Lessons Learned:** Corrosion protection systems that rely solely on surface coatings for running surfaces will require early maintenance intervention. The specification of corrosion protection for monorail finger joints should prioritize durable bulk treatments and design for inspectability and replaceability.

## 2.8 Tightening Study

To ensure good behavior on the joint, it is important to conduct a tightening study. This study will establish the parameters for manufacturing the test assembly finger plate, used to verify the condition of the tightening, the head and thread friction of the bolts and products used to control it, and the applicable tightening parameters for the method selected under Section 5.3 or 5.4.

Where the calibrated wrench method is used, the study shall establish the installation torque, the arbitration torque for verification, and the permitted rotation limit at arbitration torque. AASHTO LRFD Bridge Construction Specification, 4th Edition, Section 11.5.5.4.5, or EN 1090-2:2018+A1:2024, Annex H, may serve as a basis to establish these parameters.

Where torque-angle curve monitoring is used, the study shall establish the reference torque-angle curve for the specific bolt, anchor, coating, and plate configuration on the project, following VDI 2230 or an equivalent recognized angle-controlled tightening standard, and shall define a new torque-angle check used to detect preload loss on a previously tightened bolt, following VDA 5.2 or an equivalent recognized standard.

The study shall be repeated whenever a component such as bolt size, bolt manufacturer, coating, surface treatment, or plate material changes from the configuration originally tested that affects the friction on the bolted assembly.

# 3 Manufacturing and Quality Assurance

## 3.1 Scope and Purpose

- This document defines the detailed manufacturing processes, quality assurance (QA) fundamentals, production control, corrosion protection requirements, and testing procedures for expansion joints (i.e. finger joints) used in monorail guideway systems.
- The intent is to establish uniform manufacturing and QA standards aligned with the existing standards, regulations and industry best practices to ensure structural performance, longevity, and safety.
- It is recommended to follow these processes also in the manufacturing of the temporary blind plates used to adjust the expansion joint base plates prior to concreting the joints.
- Factory Production Control (FPC) ensures that expansion joints are consistently manufactured to the required technical specifications. The system follows Assessment and Verification of Constancy of Performance (AVCP) – System 1.

The inspection/monitoring should be carried out by an accredited inspection body that is accredited in accordance with EN ISO/IEC 17020 or holds equivalent international accreditation.

## 3.2 Applicable Standards

- EN 1090-1: Requirements for Conformity Assessment of Structural Components.
- EN 1090-2: Technical Requirements for Steel Structures.
- EN 1090-3: Technical Requirements for Aluminum Structures.
- ISO 9001: Quality Management Systems.
- ISO 12944 / ISO 1461 For Corrosion Protection Systems Where Applicable.
- AASHTO LRFD Bridge Construction Specifications
- AWS D1.1 (Steel) / AWS D1.2 (Aluminum)
- ASTM A123 / A325 / A490 / B580 / D7091
- EN 50126 - Manufacturing and validation
- EAD – European Assessment Documents
- ZTV-ING - Teil 6 Bauwerksausstattung - Abschnitt 6 Fahrbahnübergänge Aus Stahl Und Aus Elastomer (ZTV-ING – Part 6: Structural Equipment – Section 6: Steel and Elastomeric Expansion Joints)

## 3.3 Manufacturing Requirements

- Manufacturers shall be certified to the relevant standard
  [e.g. EN 1090 with Execution Class defined by project requirements (typically EXC3)].
- Finger plates, support plates, and anchorage components shall be manufactured using approved welding procedures (WPS) and qualified welders (WPQ). *[e.g. ISO 3834, EN3834-2]*.
  *Scope/manufacturing of:*
  - *Steel construction or parts for steel constructions-*
  - *Components for machine construction*
  - *Components for process engineering constructions*
- Material certificates shall be provided.
  (3.1/3.2 acc. to EN 10204 - for all load-bearing components)
- All machining tolerances shall comply with the relevant standards and the Design Guideline. (including finger gap tolerances, plate flatness, edge geometry, allowable misalignment, structural integrity and hole tolerances)
- Corrosion protection shall follow specified system (galvanizing, anodizing, coating) and avoid coatings unsuitable for tire abrasion (considering wear and abrasion from rubber tires / soft polymer coatings are not permitted).
- The manufacturer shall match the tolerance class of a bolt and its anchor thread to ensure a proper mechanical fit and prevent thread damage. Pairing these classes provides the correct clearance for assembly.
- The manufacturer of the bolt shall provide rolled threads since this type of thread can achieve a higher average preload for a given torque, compared to a cut bolt thread.
- Manufacturers need to ensure the corrosion protection of the anchor threads, consider also if the surface treatment will require a thread repass to ensure the compatibility of the bolt and anchor threads.

**Lessons Learned:** All the quality and inspection verifications to fix bolts need to observe a limit torque that will not exceed the elastic deformation of the anchor threads until the final assembly after the concrete placement in the construction site.

## 3.4 Specific Requirements

Because of the critical application of the finger plate, some specific requirements of manufacturing need to be observed, following manufacturer's tolerances for fabrication and installation.

**a. Flatness of the base plate and expansion joint finger plates:** the base plates and expansion joint finger plates need to have to mate properly, otherwise, it can create additional loads to the fastenings during the monorail operation. Minimum deviation can be assumed between the base plates and the expansion joint finger plates of the installed assembly. Any opening between base plate and the expansion joint finger plate needs to be avoided. The fasteners study can allow some tolerance at this parameter, with all the considerations about the loads and fatigue with this difference.

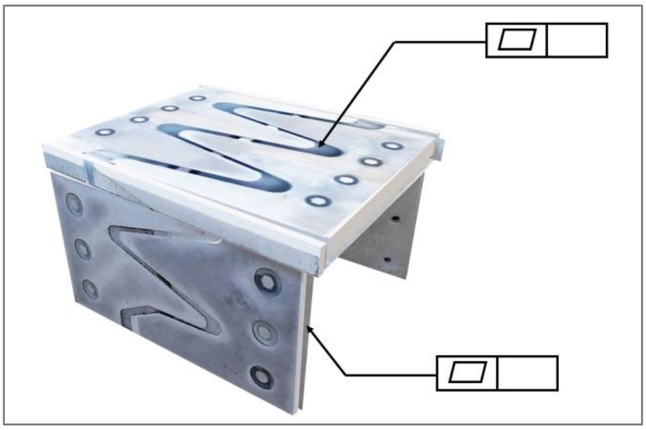


*Figure 10: Flatness of base and finger plates*

(Source: Rodolfo Szmidke, 2026)

**b. Orthogonality of the anchors:** differences in the orthogonality of the anchors can create difficulties installing the fasteners, because of the deviation between threads, creating additional moments at the head on the fasteners.

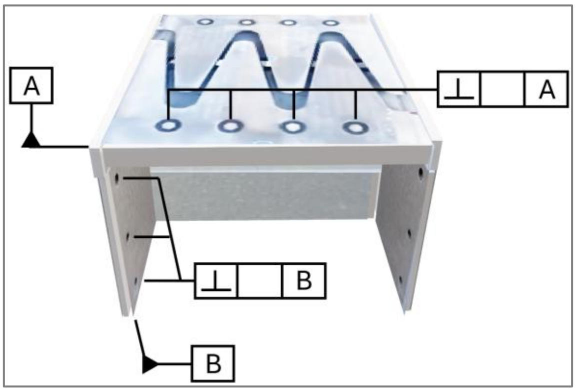



*Figure 11: Anchor orthogonality*

(Source: Rodolfo Szmidke, 2026)

**c. Leveling between assemblies:** the manufacturing process should consider the leveling between assemblies left and right and identify this set to use when the finger plates are installed, because of the minimum tolerances create specific assemblies that do not match with another assembly.

