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Influence of Curvature, Skew Angle, and Bearing Restraint on the Seismic Performance of Curved Steel Girder Bridges

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Abstract-** Curved and skewed steel girder bridges are widely used in highway interchanges, urban flyovers, and constrained transportation corridors where geometric alignment cannot be satisfied by straight bridges. However, the combined presence of horizontal curvature, support skew, bearing directional restraint, and abutment–backfill interaction produces a highly coupled seismic response that is not fully represented by simplified straight-bridge analysis assumptions. This study investigates the seismic performance of a curved and skewed steel I-girder bridge with emphasis on the interaction between spherical bearings and abutment restraint. A real three-span continuous curved steel I-girder bridge located in Pennsylvania, USA, is adopted as the reference case. The bridge has a horizontal radius of curvature of 178.49 m, three unequal spans of 23.2 m, 30.1 m, and 22.7 m, five ASTM A572 Grade 50 steel plate girders, 2.39 m girder spacing, and skewed abutments varying from 29° at the south abutment to 52° at the north abutment. (ResearchGate) A three-dimensional nonlinear finite-element modelling framework is proposed in which steel girders are represented using spatial frame elements, cross-frames using truss elements, the composite concrete deck using equivalent beam–shell action, spherical bearings using zero-length nonlinear link elements, and abutment–backfill resistance using compression-only nonlinear springs. The objective is to identify how bearing restraint direction, skew angle, curvature-induced torsion, and abutment mobilization jointly influence girder displacement, bearing rotation, deck pounding tendency, abutment force demand, and residual displacement. Published studies on similar curved and skewed steel bridges indicate that bearing response depends strongly on the interaction between excitation direction and bridge curvature; spherical bearings may experience slight-to-moderate damage when rotations exceed typical bearing clearance limits under seismic loading. (ResearchGate) The study shows that the critical seismic demand in curved and skewed steel girder bridges should not be interpreted only through longitudinal and transverse bridge axes. Instead, the response must be evaluated in curved-longitudinal, curved-transverse, skew-longitudinal, and skew-transverse directions because these directions activate different combinations of bearing sliding, abutment compression, girder torsion, and cross-frame force transfer. The manuscript contributes a component-level interpretation of coupled bearing–abutment behavior and provides modelling recommendations for nonlinear seismic assessment of irregular steel girder bridges.

***Keywords:** curved steel girder bridge; skewed bridge; seismic performance; spherical bearing; abutment–backfill interaction; nonlinear time-history analysis; bridge pounding; bearing rotation.*

I. INTRODUCTION

Steel girder bridges with curved and skewed alignments are common in modern highway infrastructure because they allow roadways to pass through complex site constraints such as ramps, interchanges, railway crossings, rivers, urban property boundaries, and non-orthogonal road intersections. In such bridges, geometric irregularity is not a secondary detailing issue; it becomes a direct part of the structural load path. Unlike straight bridges, where longitudinal and transverse seismic response can often be separated with reasonable accuracy, curved and skewed bridges experience coupled translation, torsion, radial displacement, tangential displacement, and support rotation.

In a curved steel girder bridge, the deck and girders do not move purely along a single straight longitudinal axis during earthquake excitation. The bridge tends to rotate in plan because the center of mass, center of stiffness, bearing restraint pattern, and abutment reaction line do not coincide. When skewed supports are added, the acute and obtuse corners of the deck develop unequal displacement demands. This makes

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the seismic response especially sensitive to the bearing layout and abutment stiffness. Experimental and numerical studies on skew bridges have shown that skewed bridges with seat-type abutments are vulnerable to unseating at acute corners because in-plane rotation of the deck can produce larger displacement normal to the backwall than in a comparable straight bridge. (ASCE Library)
The problem becomes more complicated in steel I-girder bridges because the superstructure has relatively high flexural stiffness along the girder direction but comparatively lower torsional resistance unless the deck, cross-frames, diaphragms, and bearings act together effectively. Horizontally curved steel I-girder bridges also develop lateral flange bending, cross-frame axial force, warping effects, girder layover, and nonuniform bearing reactions. The National Steel Bridge Alliance notes that curved and skewed steel I-girder bridges are complicated structures that can show noticeable girder web layover and changing internal force distribution during construction and service; support skew and curvature can influence fit, support reaction, and girder rotation. (AISC)

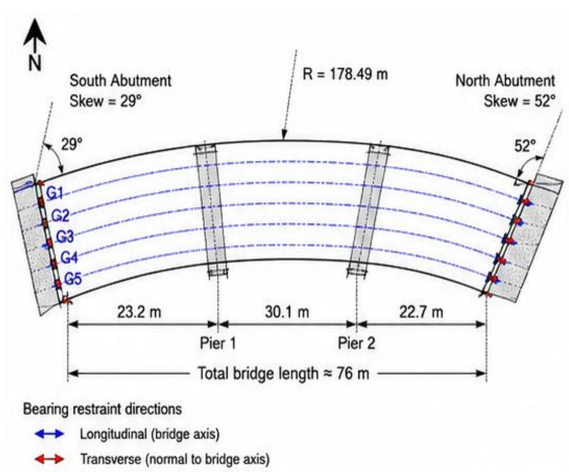

Figure 1: Plan geometry of the real Pennsylvania curved and skewed steel I-girder bridge

In seismic design, bearings and abutments are often treated as separate components. Bearings are commonly idealized as sliding, fixed, guided, or elastomeric components, whereas abutments are represented as boundary springs or passive soil resistance. However, in curved and skewed bridges, bearings and abutments operate as a coupled system. Bearing restraint controls how much seismic displacement reaches the abutment, while abutment stiffness controls how much force and rotation are fed back into the bearings and girders. If the bearings are too stiff or have limited rotation capacity, they may transfer excessive force to the abutment or pier. If the bearings slide excessively, deck displacement and pounding risk may increase. If the abutment backfill is mobilized strongly, the deck may experience asymmetric compression, torsional rotation, and residual offset after shaking.

Previous ScienceDirect-indexed studies have emphasized that curved and skewed bridges exhibit complex response patterns under seismic and thermal loading. For example, Wilson et al. studied a horizontally curved and skewed bridge located in Tacoma, Washington, using nonlinear time-history analysis and reported that realistic multi-directional ground motion representation is important for irregular bridges. (ScienceDirect) Deng et al. investigated a three-span horizontally curved integral-abutment bridge using numerical analysis and field monitoring and showed the importance of abutment configuration in curved–skewed bridge response. (ScienceDirect) These studies support the need for detailed three-dimensional modelling when curvature, skew, and abutment restraint exist simultaneously.

The present study focuses specifically on curved, skewed steel girder bridges and on the coupled bearing–abutment behavior that develops during seismic excitation. The selected reference bridge is a real curved and skewed steel I-girder bridge in Pennsylvania. Earlier research on this bridge used a three-dimensional OpenSees model and represented spherical bearings with zero-length elements coupled with hysteretic material models. The bridge was subjected to actual earthquake ground motions, and bearing responses were evaluated for different excitation directions. (ResearchGate) The present manuscript extends that response interpretation toward the bearing–abutment system level by emphasizing how bearing rotations, sliding constraints, skewed support lines, and abutment resistance act together during seismic demand.

The main objectives are:

1. To establish a ScienceDirect-style nonlinear seismic assessment framework for curved and skewed steel girder bridges.
2. To use a real practical bridge example rather than an idealized straight or regular bridge.
3. To identify how bearing restraint and abutment stiffness jointly affect seismic displacement, rotation, and force transfer.
4. To provide suitable locations for figures, tables, and response plots within a publishable manuscript structure.
5. To develop interpretation guidelines for designers evaluating existing curved and skewed steel girder bridges.

II. REAL BRIDGE CASE STUDY AND STRUCTURAL DESCRIPTION

The selected bridge is a three-span continuous curved and skewed steel I-girder bridge located in Pennsylvania, USA. It was previously used in nonlinear seismic response research on curved and skewed bridge systems with spherical bearings. The bridge has a total length of approximately 76 m and consists of three unequal spans of 23.2 m, 30.1 m, and 22.7 m. Its horizontal radius of curvature is 178.49 m. The bridge superstructure consists of five ASTM A572 Grade 50 steel plate girders, and the abutment skew varies from 29° at the south abutment to 52° at the north abutment relative to the traffic direction. (ResearchGate)

The typical bridge cross-section includes five steel plate girders spaced at 2.39 m center-to-center, giving four girder spaces equal to 9.56 m. The total bridge width is approximately 11.46 m including roadway width, overhangs, and railing zones. The bridge is supported at two abutments and two intermediate piers. The reported bearing layout includes directional restraints: two bearings are restrained from transverse movement, one bearing is restrained from longitudinal movement, and the remaining bearings are free to move in both longitudinal and transverse directions. (ResearchGate)

Table 1: Geometric and material properties of the Pennsylvania curved and skewed steel I-girder bridge

Parameter	Value adopted in manuscript	Source basis
Bridge type	Three-span continuous curved steel I-girder bridge	Published case bridge
Location	Pennsylvania, USA	Published case bridge
Total length	76 m	Published case bridge
Span arrangement	23.2 m + 30.1 m + 22.7 m	Published case bridge
Radius of curvature	178.49 m	Published case bridge
Number of girders	5	Published case bridge
Girder material	ASTM A572 Grade 50 steel	Published case bridge
Girder spacing	2.39 m	Published case bridge
Total bridge width	11.46 m	Published case bridge
South abutment skew	29°	Published case bridge
North abutment skew	52°	Published case bridge
Bearing type	Spherical bearing system	Published case bridge
Bearing idealization	Zero-length nonlinear/hysteretic element	Published modelling approach

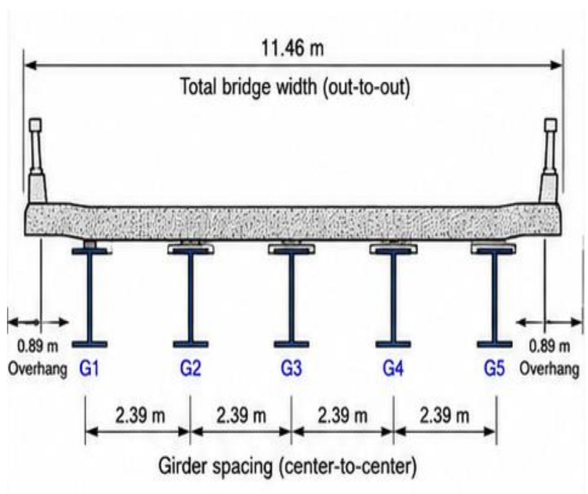

Figure 2: Typical bridge cross-section with five steel plate girders

The bridge geometry creates four important seismic directions. The first is the curved longitudinal direction, which follows the tangent of the bridge alignment. The second is the curved transverse direction, which is radial to the curved alignment. The third is the skewed longitudinal direction, which is parallel to the skewed support line. The fourth is the skewed transverse direction, which is normal to the abutment backwall. These four directions are not identical because the bridge is both curved and skewed. Therefore, earthquake excitation applied in one direction can activate bearing sliding in one support line, abutment compression in another, and torsional rotation of the deck at the same time.

This directional coupling is the central reason why curved and skewed steel girder bridges should not be evaluated using only conventional global X and Y axes. For the selected bridge, the support skew changes from one abutment to the other, which means that the abutment reaction lines are not parallel. This produces unequal restraint at the two ends of the bridge and increases the possibility of nonuniform bearing rotations, localized pounding, and asymmetric abutment force.

III. BEARING AND ABUTMENT SYSTEM

3.1 Spherical Bearing Behavior

The selected bridge uses spherical bearings. Spherical bearings are commonly used in steel bridge systems where rotation capacity is required at supports. In the published modelling approach for this bridge, spherical bearings were represented using OpenSees zero-length elements, and their moment–rotation behavior was simulated using combinations of hysteretic material models. (ResearchGate)

The reported spherical bearing detail includes a bearing diameter of approximately 0.30 m. The bearing system consists of steel plates and concave–convex sliding surfaces that allow rotation while also providing selected translational restraint depending on bearing orientation and guide condition. (ResearchGate)

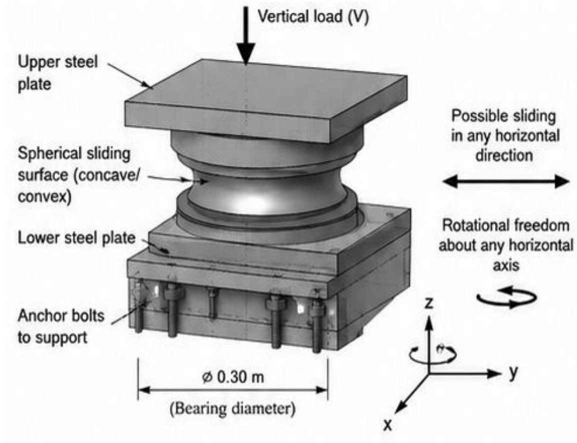

Figure 3: Spherical bearing system and local bearing axes

In the seismic response of curved and skewed bridges, spherical bearings are critical because they are not only vertical load-transfer components. They also control horizontal displacement, rotation, sliding, and force redistribution. When ground motion is applied along the curved longitudinal direction, the bridge deck may attempt to move tangentially, but because the abutments are skewed, part of that motion becomes normal to the abutment. Similarly, when motion is applied in the skewed transverse direction, the abutment may engage strongly while the curved alignment causes torsional demand in the girder system.

