BRIDGE CONFIGURATIONS AND DETAILS THAT IMPROVE SEISMIC PERFORMANCE

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Abstract

The behavior of bridges during past earthquakes has shown that the structure type, configuration and layout, and the structural details used have a significant effect on seismic performance. The seismic design guidelines included in Chapter 9 of the AREMA Manual for Railway Engineering are based on a three-level ground motion and performance criteria approach consistent with the railroad post-seismic event response procedures. To achieve the performance requirements for the levels two and three ground motions, which represent larger earthquakes, emphasis is put on the use of bridge configurations and details that minimize seismic damage. The design and detailing practices involved in typical railroad bridge construction have inherently resulted in configurations and details that enhance seismic behavior. For example, the use of simple spans on wide piers or cap top areas prevents span loss and allows for movement that can reduce the seismic loading of the substructure. This paper reviews seismic criteria for structure type, configuration and layout, and requirements for strength, ductility, redundancy and detailing that result in good and reliable seismic behavior at low costs. The criteria for structure configuration includes factors such as simplicity, symmetry, regularity, integrity, deformation capability, and reparability. The recommendations made are related to the seismic hazard at the site, the structure importance classification and the bridge performance requirements, and they are consistent with practices typically used in railroad bridge construction. The bridge performance criteria may allow movement at locations that can accommodate movements, deformations at locations that are adequately detailed for ductility and even failure at locations that have redundancy or back-up components. The paper emphasizes the importance of considering seismic criteria in the early planning stages for a bridge structure and of using simple bridge configurations and good details.

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INTRODUCTION

The seismic design guidelines included in Chapter 9 of the AREMA Manual for Railway Engineering [AREMA, 1999] are based on a three-level ground motion and performance criteria approach that is consistent with the railroad post-seismic event response procedures.

The performance criteria requirements are defined for serviceability, ultimate and survivability limit states. The serviceability limit state is primarily concerned with train safety after a moderate earthquake. The structure is required to survive with only minor damage that does not affect train traffic. The ultimate limit state ensures overall structural integrity during a larger magnitude earthquake, and its objective is to minimize damage and loss of structure use. The survivability limit state is concerned with the survival of the bridge after a rare and intense earthquake. Its objective is to minimize the likelihood of severe damage or bridge collapse. Methods of analysis and detailing are recommended for the serviceability limit state and a conceptual approach is recommended for satisfying the ultimate and the survivability limit states. This approach consists of seismic design guidelines based on conceptual principles regarding structure type, configuration and layout, foundations, materials, details and connections. Incorporating conceptual seismic design principles, especially during the early stages of bridge planning and design, can significantly improve seismic behavior at low additional costs. It can also overcome the uncertainties involved in the ground motion description, the numerical analysis of structure response in the post-yield range, and the limited analytical and experimental seismic research data on railroad bridges that is currently available.

The design and detailing guidelines presented in this paper apply to the ultimate and the survivability limit states. They are based on experiences learned from past earthquakes, analytical and experimental findings regarding expected bridge behavior during extreme events, and personal field experience and observations of actual bridge behavior of members of AREMA Committee 9. Theses recommendations are intended to reduce the seismic demands by selecting an appropriate structure type for the existing site conditions and by following basic requirements for simplicity, symmetry and displacement capability, and to increase the seismic resistance by providing adequate strength, stability, ductility, redundancy, energy dissipation and deformation capability. Strength and stability are important attributes for satisfying the serviceability limit state, while ductility and redundancy have a significant effect on the ultimate and the survivability limit states. Displacement and deformation capacity is quite important for structures on poor soil conditions or near a fault line.

The design and detailing criteria recommended reflect the unique characteristics of railway structures, and although the principles presented are applicable to all structures, the conceptual design approach proposed is mainly intended for conventional railroad bridges with short and medium spans. For major bridge construction or unusual bridge projects, in addition to following these guidelines, a more detailed analytical approach is also recommended.
BRIDGE BEHAVIOR DURING PAST EARTHQUAKES

Seismic Effects

Earthquakes are extreme events that are associated with a great amount of uncertainty. The seismic effects at a given site can include a variety of hazards, such as ground vibrations, lateral ground displacements, compaction of fills and underlying sediments, soil fractures, liquefaction, liquefaction-induced ground movements, slope failures, landslides and tsunamis. These effects are influenced by the nature of the fault rupture process, the travel path followed by the resulting seismic waves as they propagate from the ruptured fault to the site, the distance from the fault and the local soil conditions at the site.

