SEISMIC DESIGN OF STEEL BRIDGES

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Keywords

Bridges, capacity, demand, displacement, ductility, earthquake, moment-curvature, performance-based design, pushover analysis, seismic design, structural engineering.

Contents

Summary

This chapter presents an overview of seismic steel bridge practice in the United States. Bridges are categorized as either *Important* or *Ordinary* depending on the desired level of seismic performance. Important and Non-standard bridges shall be designed according to project-based criteria. Ordinary bridges are not designed to remain elastic during the design seismic event, except for structures located in low seismic regions. The following guidelines may be applicable to seismic design of steel bridges:

- All bridges shall be designed to withstand deformations imposed by the design seismic event. All structural components shall be designed to provide sufficient strength and/or ductility to ensure collapse will not take place during a Maximum Credible Event.
- Inelastic deformations are generally concentrated in the specially detailed ductile substructure elements. Desired locations of plastic hinging shall be identified and detailed for ductile response.
- Inelastic behavior in the form of controlled flexural damage may be permitted in some of the superstructure components such as the cross frames, end diaphragms, shear keys and bearings to prevent damage in other parts of structures.
- Capacity design concepts shall be used to design essentially elastic components. Design forces shall be determined from the overstrength capacity of ductile components that can be transferred through the connections to adjacent components.

Force demands in the essentially elastic components shall not exceed strength capacity determined by AASHTO LRFD Specifications.

- Details such as seat width, bearing assemblies, end ductile cross frames, splice and connections, welds, limiting slenderness ratios, concrete end diaphragms, and integral connections between concrete columns and steel girders shall be properly designed to ensure continuity of load path during earthquake and to ensure the design objectives are achieved.

1. Introduction

Seismic bridge design has been improving and advancing, based on research findings and lessons learned from past earthquakes, such as the 1989 Loma Prieta and the 1994 Northridge, USA, the 1995 Hyogo-ken nanbu (Kobe) in Japan, the 1999 Chi-Chi in Taiwan, and the 2008 Wenchuan in China. In the United States, the California Department of Transportation (Caltrans) published the performance and displacement-based Seismic Design Criteria (SDC), the first version, which focuses mainly on concrete bridges in 1999, with the current Version 1.4. The Caltrans Guide Specifications for Seismic Design of Steel Bridge (Caltrans-Guide) was published in 2001. The American Association of Highway and Transportation Officials (AASHTO) published the AASHTO Guide Specifications for LRFD Seismic Bridge Design (*AASHTO-Guide*), first edition in 2009, which is based on the ATC/MCEER's Recommended LRFD Guidelines for the Seismic Design of Highway Bridges and Caltrans SDC. In Europe, the Part 2 - Bridges of Eurocode 8 was first proposed in 1994 as the European Standard, and the updated vision was published in 2004. In Japan, Design Specifications of Highway Bridges, Part V: Seismic Design, was significantly revised in 1996 after Hyogo-ken nanbu earthquake, and the latest version was published in 2002. In New Zealand, the Transit New Zealand Bridge Design Manual was also completely revised in 1995 and the latest vision was published in 2004. Significant advances in earthquake engineering have been made during the last 20 years.

This Chapter first addresses seismic bridge design philosophies and concepts for steel girder bridges in general, and then presents effective details for seismic design of steel bridges.

Seismic design is an art that is always evolving. Through research and real life performances more information is gained and shared. This chapter addresses only some of the many issues incumbent upon bridge designers for desirable seismic performances. Engineers are always encouraged to incorporate to the best of their ability, the most recent research findings and the most recent "full-scale evidences" in real earthquakes.

2. Earthquake Damage to Steel Bridges

Recent earthquakes, particularly the 1989 Loma Prieta and the 1994 Northridge earthquakes in California, USA, the 1995 Hyogo-Ken Nanbu earthquake in Japan, the 1999 Jiji earthquake in Taiwan and the 1999 Kocaeli earthquake in Turkey, have caused collapse of, or severe damage to, a considerable number of major bridges. Past earthquakes have shown steel bridges to have many desirable performance characteristics that are not seen in concrete bridges. Damage induced in steel bridges can take many forms depending on the ground-motion, site conditions, overall configuration, and specific details of the bridge. Most of the damage to steel bridges has taken one of the following forms:

- Unseating of superstructure at in-span hinges or simple supports due to inadequate seat lengths or restraint.
- Concrete column brittle failure due to deficiencies in shear design and inadequate ductility.
- Steel column brittle failure due to the inadequate ductility.
- Anchorage assembly failure due to poor reinforcement details in concrete and end cross frame buckling. End cross frame inelastic buckling which prevented serious damage to the bridge substructures.

