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SEISMIC DESIGN OF RAILROAD BRIDGES

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INTRODUCTION

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- The primary goal for railroad operations is to keep the trains operating safely and continuously. AREMA's seismic design criteria was developed to help fulfil this goal.
- AREMA has developed seismic design procedures for railroad bridges which coordinate the train post-seismic event operation guidelines with the designed performance of the structure.
- Several sources, such as USGS, can provide immediate notification of an earthquake event to the railroads.
- Railroad train dispatchers can control traffic after a seismic event.
  - Trains within a 100 mile radius of the "reporting area" are immediately notified of the event and told to proceed at restricted speed.
  - After the epicenter and initial magnitude are available, specific guidelines are provided to the trains based on magnitude and region.

Earthquake Magnitude	Ground Motion Level	Distance from Epicenter		Action
		California & Baja	Remainder of N.A.	
0.0 – 4.99	-	n/a	n/a	none
5.0 – 5.99	1	50	100	restricted speed
6.0 – 6.99	1	150	300	restricted speed
6.0 – 6.99	2 & 3	100	200	stop & inspect
> 7.0	2 & 3	as directed, but not less than for lower magnitude		

GROUND MOTION LEVELS

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- Ground Motion Levels
  - In order to provide a framework for evaluating seismic effects on railroad structures, a three-level ground motion and performance criteria approach consistent with the railroad post-seismic event operation guidelines is employed.
  - Level 1 Ground Motion represents an occasional event with a reasonable probability of being exceeded during the life of the structure.
  - Level 2 Ground Motion represents a rare event with a low probability of being exceeded during the life of the structure.
  - Level 3 Ground Motion represents a very rare or maximum credible event with a very low probability of being exceeded during the life of the structure.
  - Levels are defined in terms of peak ground acceleration associated with a given average return period.

Ground Motion Level	Return Period (Yrs.)
1	50-100
2	200-500
3	1000-2400

GROUND MOTION LEVELS (CONTINUED)

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- Structure Importance Classification
  - Structure importance classification is used to determine the appropriate return period for each of the three ground motion levels.
  - The structure importance classification is determined by three measures.
    - Immediate Safety - Factor based on occupancy, hazardous material and community life lines.
    - Immediate Value - Factor based on railroad utilization and the detour availability.
    - Replacement Value - Factor based on span length, bridge length and bridge height.

GROUND MOTION LEVELS (CONTINUED)

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- Immediate Safety
  - The occupancy, hazardous material and community life lines factors should be summed to determine the immediate safety factor, which should not exceed 4.
    - Occupancy Factor

      Freight Service only. 1
      Less Than 10 Passenger Trains per Day . . . 2
      More than 10 Passenger Trains per Day . . . 4

    - Hazardous Material Factor

      The value of the hazardous material factor should be determined by considering the type of material being handled, the volume and the proximity of the structure to population. The hazardous material factor should be a value between 0 and 4.

    - Community Life Lines Factor

      The community life line factor should reflect the danger to community if the structure fails during a seismic event. The community life line factor should be a value between 0 and 4. If the structure is over a route that is critical for post seismic evacuation, a high community life line factor should be used.

GROUND MOTION LEVELS (CONTINUED)

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- Immediate Value
  - The Immediate Value factor should be determined by multiplying the railroad utilization factor by the detour availability factor.
    - Railroad Utilization Factor

      Under 10 million gross tons annual traffic 1
      Between 10 million and 50 million gross tons annual traffic . . . 2
      Over 50 million gross tons annual traffic. 4

    - Detour Availability Factor

      No Detour Available 1.00
      Inconvenient Detour Route 0.50
      Detour Route Readily Available 0.25

GROUND MOTION LEVELS (CONTINUED)

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- Replacement Value
  - Replacement value should be determined by multiplying the span length, bridge length and bridge height factors, but should not exceed 4.0
    - Span Length Factor