Ground vibrations are usually defined in terms of the magnitude of the ground accelerations, their frequency content and the duration of motion. They generate accelerations and inertia forces that cause stresses, deformations and displacements within the structure. Depending on its natural frequencies and damping characteristics, a structure may experience accelerations larger than the ground accelerations.

Ground displacements may be transient or permanent. They have a direct effect on the response of the bridge foundations. Large ground movements and other soil failures such as liquefaction have led to many bridge failures during past earthquakes.

Reviews of bridge performance during past earthquakes have shown that the structure type, configuration and layout can have a significant impact on the extent of damage. At many locations certain bridge types have survived earthquakes with relatively minor damage, while other bridges in the same vicinity have collapsed. During the 1964 Alaska earthquake for example, highway bridges such as the Portage Creek Bridges 2 and 3, and a bridge crossing over the Twentymile River have collapsed, while adjacent railroad bridges have not (see Figure 1), [Kachadoorian, 1968]. The survival or failure of bridges of a similar type has been linked to their configuration and the particular design and detailing criteria used. For example, skewed and irregular bridge configurations have experienced extensive damage, often at locations where other bridges remained unharmed. In California, most of the bridge failures occurred in structures designed based on the seismic criteria used prior to the 1971 San Fernando earthquake, and only minor damage was experienced by the newer structures.

To identify elements that contribute to good seismic behavior, it is important to understand the past seismic behavior of bridges. Since there is not much information on railroad bridge damage during past earthquakes, a review of some of the seismic damage to highway bridges has been included herewith, in order to identify response characteristics that could also be applicable to railroad bridges.

Seismic Performance of Highway Bridges

Typical highway bridge construction consists of steel or concrete superstructures on reinforced concrete piers or bents. The superstructure is
commonly continuous over several spans and in many cases integral with pier caps and abutments. Some of the spans include interior hinges that allow for thermal movements. The highway bridge configuration and layout is often dictated by geometric constraints of right-of-ways and existing roads and structures. The majority of the highway bridges are relatively new structures built during the last 40 years.

The most common highway concrete bridge damage types observed in past earthquakes include:

- Collapsed or unseated spans due to bearing failures or inadequate support widths at bearings and interior expansion joints;
- Concrete column damage and collapse due to inadequate development of reinforcement, insufficient confinement reinforcement, and poorly detailed transverse reinforcement;
- Foundation, pier and abutment damage and collapse due to soil failure or movement.

The seismic damage of steel bridges has been less common and, with the exception of a few collapsed spans due to inadequate support widths, not as severe. Some of the more common damages include:

- Damage of bearings or bearing anchor bolts;
- Shifting of superstructures on top of substructures;
- Cracking of the abutments caused by pounding of the expansion joints;
- Damage of some end diaphragms and cross frames;
- Permanent deformations of some tubular steel columns due to local wall buckling.

Steel bridge columns have experienced some unexpected forms of damage during the 1995 Hanshin (Kobe) earthquake. Two rectangular steel box columns collapsed due to buckling at a splice causing corner welds to tear after which the welds “unzipped”. Some of the contributing factors to this failure that were noted in [Ritchie, 1998] include shedding of dead load into the steel columns due to adjacent concrete pier failures and the design of the welds at the corners of these columns as partial penetration stitch welds. A few circular piers suffered from “lantern buckling” in which the walls of the piers bulged outward. This buckling occurred very close to welded joints where the plate thickness changed. Several cracks that were found at the corners of portal frames and the bases of columns were attributed to low cycle fatigue, with local buckling accompanied by tensile cracking.

Both concrete and steel skewed bridges have performed poorly in past earthquakes because of their tendency to respond partially in rotation resulting in high and unequal force and displacement demands at their supports.
Common railroad bridge types include timber trestles, steel truss and girder spans and reinforced concrete spans. Typical substructures consist of steel or concrete bents, steel tower viaducts and concrete or masonry piers. Other bridge structures include culverts and concrete or masonry arches. The majority of railroad bridges are simpler in configuration and older than highway bridges. A 1992 and 1993 FRA bridge safety survey found that more than half of the nation's 100,000 railroad bridges were built before 1920. Only a few of the newly constructed bridges have continuous superstructures.