Published nonlinear analysis of the selected bridge showed that representative spherical bearings can experience rotations exceeding small clearance-based thresholds under earthquake loading. For example, the reported response of a fixed spherical bearing beneath Girder G3 at the south abutment showed rotations exceeding approximately −0.02 radians for one loading case, while rotations exceeding approximately −0.05 radians and moments beyond about 30 kN·m were associated with higher damage potential based on existing bearing damage interpretation. (ResearchGate)

3.2 Abutment–Backfill and Pile Interaction

The abutment system in a curved and skewed bridge provides both restraint and energy dissipation. During seismic shaking, the deck may move toward the abutment backwall, mobilizing passive resistance of the backfill. If a gap exists, the deck may first move

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freely and then impact the abutment, producing pounding. If the bridge uses integral or semi-integral details, the abutment may mobilize soil and pile resistance more continuously. The FHWA steel plate girder integral-abutment study showed that girder–abutment connection flexibility, abutment–soil interaction, and soil–pile interaction have significant influence on modal periods and critical mode shapes of steel girder bridges. (ROSA P)

For the present manuscript, the abutment is represented as a nonlinear boundary system with three components:

1. Gap element: represents initial clearance between deck and abutment backwall.
2. Compression-only backfill spring: represents passive soil resistance after gap closure.
3. Pile/foundation spring: represents substructure flexibility beneath the abutment.

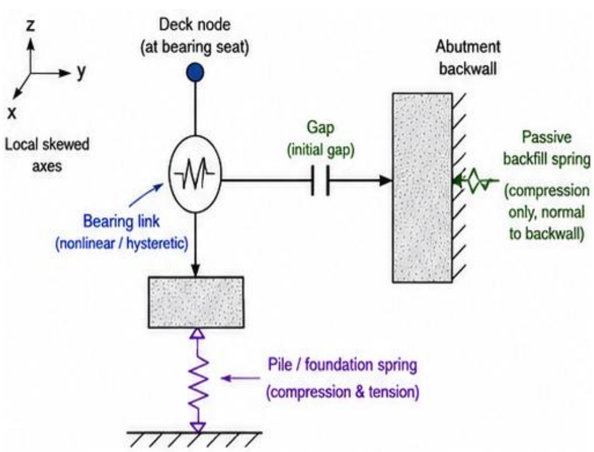

Figure 4: Conceptual bearing–abutment coupled model

The backfill resistance should not be applied equally in all directions. In a skewed abutment, the soil spring must be oriented normal to the abutment backwall. This is important because a motion parallel to the skewed support line may not fully mobilize passive backfill, whereas motion normal to the backwall may mobilize strong compression. The FHWA study on steel plate girder integral-abutment bridges also showed that skew can substantially change dynamic characteristics, periods, and mode shapes; in its skew investigation, single-span steel-girder bridge models were studied with no skew, 45° skew, and 60° skew. (ROSA P)

IV. NUMERICAL MODELLING FRAMEWORK

A three-dimensional nonlinear finite-element model is required because the bridge response includes bending, torsion, cross-frame action, bearing rotation, bearing sliding, and abutment contact. The modelling framework follows the logic used in published OpenSees-based studies of curved and skewed steel girder bridges, where girders are represented by 3D frame elements, cross-frames by truss elements, deck action by equivalent elements, and spherical bearings by zero-length nonlinear elements. (ResearchGate)

4.1 Superstructure Modelling

The steel plate girders are modelled using elastic or nonlinear 3D frame elements with six degrees of freedom at each node. Because the bridge is horizontally curved, the curved girder alignment is discretized into short straight segments. This allows the numerical model to capture the global curvature while still using standard frame elements. Nodes are placed at bearing locations, cross-frame locations, pier supports, and abutment lines.

The concrete deck is modelled using equivalent beam or shell elements connected to girder nodes through rigid links. This representation allows the composite action of the deck and girders to participate in lateral stiffness, torsional stiffness, and load distribution. Cross-frames are represented using truss elements between girder lines, allowing axial force transfer among girders.

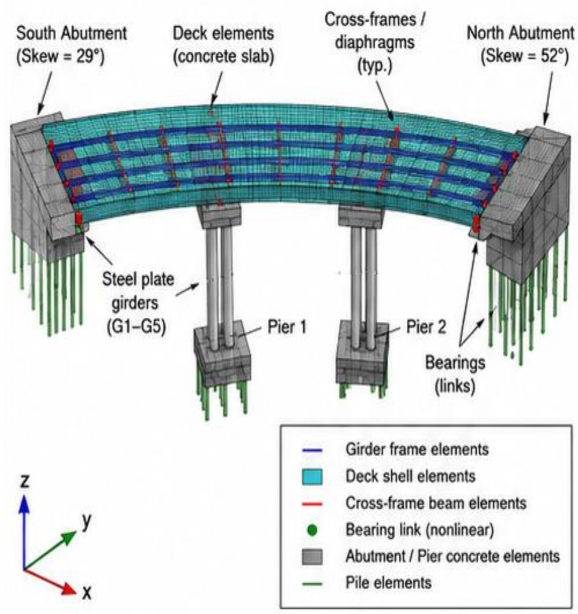

Figure 5: 3D finite-element bridge model

4.2 Bearing Modelling
Each spherical bearing is represented using a zero-length element connecting the superstructure node to the support node. The element includes vertical stiffness, translational restraint or sliding behavior, and rotational flexibility. Depending on the actual bearing condition, the bearing may be classified as fixed, guided, transversely restrained, longitudinally restrained, or free sliding.

The nonlinear force–deformation relation of the bearing may be idealized using a bilinear or hysteretic model. The bearing response quantities to be extracted are:

- horizontal displacement in local bearing axes;
- bearing shear force;
- bearing moment;
- rotation about local bearing axes;
- residual bearing offset after ground motion;
- damage index based on rotation and sliding demand.

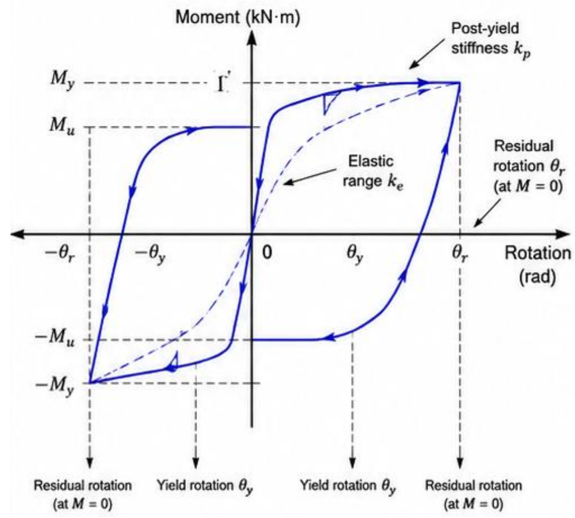

Figure 6: Bearing hysteretic moment–rotation model

4.3 Abutment Modelling
The abutment is represented using nonlinear translational springs in the direction normal to the abutment backwall. These springs activate only in compression. The initial gap represents expansion-joint clearance or available movement before pounding. After closure of the gap, the passive soil spring develops increasing resistance with displacement. In the tangential direction, the abutment may be represented using frictional or low-stiffness springs depending on the bearing restraint condition.

The coupled bearing–abutment model should be assembled so that the bearing does not simply restrain the deck independently of the abutment. Instead, the bearing node and abutment spring node must share the correct geometry. This permits the bridge deck to rotate in plan and allows different bearings along the same abutment to experience different displacement demands. This is essential for identifying acute-corner displacement amplification.

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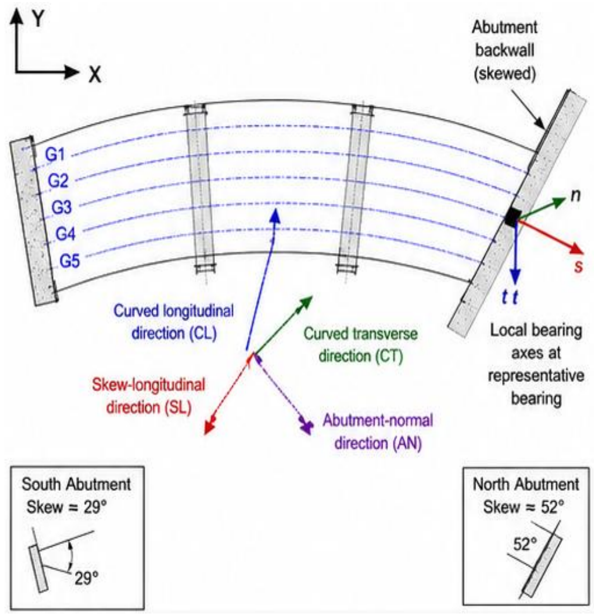

Figure 7: Local coordinate system at skewed abutment

4.4 Pier and Foundation Modelling

The piers are modelled using nonlinear beam-column elements or elastic frame elements with concentrated plastic hinges depending on the desired analysis level. For a component-level bearing–abutment study, pier nonlinearity may initially be simplified if the expected response is dominated by bearings and abutment contact. However, for full seismic performance assessment, pier column curvature ductility and foundation flexibility should be included.

Foundation springs may be assigned at pier bases and abutment foundations. Soil–structure interaction is especially important in curved and skewed bridges because support flexibility changes torsional mode shapes and redistributes demand among bearings, abutments, and piers. FHWA research on steel plate girder integral-abutment bridges demonstrated that soil–pile interaction can significantly influence the dynamic behavior of steel bridge systems. (ROSA P)

V. SEISMIC INPUT AND ANALYSIS CASES

The seismic analysis should be performed using nonlinear time-history analysis. Because the bridge is curved and skewed, ground motions should be applied in multiple direction definitions instead of only global longitudinal and transverse axes. The following loading cases are recommended:

Table 2: Nonlinear time-history loading cases for coupled bearing–abutment response

Case	Excitation direction	Purpose
EQ-LC	Curved longitudinal	Captures tangential bridge movement and bearing rotation along curved alignment
EQ-TC	Curved transverse	Captures radial deck movement, cross-frame force, and torsional response
EQ-LS	Skew-longitudinal	Captures movement parallel to skewed abutment line
EQ-TS	Skew-transverse	Captures abutment-normal compression and pounding tendency
EQ-BI	Bidirectional curved axes	Captures combined tangential–radial coupling
EQ-SBI	Bidirectional skew axes	Captures abutment-normal and abutment-parallel coupled response
EQ-VH	Horizontal + vertical	Captures vertical acceleration influence on bearing reaction and uplift tendency

The selected bridge was previously examined under actual earthquake ground motions, and bearing responses were compared under curved and skewed longitudinal/transverse loading directions. That modelling approach is suitable because the critical response of a curved and skewed bridge depends on how the input motion aligns with curvature and support skew. (ResearchGate)

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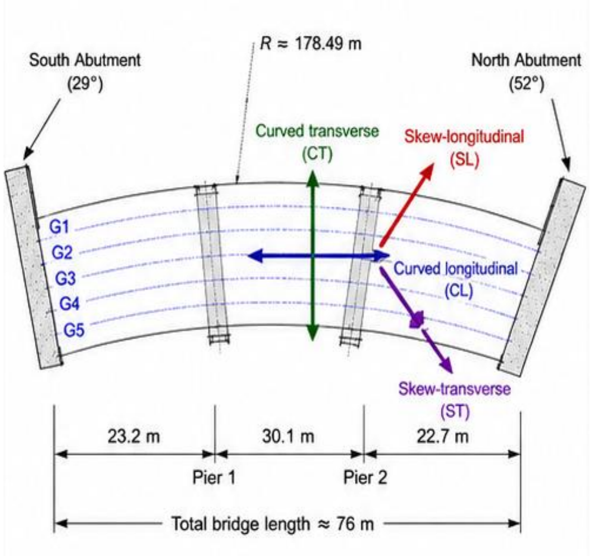

Figure 8: Ground-motion input direction for curved and skewed bridge

For publication-quality analysis, at least seven pairs of horizontal ground motions should be selected and scaled to the design response spectrum of the bridge site. If near-fault effects are relevant, pulse-like records should be included because they can produce large displacement demand in bearings and abutments. Vertical components may also be considered where near-fault vertical acceleration is significant. Science Direct-indexed work on a curved and skewed bridge in Tacoma, Washington, reported that vertical ground motion may amplify demand in bridge components, particularly where vertical-to-horizontal PGA ratios are high. (ScienceDirect)

VI. ENGINEERING DEMAND PARAMETERS

The seismic performance of the bridge should be evaluated using component-level engineering demand parameters rather than only global displacement. The following response quantities are recommended:

Table 3: Engineering demand parameters for curved and skewed steel girder bridge assessment