      Span length less than 35 feet. 1
      Span length between 35 feet and 125 feet 2
      Span length between 125 feet and 250 feet 3
      Span length greater than 250 feet. 4

    - Bridge Length Factor

      Bridge length less than 100 feet 1.0
      Bridge length between 100 feet and 1,000 feet. .. 1.5
      Bridge length greater than 1,000 feet 2.0

    - Bridge Height Factor

      Bridge height less than 20 feet 0.75
      Bridge height between 20 feet and 40 feet 1.00
      Bridge height greater than 40 feet 1.25

GROUND MOTION LEVELS (CONTINUED)

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– The structure importance classification factor is determined as the sum of the weighted factors for immediate safety, immediate value and replacement value.

Weighting Factors			Ground Motion Level
Immediate Safety	Immediate Value	Replacement Value	
0.80	0.20	0.00	1
0.10	0.80	0.10	2
0.00	0.20	0.80	3

For level 1: I = 0.80 x IS + 0.20 x IV + 0.00 x RV

I = Structure importance classification factor

IS = Immediate safety factor

IV = Immediate value factor

RV = Replacement value factor

GROUND MOTION LEVELS (CONTINUED)

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- Return Periods

  – Return periods represent the probability that a certain ground motion level will be exceeded.

Probability of Exceedance in 50 years	Return Period (Yrs.)
10%	475
5%	975
2%	2475

  – Return periods for each ground motion level are determined from the importance classification factor.

    o Interpolate between maximum and minimum acceleration for each ground motion level based on the fraction of the importance classification factor divided by 4.

Ground Motion Level	Return Period (Yrs.)
1	50-100
2	200-500
3	1000-2400

For example, level 1 ground motion with an importance classification factor of 2 would use a 75 year return period.

GROUND MOTION LEVELS (CONTINUED)

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- Base acceleration coefficients
  - Base acceleration coefficients represent the peak ground acceleration for a given return period.
  - AREMA provides ground acceleration maps for 100, 475 and 2400 year return periods.
  - Acceleration coefficients for other return periods can be determined from interpolation.
    - Note: FEMA 273, "NEHRP Guidelines for the Seismic Rehabilitation of Buildings", Section 2.6.1.3 uses natural logarithmic interpolation to determine accelerations for return periods between 475 and 2400 years. FEMA 273 uses an exponential function to determine the acceleration for return periods less than 475 years.
  - A site-specific determination of acceleration coefficients is more appropriate for areas of high seismicity, such as Southern California, since the AREMA maps are not that detailed.
  - Peak ground accelerations for a limited number of return periods is also available by zip code or latitude and longitude from USGS at http://geohazards.cr.usgs.gov/eq/

PERFORMANCE CRITERIA

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- Bridge design performance criteria is coordinated with train post-seismic event operation guidelines.
- Level 1 Ground Motion:
  - Critical structure members shall remain in the elastic stress range.
  - Trains may continue at restricted speed over bridges subjected to this ground motion level.
  - No structural damage is allowed.
- Level 2 Ground Motion:
  - Strength and stability of critical members shall not be exceeded.
  - Trains must stop until inspections are made of bridges subjected to this ground motion level.
  - Damage should be easily detected and accessible for repair.
- Level 3 Ground Motion:
  - No structure collapse.
  - Trains must stop until inspections are made of bridges subjected to this ground motion level.
  - Extensive damage to structure is allowed

DESIGN APPROACH

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- Conceptual considerations are used to select the appropriate bridge type and configuration
- Analysis for Level 1 Ground Motion is used to size the members
- Detailing provisions are incorporated to allow the structure to satisfy the performance requirements for the Level 2 and 3 ground motion.