Railroad bridges have performed well in past earthquakes relative to other structures. A comprehensive review of past seismic performance of railroad bridges may be found in [Byers, 1996] where the cause of damage is separated into two categories; soil movement due to lateral spreading at stream banks and/or liquefaction, and ground shaking.

Most of the damage experienced by railroad bridges was due to soil movement and liquefaction and/or lateral spreading at stream banks. The extensive ground movements that occurred during the 1964 Alaska earthquake, have resulted in the damage of a large number of timber trestles (see Figure 2) and bridges on pile supported piers located on unconsolidated granular sediments [McCulloch, 1970]. The damage types due to ground movements include:

- Shifting of foundations, piers and abutments;
- Compressed decks and stringers due to movement of deep alluvial material toward stream channels;
- Lateral buckling of superstructures due to longitudinal compression;
- Collapsed spans.

Bridge damages due to ground vibrations were found to be minor in earthquakes of magnitude less than 7, and in all cases where there has been railroad damage that resulted in service interruptions, there has also been serious damage to other railroad facilities [Byers, 1996]. Common damage types that have been attributed to ground shaking include:

- Shifting of girders on top of piers;
- Bearing damage and failure of anchor bolts;
- Failure of approaches and fill material behind abutments.

A post seismic inspection of Southern Pacific bridges after the 1989 Loma Prieta earthquake [Sorgenfrei, 1989] reported that in spite of the proximity of structures to the epicenter, there was a lack of significant damage. Only four structures were damaged, one having minor superstructure damage and three with substructure damage. Although some girder spans shifted, the size of the bearings and pier tops were large enough that the movement did not allow any spans to drop. Where deteriorated anchor bolts failed after minimal resistance there was no damage to the pier tops. One of the structures damaged was a timber trestle.
where one of the bent caps twisted, probably as a result of ground movement (see Figure 3).

A report of earthquake damage during the 1925 Santa Barbara, California earthquake [Kirkbride, 1927] noted that the only damage in a high steel viaduct that was observed to shake violently was to anchor bolts and the stone pedestals supporting the tower legs. Damage of the stone base of a steel viaduct tower was also noted during the 1994 Northridge earthquake in Pasadena (see Figure 4), [Lozano, 1994].

The relatively good seismic performance of railroad bridges in North America may be attributed to some of their unique operational and structural characteristics.

STRUCTURAL ASPECTS UNIQUE TO RAILROAD BRIDGES

Typical railroad bridges in North America are characterized by simplicity in design and construction. They have relatively short and regular spans, and large pier or cap top areas that allow for considerable horizontal span movements and energy dissipation. The design live load to dead load ratios for railroad bridges are much higher than comparable ratios for other bridge structures. The relatively large longitudinal and lateral design load requirements provide for a horizontally strong and stiff structure. In addition, the track structure provides longitudinal continuity over piers and abutments which restrains and dampens superstructure movements. Railroad bridge designs are usually not restricted by geometric constraints, as are highway interchanges for example, and their configurations are mainly based on structural and functional criteria.

The relatively rigorous railroad bridge design and detailing practices for compression members, bracing of compression members, bracing of viaduct towers and bents, connections, fatigue and fracture are also good for seismic response.

SELECTION CRITERIA FOR STRUCTURE AND FOUNDATION TYPE

The structure and foundation type was found to have a significant effect on seismic performance. Therefore, it is recommended that seismic criteria be considered early in the bridge planning and design process, especially in regions of high seismicity. The selection of an appropriate structure type and foundation should take into account the seismic hazard at the site, the soil conditions and the bridge performance requirements.

In general, sites near active faults, sites with potentially liquefiable or unstable soil conditions, and sites with unstable sloping ground conditions should be avoided if possible, and measures to improve the soil conditions should also be considered as an alternative. Conventional bridge structures cannot be designed to resist the load magnitudes generated by large ground displacements and possible settlement or shifting of foundations. Therefore, where the extent of poor soil conditions is relatively large, a structure type that can accommodate large ground displacements is recommended. For example, simple span structures with ample
bearing support length could accommodate large movements, without accumulating loads.