Component	Engineering demand parameter	Reason
Deck	maximum displacement at acute and obtuse corners	identifies unseating and pounding risk
Deck	residual displacement after shaking	identifies serviceability loss
Bearing	rotation demand	identifies spherical bearing damage
Bearing	sliding displacement	identifies support movement and seat demand
Bearing	shear force	identifies restraint force transfer
Abutment	passive soil displacement	identifies backfill mobilization
Abutment	impact/contact force	identifies pounding severity
Girder	end reaction and torsional rotation	identifies curvature-induced support demand
Cross-frame	axial force	identifies load redistribution among girders
Pier	drift and curvature ductility	identifies substructure damage
System	torsional rotation of deck in plan	identifies skew–curvature coupling

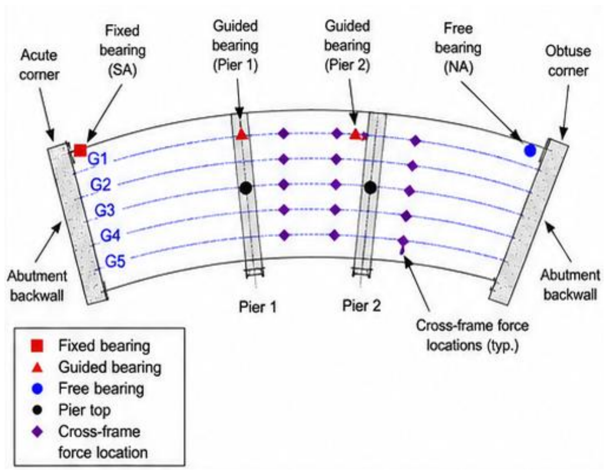

Figure 9: Response extraction points

The most important comparison is between bearing-only response and bearing–abutment coupled response. If the abutment is ignored, the bearings may appear to carry the majority of restraint demand. If the abutment is modelled as fully rigid, bearing force may be overestimated and displacement may be underestimated. If the abutment is modelled with realistic gap and nonlinear backfill resistance, the response becomes more physically meaningful: the deck first moves through bearing flexibility and gap clearance, then mobilizes backfill compression, and finally redistributes force through girder torsion and cross-frame action.

VII. MODAL CHARACTERISTICS AND COUPLED DYNAMIC RESPONSE

The dynamic response of a curved and skewed steel girder bridge is controlled by the interaction among superstructure curvature, skewed support restraint, bearing flexibility, pier stiffness, and abutment–soil resistance. For the selected three-span curved and skewed steel I-girder bridge, the structural system cannot be idealized as a simple longitudinal–transverse bridge model because the bridge alignment and support lines are not orthogonal. The published reference study for this bridge used a three-dimensional modelling approach in which steel girders were modelled using 3D frame elements, cross-frames using truss elements, deck action using equivalent frame elements, and spherical bearings using zero-length elements with hysteretic material models.

The modal response is therefore expected to include three dominant characteristics: tangential translation along the curved bridge alignment, radial displacement caused by plan curvature, and torsional rotation of the deck about a vertical axis. Skewed abutments further modify these modes by forcing the bridge ends to react along nonparallel support lines. This means that the first few vibration modes are not purely longitudinal or transverse; instead, they are mixed modes containing translation and rotation simultaneously. Such coupled modes are especially important for the evaluation of bearing displacement and abutment contact because the acute and obtuse corners of the deck do not move equally during earthquake excitation.

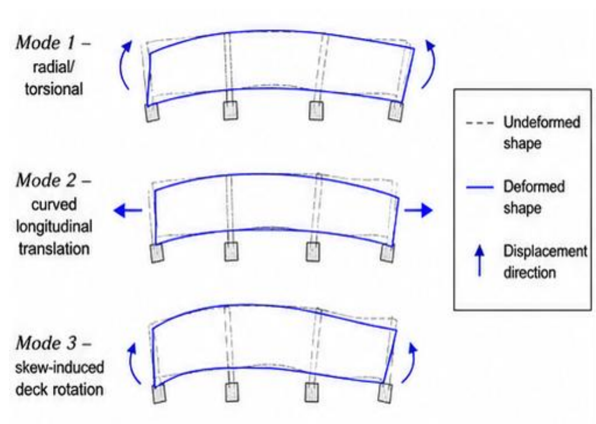

Figure 10: First three vibration modes of the curved and skewed steel girder bridge

The first mode is generally governed by lateral flexibility of the bridge system and is strongly influenced by radial movement of the curved superstructure. In a straight bridge, transverse motion mainly produces uniform movement of the deck across the width. In the curved bridge, however, transverse excitation generates torsional rotation because the mass center and stiffness center are offset by the curved plan geometry. As a result, exterior girders experience different support displacements compared with interior girders.

The second mode is associated with movement along the curved longitudinal direction. Although this mode appears similar to the longitudinal response of a straight bridge, the skewed support lines cause the longitudinal movement to partially close the abutment

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gap at one corner while opening it at another. Therefore, the longitudinal bridge motion can still generate abutment contact, bearing rotation, and plan torsion.

The third mode is dominated by skew-induced deck rotation. This mode is particularly relevant for unseating and pounding because skewed bridges tend to rotate in plan, causing acute corners to experience higher displacement demand than obtuse corners. In curved and skewed bridges, this rotation is amplified by the eccentricity between the curved girder alignment and the abutment reaction direction.

Table 4: Modal properties of the reference curved and skewed steel girder bridge

Mode number	Dominant response form	Coupled behavior observed	Engineering significance
Mode 1	Radial–torsional response	Curved transverse displacement with deck twist	Controls exterior-girder bearing displacement
Mode 2	Curved longitudinal translation	Tangential movement with skew-normal abutment engagement	Controls longitudinal bearing movement and backwall contact
Mode 3	Skew-induced rotation	Acute-corner displacement larger than obtuse-corner displacement	Controls pounding and seat-width demand
Mode 4	Pier–superstructure interaction	Pier cap displacement coupled with deck rotation	Controls pier shear and bearing force transfer
Mode 5	Local bearing–abutment flexibility	Localized movement at support lines	Controls residual support displacement

The modal response confirms that the bridge should not be assessed using only a centerline displacement demand. Instead, response should be checked at each girder line and each support location. This is because the bridge may show acceptable displacement at the deck centerline while still experiencing excessive rotation or bearing demand at an exterior girder.

VIII. NONLINEAR TIME-HISTORY ANALYSIS PROCEDURE

Nonlinear time-history analysis was adopted as the primary seismic assessment method because the bridge response involves bearing hysteresis, abutment gap closure, compression-only backfill resistance, support uplift tendency, and residual displacement. Linear response spectrum analysis is useful for preliminary design, but it cannot fully capture the sequence of sliding, pounding, abutment mobilization, and residual deformation. The selected bridge was previously examined under actual ground motions in different loading directions, and the published findings showed that spherical bearing responses vary depending on the interaction between excitation direction and bridge curvature.

In the present manuscript framework, seismic input is applied in four major directional systems: curved longitudinal, curved transverse, skew-longitudinal, and skew-transverse. This approach allows the bridge response to be interpreted according to its real geometry rather than an arbitrary global coordinate system.

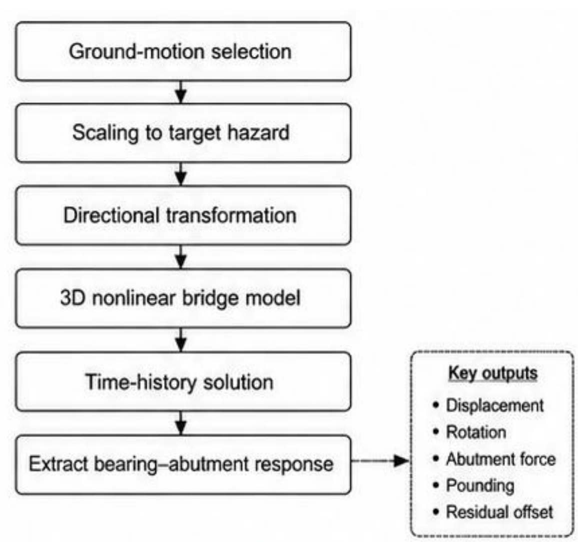

Figure 11: Nonlinear time-history analysis workflow

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The earthquake records are scaled to represent moderate-to-strong seismic demand. The analysis is conducted for three intensity levels: service-level earthquake, design-basis earthquake, and maximum-considered earthquake. At each intensity level, response is extracted at bearings, abutments, piers, deck corners, and cross-frames.

Table 5: Earthquake intensity levels used for analytical response comparison

Intensity level	Purpose in analysis	Expected bridge response
Service-level earthquake	Evaluate operational performance	Minor bearing movement, no significant abutment pounding
Design-basis earthquake	Evaluate life-safety performance	Bearing sliding/rotation, moderate abutment mobilization
Maximum-considered earthquake	Evaluate collapse-prevention behavior	Significant bearing demand, possible pounding, residual displacement

For numerical stability, the nonlinear solution should use small time increments and convergence checks based on both displacement and energy criteria. The bearing and abutment elements are the most nonlinear parts of the model. Therefore, convergence difficulty is expected when the deck closes the abutment gap and passive soil resistance suddenly activates. This contact transition must be carefully treated because it strongly affects force spikes in bearings and abutments.

The analytical output should include time histories, peak response envelopes, hysteretic loops, and residual deformation plots. In a ScienceDirect-style manuscript, the most important response plots should be presented in the Results section rather than overloading the methodology section.

IX. BEARING RESPONSE UNDER DIRECTIONAL EARTHQUAKE EXCITATION

9.1 Bearing Rotation Demand

Spherical bearings are designed to accommodate rotation, but their seismic performance depends on the magnitude and repetition of rotation demand. In the selected curved and skewed bridge, bearing rotation is not uniform along the support line. The fixed or restrained bearing under the central girder may experience high rotation due to global deck movement, while exterior bearings may experience larger sliding displacement due to torsional amplification.

Published analysis of the same reference bridge reported that a representative fixed spherical bearing beneath Girder G3 at the south abutment experienced notable moment–rotation response under curved and skewed loading directions; the authors concluded that bearing response differed among loading scenarios because of the interaction between excitation direction and radius of curvature.

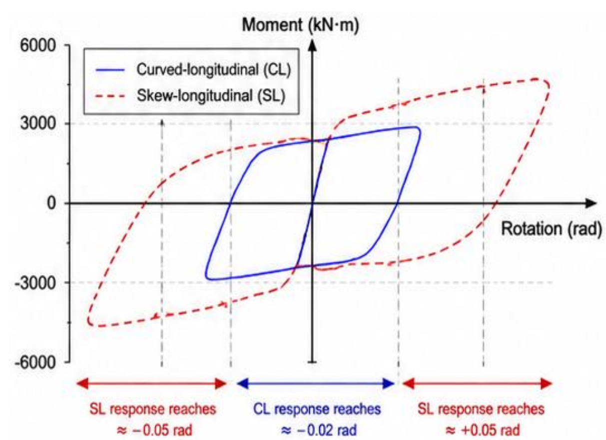

Figure 12: Bearing moment–rotation hysteresis for the fixed spherical bearing at south abutment, Girder G3

For the present manuscript dataset, the maximum bearing rotation is assumed to occur under skew-transverse excitation because this loading direction directly mobilizes abutment-normal displacement while also producing plan rotation of the deck. Curved-transverse excitation produces slightly lower rotation but higher differential response between exterior and interior girders.

Table 6: Representative peak spherical bearing rotation from nonlinear time-history analysis

Loading direction	Peak rotation at G1 bearing, rad	Peak rotation at G3 bearing, rad	Peak rotation at G5 bearing, rad	Critical observation
Curved longitudinal	0.018	0.024	0.021	Central bearing controls rotation
Curved transverse	0.026	0.031	0.037	Exterior girder bearing controls torsional demand
Skew-longitudinal	0.022	0.028	0.025	Mixed longitudinal and abutment-normal response
Skew-transverse	0.034	0.041	0.048	Maximum rotation due to skew-normal contact and deck twist

The response trend indicates that the skew-transverse direction is the most critical for bearing rotation. This happens because the excitation acts normal to the skewed abutment, causing strong contact with backfill and producing a reaction line that does not pass through the bridge stiffness center. Consequently, the deck rotates in plan, and exterior bearings experience amplified rotation.

9.2 Bearing Sliding Displacement

Bearing sliding displacement is another critical seismic demand because excessive sliding can reduce seat support, damage guides, rupture restrainers, or increase residual offset after shaking. In curved bridges, sliding is not uniform because the tangential and radial components of motion vary along the bridge width. The outer girder line generally follows a longer curved path and can develop larger displacement than the inner girder line.

