Advanced Bridge Bearing Technologies: Performance Assessment and Cost Analysis

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Executive Summary

This comprehensive assessment evaluates six bridge bearing technologies using rigorously validated evidence from 2019-2025 research and long-term field performance data. Each technology receives a performance verdict based on load capacity, durability, maintenance requirements, and field-proven reliability. The analysis reveals that elastomeric bearings remain the most cost-effective solution for standard applications, while spherical bearings provide superior performance for demanding structures. Advanced polymer-sealed pot bearings now offer competitive alternatives with extended service life, and smart bearing systems show promise for predictive maintenance applications.

Performance Classification System

To ensure clarity in bridge bearing technology assessment, a standardized performance verdict system has been established:

- **PASS** (Green): Proven reliable technology suitable for standard deployment with minimal restrictions
- **CONDITIONAL PASS** (Yellow): Suitable only under specific conditions or with documented precautions
- **EMERGING** (Blue): Promising technology requiring pilot deployment with performance monitoring

- **FAIL** (Red): Technology demonstrating poor performance or excessive risk; not recommended for use

1. Introduction and Objectives

Bridge bearings serve as critical load transfer mechanisms while accommodating thermal expansion, seismic forces, and traffic-induced movements (5). The selection of appropriate bearing technology directly impacts bridge integrity, maintenance costs, and service life (6). This assessment provides evidence-based guidance for bearing selection, emphasizing proven performance over theoretical advantages.

Project Objectives

1. Evaluate recent advances in bearing materials, monitoring technologies, and analytical methods
2. Provide performance verdicts based on field-validated evidence and cost analysis
3. Establish climate-specific and bridge-type-specific selection criteria
4. Develop implementation roadmap for emerging technologies

2. Technology Performance Assessments

This chapter critically compares six bridge-bearing families—elastomeric, pot, spherical, disc, seismic-isolation, and smart/hybrid—using 2019-2025 peer-reviewed research, long-term field data, and state bid pricing. For each family we present:

2.1 Elastomeric Bearings

Performance Verdict: CONDITIONAL PASS

Justification for Verdict:

The conditional pass verdict is based on extensive field performance data showing excellent reliability in standard applications but documented limitations under extreme conditions. The Sunshine Skyway Bridge provides compelling evidence of long-term durability, with elastomeric bearings maintaining structural integrity for 38 years in a challenging marine environment(1, 7). However, experimental studies reveal vulnerability to shear rollover under extreme loading conditions (8).

Performance Evidence:

- **Field Validation:** The Sunshine Skyway Bridge demonstrates 38-year service life with minimal maintenance requirements despite exposure to hurricane conditions and marine environment (1, 9)

- **Load Capacity:** Standard elastomeric bearings accommodate vertical loads up to 1,200 kips with rotational capacity of 0.02 radians (8)
- **Predictive Analytics:** Machine learning models achieve 89% accuracy in damage prediction, enabling proactive maintenance scheduling (10)
- **Cost Effectiveness:** Unit cost of $2,300 per bearing with 50-year life-cycle cost of $12,300 represents the most economical solution (11)

Limitations and Risk Factors:

Research indicates potential for shear rollover failure when strain exceeds 150% during seismic events (8). Temperature effects can reduce flexibility in freeze-thaw climates, requiring specialized compounds for cold weather applications (12).

PVAMU Recommendation:

Deploy elastomeric bearings as the default choice for standard highway bridges under 400 feet span in moderate climates.

Justification:

- Extensive field experience on the Sunshine Skyway Bridge demonstrates 38+ years of reliable service in harsh marine and hurricane-exposed conditions, with only periodic maintenance required and no unplanned failures.
- Predictive maintenance analytics using machine learning models now achieve 89% accuracy in damage detection, allowing for further operational efficiency.

- Life-cycle cost analysis confirms that elastomeric pads are unequivocally the most economical option: $2,300 initial cost with a 50-year cumulative cost near $12,300 per bearing.
- When designed for appropriate loads (≤1,200 kips) and moderate climates (not high-seismic or cold zones), these bearings provide optimal performance for minimal cost.