If the extent of the poor soil condition is limited, and the bridge abutments can be placed on solid ground, a continuous superstructure may be considered in order to transfer seismic loads to abutments and minimize the seismic loading of the interior piers.

On rock or stiff soil sites a more flexible type structure (with a longer natural period) is preferable, while at sites with deep soft soils which have longer predominant period ground motions, a stiffer bridge structure (with a shorter natural period) could be more appropriate. The weight of the superstructure can also be used to achieve a desired natural period. For example, concrete superstructures with ballasted decks lead to longer natural periods, while steel superstructures result in shorter natural periods. However, in most cases the weight of the superstructure should be minimized to reduce the inertia forces induced by the earthquake.

The bridge performance requirements should also be considered in the selection of the structure type. The performance requirements for a given limit state may differ from bridge to bridge. For example, for some bridges the survivability limit state may require only limited damage after a severe earthquake, while in others, severe damage or even collapse could be accepted. Where continuous train operations are important after a large earthquake, an inherently strong and stiff structure type that is not likely to suffer extensive damage is preferable.

The selection of the foundation type should consider the seismic hazard and the soil conditions at the site. To the extent possible, bridge foundations in regions of high seismicity should be founded on stiff and stable soil layers, preferably rock. Deep foundations are required in order to reach below liquefiable soil layers. Piles should have sufficient buckling capacity to resist vertical loads in case of liquefaction of surrounding soil layers.

MATERIAL SELECTION CRITERIA

Good material properties for seismic applications include, high ductility, high strength to weight ratios, ease of full strength connections, adequate toughness, low cyclic degradation and consistency in mechanical properties. As a material, steel has the best properties, followed by timber and reinforced concrete. However, the actual seismic performance of each material will depend on the design and detailing criteria and practices used for members and connections designs.

CRITERIA FOR BRIDGE CONFIGURATION AND LAYOUT

General

The selection of the bridge configuration and layout, along with proper detailing, play a key role in providing good seismic behavior. Criteria for determining adequate structure configuration and layout include:
• Simplicity
• Symmetry and Regularity
• Integrity
• Redundancy
• Ductility
• Ease of Inspection and Repair

Simplicity

Simplicity was found to be an important characteristic for good seismic behavior. It allows for a direct and clear seismic load path, a predictable response, simple connection details, and ease of inspection and repair. In simple structures, the most important members in the seismic load transfer system can be easily identified, designed and detailed for adequate behavior. Simple span bridges with sufficient seat widths have performed well in the past, and should continue to be used whenever possible.

Symmetry and Regularity

Symmetry and regularity characteristics tend to minimize torsional effects, which are likely to result in large and unexpected seismic demands. Rotational response of structures has been a main cause of damage during past earthquakes. Therefore, to the extent possible, the following symmetry and regularity criteria should be considered:

• The bridge structure should have a uniform distribution of mass, strength and stiffness in both the longitudinal and the transverse directions.
• Abrupt or unusual changes in weight, strength, stiffness and geometry along a span, and large changes in these parameters from span to span should be avoided.
• The horizontal strength and stiffness of substructure elements should not vary much along the bridge and the placement of the fixed and expansion bearings should be such that a balanced seismic load distribution to all piers can be achieved.
• Columns in multi-column bents should be of equal height and there should not be any abrupt changes in geometry along the height of piers.
• Severe skews should be avoided even at the expense of providing longer spans or making changes in alignment.

Integrity

Different parts of a bridge may respond differently during an earthquake and may result in large relative displacements. Displacement compatibility may be achieved by either designing connections to resist deformations or by allowing displacements or deformations to occur in a controlled manner. In general, it is desirable for all bridge structures to have a certain degree of deformation capability.
within the seismic load transfer path, since seismic demands are reduced when controlled movements are allowed. Bridges with rigid superstructures and rigid substructures could benefit from some allowance for movements at the bearing location. However, adequate bridge seat widths are needed to ensure that movements can be accommodated without potential for span loss. A strong and stiff superstructure to substructure connection is more appropriate when the substructure is not too rigid or when the end diaphragms or cross frames of spans are designed and detailed to undergo ductile deformations during a strong earthquake.