3. Performance-based Seismic Design Criteria

3.1. Caltrans Seismic Performance Criteria

Table 1 outlines Caltrans seismic performance criteria including the bridge classification and the service and damage level established. Bridges are categorized as “Important” or “Ordinary”. For Standard “Ordinary” bridges, the displacement-based one-level safety-evaluation design (“no-collapsed” design) is only required in the Caltrans SDC. Non-standard “Ordinary” bridges feature irregular geometry and framing (multi-level, variable width, bifurcating, or highly horizontally curved superstructures, different structure types, outriggers, unbalanced mass and/or stiffness, high skew) and unusual geologic conditions (soft soil, moderate to high liquefaction potential and proximity to an earthquake fault). In this case, project specific criteria need to be developed and approved to address their non-standard features.

Ground Motions at the Site	**Level of Damage and Post Earthquake Service**	
	Ordinary Bridge	**Important Bridge**
Functional – Evaluation Ground Motion	Service: Immediate Damage: Repairable	Service: Immediate Damage: Minimal
Safety – Evaluation Ground Motion	Service: Limited Damage: Significant	Service: Immediate Damage: Repairable

Definitions:

Important Bridge (one of more of following items present):

- Bridge required to provide secondary life safety.
- Time for restoration of functionality after closure creates a major economic impact.
- Bridge formally designed as critical by a local emergency plan.

Ordinary Bridge: Any bridge not classified as an *Important Bridge*.

Functional-Evaluation Ground Motion (**FEGM**): This ground motion may be assessed either deterministically or probabilistically. The determination of this event is to be reviewed by a Caltrans-approved consensus group.

Safety-Evaluation Ground Motion (**SEGM**): This ground motion may be assessed either deterministically or probabilistically. The deterministic assessment corresponds to the Maximum Credible Earthquake (MCE). The probabilistic ground motion for the safety evaluation typically has a long return period (approximately 1000-2000 years).

MCE-Maximum Credible Earthquake: The largest earthquake that is capable of occurring along an earthquake fault, based on current geologic information as defined in the 1996 Caltrans Seismic Hazard Map.

Service Levels:

- *Immediate:* Full access to normal traffic is available almost immediately following the earth quake.
- *Limited:* Limited access (e.g. reduced lanes, light emergency traffic) is possible with days of the earthquake. Full service is restorable within months.

Damage Levels:

- *Minimal:* Essentially elastic performance.
- *Repairable:* Damage that can be repaired with a minimum risk of losing functionality.
- *Significant:* A minimum risk of collapse, but damage that would require closure to repair.

Table 1. Caltrans Seismic Performance Criteria

The State of California has designated routes throughout the State that are critical and must be kept open even after major catastrophic events like earthquakes. These routes will allow the movement of emergency vehicles and equipment required in the aftermath of these events. Bridges which happen to be on these so-called “Life-Line” routes are labeled as “Important Bridges”. The first level of design is to ensure the performance (service) of a bridge during earthquake events that have a relatively small magnitude but may occur several times during the life of the bridge. The second level of design is to achieve the performance (“no collapse”) of a bridge under severe earthquakes that have only a small probability of occurring during the useful life of the bridge. These performance-based criteria included guidelines for development of site-specific ground motion estimates, capacity design to preclude brittle failure modes, rational procedures for joint shear design in concrete and the definition of limit states for various performance objectives.

3.2. AASHTO Seismic Performance Criteria

AASHTO-*Guide* is to achieve the minimum damage to bridge during moderate earthquake and to prevent collapse during rare earthquakes for life safety performance considering a seismic hazard corresponding to a 7% probability of exceedance in 75 years. Life safety implies that bridge has a low probability of collapse but may suffer significant damage and significant disruption to service. Significant damage includes the permanent offsets and concrete cracking, reinforcing bar yielding, major spalling of concrete, extensive yielding and local buckling of steel columns, buckling of steel braces, and cracking in the bridge deck slab at shear studs. Significant disruption to service includes limited access such as reduced lanes and emergency traffic on the bridge.