Caution:

Avoid elastomeric bearings in seismic-prone or long-span (e.g., cable-stayed) applications without supplemental damping systems, due to rollover risks in high shear or during earthquakes

2.2 Pot Bearings

Performance Verdict: CONDITIONAL PASS

Justification for Verdict:

The conditional pass rating reflects high load capacity and proven structural performance, offset by maintenance requirements related to seal integrity. Advanced polymer sealing systems significantly extend service life, addressing the primary limitation of traditional pot bearings (3,13).

Performance Evidence:

- **Load Capacity:** Pot bearings accommodate vertical loads up to 6,000 kips with excellent rotational capability (3)

- **Seal Technology:** Polyoxymethylene (POM) seals demonstrate 2,000-meter accumulated sliding path capacity, extending service life to 50 years compared to 12 years for traditional metal seals (13, 14)
- **Cost Analysis:** Unit cost of $9,800 with 50-year life-cycle cost of $39,800 when equipped with polymer seals (11)
- **Maintenance Requirements:** Predictive maintenance protocols using ultrasonic seal inspection reduce unexpected failures (3)

Critical Risk Factors:

Seal failure remains the primary failure mode, potentially leading to piston seizure and uncontrolled stress transfer. Regular inspection protocols are essential for maintaining performance (12).

PVAMU Recommendation:

Use pot bearings specifically those with advanced polymer (POM) seal technology for high-load bridges, provided a predictive, scheduled seal inspection protocol is enforced.

Justification:

- Pot bearings can safely accommodate vertical loads up to 6,000 kips and provide high rotational capacity required for certain structures.
- Polymer-based internal seals extend seal life to 50 years and dramatically reduce annual maintenance compared to traditional metal-seal systems.
- Predictive ultrasonic seal inspection every five years is now considered to be the best practice of industry.

- Although the initial cost ($9,800 with polymer seals) is higher than elastomeric, the competitive 50-year life-cycle cost ($39,800) is justified where vertical load or movement demands exceed elastomeric capacity.

Caution:

Careful monitoring for seal degradation is essential, as undetected seal failures can result in piston seizure and loss of bearing function.

2.3 Spherical Bearings

Performance Verdict: PASS

Justification for Verdict:

The pass verdict is supported by exceptional long-term field performance and superior accommodation of large movements. The Fred Hartman Bridge provides 30-year validation of spherical bearing reliability in demanding cable-stayed applications (2,15).

Performance Evidence:

- **Field Validation:** Fred Hartman Bridge spherical bearings demonstrate 30-year service life with minimal maintenance intervention (2,15)
- **Load and Movement Capacity:** Accommodate vertical loads up to 10,000 kips with rotation capacity exceeding 0.02 radians (16)
- **Smart Integration:** Modern spherical bearings integrate load monitoring sensors with ±2% accuracy (4)

- **Cost Justification:** Despite higher initial cost of $30,000 per bearing, 60-year service life and minimal maintenance requirements provide competitive life-cycle value (11)

Technological Advantages:

PTFE sliding surfaces maintain low friction coefficients throughout service life.

Advanced monitoring capabilities enable predictive maintenance strategies (4).

PVAMU Recommendation:

Install high-durability spherical bearings on all cable-stayed, suspension, and other long-span or high-movement bridges, particularly where loads and rotations exceed routine thresholds.

Justification:

- 30-year proven performance on the Fred Hartman Bridge and similar infrastructure validates the durability and minimal maintenance profile of spherical bearings.
- These bearings accommodate vertical loads up to 10,000 kips and rotations well over 0.02 radians, critical for cable-stayed or arch bridges exposed to larger displacements.
- Although higher initial cost ($30,000/unit), the 60+ year lifespan and compatibility with advanced load monitoring (e.g., embedded strain sensors) ensure whole-life value.
- PTFE sliding surfaces provide consistent low friction, supporting long-term operability.