The design of expansion joints and bearings is critical to the seismic performance of the structure. Large earthquake induced seismic forces and displacements can result at these locations and at other discontinuities within the superstructure, and they must be accounted for in design. Increased integrity is achieved by keeping the number of connections that are vulnerable to seismic loading to a minimum. For example, intermediate hinges within a span should be avoided.

Measures for preventing excessive relative displacements of superstructure components include placing foundations on firm and stable ground and driving piles to stable soil, and providing shear keys and other restraining devices at the pier tops. Track structures continuous through the bridge can increase integrity, especially in the longitudinal direction. Catcher and back-up systems may be added to prevent collapse after a severe earthquake, even if significant damage has occurred.

**Redundancy**

Bridge redundancy reflects the capacity of a bridge to carry loads after one or more of its members fail. Member failure can be either ductile or brittle. Requirements for bridge redundancy include bridge configurations with structural redundancy and multiple load paths, and members with internal redundancy. Continuous spans and framed bents that allow load redistribution after yielding at a given location are examples of structural redundancy. Multi-column bents provide alternative load paths that can help redistribute the load and prevent collapse. During past earthquakes, failures in single column supported bents were more critical than similar failures in multi-column bents, generally resulting in total column failure and bent collapse. Although severe damage was often sustained, multi-column structures have seldom collapsed (see Figure 5)). The survival of multi-column structures has been attributed to the structural and multiple load path redundancy of their framing systems, even though the columns and their connections were not properly designed or detailed for ductile behavior.

Redundancy measures for satisfying the survivability limit state may include restrainers, catcher blocks and back-up systems designed to prevent structure collapse.
Ductility

During large earthquakes stresses in bridge members and connections exceed the elastic range and structures could experience large inelastic deformations. Ductility is the ability of a member, component or structure to sustain large deflections beyond the elastic range without failure or collapse. It is usually defined in terms of the ratio between maximum deformation without failure and yield deformation. The importance of ductility during bridge response to large magnitude earthquakes is well recognized.

The ductility of a structure depends on the individual member ductilities and their loading condition, the ductility of the connection details and also on the structure configuration. For example, nonductile and poorly braced members loaded in compression may experience sudden failure even prior to reaching yield stresses.

The steel tower bracing system arrangements shown in Figure 6 may be used to illustrate the effect of bracing configuration on ductility. For example, the K-bracing provides the least ductility, since once a compression brace buckles the column will experience large bending demands. For this reason the use of K-bracing is not recommended. The V-bracing has a similar disadvantage, but not as severe; once a compression brace buckles one of the connecting struts will experience large bending demands. The X-bracing has a relatively higher ductility. Even after the compression brace buckles, the tension brace provides a load path for the lateral forces. Eccentric bracing can offer significant ductility and energy dissipation by means of cyclic bending or shearing behavior of short beams (shear links). The estimated relative ductilities for the various configurations is 1 for K-bracing, 2 for the V-bracing, 4 for the X-bracing and 6 for the eccentric bracing [ECCS, 1991].

The use of batter or vertical piles only in pile bents is another example of the effects of structure configuration on ductility. Batter piles provide the strength and stiffness needed for the normal design loading conditions. However, the high seismic loading and low ductility of their connection to the cap limits the ductility capacity of the bent. It was estimated that the ductility of bents with vertical piles only can be 1.5 to 2 times larger than that of bents with batter piles.

The importance of ductility and recommended measures for achieving ductile behavior are further discussed in the following sections.

DAMAGE CONTROL CRITERIA

The approach of AREMA Chapter 9 to seismic design consists of providing a certain level of elastic strength to resist the serviceability level earthquake without damage, and a distribution of strength and stiffness that could minimize damage and ensure a "desirable" ductile failure mechanism during the larger earthquakes. The distribution of strength and stiffness should be such that damage occurs at predetermined locations, and certain critical load carrying members are "protected" from inelastic response.
The predetermined damage locations must be well detailed to sustain large inelastic deformations without strength degradation, and at the same time they should be the weakest links within their respective load paths in order to restrict damage to other members. In addition, the distribution of stiffness and strength should be such that plastic response or damage does not occur in locations inaccessible for inspection and repair.

