20-1 SEISMIC DESIGN METHODOLOGY

Overview

Memo 20-1 outlines the bridge category and classification, seismic performance criteria, seismic design philosophy and approach, seismic demands and capacities on structural components and seismic design practices that collectively make up Caltrans' seismic design methodology.

How bridges respond during earthquakes is complex. Insights into bridge behavior and methods for improving their performance are constantly being developed. This continuous evolution requires that Caltrans periodically reviews and updates its seismic design methodology and criteria. Designers need to be conscious of emerging technology and research results and are encouraged to bring new ideas to the attention of the Office of Structures Design (OSD) management for review and approval. The process for submitting design methodology revisions to OSD management is outlined in Memo to Designers 20-11.

The Caltrans seismic design methodology applies to all highway bridges designed in California. Bridges are categorized as either Important or Ordinary depending on the desired level of seismic performance. The Ordinary category is divided into two classifications Standard and Non-standard. A bridge's category and classification will determine its seismic performance level and which methods are used for estimating the seismic demands and structural capacities.

The seismic design criteria for Ordinary Standard bridges are contained in the Caltrans Seismic Design Criteria (SDC). The seismic design criteria for Important bridges and Ordinary Non-standard bridges shall be developed by the project design team on a case-by-case basis, and approved by OSD management. The project specific criteria must establish the design parameters required to meet the level of performance outlined in Table 1. See Memo to Designers 20-11 for the project specific criteria approval process. An index to seismic related memos is contained in Attachment 1.

Richard D. Land
Bridge Design Branch A

Shannon H. Post
Bridge Design Branch B

Michael A. Barbour
Bridge Design Branch C

Memo converted to metric format.
Supersedes Memo to Designers 20-1 dated April 1990.

Bridge Category

All bridges shall be categorized as either Important or Ordinary. An Important bridge is defined as any bridge satisfying one or more of the following: [Housner, 1994]

- Required to provide post earthquake life safety; such as access to emergency facilities.
- Time for restoration of functionality after closure would create a major economic impact.
- Formally designated as critical by a local emergency plan.

The District is responsible for requesting that a bridge be designated as Important, and must submit a formal written request justifying the designation. The Engineering Service Center (ESC) will evaluate the request, and assess its impact on the project's cost, scope, and schedule. ESC management and the District must reach consensus on the bridge designation prior to the initiation of final design.

All bridges are considered Ordinary unless they have been designated as Important.

Bridge Classification

The designer is responsible for determining if an Ordinary bridge is Standard or Non-standard. Bridge features that lead to complex response during seismic events are considered Non-standard. The Type Selection panel will review the determination based on the information presented at the Type Selection Meeting. Examples of Non-standard features are:

Irregular Geometry

- Multiple superstructure levels
- Variable width or bifurcating superstructures
- Significant in-plane curvature
- Highly skewed supports

Unusual Framing

- Outrigger or C bent supports
- Unbalanced mass and/or stiffness distribution
- Multiple superstructure types

Unusual Geologic Conditions

- Soft soil
- Moderate to high liquefaction potential
- Proximity to an earthquake fault

Ordinary bridges are classified as Standard if they do not contain non-standard features.

Seismic Performance Criteria

All bridges shall be designed to meet one of the seismic performance criteria, expressed in terms of service levels and damaged levels shown in Table 1. [Housner, 1994].

Table 1 - Seismic Performance Criteria

Ground Motion at 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:

Functional - Evaluation Ground Motion: 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: 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: The largest earthquake, that is capable of occurring along an earthquake fault, based on current geologic information as defined by the 1996 Caltrans Seismic Hazard Map.

Service Levels:

- *Immediate:* Full access to normal traffic is available almost immediately following the earthquake.
- *Limited:* Limited access (e.g. reduced lanes, light emergency traffic) is possible within 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.

An explicit functional-evaluation is not required for Ordinary bridges if they meet the safety-evaluation performance criteria and the requirements contained in this memo and the SDC.