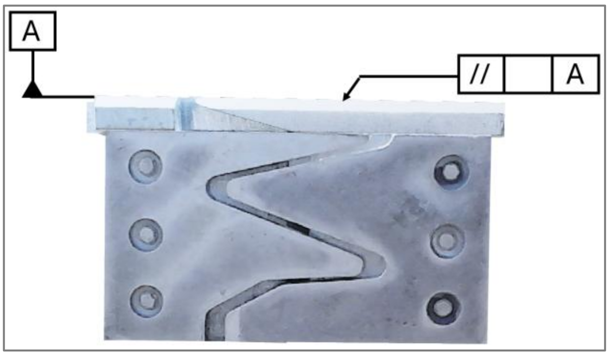



*Figure 12: Leveling between top assemblies*

(Source: Rodolfo Szmidke, 2026)

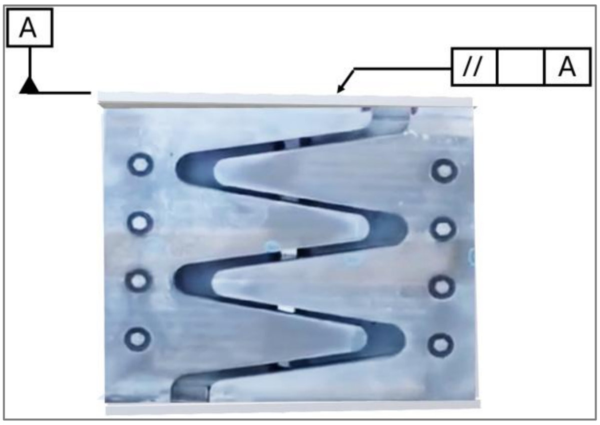



*Figure 13: Leveling between side assemblies*

(Source: Rodolfo Szmidke, 2026)

**d. Geometry of the threads:** the geometry specified on the project (before and after surface treatment) needs to be attended to avoid differences that can affect the fasteners' prestressing force. For this, it is necessary to have specifications of geometry and tolerance between the threads. These specifications shall consider the differences between the inch and the metric threads. As an example of metric thread specification, a hot dip galvanized bolt thread for M16 x 2mm with thread tolerance of 6az before the surface treatment and 6g after the surface treatment added zinc material to the thread, will fit into an anchor thread tolerance of 6H. This is to say, the bolt cut originally to a 6g tolerance will not fit into an anchor with a thread tolerance of 6H after it is galvanized. These tolerances can be verified using a “go no go” calibrated gage tool.

*Figure 14: View of some go no go calibrated gages thread verification*

(Source: https://willrich.com/how-to-use-a-thread-plug-gage-properly, visited on 26.06.25)

**e. Bolting batch:** to ensure quality control and avoid the cost of more tests, it is recommended to purchase all the bolts from the same manufacturer and if it is possible, from the same product batch.

**Note:** All measuring instruments must have a valid calibration certificate issued by an accredited body (e.g., ISO/IEC 17025).

### 3.4.1 Workflow and Milestones Identification for FPC

The workflow and process control shall consider the following:

- The production process shall be defined by the manufacturer through an approved workflow diagram that includes all key steps from raw material intake to final inspection *(Typical workflow steps include: raw material verification, cutting and machining, welding and assembly, finger plate fabrication, dimensional verification, corrosion protection, pre-assembly checks, packaging, and dispatch)*

*Links to the relevant standards shall be mentioned in the workflow plan*

- Critical process steps shall be identified (e.g. welding, machining, coating, assembly).
- In-process inspections shall be recorded, including dimensional checks, weld inspections, surface preparation, and coating thickness measurements.
- Necessary work instruction (i.e. bolting of finger plates)

**Note:** It is recommended that the workflow is covered by a valid ISO EN 9001 certificate.

### 3.4.2 Quality Assurance Processes

The manufacturer shall operate a **permanent, documented and systematic** FPC **(Factory Production Control)** system covering:

- Incoming raw materials
- Component production
- Assembly of the complete kit

The task of the inspection body (see chapter 3.7) ensures, based on the related tasks and documentation, that:

- The manufacturer's quality system **remains valid over time**, (e.g. ISO 9001)
- The product consistently achieves the declared performance levels, and
- Requirements of AVCP (Assessment and Verification of Constancy of Performance) System 1 are fully met.

This independent oversight is essential for issuing and maintaining the **Declaration of Performance (DoP)**.

### 3.4.3 Welding Quality Requirements

- All welds shall be produced in accordance with the relevant standards *(e.g. EN 1090-2/3)*.
- Weld quality levels shall follow the relevant standards. [e.g. ISO 5817 (steel) or ISO 10042 (aluminum) or AWS D1.1 (steel) or AWS D1.2 (aluminum)]
- Welding inspection shall include visual testing (VT) as standard, and additional non-destructive testing (NDT) such as MT/UT for critical welds *(e.g. EN 1090 - EXC)*
- Non-destructive testing (NDT) requirements shall be defined by component categories *(e.g. VT mandatory, MT/UT for critical welds).*
- It must be ensured that all welding is done by qualified welders. For this, a valid certificate of the welder must exist.

### 3.4.4 Documentation Requirements

- Manufacturers shall compile a Manufacturing Documentation Package (MDP).
- Documents shall include: material and weld-potions-certificates, welding records, NDT reports, dimensional inspection reports, qualification-certificate of the welding experts, coating certificates, NCR reports, factory acceptance test documentation, bolting of finger plates report (if done in house / if on site see chapter 4.), etc.

### 3.4.5 Quality Assurance Obligations

- A documented Quality Management System (QMS) shall outline processes for verification, inspection, corrective actions, and continual improvement.
- The QA system shall comply with the requirements. [(e.g. ISO 9001 and EN 1090 Factory Production Control (FPC)]
- Production Control shall ensure traceability of materials, welders, weld procedures; validation of fabrication processes and inspection personnel shall be maintained.
- Non-conformances shall be documented, and corrective actions implemented.

## 3.5 Testing and Verification Procedures

### 3.5.1 Dimensional and Functional Testing

- Dimensional inspection to verify tolerances at each production stage. *(cutting, machining, welding, assembly)*. Some important verifications are the flatness of the base plate and expansion joint finger plates, orthogonality of the anchors, leveling between assemblies, and the geometry of the threads. The figures below show some of these verifications:

*Figure 15: Verification of the levelness of the base plate*

(Source: Rodolfo Szmidke, 2021)