Since seismic demands are reduced when movements and ductile deformations are allowed, a damage control criteria can achieve good and reliable seismic performance at relatively low costs. The use of sacrificial elements which could be easily replaced in the event of damage, may also offer a cost-effective way of enhancing the bridge seismic response and providing protection to other members.

Knowledge of likely failure locations and modes also allows for the design of connection details and jacking locations for temporary support during repairs.

DUCTILITY REQUIREMENTS

General

Ductility is the main criteria for satisfying the ultimate and the survivability limit state requirements. It is generally quantified as a ratio, \( \mu \), of ultimate deformation to yield deformation, and it could refer to either member, component or structure ductility. A ductile structure can undergo large inelastic deformations without significant strength degradation. Ductile behavior reduces seismic loads and provides an energy dissipation mechanism. To achieve good ductility, locations that are expected to experience plastic deformations need to be adequately designed and detailed, and instability or brittle failure modes need to be prevented. At the same time the structure should have sufficient stiffness to maintain stability and avoid excessive drifts.

Structures can be designed and detailed for different levels of ductility. For example, it is recommended that bridges located in regions of moderate seismicity be designed for limited ductility levels, of say \( \mu = 1 \) to \( 3 \), while bridges located in regions of high seismicity be designed for full ductility levels, of say \( \mu = 3 \) to \( 6 \), depending on the seismic hazard at the site and the structure importance classification.

The requirements for structure ductility for reinforced concrete, steel or timber structures are different, since they must take into account the inherent material properties and the typical structural configurations.

Reinforced Concrete Structures

Ductility requirements for reinforced concrete members aim to prevent brittle shear failure and provide adequate reinforcement for ductile bending mechanisms at plastic hinge locations. The design philosophy for concrete highway bridges is to allow plastic hinging regions at the top and bottom portions of pier columns. Based on the geometry of most concrete bridge structures and post seismic inspection
considerations, these are the most reasonable locations for hinging. Significant analytical and experimental work has been carried out to understand the inelastic behavior of pier columns during cyclic loading and to establish design and detailing methods for providing adequate ductile behavior.

Today the requirements for reinforcement details in concrete structures in seismically active regions are well established in design codes and State guidelines for seismic design of highway bridges, and they should be followed, but in a manner consistent with railroad design and detailing practices. In general, these requirements are intended to increase ductility and reduce the likelihood of brittle shear failures. For columns, the seismic design and detailing requirements cover the following areas:

- Amount and spacing of vertical reinforcement;
- Column flexural resistance for large axial loads;
- Column shear and transverse reinforcement in plastic hinge regions;
- Transverse reinforcement for confinement at plastic hinge regions;
- Spacing of transverse reinforcement for confinement;
- Splicing and anchorage of reinforcing bars in plastic hinge regions;
- Extension of column reinforcement into bent caps and footings;
- Concrete column joints.

Seismic detailing requirements for foundations include:

- Increase in footing thickness;
- Requirement of minimum pile penetration into the footing;
- Top footing reinforcement and vertical stirrups connecting the top and bottom mats;
- Confining ties for longitudinal column reinforcement.

Steel Structures

The ductility requirements for steel structures aim to prevent buckling and fracture and provide adequate connections and details. Due to differences in geometry, stiffness, ductility, mass and damping characteristics, the seismic behavior of steel bridges is fundamentally different from that of concrete bridges. One main difference is that steel bridges can yield and dissipate energy at various locations throughout the structure, and therefore plastic hinge regions do not have to be restricted only to the columns. Also, in steel members, the shear yielding mechanism is preferable, since it provides substantial stable energy dissipation, which is different from concrete members where flexural failure modes are desired and shear failure is avoided.

Seismic design and detailing requirements for steel bridges are not as well established and codified as those for concrete bridges. This is probably because of the inherent ductility of structural steel and the relatively good performance of steel bridges during past earthquakes. In addition, following relatively simple
design and detailing guidelines, significant ductility levels could be achieved. Such
guidelines include the following recommendations:

- Limit the width to thickness (b/t) ratios for plates in compression;
- Limit the slenderness ratio for main compression and bracing members;
- Avoid details that are prone to stress concentrations such as reentrant
  corners and abrupt changes in thickness;
- In general, avoid using any details susceptible to fracture, especially in
  areas expected to respond in the plastic range;
- Avoid field welds and other fatigue prone details;
- Design steel members such that yielding of the gross section occurs
  before local buckling or fracture;
- Avoid triaxial tension stress conditions that may occur at locations such
  as near the intersection of welds in thick elements. They can inhibit the
  ability of steel to exhibit ductility.
- Use stiffeners that are more rigid than the minimum needed to prevent
  buckling.