Seismic Design Philosophy

The following fundamental philosophies shall be utilized in the seismic design of all bridges to ensure satisfactory performance during seismic events.

Collapse Limit State

The collapse limit state is defined as the condition where any additional deformation will potentially render a bridge incapable of resisting the loads generated by its self-weight. Structural failure or instability in one or more components usually characterizes collapse. All forces (axial, flexure, shear and torsion) and deformations (rotation and displacement) shall be considered when quantifying the collapse limit state.

All bridges shall be designed to withstand deformations imposed by the design earthquake. All structural components shall be designed to provide sufficient strength and/or ductility, with a reasonable amount of reserve capacity, to ensure collapse will not take place during the MCE.

Ductility

Ductility is mathematically defined as the ratio of ultimate deformation to the deformation at yield. Ductile response of structural components is characterized by several cycles of inelastic deformation without significant degradation of strength or stiffness. The most desirable type of ductile response in bridge systems is sustained hysteric force-deformation cycles that dissipate energy. This type of response can be generated either internally, within the structural members, by the formation of flexural plastic hinges or externally with isolation bearings or external dampers. The analytically derived deformations are limited so the structure will not exceed its inelastic deformation capacity.

Ordinary bridges are not designed to respond elastically during the design earthquake because of economic constraints and the uncertainties in predicting seismic demands. Caltrans takes advantage of ductility and post elastic strength to meet the performance criteria with a minimum capital investment. This philosophy is based on the relatively low probability that a major earthquake will occur at a given site, and the willingness to absorb the repair cost at a future date if a major earthquake occurs.

Pre-determined Locations of Damage

Inelastic behavior shall be limited to pre-determined locations within the bridge that can be easily inspected and repaired following an earthquake. Continuous column/pile shaft combinations are an exception since inelastic behavior may occur below ground. Preferable locations for inelastic behavior on most bridges include columns, pier walls, backwalls, wingwalls, seismic isolation and damping devices, bearings, shear keys and steel end-diaphragms.

Significant inelastic response in concrete superstructures is not desirable because they are difficult to inspect and repair. Furthermore, superstructure damage may prevent the bridge from being repaired to a serviceable condition.

Capacity Design

An adequate margin of strength shall be provided between the designated ductile failure mode and non-ductile failure modes. Desired locations of plastic hinging shall be identified and detailed for ductile response. Enough overstrength shall be provided to assure the desired yielding mechanism occurs and undesirable non-ductile failure mechanisms, such as concrete crushing, shear cracking, elastic buckling and fracture are prevented from forming.

Redundancy

Redundancy shall be provided in all bridge systems, whenever practical, by means of alternative load paths. In bridge systems such as single column bents for example, redundancy can be improved by establishing a greater margin between the component's dependable capacity and its expected response to seismic action, continuity at expansion joints with reliable shear keys and restrainers, and load transfer to the abutments.

Essentially Elastic Behavior

Components not explicitly designed for ductile performance or as sacrificial components shall be designed to remain essentially elastic under seismic loads. The effects of the inelastic response in essentially elastic components shall not diminish the bridge's ability to meet its specified performance criteria and shall not prevent the bridge from eventually being repaired and restored to normal service conditions. The inelastic response of essentially elastic concrete components shall be limited to minor cracking and/or incremental material strains that will not significantly diminish the component's stiffness. The force demands in essentially elastic concrete components shall not exceed the strength capacity limits identified in the Caltrans SDC.

The force demands in essentially elastic steel components shall not exceed the strength capacity determined by the current Caltrans Bridge Design Specifications.

Seismic Design Approach

Displacement Ductility Approach

The displacement ductility approach requires the designer to ensure that the structural system and its individual components have enough capacity to withstand the deformations imposed by the design earthquake.