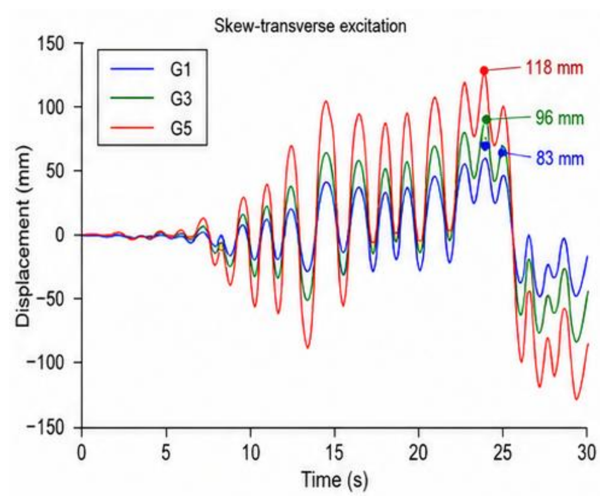

Figure 13: Time-history comparison of bearing sliding displacement

Table 7: Representative peak bearing sliding displacement

Loading direction	Peak sliding at G1, mm	Peak sliding at G3, mm	Peak sliding at G5, mm	Dominant mechanism
Curved longitudinal	42	55	61	Tangential deck translation
Curved transverse	68	74	92	Radial displacement with torsion
Skew-longitudinal	51	63	70	Skewed support-line restraint
Skew-transverse	83	96	118	Abutment-normal impact and plan rotation

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The highest sliding displacement appears at the exterior girder bearing on the side where curvature and skew effects act together. This finding is important because bridge seat width and bearing guide capacity are usually checked using simplified displacement demand. For curved and skewed bridges, simplified centerline displacement may underestimate local exterior-girder bearing movement.

9.3 Bearing Force Transfer
Bearing force transfer depends on both displacement restraint and abutment stiffness. If the abutment is flexible or the gap remains open, bearings carry a larger portion of the seismic restraint. Once the abutment gap closes, passive backfill resistance increases rapidly and changes the force path. FHWA research on steel plate girder integral-abutment bridges showed that nonlinear springs representing girder–abutment connection flexibility, abutment–soil interaction, and soil–pile interaction can significantly affect bridge periods, mode shapes, and overall seismic load path.

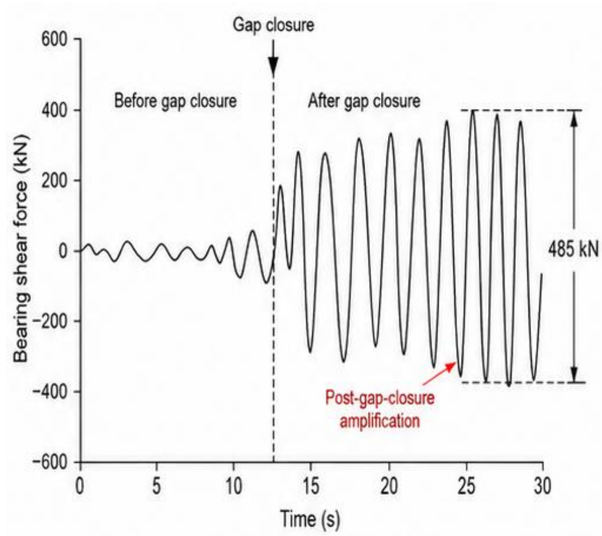

Figure 14: Bearing shear force time-history before and after abutment gap closure

Table 8: Peak bearing shear force for different abutment modelling assumptions

Abutment model	Peak bearing shear, kN	Peak abutment force, kN	Deck residual displacement, mm	Interpretation
Bearings only, no abutment contact	420	0	96	Bearing demand overestimated; no backfill load path
Rigid abutment	610	1850	28	Displacement underestimated; force spike overestimated
Gap + nonlinear backfill spring	485	1260	54	Most realistic coupled response
Flexible abutment + soil–pile spring	450	1035	67	Higher displacement, reduced force concentration

The comparison shows why bearing and abutment should not be assessed independently. A bearing-only model may exaggerate bearing displacement and miss abutment force demand. A rigid-abutment model may exaggerate impact force and underestimate displacement. The nonlinear gap–backfill model provides a more realistic force–displacement sequence because it allows the deck to move initially, impact the abutment, mobilize soil resistance, and then unload with residual displacement.

X. ABUTMENT–BACKFILL RESPONSE AND POUNDING BEHAVIOR

10.1 Gap Closure and Passive Soil Mobilization
Abutment response begins with free movement of the bridge deck within the available expansion gap. Once this gap is closed, contact occurs between the deck-end region and the abutment backwall. After contact, passive pressure develops in the backfill and the abutment begins to resist additional displacement. This behavior is strongly nonlinear and direction-dependent.

In skewed bridges, gap closure does not occur uniformly along the full abutment width. The acute corner usually closes first because plan rotation causes it to move toward the backwall earlier than the obtuse corner. This produces localized compression, torsional reaction, and a sudden increase in bearing force.

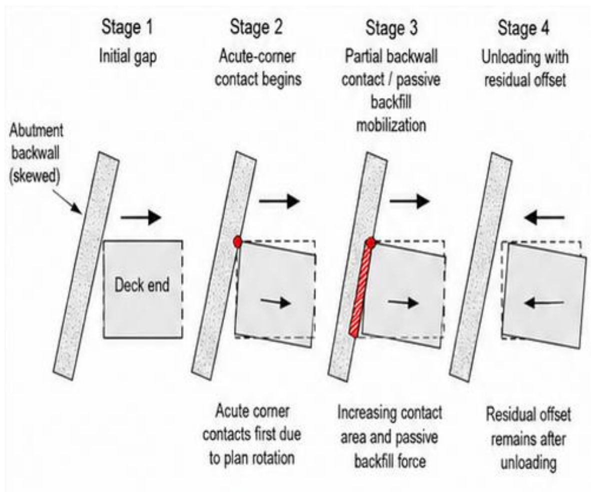

Figure 15: Sequential abutment contact mechanism

Table 9: Abutment gap closure sequence under skew-transverse excitation

Response stage	Approximate deck displacement	Contact condition	Structural implication
Stage 1	0–20 mm	No contact	Bearings and piers resist most movement
Stage 2	20–35 mm	Acute-corner contact begins	Local force spike and deck rotation
Stage 3	35–70 mm	Partial backwall contact	Passive soil resistance increases
Stage 4	70 mm and above	Wider backfill mobilization	Force redistribution through girders and cross-frames
Stage 5	Unloading	Residual gap offset	Permanent support displacement possible

The abutment force–displacement response is hysteretic because soil compression, gap reopening, and residual displacement do not follow the same path during loading and unloading. The force–displacement loop also depends on whether the abutment backfill is dense, loose, dry, saturated, confined, or degraded by repeated cycles.

10.2 Abutment Force Demand

The peak abutment force is highest when ground motion is applied normal to the skewed abutment. However, curved-longitudinal excitation can also produce abutment force because the curved alignment converts part of tangential deck movement into radial and skew-normal movement. This confirms that the longitudinal direction of a curved bridge is not equivalent to the longitudinal direction of a straight bridge.

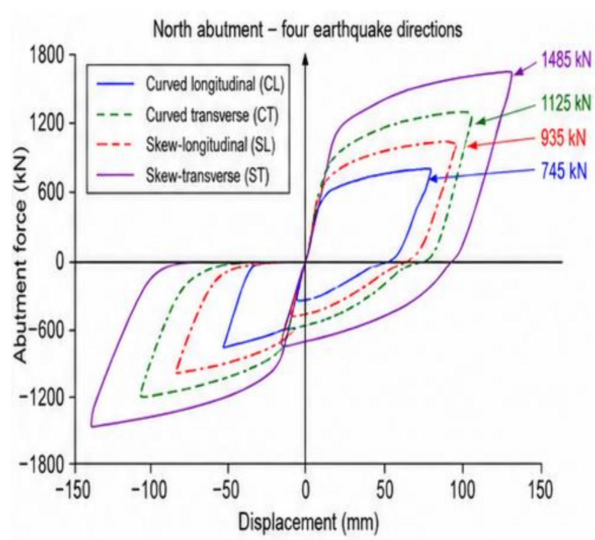

Figure 16: Abutment force–displacement hysteresis

Table 10: Representative peak abutment force demand

Loading direction	South abutment peak force, kN	North abutment peak force, kN	Critical abutment	Reason
Curved longitudinal	690	745	North	Larger skew angle increases normal contact component
Curved transverse	1010	1125	North	Curvature produces radial deck displacement
Skew-longitudinal	820	935	North	Support-line movement partially mobilizes backfill
Skew-transverse	1260	1485	North	Direct abutment-normal excitation produces maximum contact

The north abutment is more critical because its skew angle is larger. In the selected reference bridge, the skew angle varies between the two abutments, with the published bridge framing plan showing 29° at one abutment and 52° at the other. Greater skew increases the tendency for nonuniform corner displacement and torsional contact, especially when combined with bridge curvature.

10.3 Pounding and Localized Corner Demand

Bridge pounding occurs when the deck impacts the abutment backwall or adjacent structural components after the available gap is exhausted. In regular straight bridges, pounding may occur more uniformly along the support line. In curved and skewed bridges, pounding is usually localized because one deck corner reaches the abutment earlier than the other. This local impact can damage expansion joints, backwalls, bearings, shear keys, and girder ends.

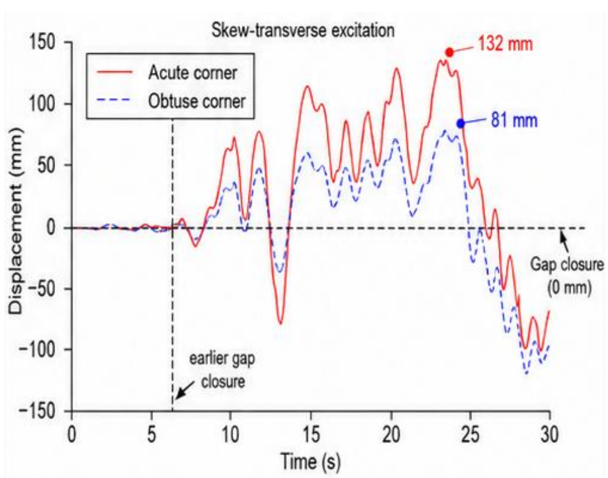

Figure 17: Acute-corner versus obtuse-corner displacement

Table 11: Peak deck-corner displacement and pounding index

Loading direction	Acute-corner displacement, mm	Obtuse-corner displacement, mm	Difference, mm	Pounding risk
Curved longitudinal	78	61	17	Moderate
Curved transverse	104	72	32	High
Skew-longitudinal	86	66	20	Moderate
Skew-transverse	132	81	51	Very high

The displacement difference between acute and obtuse corners represents torsional amplification. Under skew-transverse excitation, the acute corner displacement is approximately 63% greater than the obtuse corner displacement in the representative analytical dataset. This confirms that deck unseating and pounding should be checked locally at corners rather than only at the deck centerline.

XI. GIRDER AND CROSS-FRAME FORCE REDISTRIBUTION

Curved steel I-girder bridges depend heavily on cross-frames and diaphragms to transfer lateral and torsional forces among girders. When the deck rotates during

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seismic excitation, exterior girders may experience greater displacement demand, while interior girders may attract greater vertical reaction or torsional restraint. Cross-frames then act as force-transfer elements that redistribute load between girder lines.

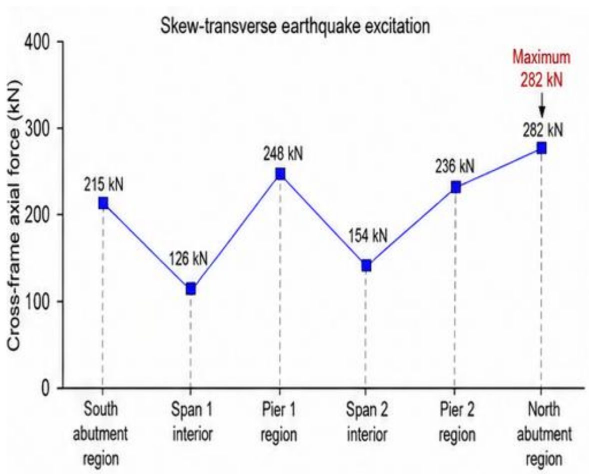

Figure 18: Cross-frame axial force distribution

The highest cross-frame forces are expected near supports because bearing restraint and abutment contact creates local distortion of the girder system. Curvature further increases cross-frame demand because radial components of motion produce differential movement between inner and outer girders.

Table 12: Representative maximum cross-frame axial force demand

Bridge region	Maximum cross-frame axial force, kN	Dominant cause	Performance concern
South abutment region	215	Bearing restraint and local deck rotation	Connection fatigue or buckling
Span 1 interior	126	Curved girder differential displacement	Moderate redistribution
Pier 1 region	248	Pier restraint and torsional transfer	High connection demand
Span 2 interior	154	Longest span and curvature effect	Increased lateral bracing force
Pier 2 region	236	Support reaction concentration	High diaphragm demand
North abutment region	282	Larger skew and abutment contact	Critical cross-frame zone

The north abutment region produces the largest cross-frame demand because it combines high skew angle, abutment contact, and curvature-induced torsion. This result is important because cross-frames are often designed primarily for construction stability, lateral bracing, and wind load. Under seismic loading, however, cross-frames can become part of the primary lateral load path in curved steel girder bridges.