CONCEPTUAL CONSIDERATIONS

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- Conceptual considerations should be used to select the appropriate bridge type and configuration.
- The design should maintain a balance between functional requirements, cost and seismic resisting features.
- Preferred Bridge Configuration

PREFERRED CONFIGURATION	SPECIAL CONSIDERATION
Straight bridge alignment	Curved bridge alignment
Normal piers	Skewed piers
Uniform pier stiffness	Varying pier stiffness
Uniform span stiffness	Varying span stiffness
Uniform span mass	Varying span mass

- Preferred Superstructure Characteristics

PREFERRED SUPERSTRUCTURE	SPECIAL CONSIDERATION
Simple spans	Continuous spans
Short spans	Long spans
Light spans	Heavy spans
No hinges	Intermediate hinges

- Preferred Substructure Characteristics

PREFERRED SUBSTRUCTURE	SPECIAL CONSIDERATION
Wide seats	Narrow seats
Seat bent caps	Integral bent caps
Multiple column	Single column

LEVEL 1 ANALYSIS

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- Overview
  - Analysis is used to satisfy the performance criteria for Level 1 ground motion.
  - The structure response is a function of the site characteristics, structure stiffness and damping.
  - Equivalent static analysis or modal analysis is used to determine the seismic loads.
  - Seismic and static loads are combined to determine the total member loads.
  - Members are sized to satisfy the Level 1 response limits.

PROCEDURE SELECTION

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- The analysis procedure is selected based on the bridge configuration.

BRIDGE CONFIGURATION	ANALYSIS PROCEDURE
Single-span	No analysis required
Two-span	Equivalent Lateral Force or Modal Analysis Procedure
Multi-span regular	Equivalent Lateral Force or Modal Analysis Procedure
Multi-span irregular	Modal Analysis Procedure

- Single-span bridges do not require formal analysis, however they should have abutment seat widths which satisfy the detailing requirements in Section 9-1.4.7.4.1 to prevent span collapse.

- Two-span bridges are considered regular since they have only one bent which precludes stiffness irregularity.

- Irregular bridges may have high curvature or abrupt changes in stiffness or mass along the length.

STRUCTURE RESPONSE

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- Seismic Response Coefficient quantifies structure response to a given ground motion.

$$C_m = \frac{1.2ASD}{T_m^{2/3}} \leq 2.5AD$$

C_m = Seismic Response Coefficient for the m^{th} mode
A = Base Acceleration Coefficient
S = Site Coefficient
D = Damping Adjustment Factor
T_m = Period of vibration of the m^{th} mode in seconds

- The Seismic Response Coefficient is the basis for determining the structure design loads for both the Equivalent Lateral Force Procedure and the Modal Analysis Procedure.

- The Equivalent Lateral Force Procedure only uses a single value based on the natural period of vibration of the structure for each of the two principal directions of the structure.

- The Modal Analysis Procedure combines values for multiple modes of vibration in each of the two principal directions of the structure.

- For areas with soft soil conditions and high seismicity, or close proximity to known faults, or for special bridge projects, a site-specific hazard analysis is preferred.

SITE COEFFICIENT

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- Site coefficient is determined based on the foundation soil characteristics.

Soil Type	Description	Site Coefficient
1	Rock of any characteristic, either shale-like or crystalline in nature, that may be characterized by a shear wave velocity greater than 2,500 feet per second, or stiff soil conditions where the soil depth is less than 200 feet and the soil types overlying the rock are stable deposits of sands, gravel, or stiff clays.	1.0
2	Deep cohesionless or stiff clay conditions where the soil depth exceeds 200 feet and the soil types overlying rock are stable deposits of sands, gravel, or stiff clays.	1.2
3	20 to 40 feet of soft to medium-stiff clays with or without intervening layers of cohesionless soils.	1.5
4	Soil containing more than 40 feet of soft clays or silts, that may be characterized by a shear wave velocity of less than 500 feet per second.	2.0

DAMPING ADJUSTMENT FACTOR

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- Damping adjustment factor is calculated from the following formula.

$$D = \frac{1.5}{(0.4\xi + 1)} + 0.5$$

D = Damping Adjustment Factor
ξ = Percent Critical Damping (i.e. 5%)

- In the absence of more definitive information, a damping adjustment factor of 1.0 shall be used.