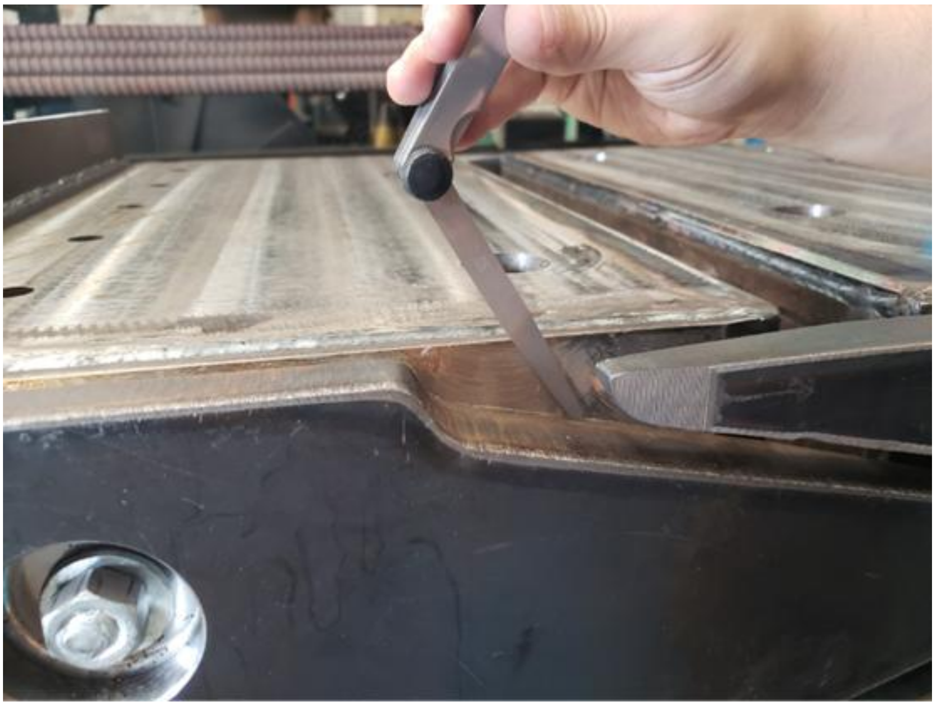


*Figure 16: Verification the opening between finger and base plates*

(Source: Rodolfo Szmidke, 2021)

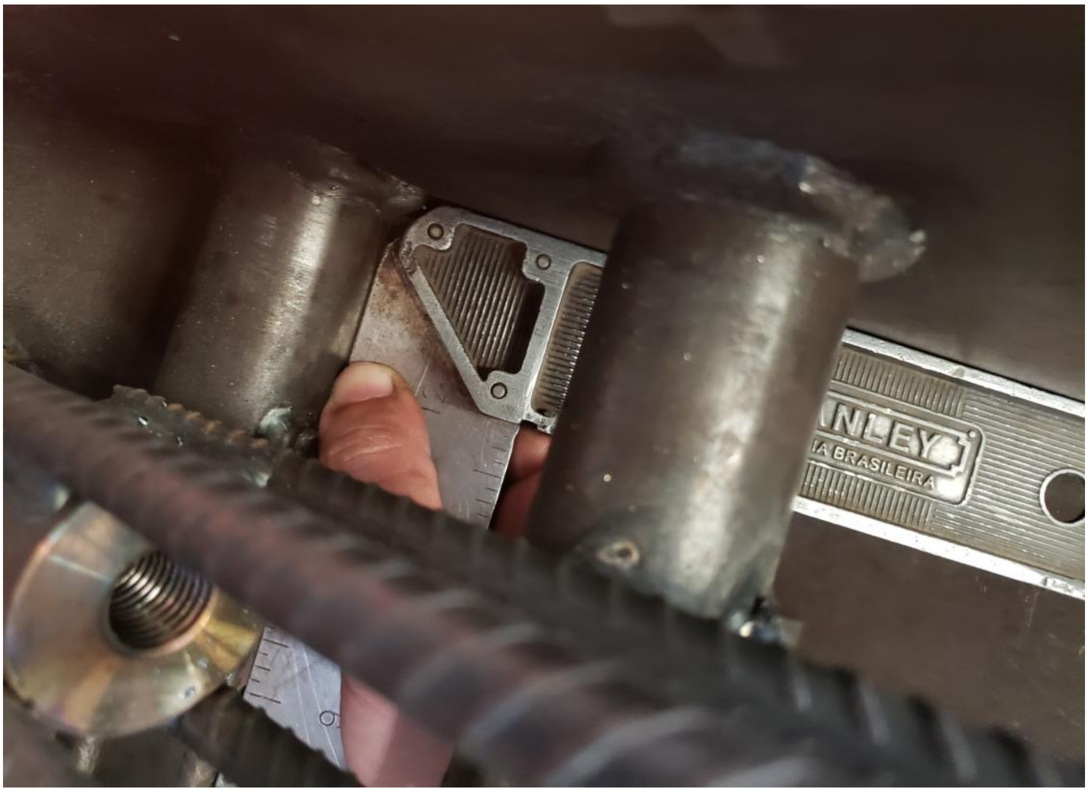


*Figure 17: Verification of the anchor orthogonality*

(Source: Rodolfo Szmidke, 2021)

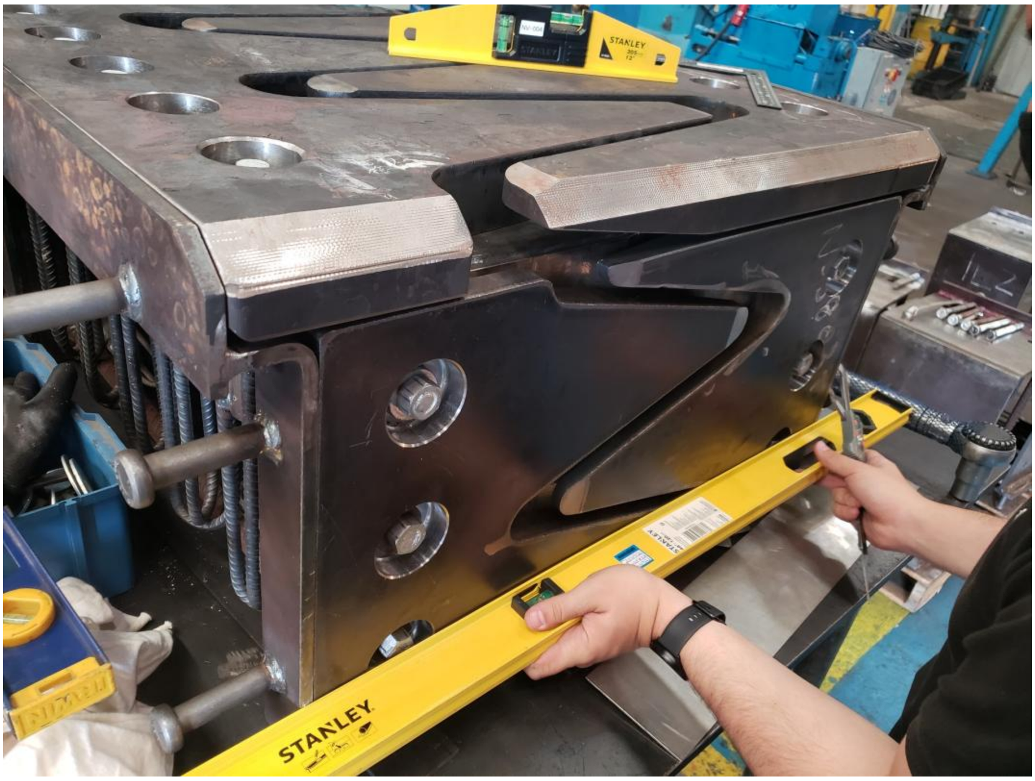



*Figure 18: Verification of leveling between assemblies before galvanization*

(Source: Rodolfo Szmidke, 2021)