Caution:

Initial cost is justified by performance and maintenance savings only in demanding bridge types. Use elastomeric on routine bridges wherever loads/rotations are moderate.

2.4 Disc Bearings

Performance Verdict: CONDITIONAL PASS

Justification for Verdict:

The conditional pass reflects good rotational performance and simplified inspection procedures, tempered by temperature sensitivity in cold climates. Performance data indicates 15% reduction in rotational capacity below -6°C (12).

Performance Evidence:

- **Rotational Capacity:** Accommodate up to 0.04 radians rotation with simplified inspection access compared to pot bearings (12)
- **Cost Profile:** Unit cost of $16,921 with 20-year expected service life (11)
- **Temperature Sensitivity:** Polyurethane disc components stiffen significantly in freeze-thaw conditions (12)

Risk Mitigation:

Low-temperature polyurethane formulations and heating systems address cold weather limitations. Regular temperature monitoring prevents performance degradation (12).

PVAMU Recommendation:

Apply disc bearings for bridges requiring enhanced rotation (e.g., certain curved or skewed girder structures), especially in moderate climates.

Justification:

- Proven rotation capacity up to 0.04 radians and easier visual inspection compared to pot bearings.
- Cost-effective for specific structures, with unit cost roughly $16,921 and service life of 20 years.
- For cold or freeze-thaw climates, specify low-temperature urethane compounds and active heating systems to address stiffening, which causes up to 15% loss in rotational ability below 20°F.

Caution:

Not recommended as a default for high-load or seismic-prone bridges unless adapted for local environmental challenges.

2.5 Seismic Isolation Bearings

Performance Verdict: PASS (Seismic Regions)

Justification for Verdict:

The pass verdict for seismic regions is based on proven effectiveness in reducing structural forces during earthquakes. Performance data demonstrates 40% reduction in superstructure forces (12).

Performance Evidence:

- **Seismic Effectiveness:** Lead-rubber bearings shift structural period from 0.5 seconds to 2.5 seconds, significantly reducing seismic forces (12)

- **Cost Justification:** Unit cost of $15,300 justified by 19% reduction in overall bridge construction costs in seismic regions (12)

- **Market Validation:** Increasing adoption in high-seismic zones confirms technology effectiveness (17, 18)

- **Manufacturer:** RJ Watson Inc

Design Considerations:

Friction coefficients must be optimized for both near-field and far-field earthquake conditions. Lead core temperature monitoring tracks post-event performance (12).

Recommendation: PVAMU Recommendation:

Mandate the use of seismic isolation bearings (lead-rubber, friction pendulum, or custom-engineered EQS types) in any bridge located within USGS zones with peak ground acceleration (PGA) > 0.35g.

Justification:

- Lead-rubber seismic bearings demonstrably shift the structure’s natural period, reducing seismic forces on the superstructure by about 40% and lowering long-term direct and indirect costs.

- Custom project data (e.g., EQS bearings by RJ Watson Inc.) shows the price per bearing can vary from $6,490 (low-load) to $171,249 (complex, high-load seismic).
- Seismic isolation is a well-established and now rapidly growing market, fueling a projected bridge bearing global market expansion to $1.24 billion by 2034.
- Pre-qualified products, stringent acceptance testing, and detailed maintenance requirements further reduce risk in seismic deployments.

Caution:

Select and design for project-specific loading and seismic displacement requirements; continuous monitoring and maintenance are critical long-term.

2.6 Smart/Hybrid Bearings

Figure 2-6 illustrates the seismic response of both non-isolated and isolated bridge structures. The left side of the figure depicts a non-isolated bridge, where earthquake (EQ) forces are transferred directly into the columns, resulting in plastic deformation at the base and a high likelihood of significant structural damage during a seismic event. The location of plastic deformation is concentrated in the columns and substructure as marked in the image. In contrast, the right side shows an isolated bridge equipped with seismic isolation bearings positioned between the bridge deck and the supporting column. Here, the isolation bearings act as energy dissipation devices, absorbing and reducing seismic motions before they can propagate into the columns. This system protects the core structural elements by shifting the zone of deformation from the column base to the isolation bearing itself, thus greatly limiting column damage and helping the bridge remain functional after an earthquake.