4. Seismic Design Considerations

For typical steel girder bridges, structural components can be identified as either ductile or capacity-protected (essentially elastic) components as recommended in Table 2. Ductile components are components that are expected to experience repairable damage during the functional evaluation earthquake (FEE) and significant damage but without causing collapse of a bridge during the safety evaluation earthquake (SEE). The components shall be pre-identified and well detailed to behave inelastically without significant degradation of strength or stiffness. On the other hand, capacity-protected (essentially elastic) components are components that are expected to experience minimum damage and to behave essentially elastic during both the FEE and the SEE.

Direction	Structural System	Component Classification		
		Ductile		Capacity-protected
Longitudinal	Integral/Nonintegral Bent Connections	Columns Piers		Bent caps Superstructures Foundations
		Isolation Bearings		Bent Caps Superstructures Substructures
Transverse	Non-integral Bent Connections	Isolation Bearings		Bent Caps Superstructures Substructures
	Ductile End-Diaphragm System	Concentrically Braced Frames	Bracing members	Bracing connections Girders Substructures
		Eccentrically Braced Frames	Links	Diagonal braces Beam outside of Links Girders, Connections Substructures
	Ductile Substructure Systems	Moment Resisting Frames	Columns	Bent Caps Superstructures Connections Foundations
		Eccentrically Braced Frames	Links	Superstructures Diagonal braces Beam outside of Links Connections, Columns Foundations
		Concentrically Braced Frames	Bracing members	Superstructures Bracing connections Beams, Columns Foundations

Table 2. Structural Components for Steel Bridges

The following three seismic resisting systems may be considered:

- Type 1 - a ductile substructure with an essentially elastic superstructure
- Type 2 - an essentially elastic substructure with a ductile superstructure
- Type 3 - an elastic superstructure and substructure with a fusing mechanism at the interface between the superstructure and the substructures

5. Seismic Design Requirements

5.1. Displacements

The displacements in a global and local ductile substructure system shall satisfy the following requirement:

$$\Delta_D \leq \Delta_C \tag{1}$$

where Δ_D is displacement demand along the local principal axis of the ductile member, determined by an equivalent static analysis or elastic dynamic analysis with consideration of effective section properties (mm); Δ_C is displacement capacity along the local principal axis of the ductile member, determined by using a static push over analysis in which both material and geometric non-linearities are considered (mm).

5.2. Forces

The forces in a capacity-protected component shall satisfy the following requirement:

$$F_D \leq F_C \tag{2}$$

where F_D is force demand (axial/shear force, moment, as appropriate) on a capacity-protected component determined by the joint equilibrium of overstrength capacities of adjacent ductile components or elastic seismic forces if there is no yielding in ductile members; F_C is nominal strength (axial/shear force, moment, as appropriate) of a capacity-protected component, determined in accordance with AASHTO-LRFD design specifications.

6. Displacement Capacity

6.1. Definition of Displacement Capacity

The deformation (displacement or ration) capacity of a steel component or a frame is usually defined as the deformation corresponding to the expected damage level limit as specified in Table 3, not to exceed the deformation when the lateral resistance degrades to a minimum of 80 percent of the peak resistance. Table 3 provides quantitative strain and ductility limits corresponding to the three damage levels specified in the Caltrans Seismic Performance Criteria in Table 1. Figure 1 show typical load-deformation curves. The displacement and rotation measurements are commonly used for a structural system and an individual member, respectively.

Damage Level	Strain	Ductility	
	ε	μ_θ	μ_Δ
Significant	ε_{sh}	8	4
Repairable	Larger of $\begin{cases} 0.008 \\ 2\varepsilon_{sh}/3 \end{cases}$	6	3
Minimum	Larger of $\begin{cases} 0.003 \\ 1.5\varepsilon_{y} \end{cases}$	2	1.5
ε_{sh} = strain at the onset of strain hardening of steel ε_y = yield strain of steel μ_Δ = displacement ductility, ratio of ultimate-to-yield displacement (Δ_u / Δ_y) μ_θ = rotation ductility, ratio of ultimate-to-yield rotation (θ_u / θ_y)			