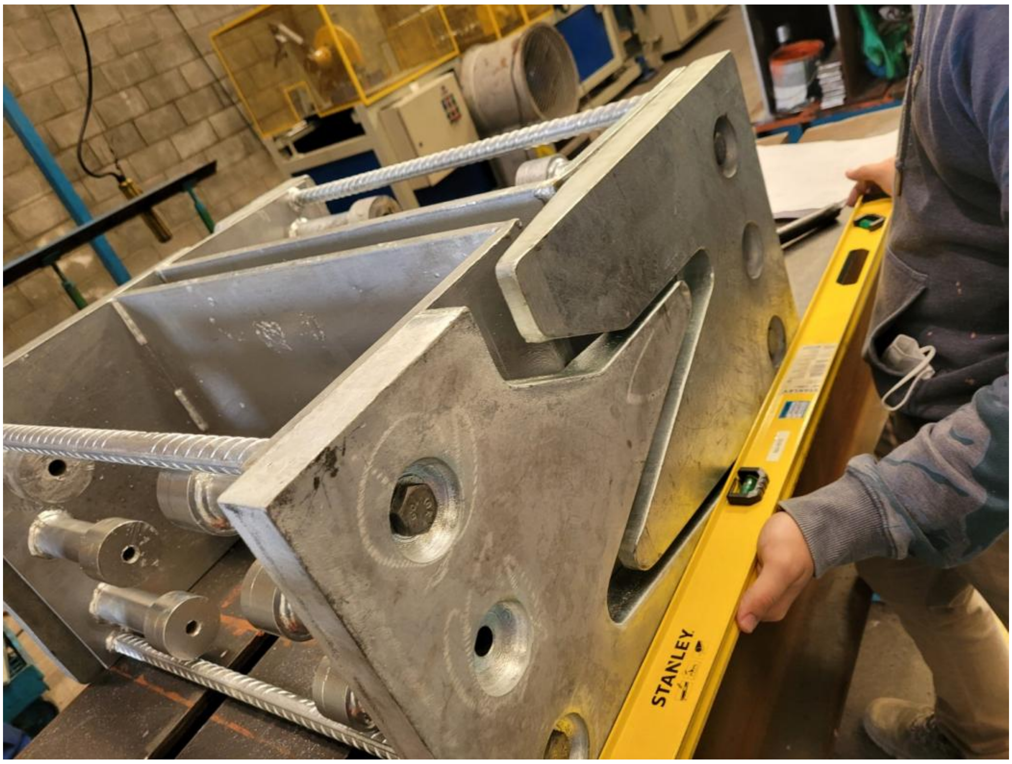



*Figure 19: Verification of leveling between assemblies after galvanization*

(Source: Rodolfo Szmidke, 2021)


*Figure 20: Verification of threads tolerance*

(Source: Rodolfo Szmidke, 2021)

- Finger alignment inspection ensuring correct overlapping geometry and unrestricted movement *(incl. consideration of thermal and dynamic loads).*
- Functional cycling tests (if required by design) shall include vertical load and braking load simulation.
- Inspection equipment shall be calibrated and traceable to relevant standards.

### 3.5.2 Material and Component Testing

- Fatigue testing and notch class definition of finger plates
- Tensile strength verification for bolts (EN ISO 898-1).
- Testing of anchorage components (including pull-out tests and/or shear tests)
- Corrosion resistance testing (only if required beyond standard coating specifications).

### 3.5.3 Factory Acceptance Tests (FAT)

- shall verify conformity with the Design Guideline and include functional testing where applicable.
- shall demonstrate full assembly fit, load distribution, finger alignment and movement capacity and documentation compliance.
- It is recommended that at least for one full process-cycle, the FAT is witnessed by a suitable inspection body (e.g. EN ISO/IEC 17020).

### 3.5.4 Inspections / Surveillance

- Initial inspection of both the factory and the factory production control system. It is recommended to make an initial inspection on a prototype finger plate, to verify all the components and interaction between the assemblies.
- The guide of the inspection can follow these parameters:

  a. Verification of the measures of the different pieces of the finger plate;

  b. Verification of the mounted assemblies before applying the surface treatment;

  c. Verification of the quality and thickness of the surface treatment;

  d. Verification of the mounted assemblies after applying the surface treatment;
- Continuous surveillance and assessment of the Factory Production Control (FPC) system. The intervals between individual inspections within the ongoing monitoring or initial inspection shall comply with the requirements. *(e.g. Table B.3 of the EN 1090: Intervals after initial inspection for EXC3 = 1-1-2-3-3 y)*
- It is recommended to internally inspect 100% of the assembled pieces to verify the seating between base and finger plates, and the leveling between the left and right assemblies. For the internal inspection, it is fundamental that documentation will be done.

### 3.5.5 Packing, Transport and Storage

The finger plate assemblies need to be protected to avoid shocks that can deviate the alignments and/or affect the surface treatment when the pieces are being prepared for transport, during transport, and store at the construction site.

It is recommended that the components be stored in a protected area, avoiding bad weather and construction site contamination. This also applies to raw materials.

## 3.6 Initial Material and Component Approval Testing

### 3.6.1 Elastomer Components (Sealing Elements, Gutters)

Required tests include:

- Density (ISO 2781), Frequency: Every batch/delivery
- Hardness (ISO 48-2 / 48-4), Frequency: Every batch/delivery
- Tensile strength & elongation at break (ISO 37), Frequency: Every batch/delivery
- Tear resistance (ISO 34-1), Frequency: Every 3 months
- Compression set (ISO 815-1), Frequency: Every batch/delivery
- Thermogravimetric analysis, TGA (ISO 9924-1/3), Frequency: Once per year

### 3.6.2 Steel / Stainless Steel / Cast Iron / Reinforcement Components

Tests include:

- Yield strength
- Tensile strength
- Elongation
- Charpy V-notch (for dynamically loaded parts)
- Chemical composition
- Ductility
- Weldability
- Bendability
- Bond properties
- Corrosion protection checks (layer thickness, surface condition

**Frequency:** each delivery.

### 3.6.3 Aluminum Components

Tests include:

- 0.2% proof stress
- Tensile strength
- Elongation
- Charpy V-test (if dynamically loaded)
- Chemical Composition
- Ductility (for finger plates)
- Stress-strain behavior

**Frequency:** each delivery.

### 3.6.4 Bolts for Dynamical Loaded Applications (ISO 898-1)

Tests include:

- Material
- Tensile (DIN EN ISO 898-1)
- Elongation (DIN EN ISO 898-1)
- Elongation at break (DIN EN ISO 898-1)
- Charpy V-notch (for dynamically loaded parts)
- Torsion test (Pretensioning)

- Friction test bolt to nut (**DIN EN ISO 16047**)
- Hardness
- Vibration test (Junker-Test)
- Fatigue Strength
- Chemical Composition

**Frequency:** each delivery / each bolts size

### 3.6.5 Welded Dowels (for Dynamically Loaded Components)

- Testing as per EN ISO 13918
- Each delivery

**Frequency:** each delivery.

## 3.7 Tasks of the Inspection Body

In essence, the notified body is responsible for an independent third-party verification that the product placed on the market consistently performs as declared by the manufacturer. Its tasks include:

- **Initial inspection**
  The notified body carries out an initial inspection of the manufacturing plant and the factory production control (FPC) system to verify that manufacturing conditions and procedures comply with the requirements laid down in the EAD.
- **Assessment of factory production control (FPC)**
  It evaluates whether the manufacturer has established, documented, and effectively implemented an FPC system capable of ensuring consistent product performance in line with the declared characteristics.
- **Continuous surveillance, assessment, and evaluation**
  After certification, the notified body performs ongoing surveillance of the manufacturing plant and FPC. This includes periodic audits to confirm continued compliance with the EAD and the approved production system.
- **Certification activities**
  Based on the successful completion of the above tasks, the notified body issues and maintains the relevant certificate of constancy of performance (or equivalent certification specified by the applicable AVCP system).