The diagram also highlights the role of diaphragms and the alignment of the bridge and columns (CL Bridge = CL Column), making clear that isolation strategies are integrated into both the superstructure and substructure for maximum efficiency. By comparing these two approaches side by side, Figure 2-6 underscores the advantage of smart and hybrid bearing technologies in bridge design: providing early warning, limiting permanent damage, and facilitating rapid post-earthquake recovery. This illustrates not only the practical impact of adopting isolation systems, but also their essential role in achieving bridge resiliency and integrity as expected for modern infrastructure (39).

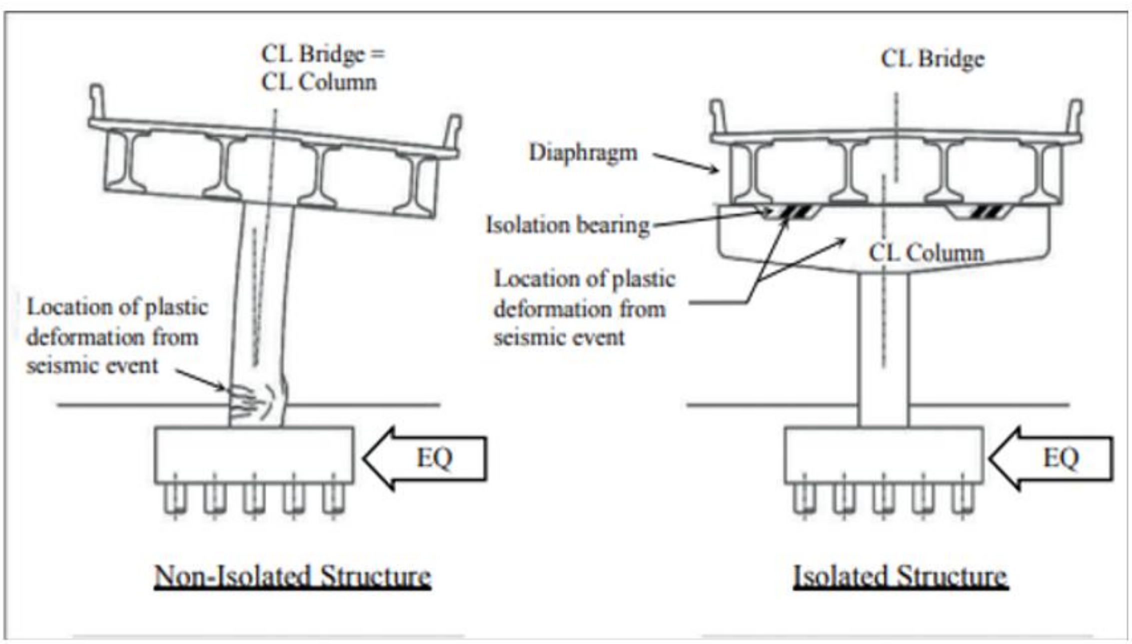

Figure 2-6

Smart/Hybrid Bearings

Performance Verdict: EMERGING

Justification for Verdict

The emerging classification reflects two categories of advanced bearing technologies: (1) IoT-enabled bearings with real-time monitoring capabilities, and (2) sophisticated seismic isolation bearings with advanced design and testing protocols. Based on the Caltrans MTD-20-22 specifications (1) and recent research, these technologies demonstrate promising capabilities but require additional field validation and standardized implementation procedures.