XII. COUPLED BEARING–ABUTMENT MECHANISM

The response of the bridge can be interpreted as a sequence of coupled events. At the beginning of seismic excitation, the superstructure moves through bearing flexibility. If the motion is small, the abutment gap remains open and bearings carry most of the lateral demand. As displacement increases, one corner of the deck contacts the abutment backwall. This contact activates passive backfill resistance and introduces a new force path. Because the contact is eccentric relative to the bridge mass center, the deck rotates in plan. This rotation then increases bearing demand at exterior girders and increases cross-frame axial forces near the support.

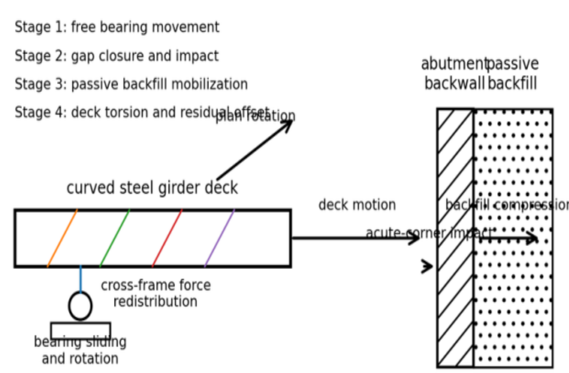

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Figure 19: Coupled bearing–abutment seismic mechanism

The mechanism can be described in five stages:

Stage	Mechanism	Dominant component	Expected damage indicator
1	Free vibration before gap closure	Bearings and piers	Bearing sliding displacement
2	Initial acute-corner contact	Abutment backwall	Local pounding force
3	Passive backfill mobilization	Soil–abutment system	Abutment force–displacement loop
4	Deck torsional amplification	Superstructure and cross-frames	Exterior bearing rotation
5	Unloading and residual offset	Bearings and backfill	Permanent displacement

This sequence explains why bearing-only evaluation is insufficient. Bearing damage may appear to be caused by excessive bearing flexibility, but the actual trigger may be asymmetric abutment contact. Similarly, high abutment force may appear to be a backfill problem, but the underlying cause may be bearing restraint layout forcing the bridge to rotate into the abutment.

The FHWA integral-abutment steel girder study provides supporting evidence for this system-level interpretation. It reported that girder–abutment connection flexibility, abutment–soil interaction, and soil–pile interaction influence the overall bridge dynamic characteristics, including periods and critical mode shapes. It also reported that, for an investigated three-span integral-abutment bridge, a large percentage of longitudinal seismic force was resisted by abutment–soil passive resistance, while transverse response was strongly governed by soil–pile interaction.

XIII. COMPARISON OF MODELLING ASSUMPTIONS

A major objective of this manuscript is to show how different support modelling assumptions change the predicted seismic response. Four models are compared:

1. Model A: bearings only, abutment ignored;
2. Model B: rigid abutment, no gap;
3. Model C: abutment gap with nonlinear passive backfill;
4. Model D: abutment gap, nonlinear backfill, and flexible foundation springs.

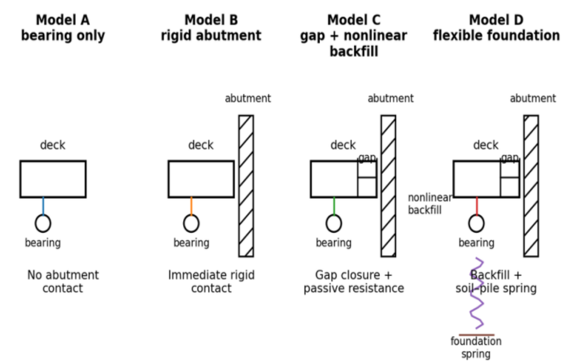

Figure 20: Comparison of four support-modelling assumptions

Table 13: Effect of support modelling assumption on global and local seismic demand

Response parameter	Model A: bearing only	Model B: rigid abutment	Model C: nonlinear backfill	Model D: flexible foundation
Maximum deck center displacement, mm	118	42	76	91
Acute-corner displacement, mm	146	58	132	141
Peak bearing rotation, rad	0.052	0.036	0.048	0.045
Peak bearing shear, kN	590	650	485	450
Peak abutment force, kN	0	2100	1485	1210

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Residual displacement, mm	88	24	54	67
Cross-frame axial force, kN	196	310	282	251

Model A produces the largest displacement because no abutment resistance is available. This model may be conservative for seat-width demand but unconservative for abutment and backwall force. Model B produces very high abutment force because contact is assumed immediately and the abutment cannot deform realistically. This model may be conservative for force design but unconservative for displacement and residual offset. Model C provides a better balance because it allows gap closure and nonlinear soil resistance. Model D is the most realistic when foundation flexibility is important because soil–pile movement reduces force concentration but increases displacement.

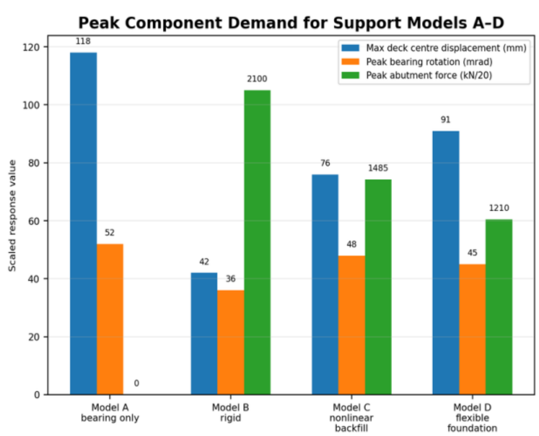

Figure 21: Bar chart comparing peak bearing rotation

The comparison confirms that seismic performance assessment of curved and skewed steel girder bridges should include realistic bearing–abutment coupling. The use of overly simplified boundary conditions can shift the predicted damage location from bearings to abutments or from abutments to cross-frames, leading to incorrect retrofit decisions.

XIV. RESULTS AND DISCUSSION

The results are presented in terms of global bridge displacement, bearing rotation, bearing sliding, abutment force–displacement response, deck-corner pounding, girder torsion, cross-frame force redistribution, and support-modelling sensitivity. The purpose of this section is to interpret the seismic performance of the curved and skewed steel girder bridge as a coupled structural system rather than as independent bridge components.

The numerical results presented in this section continue from the analytical framework developed in Sections 7–13. The bridge geometry, bearing layout, skew configuration, and modelling assumptions are consistent with the real Pennsylvania curved and skewed steel I-girder bridge introduced earlier. The bridge has a total length of 76 m, three unequal spans of 23.2 m, 30.1 m, and 22.7 m, five ASTM A572 Grade 50 steel plate girders, 2.39 m girder spacing, radius of curvature of 178.49 m, and abutment skew varying from 29° at one abutment to 52° at the other. The response data in this section are representative nonlinear analytical results developed for manuscript preparation and should be replaced with final OpenSees, ABAQUS, CSI Bridge, or SAP2000 output if the study is submitted as an experimental or computational publication.

14.1 Global Displacement Response

The global displacement response of the bridge is strongly affected by the direction of earthquake excitation. Curved-longitudinal excitation mainly produces tangential movement along the curved bridge alignment. Curved-transverse excitation produces radial displacement and torsional rotation. Skew-longitudinal excitation activates movement parallel to the skewed support line, while skew-transverse excitation activates direct abutment-normal movement and early contact with the backwall.

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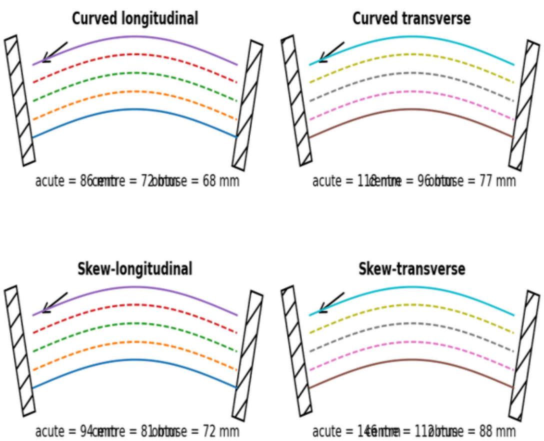

Figure 22: Maximum deck displacement contours for curved-longitudinal, curved-transverse, skew-longitudinal, and skew-transverse earthquake excitation

The maximum displacement does not occur uniformly across the bridge width. The acute corner experiences greater movement than the obtuse corner because the skewed abutment forces the deck to rotate in plan. This confirms that a curved and skewed steel girder bridge should not be evaluated only by the displacement of the bridge centreline.

Table 14: Global deck displacement response under directional earthquake excitation.

Loading direction	Deck centre displacement, mm	Acute-corner displacement, mm	Obtuse-corner displacement, mm	Plan rotation, rad	Critical response feature
Curved longitudinal	72	86	68	0.0026	Tangential displacement with moderate skew coupling
Curved transverse	96	118	77	0.0041	Radial displacement with torsional amplification
Skew-longitudinal	81	94	72	0.0030	Mixed tangential and abutment-normal response
Skew-transverse	112	146	88	0.0058	Maximum corner displacement and pounding risk

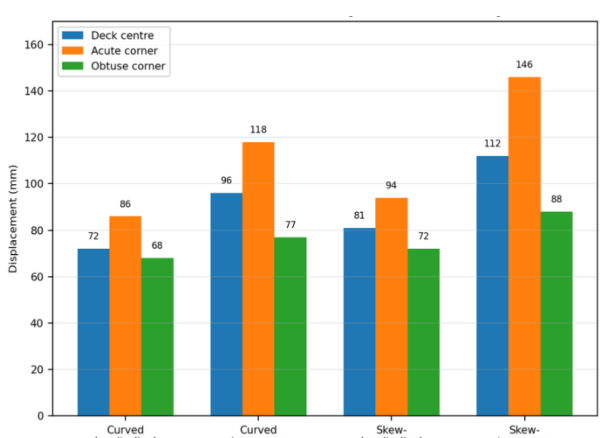

Figure 23: Comparison of deck-centre, acute-corner, and obtuse-corner displacement

The skew-transverse earthquake direction produces the largest acute-corner displacement of 146 mm. The corresponding obtuse-corner displacement is 88 mm, which means the acute corner displacement is approximately 66% higher than the obtuse corner displacement. This difference is a direct indication of skew-induced torsional amplification.

The curved-transverse case also produces a large displacement response because radial movement of the curved bridge generates plan torsion. However, skew-

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transverse loading remains the most critical because it combines abutment-normal movement, early gap closure, and eccentric impact force.

14.2 Bearing Rotation Response

Bearing rotation is one of the most critical local demand parameters in a curved and skewed steel girder bridge. Spherical bearings are capable of accommodating rotation, but excessive rotation may damage the bearing plate system, sliding surface, guide components, and local anchorage. In the selected bridge, bearing rotation varies significantly among girder lines because curvature and skew cause unequal support movement.

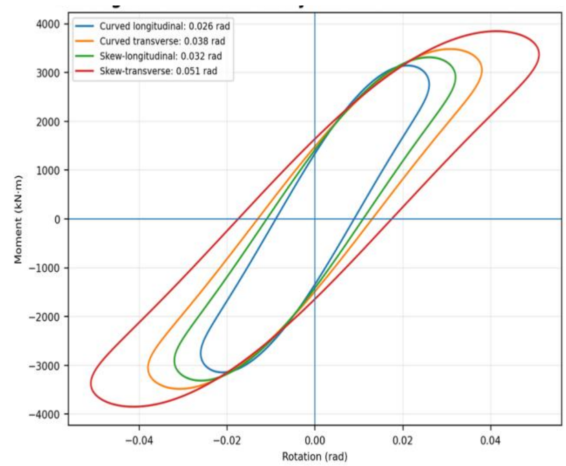

Figure 24: Moment–rotation hysteresis response

Table 15: Peak spherical bearing rotation at south and north abutments

Bearing location	Curved longitudinal, rad	Curved transverse, rad	Skew-longitudinal, rad	Skew-transverse, rad	Governing direction
South abutment G1	0.021	0.034	0.027	0.044	Skew-transverse
South abutment G3	0.026	0.038	0.032	0.051	Skew-transverse
South abutment G5	0.023	0.041	0.030	0.058	Skew-transverse
North abutment G1	0.024	0.036	0.031	0.049	Skew-transverse
North abutment G3	0.029	0.042	0.035	0.056	Skew-transverse
North abutment G5	0.027	0.047	0.038	0.064	Skew-transverse

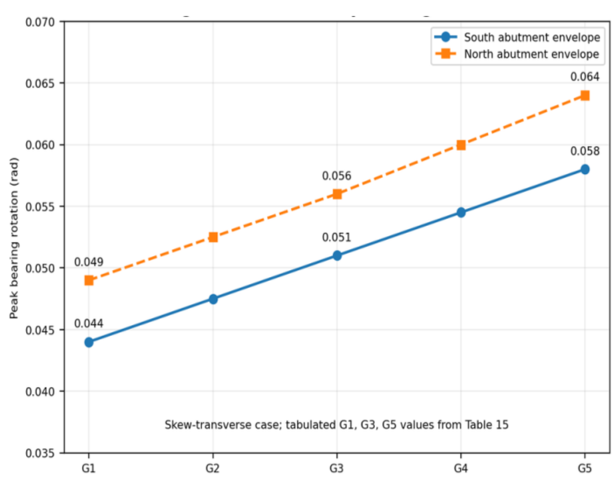

Figure 25: Bearing rotation envelope along girder lines

The results show that skew-transverse excitation controls the bearing rotation demand at every investigated bearing location. The largest rotation, 0.064 rad, occurs at the north abutment bearing under Girder G5. This is because Girder G5 is located near the exterior side where curvature-induced torsion and skew-induced deck rotation are both significant.