# 4 Installation

## 4.1 General

This section establishes the recommendations for the installation of guideway beam Expansion Joints used in monorail systems. The objective is to ensure proper installation, long-term structural performance, and safe vehicle operation.

Expansion joints are typically located at the beginning or end of each structural frame and may occur approximately every 120 m along the guideway, as well as at switches and station areas depending on span configuration.

Strict adherence to specialized installation and maintenance protocols is not merely a recommendation: it is a prerequisite for operational safety.

**Manufacturer Installation Requirements**

The Expansion joint system shall be installed strictly following the procedures defined by the manufacturer and reviewed by the designer. These procedures shall include:

- Handling and storage requirements
- Base plate installation procedures
- Alignment verification
- Bolt tightening procedures
- Quality control documentation

**Construction Site Supervision**

Guideway beam expansion joints are more than structural gaps; they are high-precision mechanical interfaces integrated into civil infrastructure, and incorrect installation of these components directly dictate vehicle ride quality, noise emissions, and structural longevity.

Before the evaluation of the expansion joint, it is important to verify the alignment of the side and top running surfaces and the superelevation of the guide beams, because differences in the alignment across the joint will directly affect the quality of the expansion joint installation.

The project needs to verify the position and interaction of the closure pour steel bars, especially when the closure pour has two steps of concrete, the starter bars prevent the positioning of the finger plate assembly.

The project needs to predict the torque value of the fasteners used for the temporary blind plates, to avoid excesses of torque that can affect the internal thread of the anchors. The bolts used in this process can be reused on other closure pours, but never on the fixation of the final finger plates.

Therefore, the following supervision requirements are recommended:

- Installation shall be supervised by qualified personnel experienced in Expansion joint installation.
- Supervisors shall be trained or certified by the manufacturer and system supplier.
- Critical activities requiring supervision include:
  - *Base plate positioning and Alignment verification*
  - *Closure pours inspection (ensuring zero-void consolidation)*
  - *Bolt tightening procedure*
  - *Final installation of finger plates*

**Proposal for Mandatory Supervision**

To avoid installation failures, it is recommended that project specifications include:

- Mandatory manufacturer supervision and system supplier during the first installations
- Qualification requirements for installation personnel
- Formal installation checklists signed by the responsible engineers

**Note:** It is recommended that at least for the first point above, an independent inspection body witness the first installation.

## 4.2 Installation Procedure Overview

The typical installation sequence shall follow these steps:

*Table 3: Installation Procedures*

| Phase | Key Activity | Quality Objective |
|---|---|---|
| **I. Preparation** | Precast beam alignment and rebar cage assembly | Ensure a stable foundation for the joint. |
| **II. Integration** | Base plate setting via temporary templates (Blind plates) | Maintain geometric continuity with beam surfaces. |
| **III. Casting** | Closure pours with high-frequency vibration (Proper vibration and consolidation) | Eliminate air pockets beneath load-bearing base plates. |
| **IV. Assembly** | Removal of templates and finger plate install | Transition from "civil" to "mechanical" tolerances. |
| **V. Finalization** | Tightening per Section 5.3 or 5.4 | Establish calibrated, permanent bolt preload. |

*Figure 21: Preparation to install the base plates*

(Source: São Paulo Metro, 2026)

*Figure 22: Installation of the blind plates*

(Source: São Paulo Metro, 2026)

*Figure 23: Note the concrete filling the holes in the base and blind plates*

(Source: São Paulo Metro, 2026)

*Figure 24: Removal of the blind plates after concrete placement*

(Source: São Paulo Metro, 2026)

*Figure 25: Finger plates installed following bolt installation per procedure*
(Source: São Paulo Metro, 2012)

Along with this process there are some specific points that need to be observed:

- All the assemblies need to be inspected in conformity to the procedure of inspection at the factory.
- If the assembly is composed of separate parts, it is recommended to have them welded to guarantee stiffness, because the transport and installation can affect the alignment of the assembly.
- The assemblies need to be cleaned, especially the areas between the base and finger plates, and inside the anchors.
- The opening of the joint needs to be observed when the assemblies are being installed, since depending on the site temperature, the opening is different, and could have undesirable alignment to the assembly, which could affect the correct performance.
- To avoid excessive loads at the anchor threads, it is necessary to specify a torque limit for the bolts during assembly of the temporary templates. Another important aspect is to avoid delays in installing the finger plates after the concrete placement, to avoid corrosion of the anchor threads.

**Lessons Learned:** The "Invisible" Failure Point

Experience from previous projects and deployments confirms that the area beneath the expansion joint base plate is the most common site of structural non-conformance.

**The Issue:** Standard concrete mixes often fail to penetrate congested reinforcement zones under the base plates.

**The Consequence:** Air pockets lead to uneven load distribution and premature anchor joint failure.

**The Solution**: Design shall contemplate "Field-Friendly" geometry and/or “burping holes for the concrete” allowing enough space for vibration equipment and ensuring the concrete mix design supports high fluidity without segregation.

**Lessons Learned**: Precision Handling & Support Systems

**The Challenge**: The Weight of Misalignment Expansion joints are often underestimated as "simple embeds," yet their weight makes manual positioning nearly impossible to sustain. When workers struggle with heavy components, ergonomics suffer and geometric precision is lost, leading to permanent alignment errors once the concrete is cast.

**The Solution:** Mechanical infrastructure to bridge the gap between design and field conditions; it is essential to use dedicated support frames and magnetic lifting tools.

**Stability**: Custom frames allow joints to "float" at the exact elevation while reinforcement is secured and concrete cast.

**Precision**: Taking the load off the workers enables micro-adjustments that ensure a smooth vehicle transition.

**Safety**: Specialized handling reduces injury risk and accelerates the installation cycle.

**Recommendation:** Project specifications shall mandate a Handling Method Statement to ensure contractors utilize proper lifting and support infrastructure.

# 5 Bolt Tightening

## 5.1 General Considerations

Bolted connections in monorail expansion joints are not merely fasteners; they are the primary mechanism for maintaining clamp force so that operational loads are transferred through friction at the plate interface rather than through bolt shank bearing. This is essential to preserve the fatigue assumptions used in Chapter 2, the installation quality objectives in Chapter 4, and the maintenance verification program in Chapter 7.

**Consequences of Sub-Optimal Clamp Force:**

- **Micromovement:** Transversal displacement and joint opening.
- **Parasitic Loading:** Induction of bending stress in bolts not designed for shear.
- **Fatigue Acceleration:** Rapid progression toward bolt failure due to sliding effects.

## 5.2 Advanced Bolting Strategies: Beyond Torque

Traditional tightening methods based solely on torque control are widely used due to their simplicity; however, they present significant limitations in applications where high reliability is required.

In torque-controlled tightening, the applied torque is used as an indirect indicator of the tension generated in the bolt. However, experimental studies show that the majority of applied torque is dissipated in friction between threads and bearing surfaces rather than converted into tensile force.

Because friction coefficients vary significantly depending on lubrication conditions, surface coatings, and galvanization thickness, torque-only tightening can produce large scatters in the resulting bolt preload.

This variability is particularly critical for **galvanized bolts**, where coating thickness and lubrication conditions further increase friction variability.