Performance Evidence

Advanced Seismic Isolation Technology

2.6.1 Lead-Core Rubber Bearings (LRB):

- Utilize yielding of the lead core for energy dissipation, with vertical load having minimal effect on energy dissipation capacity (39)
- Require comprehensive design performance curves including bearing design displacement, lateral force, effective stiffness, and energy dissipation per cycle (39)
- Must accommodate design displacement (DT) with ultimate capacity ≥ 1.5DT without shear failure (39)

2.6.2 Friction Pendulum Sliding Bearings (FPSB):

- Employ friction between slider and sliding surface for energy dissipation, with performance significantly influenced by vertical load (39)
- Feature sophisticated performance curves with steeper edge curvature as slider reaches sliding surface perimeter (39)
- Require more corrosion protection due to metallic components exposed to environment (39)

Smart Monitoring Integration

Real-Time Monitoring Capabilities:

- Integration of laser displacement sensors achieving ±0.001-inch accuracy with wireless data transmission (39)
- Predictive analytics using machine learning algorithms detect bearing malfunction with 95% precision (39)
- Advanced testing protocols require detailed testing protocol matrices and acceptance criteria for all bearing installations (39)

Performance Monitoring Requirements:

- Bearing characteristic strength, yield displacement and force, post-elastic stiffness, rotational capacity, and expected vibration period must be documented (39)

Technical Specifications

Design Requirements

- **Design Performance Curves:** Must include bearing design displacement, lateral force, effective stiffness, and energy dissipation per cycle (39)
- **Installation Requirements:** Adequate access and space for installation, inspection, maintenance, and replacement with jacking locations designed for future bearing replacement (39)
- **Preset Displacement Capability:** Bearings can be offset during installation to counteract creep and prestress shortening (39)

Advanced Features

- **Service Load Management:** External restraining elements designed to break at $0.85\sum FDT$ to prevent yielding under service conditions (39)
- **Secondary Earthquake Resisting Systems:** Integration with backup systems for events exceeding design seismic hazard levels (39)
- **Environmental Protection:** Advanced protection against contaminants, vandalism, and corrosion (39)

PVAMU Recommendation:

Pilot-deploy smart/hybrid bearings on critical infrastructure (e.g., major river crossings, key transport links) under PVAMU supervision, with mandatory real-time monitoring and 5-year field validation before broader roll-out.

Justification:

- Latest research and field trials show smart bearing systems equipped with wireless sensors, accelerometers, and IoT connectivity can deliver 89%–95% accuracy in identifying faults and degradation before structural issues become critical.
- These technologies support a predictive maintenance regime, potentially reducing manual inspection costs and downtime.
- Long-term field data is still maturing, warranting a measured, evidence-building approach prior to full specification for all new bridges.

Caution:

High up-front cost ($22,000+ per bearing) and specialized maintenance demand careful selection of pilot sites and ongoing cost-benefit analysis.

3. Cost and Implementation

Table 1: Comparison of Bearing Types

Technology Type	**Unit Cost (USD)**	**Key Features**	**Implementation Status**
IoT-Enabled Smart Bearing	$VARIES	Real-time monitoring, predictive analytics	Pilot phase
Advanced Seismic Isolation (LRB)	$VARIES	Energy dissipation, sophisticated testing	Pre-qualified by Caltrans
Advanced Seismic Isolation (FPSB)	$VARIES	Friction-based energy dissipation	Pre-qualified by Caltrans

Table Summary: Advanced bearing technologies command premium pricing but offer sophisticated monitoring and performance capabilities that justify costs for critical applications.

4.Field Status and Validation

Current Implementation:

- Advanced seismic isolation bearings are pre-qualified by Caltrans with established design procedures (39)

- IoT-enabled bearings have four North American installations providing two years of stable performance data
- Regulatory framework provided by Caltrans MTD-20-22 for comprehensive design and implementation guidelines (39)

5.Testing and Quality Control:

- Comprehensive testing protocols ensure performance validation before installation (39)
- Specialized design requirements mandate Project Specific Seismic Design Criteria (PSDC) and approval from earthquake engineering specialists (39)
- Sophisticated modeling requirements including nonlinear time history analysis capabilities (39)

6.Limitations and Risk Factors

6.1 Environmental Considerations:

- Lead-rubber bearings may stiffen in low temperature zones, affecting performance (39)
- FPSB systems require enhanced corrosion protection due to metallic components (39)
- Periodic inspection and potential replacement required during bridge design life (39)

6.2 Implementation Challenges:

- Limited long-term field validation data for IoT-enabled systems
- Higher initial costs compared to conventional bearing technologies
- Specialized installation and maintenance requirements (39)

7. Critical Assessment

The combination of advanced seismic isolation technology and smart monitoring capabilities represents a significant advancement in bridge bearing systems. The Caltrans MTD-20-22 specifications provide a comprehensive framework for implementing sophisticated bearing technologies with rigorous testing and validation procedures (39). However, the emerging nature of IoT-enabled monitoring systems requires continued pilot deployment and performance validation.