Table 3. Damage Levels, Strain and Ductility in Structural Steel

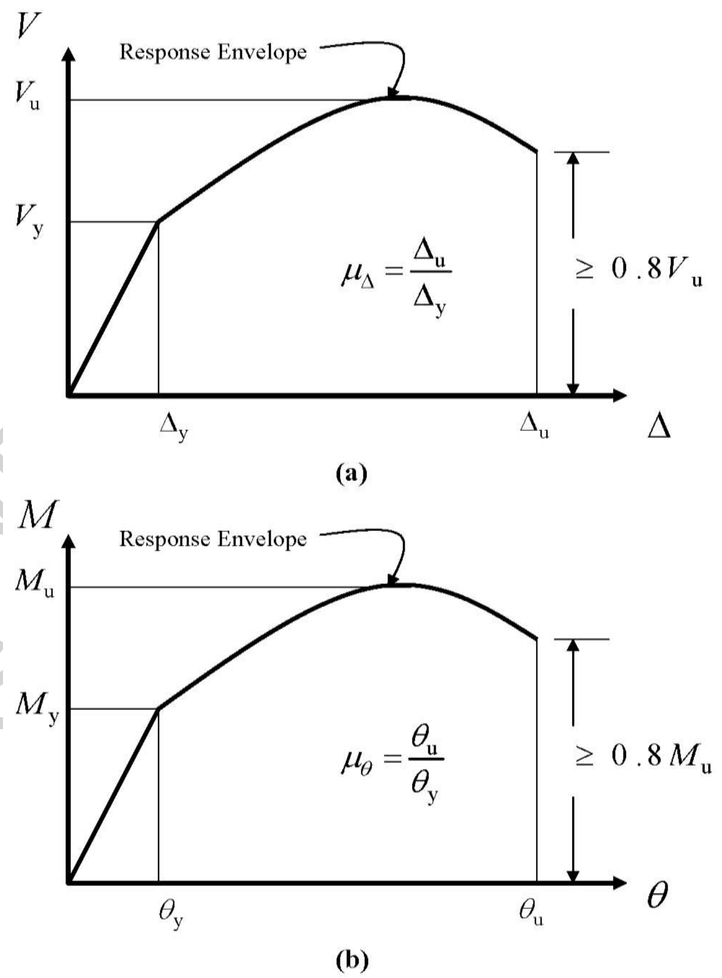

Figure 1. Load-Deformation Curves

In Figure 1, Δ_y is yield displacement which is the lateral displacement of a component or a frame at the onset of forming the first plastic hinge; θ_y is yield rotation which is the rotation at the onset of yielding in the extreme tension fiber; Δ_u is ultimate displacement capacity; θ_u is ultimate rotation capacity; M_y is yield moment at the onset of yielding of an extreme fiber. M_u is ultimate moment at the peak moment capacity; V_y is yield lateral load at the onset of forming the first plastic hinge; V_u is peak lateral load.

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Biographical Sketch

Lian Duan was born in China in 1954. He received his Diploma in civil engineering in 1975, M.S. in structural engineering in 1981 from Taiyuan University of Technology, China and Ph.D. in structural engineering in 1990 from Purdue University, USA. He is a Senior Bridge Engineer and Structural Steel Committee Chair with the California Department of Transportation, Sacramento, California, USA. He had worked at the North China Power Design Institute from 1975 to 1978 and taught at Taiyuan University of Technology from 1981 to 1985. His research interests cover areas including inelastic behavior of reinforced concrete and steel structures, structural stability, seismic bridge analysis and design. With more than 70 authored and co-authored papers, chapters, and reports, his research focuses on the development of unified interaction equations for steel beam-columns, flexural stiffness of reinforced concrete members, effective length factors of compression members, and design of bridge structures. He is co-editor of the *Bridge Engineering Handbook*, (CRC Press, 1999), winner of a Choice magazine's Outstanding Academic Title award for 2000. He received the prestigious 2001 Arthur M. Wellington Prize from the American Society of Civil Engineers (ASCE) for the paper, "Section Properties for Latticed Members of San Francisco-Oakland Bay Bridge", Journal of Bridge Engineering, May 2000 " He received the Professional Achievement Award from Professional Engineers in California Government in 2007. Dr. Duan has over 30 years experience in structural and bridge engineering. He was lead engineer for the development of Caltrans Guide Specifications for Seismic Design of Steel Bridges. He is registered Professional Engineer in California. He served the member for the several National Highway

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