For this reason, the tightening procedure for final finger plate installation shall be defined by a tightening study and shall not rely on torque alone. Modern engineering practice increasingly employs advanced tightening strategies, including the Torque-Angle (Turn-of-Nut) method, supported by project-specific verification.

## 5.3 Tightening Method

The method described in this section applies to bolted connections. Tightening method selection shall follow Section 5.4.

- **Stage 1: Snug-Tight (The Baseline):** Establishes full surface-to-surface contact (threshold torque).
- **Stage 2: Controlled Preload:** This can be achieved in two ways:

a. via a Calibrated Mechanical Torque Wrench to reach its preset value, or

b. via a Digital Torque Angle Wrench (shown below), applying a precise angular displacement (for example 90°).

*Figure 26: Sample of a torque angle method application*

(Source: São Paulo Metro)

**Key advantages to the Calibrated Mechanical Torque Wrench:**

- Common procedure in most of the world with local personnel previously trained
- Mechanical equipment commonly used and inexpensive
- Easily available in most of the world

**Key Advantages to the Torque Angle:**

- **Friction Neutrality:** Dramatically reduces sensitivity to coating and lubrication variations.
- **Data Traceability:** Enables the recording of torque-angle curves for digital quality assurance, see the figure below.
- **Repeatability:** Provides consistent assembly force across thousands of joint locations.

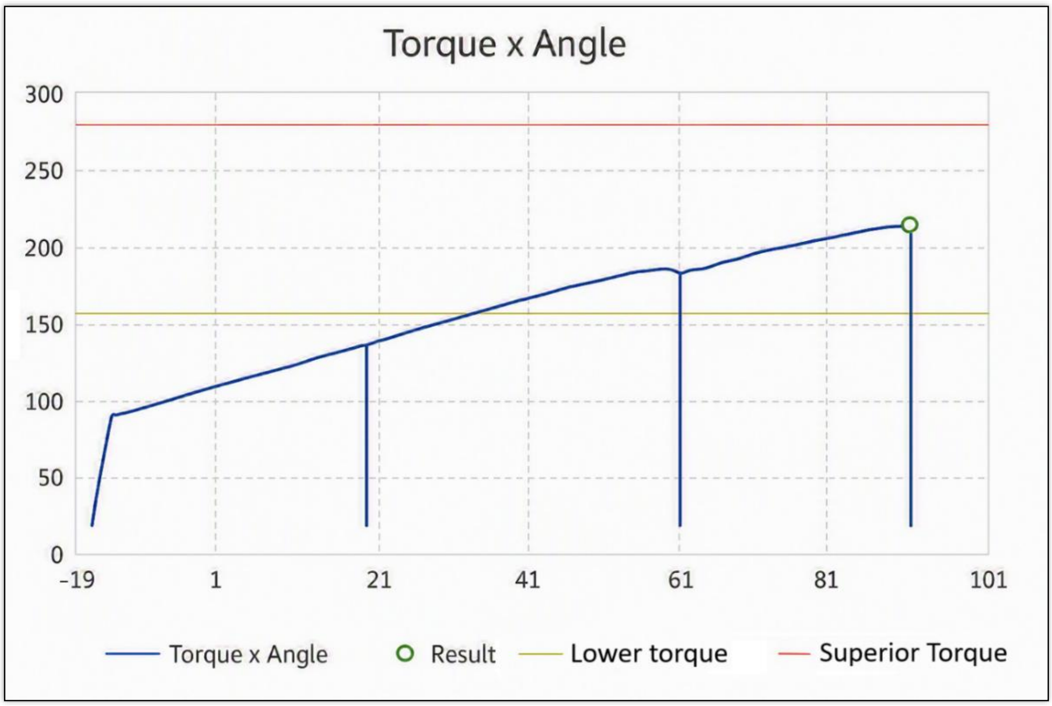



*Figure 27: Example of torque angle graph*

(Source: São Paulo Metro)

## 5.4 Tightening Method Selection for Anchors with Cut or Reused Threads

Anchors cast into the concrete guideway commonly use cut threads rather than rolled threads, and in many installations these threads are reused across the anchor's service life.

For bolted connections using cut thread or reused-thread anchors, the fabricator or engineer of record shall select one of the two methods below. Selection shall be based on the outcome of a project-specific tightening study performed in accordance with Section 2.8. A generic method or acceptance table from another project shall not be substituted for this study, because friction coefficient, coating condition, bolt geometry and plate stiffness are project-specific and directly affect the torque-angle or torque-preload relationship.

**Lessons Learned:** reuse of cut threads in the anchor shall require effective prestress ensuring the cut threads remain in the elastic range.

**Method A: Calibrated Wrench Method with Arbitration Torque Verification**

The installation torque and the verification (arbitration) torque shall be established by the tightening study, using the installation torque plus a margin (nominally 10 percent) as the arbitration torque. If the anchor has cut threads, the cut thread stresses shall remain in the elastic range.

Loss of preload shall confirm that the bolt head, or nut rotates no more than 30 degrees under the arbitration torque. If a bolt exceeds this limit, this bolt and all bolts at the related specific finger plate should be replaced as well.

A washer, or a bolt head geometry demonstrated by the tightening study to provide equivalent bearing performance, shall be installed under the turned element, consistent with AASHTO LRFD Bridge Construction Specification or EN 1090-2:2018+A1:2024.

**Method B: Torque-Angle Curve Monitoring**

Tightening shall be performed using calibrated equipment capable of recording the full torque-angle curve for each bolt.

The tightening study shall establish the reference (target) curve for the specific bolt, anchor, coating, and plate configuration used on the project, following VDI 2230 or an equivalent recognized angle-controlled tightening standard. If the anchor has cut threads, the cut thread stresses shall remain in the elastic range.

Recorded curves shall be compared against the reference curve to confirm proper seating, absence of thread damage, and achievement of target preload. Deviating curves shall be investigated before the joint is accepted.

Loss of preload shall be verified using an arbitration-torque check against the recorded curve (per VDA 5.2 or equivalent), not by rotation alone, since rotation-only verification does not indicate the magnitude of preload loss on a previously torque-angle-tightened bolt.

A washer, or a bolt head geometry demonstrated equivalent by the tightening study, shall be installed under the turned element.

## 5.5 Bolt Reuse

Bolt reuse shall be controlled according to the purpose for which the bolt is being handled. The working group distinguishes between routine torque verification, temporary removal for maintenance access, and final repair or replacement of damaged components.

**Routine torque verification.** During routine sampling inspections, including the recommended 4% torque testing described in Section 7.2, bolts are not considered "removed" or "reused" when they are re-torqued in place to verify loss of pre-stress. Loss if preload shall be verified as stated above for Methods A and B.

**Temporary removal for maintenance.** Where bolts must be removed temporarily to allow maintenance or repair work that cannot be completed within a single access period, such as repair of voids below the base plate or replacement preparation for damaged finger plates, the same bolts may be reinstalled temporarily to maintain the joint in service until the repair is completed. This temporary reuse shall be documented, limited to the shortest practicable period, and subject to the tightening study and inspection criteria.

**Final repair or replacement.** Once a finger plate, base plate, anchor interface, or other joint component has been damaged or repaired due to cracking, voids, loss of support, or similar defects, all bolts associated with that repair area shall be replaced with new bolts for the final permanent installation. Bolts that were temporarily reused during the repair shall not be retained in the final installation.

This distinction recognizes that routine verification does not require automatic bolt replacement, while final restoration of a damaged component requires new fasteners to ensure traceability, preload reliability, coating integrity, and fatigue performance.