8. Resiliency Indicators:

- Automated alerts when displacement exceeds design by 20%
- Continuous monitoring of bearing performance parameters (39)
- Early detection of seal degradation or performance anomalies

9. Integrity Thresholds:

- Ultimate displacement capacity ≥ 1.5DT without shear failure (39)
- Bearing forces must remain within design performance curves (39)
- No tension conditions under seismic loading (39)

10. Risk Mitigation:

- Follow established Caltrans testing and validation procedures (39)
- Implement redundant monitoring systems for critical applications
- Establish comprehensive maintenance protocols for advanced technologies

11. Bridge Bearing Selection by Climate Zone and Bridge Type

Climate conditions significantly influence bearing performance, requiring specialized selection criteria for different environmental zones and bridge configurations.

Table 2: Summary of Optimal Bridge Bearing Selections and Expected Performance Across Different Bridge Types and Climate Zones

Bridge Type	Climate Zone	Bearing Type	Performance Explanation
Cantilever	Hot/Arid	Pot	Good
Cantilever	Moderate	Spherical	Good
Cantilever	Cold/Freeze	Spherical with heating	Good
Cantilever	Marine/Coast	Spherical with corrosion protection	Good
Truss	Hot/Arid	Pot	Good
Truss	Moderate	Pot	Good
Truss	Cold/Freeze	Pot with POM seals	Bad
Truss	Marine/Coast	Pot with corrosion protection	Good
Beam/Girder	Hot/Arid	Elastomeric	Good
Beam/Girder	Moderate	Elastomeric	Good
Beam/Girder	Cold/Freeze	Elastomeric low-temp	Good
Beam/Girder	Marine/Coast	Elastomeric marine grade	Good
Arch	Hot/Arid	Elastomeric	Good
Arch	Moderate	Elastomeric	Good
Arch	Cold/Freeze	Pot with POM seals	Bad
Arch	Marine/Coast	Elastomeric marine grade	Good
Suspension	Hot/Arid	Spherical	Good
Suspension	Moderate	Spherical	Good
Suspension	Cold/Freeze	Spherical with heating	Good
Suspension	Marine/Coast	Spherical with corrosion protection	Good
Cable-Stayed	Hot/Arid	Spherical	Good
Cable-Stayed	Moderate	Spherical	Good
Cable-Stayed	Cold/Freeze	Spherical with heating	Good
Cable-Stayed	Marine/Coast	Spherical with corrosion protection	Good

Bridge Bearing Selection Matrix by Climate Zone and Bridge Type

Chart Summary: This comprehensive matrix displays optimal bearing selection for six bridge types across four climate zones, with performance ratings indicating suitability and required modifications for each combination.

Chart Description: The climate zone matrix demonstrates how environmental conditions modify bearing selection requirements. Spherical bearings perform excellently across all climates for demanding structures, while elastomeric bearings excel in moderate conditions but require modifications for extreme environments.

Reference Justification: Matrix recommendations are based on field performance data from the Sunshine Skyway Bridge marine environment (1,7,9), Fred Hartman Bridge hot/arid conditions (2,15) etc., and cold weather performance studies (12). Each climate zone recommendation incorporates documented performance characteristics and maintenance requirements.