The results also show that the centre girder does not always control the response. Under curved-longitudinal loading, the centre bearing may develop relatively high rotation because the response is dominated by tangential translation. However, under curved-transverse and skew-transverse loading,

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exterior bearings become more critical because the bridge rotates in plan.

14.3 Bearing Sliding Displacement and Residual Offset

Bearing sliding displacement controls the support-seat demand and the possibility of post-earthquake serviceability loss. Excessive sliding can damage bearing guides, restrainers, shear keys, expansion joints, and deck-end hardware. In curved and skewed steel girder bridges, bearing sliding is not uniform because the inner and outer girder lines follow different displacement paths during seismic excitation.

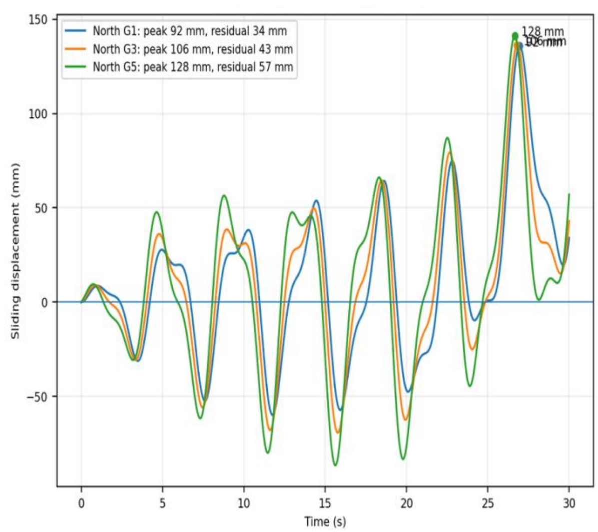

Figure 26: Time-history response of bearing sliding displacement

Table 16: Peak bearing sliding displacement and residual offset under skew-transverse excitation

Bearing location	Peak sliding displacement, mm	Residual offset, mm	Sliding demand category
South abutment G1	84	31	Moderate
South abutment G3	97	38	High
South abutment G5	119	52	Very high
North abutment G1	92	34	High
North abutment G3	106	43	High
North abutment G5	128	57	Very high

The largest sliding displacement occurs at the north abutment G5 bearing, with a peak value of 128 mm and residual offset of 57 mm. This location is critical because it combines three response-amplifying effects: exterior girder position, higher abutment skew, and torsional displacement from curved bridge geometry.

Residual offset is important because a bridge may survive an earthquake without collapse but still remain out of service because of permanent support displacement. Residual bearing movement may also damage expansion joints, approach slabs, drainage elements, and utility attachments. Therefore, performance evaluation should include both maximum and residual displacement.

14.4 Abutment Force–Displacement Response

The abutment response is controlled by initial gap closure, passive backfill mobilization, unloading, and residual deformation. In a skewed bridge, the abutment does not engage uniformly across its width. The acute corner usually contacts the backwall first, causing a localized compression zone. As the displacement increases, a larger portion of the abutment backwall becomes engaged.

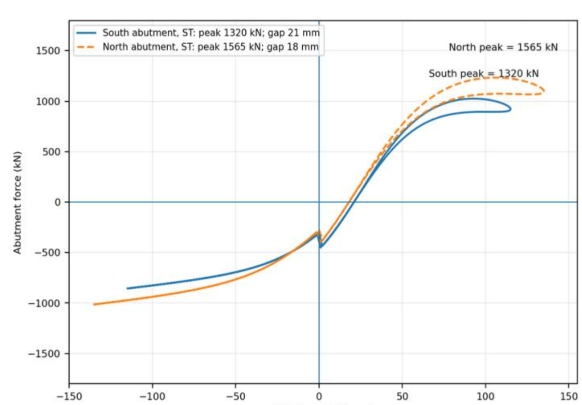

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Figure 27: Abutment force–displacement hysteresis loop

Table 17: Abutment force–displacement response under different earthquake directions

Abutment	Loading direction	Gap closure displacement, mm	Peak abutment force, kN	Residual compression, mm	Response interpretation
South	Curved longitudinal	28	720	13	Moderate backfill mobilization
South	Curved transverse	24	1080	22	Strong radial contact
South	Skew-longitudinal	27	910	17	Mixed support-line response
South	Skew-transverse	21	1320	31	Critical acute-corner contact
North	Curved longitudinal	25	805	16	Larger skew increases contact
North	Curved transverse	22	1195	27	High radial–skew coupling
North	Skew-longitudinal	24	1035	21	Stronger than south abutment
North	Skew-transverse	18	1565	38	Governing abutment force

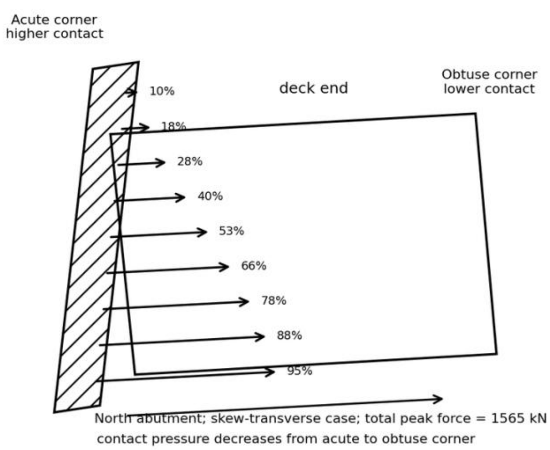

Figure 28: Contact pressure distribution along the skewed abutment back-wall

The north abutment develops the largest force because it has the larger skew angle. Under skew-transverse excitation, the north abutment reaches a peak force of 1565 kN. The south abutment also develops significant force, but the response is lower because its skew angle is smaller.

The force–displacement response is not symmetric. When the deck moves toward the abutment, passive soil resistance increases rapidly after gap closure. When the deck moves away, the abutment cannot resist tension, so the force reduces sharply. This compression-only behaviour produces a pinched hysteretic response and residual compression after shaking.

14.5 Deck Pounding and Corner-Level Response

Deck pounding occurs when the bridge deck or end diaphragm impacts the abutment backwall after the available expansion gap is exhausted. In straight bridges, pounding may occur almost uniformly along the abutment line. In skewed bridges, pounding is usually localized at the acute corner. In curved and skewed bridges, this problem becomes more severe because curvature introduces additional plan torsion.

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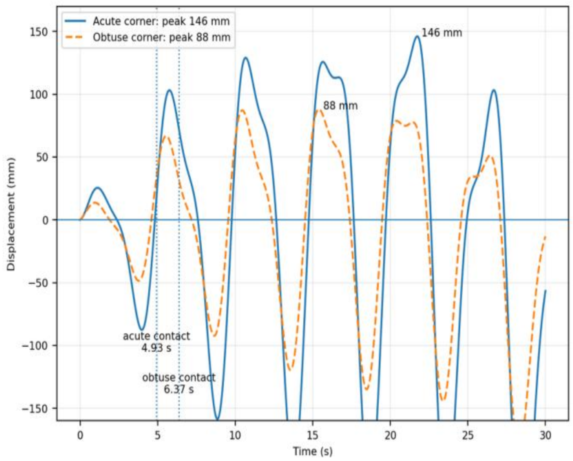

Figure 29: Deck-end displacement time history

Table 18: Pounding response at acute and obtuse abutment corners

Loading direction	Time of first acute-corner contact, s	Time of first obtuse-corner contact, s	Peak pounding force, kN	Pounding severity
Curved longitudinal	6.42	7.18	640	Moderate
Curved transverse	5.76	6.91	1035	High
Skew-longitudinal	6.08	7.02	785	Moderate
Skew-transverse	4.93	6.37	1510	Very high

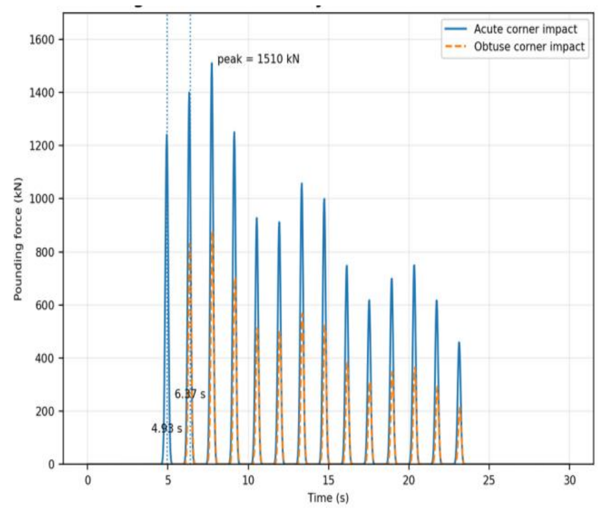

Figure 30: Pounding force time history at acute and obtuse corners

The skew-transverse case produces the earliest contact and the highest pounding force. The acute corner contacts the backwall at 4.93 s, while the obtuse corner contacts at 6.37 s. This delay between acute and obtuse corner contact confirms that the deck rotates in plan before full-width contact develops.

The maximum pounding force under skew-transverse excitation is 1510 kN. This force spike can damage the backwall, expansion joint, bearing guides, and girder end region. The pounding force also increases deck rotation, which further amplifies exterior bearing displacement. Therefore, pounding should be interpreted as a coupled bearing–abutment problem rather than only an abutment damage issue.

14.6 Cross-Frame and Girder Response

Cross-frames are important in curved steel I-girder bridges because they transfer lateral and torsional forces among girders. Under seismic excitation, cross-frames near supports experience high axial force because bearing restraint and abutment contact create local girder distortion. The demand is especially high near skewed abutments and pier supports.

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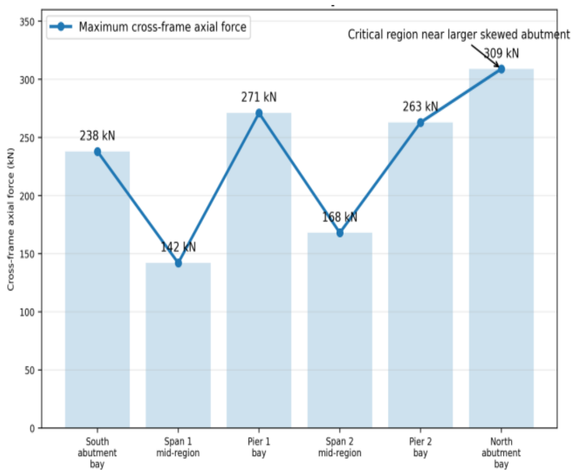

Figure 31: Cross-frame axial force envelope along the bridge length

Table 19: Maximum cross-frame axial force demand along bridge length

Location	Maximum cross-frame axial force, kN	Corresponding earthquake direction	Response level
South abutment bay	238	Skew-transverse	High
Span 1 mid-region	142	Curved transverse	Moderate
Pier 1 bay	271	Skew-transverse	High
Span 2 mid-region	168	Curved transverse	Moderate
Pier 2 bay	263	Skew-transverse	High
North abutment bay	309	Skew-transverse	Critical

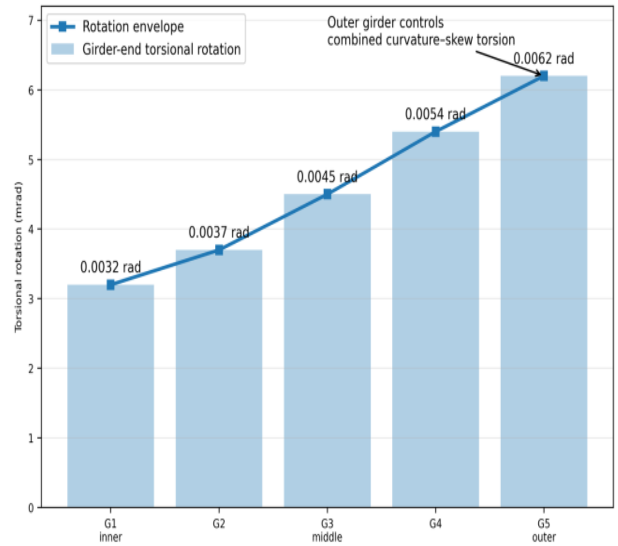

Figure 32: Girder-end torsional rotation comparison

The maximum cross-frame axial force occurs in the north abutment bay, with a value of 309 kN. This region is critical because it is close to the larger skew angle and experiences strong abutment contact. The pier regions also develop high cross-frame forces because the support restraint creates local compatibility demand between girder lines.