**Lessons Learned:** Bolt reuse decisions depend on the maintenance scenario, not on a single blanket rule. Routine 4% torque verification does not require automatic bolt replacement: bolts may remain in service if the permitted rotation limit is not exceeded.

Temporary reuse is acceptable only as a controlled, documented, short-duration measure when bolts must be removed to keep the joint in service during an unfinished maintenance repair.

For the final permanent condition after any repair or replacement of damaged components, all bolts in the affected repair area shall be replaced with new bolts and tightened using the approved procedure, preserving preload reliability, fatigue performance, coating integrity, and traceability.

## 5.6 International Approaches to Bolt Verification

Different engineering regions apply different procedures to verify bolt pretension during installation.

Although the objective remains the same ensuring that the required clamp load is achieved, implementation practices differ between North American and European standards.

**United States Approach**
In North American practice, bolt tightening verification commonly includes daily calibration and verification tests of the installation tool using specialized equipment such as the Skidmore-Wilhelm Bolt Tension Calibrator.

This device allows direct measurement of the clamp force generated by a tightening procedure and is used to verify that the applied torque or tightening method produces the required bolt tension.

Typical US practice includes:

- Verification testing of the installation tool at the start of each work shift
- Testing of representative bolts from each lot
- Calibration of tightening equipment
- Documentation of tightening procedures

This approach focuses on field verification of the tightening method to ensure that the installation procedure produces the required preload.

**European Approach**
European standards typically emphasize prequalification of tightening procedures through laboratory testing.

Under this approach, the tightening procedure is developed and validated through controlled testing prior to field application.

Typical procedures include:

- Laboratory determination of torque-angle relationships
- Characterization of friction coefficients
- Qualification testing of bolts and coatings
- Development of installation procedures

Once validated, the tightening procedure can be applied in the field with a high level of confidence in the resulting clamp load.

This approach focuses on process qualification and engineering validation prior to installation rather than daily field testing.

*Table 4: International Approaches to Bolt Verification*

| Feature | North American (Skidmore) Approach | European (Prequalification) Approach |
|---|---|---|
| **Philosophy** | Continuous Field Verification | Process Prequalification |
| **Tooling** | Daily use of Skidmore-Wilhelm Calibrators | Laboratory Friction & Torque Characterization |
| **Execution** | Testing of representative bolts from every lot/shift | Strict adherence to a pre-validated laboratory procedure |
| **Strength** | Real-time adjustment to site conditions | High confidence in engineered process control |

## 5.7 Complementary recommendations

Independently of the process applied to torque the bolts, it is recommended to apply a sealant on the joint to prevent oxidation of the threads and guarantee the durability of the fixation.

After the installation of the bolts, it is important to mark with an indelible marking along the head of the bolt and the surface of the finger plate on each bolt (remembering that will have the friction of the train tires), to enable the maintenance verification of casual torque loss of the bolts.

The tightening study (see Section 2.8) usually will recommend making some complementary verification on a sampling bolt for loss of clamping that can occur after the installation, especially after starting operation and the dynamic efforts by train.

# 6 Installation Tolerances

Vehicle ride quality and long-term durability in monorail systems are fundamentally governed by the continuity of the guideway running surfaces. Unlike conventional rail systems, monorail vehicles rely on rubber tires operating directly on the guideway beam surfaces. For this reason, even small steps, gaps, offsets, or local discontinuities at expansion joints may generate impact, tire wear, vibration, noise, increased fatigue demand, and loss of ride comfort.

The tolerance requirements for each expansion joint shall comply with the project-specific criteria defined by the system supplier. However, based on current industry practice and supplier experience, the tolerances presented in this chapter are recommended as minimum acceptance criteria for monorail expansion joints.

The expansion joint shall be installed in a manner that satisfies all critical operational conditions defined by the system supplier, including maximum passenger loading, suspension deflection, tire deformation, and degraded tire conditions, such as deflated or burst tires, where applicable to the vehicle design criteria.

## 6.1 General Tolerance

Installation tolerances shall control not only the position of the steel plates, but also the transition between the steel components and the adjacent concrete or metallic guideway surfaces.

The objective is to maintain a continuous and smooth tire contact surface through the expansion joint area, without steps, ledges, excessive gaps, uncovered tire contact areas, or interference between adjacent finger plates.

## 6.2 Recommended Installation Tolerances

The following table provides recommended acceptance criteria for installation tolerances. These limits shall be confirmed against the project-specific vehicle interface requirements.

*Table 5: Recommended Installation Tolerances*

| Parameter | Recommended Limit |
|---|---|
| Expansion joint gap spacing | Design gap ±10 mm |
| Vertical level deviation between concrete/metallic guideway surface and expansion joint plate | ±1.5 mm recommended; ±2.0 mm maximum only if accepted by system supplier |
| Vertical level deviation between opposite expansion joint assemblies | ±1.5 mm recommended; ±3.0 mm maximum only if accepted by system supplier and justified by vehicle interface analysis |
| Step or ledge between adjacent finger plate segments | 1.5 mm maximum |
| Clearance between adjacent or opposing finger plates throughout the full movement range | No contact permitted under any design movement condition |
| Continuity of tire contact/riding surface through the expansion joint area | No uncovered tire contact area permitted under the worst vehicle condition |

## 6.3 Vehicle Envelope and Worst-Case Tire Condition

In addition to geometric tolerance checks, the expansion joint shall be verified against the vehicle tire envelope.

The expansion joint shall be installed so that it provides continuous support to all tire contact/riding surfaces through the expansion joint area. Under the worst vehicle conditions, the joint shall provide a smooth transition across the expansion area.

This verification shall consider, as applicable, maximum passenger loading, suspension deflection, tire deformation, tire wear, and degraded tire conditions such as deflated or burst tires, in accordance with the vehicle design criteria defined by the system supplier.

# 7 Maintenance

## 7.1 General

Expansion joints installed in monorail guideway beams are critical mechanical components responsible for accommodating structural movements while maintaining a continuous and smooth-running surface for the vehicle.

Due to their exposure to repeated dynamic loading, environmental conditions, and potential water infiltration, expansion joints require periodic inspection and maintenance to ensure long-term operational performance and safety.

Maintenance activities for expansion joints shall focus on the following key aspects:

- Verification of bolt preload and joint integrity
- Inspection of finger plates and base plates condition
- Inspection of corrosion protection systems
- Verification of sealing systems to prevent water infiltration
- Monitoring of joint alignment and structural interface conditions

Expansion joints are typically designed to match the design service life of the guideway structure. However, achieving this design life depends on implementing a structured maintenance program with periodic inspections and corrective actions when required.

One important issue that needs to be observed is the application of the finger plate supplier manual, with all the actions needed to be released at the period indicated. The tightening report needs to be observed too, because it has some verifications and concerns after the installation of the bolts.

The maintenance needs to identify the critical pathological manifestations, which affect directly the security and operation of the system. Some of them are related on the table below:

*Table 6: Pathology of Bolt Conditions*

| Pathological Manifestation | Impact |
|---|---|
| Bolt breakage | Risk of breakage of another bolts and finger plate falling |
| Bolt loss of torque | Risk of bolt breakage with its consequences |
| Thread loss in the anchor | Risk of bolt breakage with its consequences |

Other possible pathological manifestations like corrosion, loss of seal, differences between plates and/or between finger and base plates, voids under the base plates, and fissures on the base plates can be solved by planning specific repair procedures.

**Supervision Requirements**

Maintenance operations shall be conducted under the supervision of qualified personnel experienced in structural bolted connections and mechanical joint systems.