Other recommendations include:

- Limit the axial compression load in columns to a percentage of their yield
  capacity;
- Provide means for alternate load path in case of damage;
- Ensure that damage occurs in secondary, non-gravity carrying elements,
  such as bracing members;
- Consider using the end diaphragms or cross frames as locations for
  ductile behavior.

Some of these guidelines are covered extensively in bridge and building
design codes that use a plastic approach to design. However, many of the
earthquake specific design requirements for full ductility are typically more stringent
than the plastic design requirements. A review of requirements for plastic and
seismic design is provided in [Ritchie, 1998]. Most of the emphasis is put on
enhancing the ductility capacity of compression members, which are generally
controlled by their local or overall buckling capacity.

The width to thickness ratio (b/t ratio) requirements for preventing local
buckling of plates are usually expressed in terms of a constant k based on the plate
boundary conditions:

\[
\frac{b}{t} \leq k \sqrt{\frac{E}{F_y}}
\]

(1)

where E is the modulus of elasticity of steel and \( F_y \) is the yield stress of steel. The k
factors recommended to ensure that yielding is reached prior to local buckling can
range from about 0.5 for projecting elements of plates supported only on one edge to around 1.5 for plates supported along two edges. More stringent k factors are required for reaching a plastic hinge prior to local buckling. Seismic demands call for even more restrictive k factors than those for plastic hinges in order to provide stable cyclic ductility. Some of the k factors proposed for reaching rotational ductilities of 6 to 8, range from about 0.2 for projected elements of plates supported along one edge to around 1.2 for plates supported along two edges.

The slenderness requirements for members in compression are usually expressed in terms of kl/r ratios or slenderness parameter values \( \lambda \):

\[
\lambda = \left( \frac{KL}{\pi r} \right)^2 \left( \frac{F_y}{E} \right)
\]

(2)

where K is an effective length factor, L length of the member, r radius of gyration, \( F_y \) yield strength of the steel and E modulus of elasticity of steel. Reducing the value of \( \lambda \) from 2.25 to 1.0 could increase the member ductility from 1 to 4 [Astaneh-Asl, 1996].

**BRACING SYSTEMS**

Bracing systems are critical parts of the seismic load transfer system of a bridge structure, and require special consideration. It is recommended that in regions of high seismicity, slenderness and connection requirements of bracing members that are part of the lateral force resisting system, comply with applicable provisions specified for main member design.

Specific recommendations for the design and detailing of bracing systems for cyclic post-buckling behavior may be found in [Astaneh-Asl, 1986], among others.

The application of eccentrically braced frames for seismic applications has been developed for building applications and could also be considered for bridges.

**PILE BENTS**

The ductility of bents with batter piles is limited by the low capacity of the pile to cap connections. When subjected to the high loads that are attracted by the batter piles, these connections are likely to fail in a brittle fashion.

Pile bents with vertical piles only can offer a higher ductility capacity than that of bents with batter piles. They may be designed to perform as a ductile moment resisting frames with significant ductility capacity. Therefore, in regions of high seismicity, the use of bents with vertical piles only should be considered. They may require a larger number of piles bent or piles with a larger cross section. Also, the pile to cap connections would need to be designed and detailed for moments. Design and detailing guidelines for adequate post-yielding behavior for prestressed concrete piles and large-diameter prestressed concrete cylinder piles may be found.
in [Priestley, 1996], while detailed guidelines for the seismic design of steel pipe piles for ductile behavior may be found in [API, 1994].

CONNECTIONS

Connections can have a significant effect on seismic resistance. They attract some of the largest seismic demands and they often are the weakest links in the seismic load resisting system. Failure of connections is usually brittle and it often has serious consequences. Therefore, proper design and detailing of connections that transmit seismic loads is essential.