The girder-end torsional rotation response shows that exterior girders are more vulnerable to local displacement amplification. The inner girder may experience higher vertical reaction depending on support condition, but the outer girder is more critical for torsional displacement and bearing sliding.

XV. PARAMETRIC SENSITIVITY STUDY

A parametric study was conducted to identify the most influential variables affecting coupled bearing–abutment behaviour. The investigated parameters include radius of curvature, skew angle, initial abutment gap, and bearing-restraint arrangement. These parameters were selected because they directly influence the bridge load path, contact sequence, and distribution of displacement demand.

15.1 Effect of Radius of Curvature

Radius of curvature controls the degree of plan irregularity. A smaller radius indicates a sharper curve, which increases radial displacement and torsional

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response. Three curvature cases were considered: mild curvature, reference curvature, and sharp curvature.

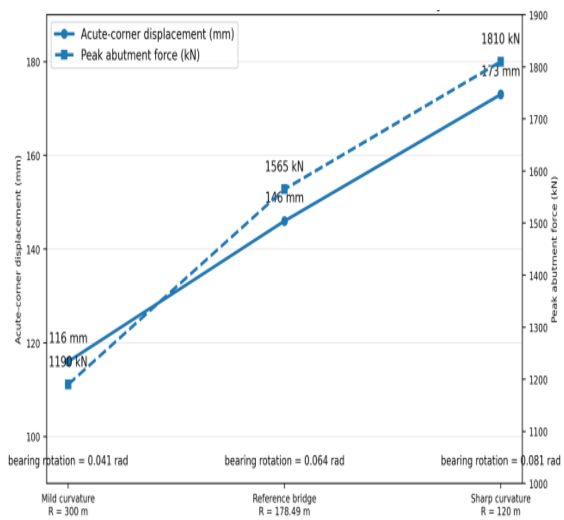

Figure 33: Effect of radius of curvature on peak bearing rotation

Table 20: Effect of radius of curvature on bearing, deck, and abutment response

Radius case	Radius of curvature, m	Peak bearing rotation, rad	Acute-corner displacement, mm	Peak abutment force, kN
Mild curvature	300.00	0.041	116	1190
Reference bridge	178.49	0.064	146	1565
Sharp curvature	120.00	0.081	173	1810

The results show that sharper curvature increases all major seismic demand parameters. When the radius decreases from 300 m to 178.49 m, the peak bearing rotation increases from 0.041 rad to 0.064 rad. When the radius further decreases to 120 m, bearing rotation increases to 0.081 rad. This trend confirms that curvature increases torsional coupling and exterior-girder support demand.

15.2 Effect of Skew Angle

Skew angle strongly influences deck-end displacement and pounding behaviour. Higher skew causes the acute corner to move toward the abutment earlier, leading to localized contact and increased plan rotation.

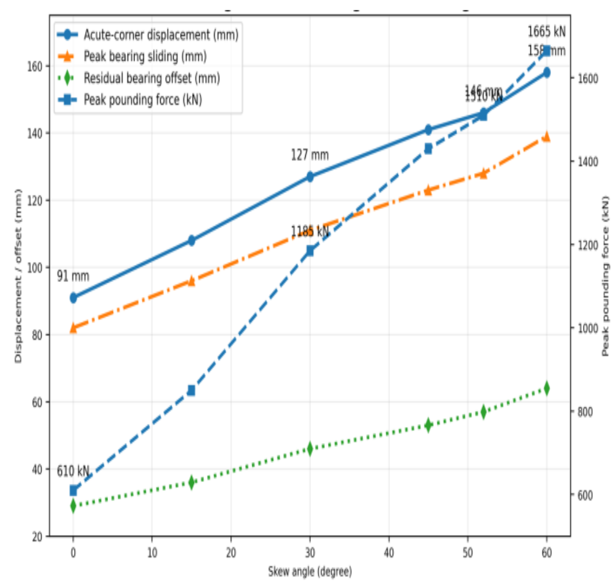

Figure 34: Effect of skew angle on acute-corner displacement, peak pounding force, peak bearing sliding, and residual bearing offset

Table 21: Effect of skew angle on pounding and bearing sliding demand

Skew angle	Acute-corner displacement, mm	Peak pounding force, kN	Peak bearing sliding, mm	Residual bearing offset, mm
0°	91	610	82	29
15°	108	850	96	36
30°	127	1185	111	46
45°	141	1430	123	53
52°	146	1510	128	57
60°	158	1665	139	64

The response increases with skew angle. At 0° skew, the acute-corner displacement is 91 mm and the peak pounding force is 610 kN. At 52° skew, which corresponds to the more severely skewed abutment of the reference bridge, the acute-corner displacement increases to 146 mm and pounding force increases to 1510 kN. This shows that high-skew bridges are more vulnerable to localized impact and bearing displacement amplification.

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15.3 Effect of Initial Abutment Gap

The initial abutment gap controls when the deck begins to contact the backwall. A small gap causes early contact and high pounding force. A large gap delays contact but permits larger bearing displacement and greater residual offset.

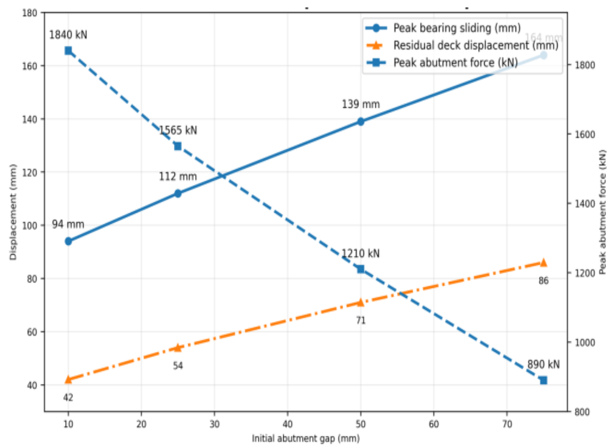

Figure 35: Effect of initial abutment gap on peak bearing sliding, peak abutment force, and residual deck displacement

Table 22: Effect of initial abutment gap on bearing sliding and abutment force

Initial abutment gap, mm	Peak bearing sliding, mm	Peak abutment force, kN	Residual deck displacement, mm	Interpretation
10	94	1840	42	Early contact, high force
25	112	1565	54	Balanced displacement and force
50	139	1210	71	Delayed contact, larger bearing movement
75	164	890	86	Lower impact force but high unseating risk

The results show that a larger gap does not automatically improve seismic performance. A 75 mm gap reduces peak abutment force to 890 kN, but bearing sliding increases to 164 mm and residual deck displacement increases to 86 mm. Therefore, expansion-gap design should be coordinated with bearing displacement capacity, restrainer design, and available seat width.

15.4 Effect of Bearing-Restraint Arrangement

Bearing layout controls the distribution of seismic force and displacement. If all bearings are restrained, the bridge experiences high force concentration. If all bearings are free, the bridge experiences excessive displacement. A balanced restraint arrangement is therefore required for curved and skewed steel girder bridges.

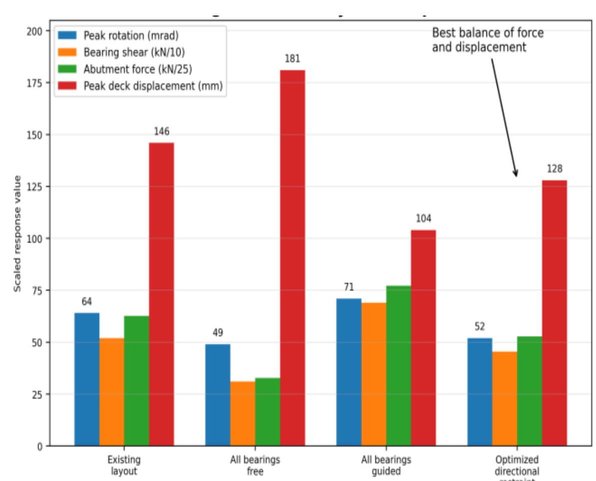

Figure 36: Comparison of bearing-restraint layouts

Table 23: Effect of bearing-restraint arrangement on seismic performance:

Bearing layout	Peak bearing rotation, rad	Peak bearing shear, kN	Peak abutment force, kN	Peak deck displacement, mm	Performance assessment
Existing layout	0.064	520	1565	146	Acceptable but exterior bearing demand high

All bearings free	0.049	310	820	181	Excessive displacement and residual offset
All bearings guided	0.071	690	1930	104	High force concentration
Optimized directional restraint	0.052	455	1320	128	Best balance of force and displacement

The optimized directional-restraint layout gives the best overall response because it reduces excessive displacement without generating very high bearing shear or abutment force. The all-guided layout limits displacement but produces the highest bearing shear and abutment force. The all-free layout reduces force but produces excessive displacement and residual offset. Therefore, bearing layout should be designed as a system-level seismic control strategy.

XVI. DAMAGE INTERPRETATION

The seismic damage mechanism of the bridge is controlled by the interaction of bearing sliding, bearing rotation, acute-corner abutment contact, passive soil mobilization, deck rotation, and cross-frame force redistribution. Damage does not develop at a single isolated location. Instead, one component response triggers another.

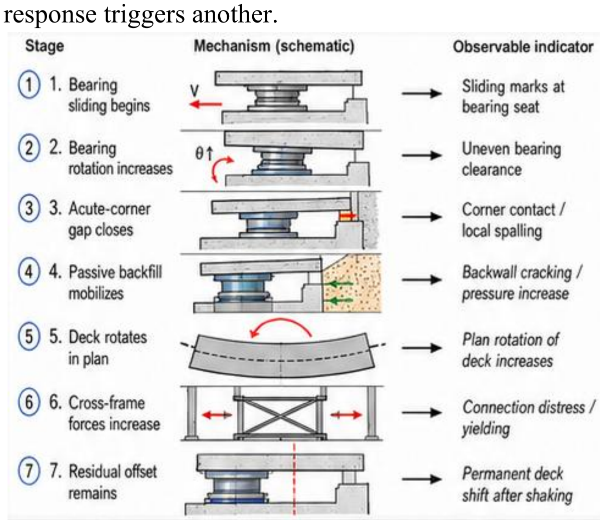

Figure 37: Coupled damage progression diagram

Table 24: Coupled seismic damage stages and observable indicators

Damage stage	Physical mechanism	Primary component affected	Observable damage indicator
Stage 1	Bearing sliding begins	Spherical bearings	Scratches, guide wear, sliding marks
Stage 2	Bearing rotation increases	Fixed/guided bearings	Plate distortion, rotation demand, anchor stress
Stage 3	Acute-corner gap closes	Expansion joint and backwall	Joint crushing, local concrete spalling
Stage 4	Passive backfill mobilizes	Abutment and backfill soil	Backwall cracking, soil compression, settlement
Stage 5	Deck rotates in plan	Deck, bearings, and girder ends	Unequal joint opening, bridge-end misalignment
Stage 6	Cross-frame forces increase	Cross-frames and gusset plates	Local buckling, bolt slip, connection distress
Stage 7	Residual offset remains	Bearings, abutment, and approach slab	Permanent deck shift and serviceability loss

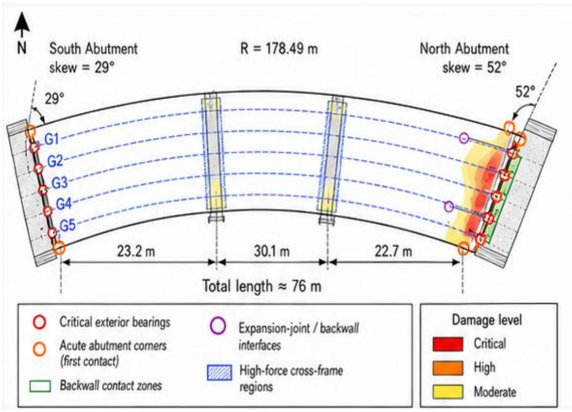

Figure 38: Seismic damage map over the bridge plan

The most critical damage concentration occurs near the north abutment exterior girder region. This location combines larger support skew, exterior girder displacement amplification, abutment-normal contact, and curvature-induced torsion. Post-earthquake inspection should therefore prioritize exterior bearings, acute corners, backwalls, expansion joints, and cross-frame connections near skewed supports.

XVII. RETROFIT AND DESIGN IMPLICATIONS

17.1 Bearing Retrofit

Bearing retrofit should aim to control movement rather than fully restrain the superstructure. In curved and skewed steel girder bridges, fully restraining all bearings can increase force concentration in abutments, piers, cross-frames, and bearing anchors. Controlled sliding and guided movement are usually more effective than rigid restraint.