Recommended supervision requirements include:

- Maintenance engineers trained in structural bolted connection systems
- Personnel familiar with the tightening procedures used during installation
- Inspection staff capable of identifying bolt preload loss, corrosion damage, and plate misalignment
- Implementation of documented inspection procedures and maintenance records

All inspection results and maintenance actions shall be properly documented as part of the infrastructure maintenance management system.

## 7.2 Maintenance Recommendations

Maintenance procedures should be implemented through periodic inspections, operational monitoring, and preventive maintenance actions.

Recommended maintenance activities include:

**Visual & Operational Monitoring**

- Acoustics/Vibration: Monitor for unusual noise during train passage.
- Torque Marks: Instant visual verification of bolt movement.
- Debris Management: Regular cleaning to prevent thermal expansion "locking" or abrasion.
- Fissures: If there is welding on the base plates.

**Bolt Preload Verification**

The first inspection of bolt preload should occur after approximately 1,000 operational cycles or during the early operational period of the line, on 4% of the bolts or on one bolt per assembly. It is recommended to select bolts that presented difficulty during installation, bolts from assemblies with reported torque loss, or bolts in locations with higher operational demand. During this routine verification, the bolt is re-torqued in place using the methodology adopted for Method A or B in section 5.4.

During inspection:

- Routine torque verification shall not by itself require replacement of every checked bolt. Replacement is required when the permitted torque or rotation limit is exceeded, when damage or corrosion is observed, or when the tightening study or project specification requires replacement.

- Where bolts must be removed temporarily to complete maintenance that cannot be finished in one access period, the same bolts may be reinstalled temporarily until the repair is completed; however, new bolts shall be installed and torqued for the final permanent condition.
- For final repair or replacement of damaged components, including damaged finger plates, void-related repairs, cracked plates, or other defects affecting the bolted joint, all bolts associated with the repair area shall be replaced with new bolts and tightened using the approved procedure.

If preload losses exceed these values, further investigation should be conducted to identify potential causes, such as:

- Bolt relaxation
- Plate deformation
- Thread damage
- Improper original installation

**Corrosion Protection Inspection**

Inspection should confirm the integrity of protective coatings applied to expansion joint components, including:

- Galvanized bolts (ASTM F3125 requirements)
- Zinc-coated or galvanized plates
- Protective sealing compounds

Any evidence of corrosion or coating degradation should be addressed promptly.

**Sealing and Water Protection**

The expansion joint design typically includes sealing materials applied to bolt recesses and cavities to prevent water infiltration.

Inspection shall verify:

- Condition of sealing materials
- Absence of water infiltration in bolt holes
- Integrity of protective coatings

Loss of sealing protection may accelerate corrosion and reduce bolt performance.

## 7.3 Lessons Learned from Previous Projects

Operational experience from multiple monorail and Automated People Mover systems has identified several recurring issues associated with expansion joint performance.

Key lessons learned include:

- Incorrect alignment of base plates during installation is the most frequent cause of expansion joint problems. Even small deviations can lead to plate misalignment and operational noise.
- Improper bolt tightening procedures often result in premature loss of bolt preload and increased maintenance requirements.
- Insufficient installation supervision significantly increases the likelihood of installation defects.
- Poor concrete consolidation during closure pours may create voids beneath base plates, reducing support and causing long-term alignment issues.
- Post-installation corrections are costly and complex, often requiring replacement plates or significant field adjustments.

These lessons emphasize the importance of:

- Strict installation procedures
- Proper bolt tightening verification
- Quality control during construction

Early detection and correction of installation deficiencies significantly reduce long-term maintenance costs.

## 7.4 Maintenance Checklist

A structured inspection checklist shall be used during maintenance activities to ensure that all critical aspects of the expansion joint system are evaluated.

**Visual Inspection**

- Verification of plate alignment relative to beam surfaces
- Inspection of plate wear or deformation
- Detection of corrosion or coating deterioration
- Inspection of finger plate edges and teeth for damage

**Bolt Inspection**

- Verification of bolt marking and identification

- Confirmation of bolt tightness and preload condition
- Inspection of signs of loosening or movement
- Examination of threads and bearing surfaces

**Seal Protection**

- Verification of sealing material condition
- Inspection of bolt hole sealing
- Detection of water infiltration or moisture accumulation

**Structural Interface**

- Inspection of surrounding concrete for cracking
- Verification of expansion joint movement capacity
- Confirmation that plates remain properly seated on base plates

All inspections and maintenance actions shall be recorded and maintained within the project's asset management or maintenance documentation system, ensuring traceability and facilitating long-term performance monitoring.

## 7.5 Maintenance Actions

The maintenance guide needs to address actions for certain types of pathological manifestations. Here are some specific recommendations for different types of pathologies:

**Bolt breakage:** as the finger plate is a critical component, all broken bolt events require a failure analysis, verifying all the possible causes that could contribute to the breakage. It is important to keep the pieces of the broken bolt separate, because it can affect laboratory analysis. If possible, take pictures zooming on bolt broken faces to aid the analysis. It is recommended to replace all the bolts on the same plate where the breakage occurred, once the first bolt broke, the others received additional loads.

**Loss of torque**: If the team doesn't have time to replace the bolt at the current access, apply an interim torque per the project's tightening study to maintain clamping force, and program the bolt for replacement at the next access. The replacement bolt shall be tightened using the method established under Section 5.3 or 5.4, as applicable to that connection. Interim re-torquing of a bolt scheduled for later replacement shall be treated as temporary reuse under Section 5.5 and is subject to the same documentation and time limits.

**Fissures at the base plate:** it is important to make a failure analysis to understand why the fissure occurred. To restore the base plate by welding, it is necessary to have a field procedure that includes a welding inspector to ensure that the proper steps are followed. Consider that the activity might be done in adverse schedule and weather conditions in the guideway of the line. Also consider the interface with the surface treatment, which needs to be restored after the welding activities.

**Broken bolt inside the anchor:** if a piece of a bolt remains inside the anchor and is impossible to remove, the anchor needs to be replaced. To perform this operation, there is a need for new anchor calculations, considering the adhesive material and the interface between the surface of the new anchor and the hole made when the old one was removed. The extraction and the setting of the new anchor need to consider and control the anchor's orthogonality to avoid problems when the new bolt is installed.

**Loss of nut thread:** usually the anchors of the finger plates have a nut welded or machined at the end of the anchor, so it is impossible to change the nut only using simple tools. One possibility is to extract and change the anchor as detailed above when the bolt breaks inside the anchor. Another possibility is to use a threaded insert, an item that could be installed inside the anchor after enlarging the original thread. This solution needs to be verified by the designer and inserted at the tightening study,

**Differences between plates / between finger and base plates:** the correction of these differences usually requires grinding the plate to achieve the needed alignment. It is not recommended to grind the plate running surface, because it will lose the surface treatment and an application of cold zinc will disappear due to tire friction. On these cases is recommended to remove the plate and correct the plate back side and apply the proper the surface treatment. If it is necessary to grind the running surface, it is recommended to remove the piece and apply the proper plate surface treatment.

**Note:**
It might be possible that permanent monitoring of the system may lead to a different approach to the maintenance activities. Careful monitoring can lead to a cost reduction in maintenance and ensure the functionality of the expansion joints and increase of safety. Thus, leading to higher availability of the system.

INTERNATIONAL MONORAIL ASSOCIATION

# Guideline for Expansion Joints (Finger Joints) in Monorail Guideway Systems

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