- The Damping Adjustment Factor provides a simplistic method for scaling the seismic response coefficient to account for different structure types and conditions.

- The percent critical damping varies based on the structure material and system, effect of structure attachments (i.e. track and ballast), whether the structure responds in the elastic-linear or post-yield range, and whether or not the structure response is dominated by the foundation or abutment response.

- The percent critical damping (ξ) preferably should be based on actual test data from similar structure types.

EQUIVALENT LATERAL FORCE PROCEDURE

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- The Equivalent Lateral Force Procedure may be used for two-span bridges or multi-span regular bridges.

  1. Calculate the Seismic Response Coefficient (C_m) for each of the two principal directions of the structure

     a. Calculate the natural period of vibration (T_m) for each of the two principal directions of the structure.

        The following simple formulation may be used:

        $$T_m = 2\pi\sqrt{\frac{W}{gK}}$$

        W = Total weight of the bridge
        g = acceleration due to gravity
        K = The total structure stiffness.

     b. Calculate the Seismic Response Coefficient (C_m) for each of the two principal directions.

ELF PROCEDURE (CONTINUED)

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2. Perform static analysis on the bridge in each of the two principal directions.

   a. Calculate the distributed seismic load in each direction from the following formula.

      $p(x) = C_m w(x)$

      $p(x)$ = distributed seismic load per unit length of bridge
      C_m = Seismic Response Coefficient
      $w(x)$ = distributed weight of bridge per unit length

   b. Distribute the seismic load to individual members based on the stiffness and support conditions.

3. Combine the loads in each of the two principal directions of the structure to get the final seismic design loads.

   a. Combination 1: Combine 100% of the forces in principal direction 1 with 30% of the forces from principal direction 2.

   b. Combination 2: Combine 100% of the forces in principal direction 2 with 30% of the forces from principal direction 1.

MODAL ANALYSIS PROCEDURE

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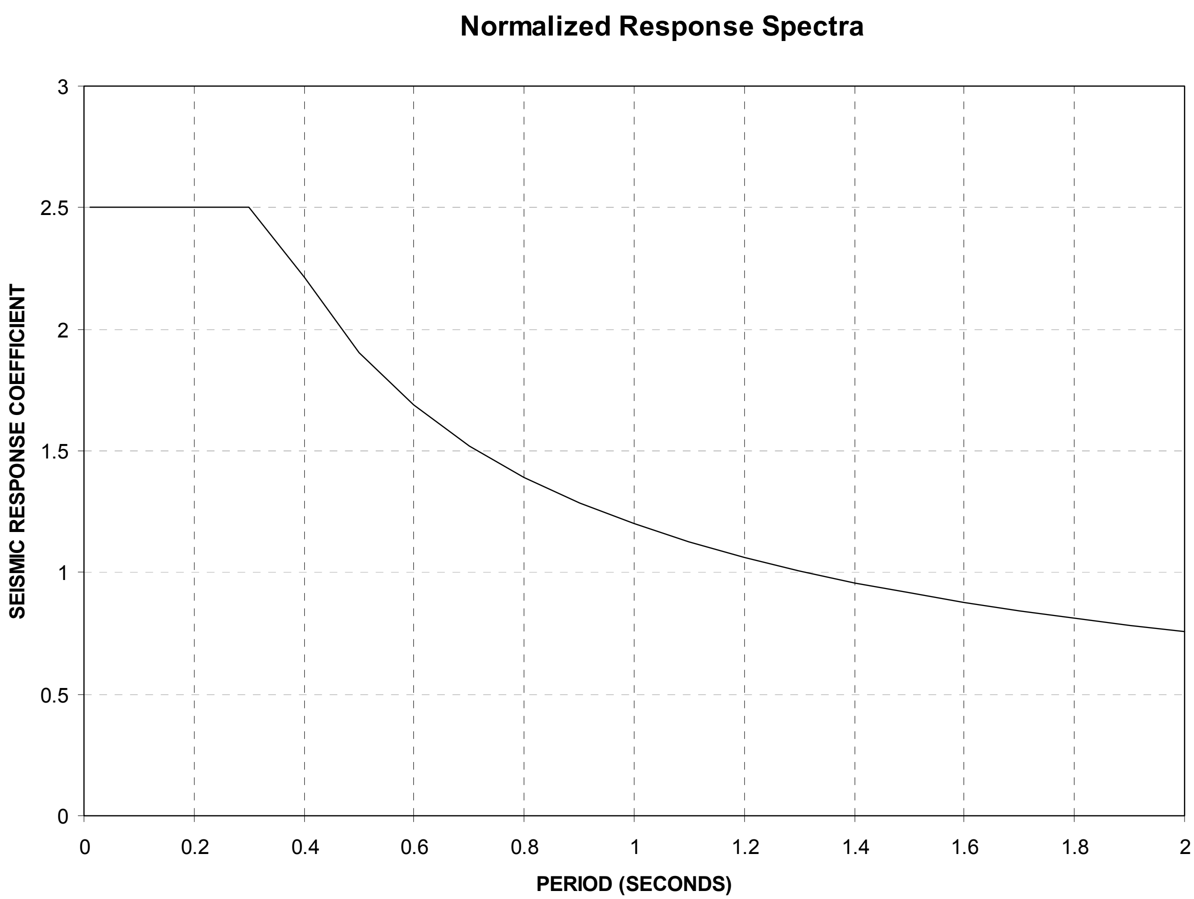
- The Modal Analysis Procedure may be used for any structure configuration.