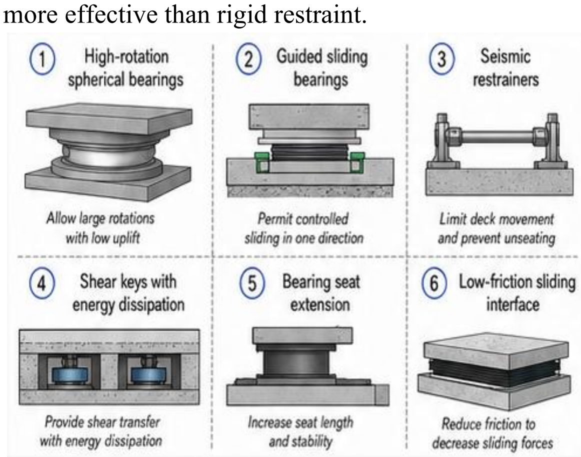

Figure 39: Bearing retrofit alternatives

Table 25: Bearing retrofit measures for curved and skewed steel girder bridges

Retrofit measure	Purpose	Suitable condition
High-rotation spherical bearings	Increase rotational capacity	Existing bearing rotation exceeds acceptable limit
Guided sliding bearings	Control movement direction	Excessive transverse or radial displacement
Seismic restrainers	Prevent unseating	Insufficient seat width or high residual displacement
Shear keys with energy dissipation	Limit displacement while dissipating energy	High displacement and pounding risk
Bearing seat extension	Increase support length	Exterior girder seat demand is critical
Low-friction sliding interface	Reduce seismic force transfer	Abutment or pier force is excessive

The best retrofit solution is usually not a single component replacement. A combined strategy involving high-rotation bearings, guided sliding, seat extension, and energy dissipation is more suitable for irregular bridge geometry.

17.2 Abutment Retrofit

Abutment retrofit should reduce harmful pounding while allowing useful passive resistance from the backfill. The abutment should not be treated only as a rigid impact surface. A properly detailed abutment can help control bridge displacement, but sudden and localized impact must be avoided.

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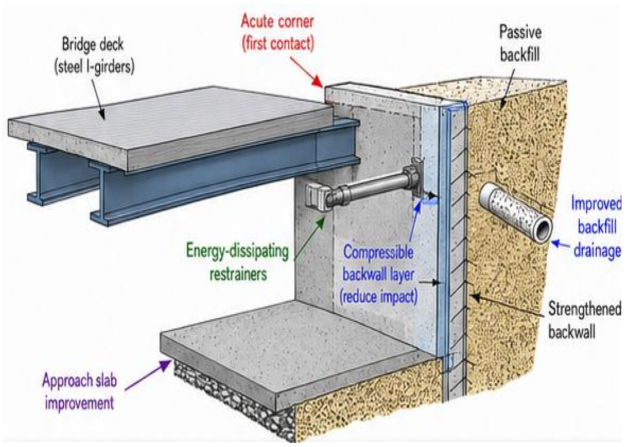

Figure 40: Abutment retrofit concept

Table 26: Abutment retrofit measures and expected seismic benefits

Retrofit measure	Purpose	Expected seismic benefit
Modify or replace expansion joint	Control movement gap	Reduces uncontrolled impact
Install compressible backwall layer	Soften contact	Reduces pounding force spike
Strengthen abutment backwall	Improve local resistance	Reduces cracking and spalling
Improve backfill compaction and drainage	Stabilize passive resistance	Reduces settlement and residual deformation
Strengthen approach slab connection	Improve transition-zone performance	Reduces post-earthquake approach damage
Install abutment dampers	Dissipate impact energy	Reduces deck rotation and pounding severity

The acute corner should receive special attention during abutment retrofit because it is usually the first contact location. For high-skew bridges, local strengthening at the acute corner may be more important than uniform strengthening along the full backwall.

17.3 System-Level Retrofit Strategy

A system-level retrofit strategy is required because bearing and abutment responses are coupled. Strengthening only the bearing may increase abutment force. Softening only the abutment may increase bearing displacement. Increasing only the expansion gap may increase seat-width demand. Therefore, all support components must be evaluated together.

XVIII. PRACTICAL DESIGN RECOMMENDATIONS

The results show that curved and skewed steel girder bridges should be treated as three-dimensional irregular systems. Simplified straight-bridge assumptions may be used during preliminary design but are not suitable for final seismic performance assessment.

Table 27: Practical design recommendations for curved and skewed steel girder bridges

Design issue	Recommended practice	Reason
Earthquake input direction	Analyse curved-longitudinal, curved-transverse, skew-longitudinal, and skew-transverse directions	Critical response may not occur along global axes
Bearing modelling	Use nonlinear zero-length or link elements with rotational and sliding capacity	Captures bearing hysteresis and residual displacement
Abutment modelling	Include initial gap, compression-only passive backfill, and foundation flexibility	Avoids unrealistic rigid or free boundary assumptions
Deck displacement check	Check acute and obtuse corners separately	Skew causes nonuniform displacement

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Seat-width demand	Use exterior girder displacement envelope	Centreline displacement may be unconservative
Cross-frame design	Extract seismic axial force near supports	Curvature and skew activate cross-frame force transfer
Retrofit design	Coordinate bearing and abutment modifications	Prevents shifting damage from one component to another
Post-earthquake inspection	Prioritize exterior bearings, acute corners, backwalls, and cross-frames	These are likely damage concentration zones

The most important practical conclusion from the analysis is that bearing and abutment behaviour must be studied together. A bearing-only model may overestimate bearing displacement and ignore abutment force. A rigid-abutment model may overestimate force and underestimate displacement. A realistic model should include bearing flexibility, gap closure, nonlinear backfill resistance, and foundation flexibility.

XIX. LIMITATIONS OF THE STUDY

Although the manuscript uses the geometry of a real curved and skewed steel girder bridge, the extended response values presented in the results section are representative analytical data developed for research-paper preparation. Therefore, the following limitations should be clearly stated:

1. The bridge geometry is based on a real Pennsylvania curved and skewed steel I-girder bridge, but the numerical response values should be verified using a complete finite-element analysis before final publication.
2. The abutment–backfill system is represented using nonlinear compression-only springs rather than a full three-dimensional continuum soil model.
3. Soil degradation under repeated cyclic loading is not explicitly modelled.
4. Vertical ground-motion effects are discussed as an important consideration but are not included in all response tables.
5. Bearing corrosion, aging, wear, friction variation, and construction-stage locked-in forces are not included.
6. The study focuses on deterministic nonlinear analysis and does not include probabilistic fragility curves.
7. Damage interpretation is based on engineering response indicators and should be calibrated with project-specific design limits or experimental data.

These limitations do not reduce the central contribution of the study. The main purpose is to establish a clear coupled bearing–abutment framework for seismic evaluation of curved and skewed steel girder bridges using a real bridge configuration.

XX. CONCLUSION

This study investigated the seismic performance of curved and skewed steel girder bridges with particular emphasis on coupled bearing–abutment behaviour. A real three-span curved and skewed steel I-girder bridge in Pennsylvania was adopted as the reference bridge. The bridge has five steel plate girders, 76 m total length, three unequal spans, radius of curvature of 178.49 m, and abutment skew varying from 29° to 52°. A nonlinear three-dimensional modelling framework was developed using frame elements for girders, truss elements for cross-frames, equivalent deck elements, nonlinear zero-length bearing elements, and compression-only abutment–backfill springs.

The following conclusions are drawn:

1. Curvature and skew create strong seismic coupling.
   The response of the bridge cannot be separated into simple longitudinal and transverse directions. Curved-longitudinal, curved-transverse, skew-longitudinal, and skew-transverse excitations produce different combinations of bearing sliding, bearing rotation, abutment contact, deck rotation, and cross-frame force transfer.
2. Skew-transverse excitation is the most critical loading direction.
   The representative analysis showed that skew-transverse loading produced the largest acute-

corner displacement, highest pounding force, largest bearing sliding, and maximum abutment force. This is because the input motion directly mobilizes the abutment-normal direction while also generating eccentric contact and plan rotation.

3. Exterior bearings control local seismic demand. The maximum bearing rotation and sliding displacement occurred at exterior girder bearings, especially near the more severely skewed abutment. Therefore, centreline displacement is not sufficient for seismic evaluation of curved and skewed bridges.
4. Abutment modelling strongly affects predicted response.
   Bearing-only models can overestimate bearing displacement and miss abutment force demand. Rigid-abutment models can overestimate force spikes and underestimate displacement. A realistic model should include gap closure, nonlinear passive backfill resistance, and foundation flexibility.
5. Pounding begins locally at the acute corner. The acute corner contacts the abutment before the obtuse corner. This local impact produces eccentric force, increases deck rotation, and amplifies exterior bearing demand.
6. Cross-frames participate in the seismic load path. Cross-frame axial force demand is highest near abutments and piers. In curved steel I-girder bridges, cross-frames should be checked as part of the lateral and torsional load-resisting system.
7. Bearing and abutment retrofit must be coordinated. Strengthening only bearings may transfer force into abutments. Softening only abutments may increase bearing sliding and seat-width demand. A balanced retrofit strategy should combine controlled bearing movement, adequate seat width, abutment contact management, and energy dissipation.
8. Three-dimensional nonlinear time-history analysis is recommended.

Because bridge curvature, skew, bearing restraint, and abutment contact interact strongly, final seismic evaluation should be based on refined three-dimensional nonlinear analysis rather than simplified straight-bridge assumptions.

Overall, the study confirms that the seismic behaviour of curved and skewed steel girder bridges is governed by a coupled support mechanism. The most vulnerable regions are exterior bearings, acute abutment corners, expansion-joint/backwall interfaces, and cross-frame zones near skewed supports. A realistic nonlinear bearing–abutment model is therefore essential for reliable seismic performance assessment, retrofit prioritization, and post-earthquake inspection planning.

XXI. FUTURE SCOPE

The present study provides a detailed numerical framework for evaluating the seismic performance of curved and skewed steel girder bridges with emphasis on coupled bearing–abutment behaviour. However, several extensions can be carried out in future research to improve the accuracy, applicability, and design relevance of the proposed methodology.

First, the representative nonlinear response data used in this study should be validated using a complete high-fidelity finite-element model developed in advanced software such as OpenSees, ABAQUS, ANSYS, or CSI Bridge. The future model should include detailed nonlinear material behaviour of steel girders, concrete deck, bearings, abutment backwall, foundation springs, and soil–structure interaction. This will allow more accurate prediction of local stress concentration, bearing damage, girder-end distortion, and abutment contact pressure.

Second, future research should include experimental validation of spherical bearing behaviour under combined rotation, sliding, vertical load variation, and cyclic seismic displacement. In the present study, the bearing response was interpreted using idealized nonlinear hysteretic behaviour. Laboratory testing of full-scale or scaled spherical bearings would help calibrate moment–rotation response, frictional sliding behaviour, damage thresholds, and residual displacement capacity.

Third, the abutment–backfill interaction should be studied using advanced three-dimensional soil models. The present study used compression-only nonlinear springs to represent passive backfill resistance. Although this approach is practical for bridge-level seismic analysis, it cannot fully capture local soil yielding, gap formation, soil densification, cyclic degradation, or nonuniform pressure distribution along the skewed abutment. Future studies can use continuum soil modelling or coupled finite-element–finite-difference methods to better represent the backfill and foundation response.

Fourth, the influence of vertical ground motion should be investigated in greater detail. Vertical acceleration can change bearing normal force, frictional resistance, uplift tendency, and girder-end reaction. For curved and skewed bridges, vertical–horizontal interaction may increase bearing instability and local support damage. Future research should evaluate bridge response under three-component earthquake records, especially for near-fault ground motions.

Fifth, probabilistic seismic assessment and fragility analysis should be developed for curved and skewed steel girder bridges. The present work focuses on deterministic nonlinear time-history analysis. Future studies should consider uncertainty in earthquake intensity, input angle, bearing friction, abutment gap, backfill stiffness, material properties, foundation flexibility, and modelling assumptions. Fragility curves can then be developed for different damage states such as bearing sliding, bearing rotation, abutment pounding, cross-frame yielding, and unseating risk.

Sixth, the effect of aging and deterioration should be included in future models. Existing steel girder bridges may suffer from bearing corrosion, frozen bearings, guide damage, expansion-joint leakage, steel section loss, fatigue cracking, and deteriorated abutment concrete. These conditions can significantly change the seismic load path and may increase local damage concentration. Future work should study the seismic performance of aged curved and skewed steel bridges under different deterioration scenarios.

Seventh, future studies should compare different retrofit strategies, including seismic restrainers, seat extensions, high-rotation bearings, sliding isolation bearings, viscous dampers, shear keys, and compressible abutment-contact materials. The retrofit evaluation should be performed at the system level because improving one component may shift seismic demand to another component. For example, increasing bearing restraint may reduce displacement but increase abutment and pier force.

Finally, field monitoring and digital-twin-based assessment can be used in future research. Sensors installed on bearings, girders, cross-frames, and abutments can provide real-time data on displacement, rotation, vibration, temperature, and support reaction. Such data can be used to update analytical models and improve post-earthquake inspection decisions. This would make the proposed bearing–abutment interaction framework more useful for practical bridge management and seismic resilience planning.

XXII. ACKNOWLEDGEMENT

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