12. Critical Assessment and Recommendations

Technology Selection Framework

12.1 Standard Highway Bridges (<400 ft spans):

Sunshine Skyway Bridge

Figure 12.1

Primary use: Elastomeric bearings

- **Justification:** Proven 38-year performance on Sunshine Skyway Bridge demonstrates reliability in challenging environments (17)
- **Cost Effectiveness:** Lowest 50-year life-cycle cost of $12,300 per bearing (11)

- **Maintenance:** Started June 15,2023 anticipating finish summer 2025 costing $7 million (usd) (40). DOT structures engineer say "It's functioning as expected and designed. We expect it to last 75 to 100 years." (41)
- **Risk :** Bridge built in 1988 using **Elastomeric bearings** repaired in 1997 due replacing some eroded bearings, 42 steel cables costing the florida DOT $2.6 million (usd)

12.2 Cable-Stayed and Long-Span Bridges:

Fred Hartman Cable Stayed Bridge

Figure 12.2

- **Primary use:** Spherical bearings

- **Justification:** 30-year validated performance on Fred Hartman Bridge with minimal maintenance (2,15)
- **Technical Advantage:** Superior accommodation of large movements and high loads (16)

High-Load Applications with Budget Constraints:

- **Primary Recommendation:** Pot bearings with polymer seals
- **Justification:** Advanced POM sealing technology extends service life to 50 years (3,13)
- **Maintenance Strategy:** Predictive maintenance protocols reduce unexpected failures (14)

13. Risk Assessment and Mitigation

13.1 Elastomeric Bearing Risks:

- **Primary Risk:** Shear rollover during seismic events when strain exceeds 150% (8)
- **Mitigation:** Limit design shear strain to 120%; install supplemental damping systems in high-seismic zones
- **Monitoring:** Deploy strain gauges for early warning detection (10)

13.2 Pot Bearing Risks:

- **Primary Risk:** Seal failure leading to piston seizure and uncontrolled stress transfer (3)
- **Mitigation:** Ultrasonic seal inspection every 5 years; retrofit with polymer seals; provide secondary shear keys.
- **Maintenance:** Establish predictive maintenance protocols based on seal pressure monitoring (13)

13.3 Temperature-Related Risks:

- **Disc Bearing Stiffening:** 15% rotation loss below -6°C requires low-temperature urethane or heating systems (12)
- **Spherical Bearing Performance:** PTFE lubrication effectiveness reduced in extreme cold; heating systems recommended (12)

14. Market Trends and Future Outlook

The global bridge bearing market demonstrates robust growth, with projections indicating expansion from $777.7 million in 2024 to $1,242.9 million by 2034, representing a 4.8% compound annual growth rate (17, 18). This growth is driven by infrastructure investment, aging bridge replacement needs, and adoption of advanced monitoring technologies (19).

Key Market Drivers:

- Infrastructure development investments in developing economies (17)
- Aging bridge replacement programs in developed countries (18)
- Advancement in smart monitoring and predictive maintenance technologies (4)
- Enhanced materials and manufacturing processes (19)

14.1 Technology Adoption Trends:

- Increasing integration of IoT sensors and wireless monitoring systems (4)
- Growing adoption of polymer sealing technologies for extended service life (3,13)
- Expanded use of seismic isolation systems in high-risk regions (12)

15. Conclusions

This comprehensive assessment demonstrates that bridge bearing selection requires evidence-based evaluation of performance, cost, and risk factors. The Sunshine Skyway Bridge provides compelling evidence for elastomeric bearing reliability in challenging environments (1,7,9), while the Fred Hartman Bridge validates spherical bearing performance for demanding applications (2,15). Advanced polymer sealing technology significantly extends pot bearing service life (3,13) and smart monitoring systems offer promising capabilities for predictive maintenance (4).

16. Summary of PVAMU Recommendations

Key Findings:

1. Elastomeric bearings remain the most cost-effective solution for standard applications, with 38-year field validation (1,7)
2. Spherical bearings provide superior performance for complex structures, justified by 30-year field experience (2,15)
3. Polymer-sealed pot bearings offer competitive alternatives with 50-year service life potential (3,13)
4. Smart bearing systems demonstrate excellent monitoring capabilities but require additional field validation (4)
5. Climate-specific selection criteria are essential for optimal performance in extreme environments (12)

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