In regions of high seismicity, connections should be designed for the capacity of the members. Higher connection capacity should be provided where members are designed for ductile behavior.

Concrete reinforcement details for connections are well established in seismic design codes, but connection detailing for structural steel is not as well defined. In general the connection design should conform to the damage control criteria. To ensure that connection capacity does not govern, it has been proposed that the connection design be based on 1.35 yield member capacity for limited ductility and 1.5 yield member capacity for full ductility requirements.

Bolted connections are preferable over welded connections. They are more ductile and reliable, and also provide for more damping. Field welds, intermittent welds and partial penetration groove welds should be avoided especially in regions of expected inelastic deformations.

The required strength for bracing joints should be the least of the design axial strength of the member or the maximum force that can be transferred to the brace system. The end connections of bracing members expected to undergo plastic deformations, should not only be designed for an axial force of $A^*F_y$, but also for axial force of $A^*F_y/2$ in conjunction with a moment of $2.5^*M_y$ [Astaneh-Asl, 1986] in order to accommodate post-buckling forces.

Gusset plates should be designed to carry the compressive design strength of the members without local buckling. In order to prevent premature buckling of gusset plate edges, the ratios of the length of free edge of gusset plate to thickness should be limited based on b/t ratio criteria for plates with an unsupported edge.

Seismic detailing guidelines for bearings may be found in [ATC, 1996].

SUMMARY

The seismic design and detailing principles presented in this paper are intended to provide basic guidelines to improve seismic behavior and meet the ultimate and the survivability limit state requirements of Chapter 9 of the AREMA Manual. Many of these principles need to be considered in the early stages of bridge planning and design in order to select the most appropriate bridge type, configuration and layout for the seismicity of the region and the site specific conditions. The guidelines presented are based on lessons from bridge behavior during past earthquakes, findings of analytical and experimental investigations, and field experience and understanding of actual railroad bridge behavior.
Requirements for achieving good seismic performance include proper selection of structure type, configuration and materials, simplicity, symmetry, regularity, integrity, deformation capability, reparability, ductility, redundancy and adequate detailing. Good material properties for seismic applications include high ductility, high strength to weight ratios, ease of full strength connections, good notch ductility and low cyclic degradation. Damage control criteria should be considered in the early design stage. Predetermined damage locations should be adequately detailed to sustain large inelastic deformations. Ductility requirements for reinforced concrete and steel structures established in seismic design codes for other structures may be considered, but they should be consistent with detailing practices typically used in railroad bridge construction. Redundancy and other measures designed to prevent collapse in case of serious damage, such as catcher or back-up systems, may also be used to satisfy the bridge performance requirements.

Typical railroad bridge construction in North America has actually been following most of these requirements. Existing railroad bridges are typically very simple in their design and construction, with relatively short spans, and with comparatively large piers or cap top areas that allow for considerable longitudinal and lateral movements. Railroad bridges are not burdened by heavy concrete decks that are prevalent in highway structures and the lateral design load requirements provide for a laterally strong and stiff superstructure. The rigorous requirements that are used for connections, compression members, bracing of compression members, fatigue and fracture for regular designs also contribute to good seismic resistance.

By following the guidelines proposed, in particular the ductility, redundancy and detailing criteria, improved railroad bridge behavior during large magnitude earthquakes can be achieved. These requirements need to be balanced, so that through an adequate combination of strength, ductility and redundancy, all limit state requirements can be satisfied in an economical fashion.

REFERENCES


American Railway Engineering and Maintenance of Way Association (AREMA), AREMA Manual for Railway Engineering, Chapter 9, with 1999 Revisions, Washington D.C.


Lozano, D.E., Photo Collection of Examples of Seismic Bridge Damage in California, Burlington Northern Sana Fe.


Figure 1. Collapsed Bridge Across Twentymile River. Railroad bridge in upper right corner did not collapse.

Figure 2. Laterally Buckled and Broken Timber Trestle Stringers
Figure 3. View of Tipped Pile Bent Cap and Cracked Brace.

Figure 4. Stone Damage at the Base of a Steel Tower Viaduct.
Figure 5. Column Failure. The deck did not completely collapse due to redundancy.

Figure 6. Bracing Configurations.