    1. Develop elastic response spectra with the Seismic Response Coefficient.



MA PROCEDURE (CONTINUED)

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2. Perform dynamic analysis on the structure in each of the two principal directions using the elastic response spectra to determine the individual member loads.

   a. A mathematical model should be used to calculate the mode shapes, frequencies and member forces. The model should accurately represent the structure mass, stiffness and support conditions.

   b. An adequate number of modes should be included so that the response in each principal direction includes a minimum 90% mass participation.

3. Combine the loads in each of the two principal directions of the structure using one of the following methods to get the final seismic design loads.

   a. SRSS Method - Combine forces in individual members using the square root of the sum of the squares from each principal direction.

   b. Alternate Method - Perform two load combinations for investigation.

      i. Combination 1: Combine the forces in principal direction 1 with 30% of the forces from principal direction 2.

      ii. Combination 2: Combine the forces in principal direction 2 with 30% of the forces from principal direction 1.

LOAD COMBINATIONS

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- The loads shall be combined based on the structure material.

Material	Design Method	Combination[1]
Steel	Allowable Stress Design	D + E + B + EQ
Concrete	Load Factor Design	1.0D + 1.0E + 1.0B + 1.0PS + 1.0EQ

D = dead load

EQ = earthquake load

E = earth pressure

B = buoyancy

PS = secondary forces from prestressing

– Effects of other loads, such as stream flow pressure, live load and friction shall be included if they have a significant probability of acting concurrently with earthquake loads. The effects of friction should only be included if they increase the effects of the earthquake loading.

– Buoyancy loads should be based on the water level that has a significant probability of occurring concurrently with earthquake loads and produces the most conservative load combination.

RESPONSE LIMITS

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- The response limits shall be satisfied based on the structure material

Material	Stress
Steel	The allowable stresses used in Chapter 15 “Steel Structures, Part 1 - Design” may be increased by 50%.
Concrete	The design strengths should be used as specified in Chapter 8 “Concrete Structures and Foundations.”

- The stress limits are provided to satisfy the performance requirements of the serviceability limit state. The seismic loads are calculated at the yield level rather than at the working stress level, so it is appropriate to use a 50% allowable stress increase for steel and a 1.0 load factor for concrete.

- Specific lateral deflection limits are not provided, however, the bridge must satisfy the performance requirements of Article 1.3.4. $P\Delta$ effects should be considered if they are significant enough to affect the performance of the bridge.

- The lateral deflection of the bridge must not preclude train operations outlined in Paragraph 1.2.2.1. After a level 1 ground motion event, the trains are allowed to continue at restricted speed. It is the responsibility of the bridge designer to determine how much permanent track deformation will result from the elastic deflection of the structure.

DETAILING PROVISIONS

- Detailing provisions shall be incorporated into the structure to meet the performance requirements for the Level 2 and 3 Ground Motion.

  – Continuity Provisions: *A load path to transfer lateral forces from the superstructure to the ground*.

  – Ductility Provisions: *Allow the structure to respond in the inelastic range*.

  – Provisions to Limit Damage: *Limit damage to areas which are accessible for inspection and repair*.

  – Redundancy Provisions: *Alternate load paths to increase survivability*.

CONTINUITY PROVISIONS

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- SUPERSTRUCTURE
  - The superstructure shall be designed to carry the lateral forces to the bearings or shear connectors.
  - The lateral forces from the span may be carried to the end supports by the following load paths:
    - Lateral bracing system.
    - Lateral bending of the girders, including torsional effects as applicable.
    - Diaphragm action of concrete decks or steel ballast pans provided that the deck is adequately connected to the girders.
  - End cross frames or diaphragms shall be designed to carry the lateral forces to the bearings or shear connectors.
- BEARINGS
  - The bearings shall be designed to transfer the lateral forces to the substructure.
  - Bearings may be supplemented by shear connectors to help transfer the lateral forces provided that the movement required to engage the shear connectors does not cause failure of the bearing device.

DUCTILITY PROVISIONS

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- LONGITUDINAL REINFORCING CONFINEMENT
  - Longitudinal reinforcing in concrete columns, pier walls and piles shall be adequately confined to allow the member to respond in the post-yield range.
- SPLICES IN REINFORCING
  - Lap splices are not allowed in a main load carrying member within a distance “d” (effective depth) of any area designed to respond in the post-yield range.

PROVISIONS TO LIMIT DAMAGE

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- WEAK COLUMN PROVISIONS
  - Reinforced concrete columns which are designed to respond in the post-yield range shall be detailed to prevent damage to adjacent superstructure, bent cap and foundations.
    - The bent cap and foundation shall be designed for the lesser of 1.3 times the nominal column strength or the Level 3 ground motion load.
    - The plastic hinge zone should be designed to occur in locations that can be inspected.
- CONCRETE JOINTS
  - The joint shall be configured and reinforced to reduce the likelihood of damage to the superstructure and bent cap and foundation.
    - Provide adequate longitudinal column reinforcement embedment and confinement.
    - Provide joint shear reinforcement.
- STEEL JOINTS
  - Joints in main lateral load carrying steel members shall be designed to be stronger than the adjoining member. This requirement may be met by designing the connections for the lesser of 1.3 times the connecting member yield strength or the Level 3 ground motion load.

REDUNDANCY PROVISIONS

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- BEARING SEATS
  - Bearing seats should be proportioned to accommodate the maximum relative movements caused by earthquakes.
- SHEAR CONNECTORS
  - Shear connectors may be provided to resist the maximum seismic loads. The shear connectors should be positioned so that they are engaged prior to failure of the bearing device.
- SPAN TIES
  - Span ties may be used to reduce the likelihood of unseating during the higher level ground motion events.
  - The span ties shall be designed to allow for the effects of thermal movement of the span.
- FOUNDATION ROCKING
  - Foundation rocking response may be used to satisfy the performance requirements for the Level 3 Ground Motion for non-ductile single pier foundations..
- CONTINUOUS WELDED RAIL
  - Continuous welded rail (CWR) may be evaluated as a redundant load path for seismic loads or to increase bridge damping.