A bridge's displacement capacity is dependent on the structural configuration and the formation and rotational capacity of flexural hinges. The displacement capacity of a bridge can be assessed with an inelastic static "pushover" analysis that incorporates non-linear inelastic load/deformation behavior of selected components. This enables the designer to determine the location and sequence of hinging within the bridge and provide adequate ductility in the appropriate locations. The designer can control the amount of anticipated inelastic flexural behavior by limiting the allowable material strains in ductile components.

Seismic Demands on Structural Components

Ground Motion Representation

The Safety-Evaluation ground motion for Ordinary bridges shall be based on a deterministic assessment corresponding to the MCE. The ground motion at the bridge site is dependent upon the earthquake magnitude, fault type, geology, and distance between the earthquake source and the site.

The Safety-Evaluation and Functional-Evaluation ground motions for Important bridges may be determined either deterministically or probabilistically. These determinations will be made on a case-by-case basis and will be incorporated into the Important bridge design criteria.

Horizontal Acceleration

The horizontal spectral acceleration for Ordinary bridges shall be estimated from elastic acceleration response spectra (ARS) curves. The shape and magnitude of the ARS curves are dependent upon the peak rock acceleration, depth of bedrock, fault distance, earthquake moment magnitude, damping ratio, and geotechnical site conditions.

The effective mass of a bridge shall be based on its self-weight. The designer must account for any known future modifications to the bridge that may impact its mass such as; overlays, barriers and soundwalls.

Vertical Acceleration

Bridges with non-standard structural components, long spans, or close proximity to earthquake faults may undergo appreciable excitation from vertical ground motion. Vertical acceleration should be considered if these conditions exist. For Ordinary Standard bridges vertical acceleration can be approximated by an equivalent static vertical force applied to the superstructure.

Combination Effects

The earthquake demands must include the combined effects of multi-directional components of horizontal acceleration.

Consideration of the combined effects of horizontal and vertical acceleration is not required for Ordinary Standard bridges. A "rational" superposition of vertical and horizontal demands based on a realistic assumption of behavior shall be used for Non-standard and Important bridges vulnerable to vertical ground motion.

Displacement Demands

The displacement demands for Ordinary bridges shall be estimated from a linear elastic response spectra analysis that includes the effective stiffness of its members. Estimating inelastic displacements with elastic analysis is based on the equal displacement observation for single-degree-of-freedom systems. The equal displacement rule assumes that displacements can be reasonably estimated with linear elastic analysis for bridges with fundamental structural periods (T) that fall within the displacement conservation region of the elastic response spectra typically defined as the region between 0.7 seconds and 3 seconds.

For longer period bridges, linear elastic analysis increasingly overestimates the inelastic displacements. The displacements for long period structures ($T > 3$ seconds) should be predicted by the linear elastic displacement response spectra.

For short period bridges, linear elastic analysis underestimates the inelastic displacements. The inability to accurately predict displacements for short period structures with elastic analysis can be overcome by one of the following methods: designing the bridge to perform elastically, multiplying the elastic displacements by an amplification factor, or use protective systems like isolation or sacrificial members to modify the seismic response. Global and local structural stability must be maintained when utilizing isolation to reduce earthquake demands.

The appropriate method for estimating deformations for Important bridges and Ordinary Non-standard bridges shall be determined on a case-by-case basis.

Force Demands

Design forces shall be determined from the overstrength capacity of ductile components that can be transferred through the joint regions to adjacent components. Force demands calculated with linear elastic analysis shall not be used since linear elastic analysis does not recognize the force limit state associated with yield and computes unrealistic moment and shear demands.

Seismic Capacity of Structural Components

Component Capacities

Moment-curvature analysis or finite element analysis shall be used to calculate the strength and deformation capacity of ductile components. Strength formulas specified in the current Caltrans SDC, Bridge Design Specifications, moment curvature analysis, or finite element analysis shall be used to calculate the strength capacity of essentially elastic components.

Strength Capacity

The capacity of all components to resist seismic demands shall be based on the most probable or expected material properties. The capacity assessment shall account for anticipated flexural damage. The required strength of essentially elastic components adjacent to ductile components shall be equal or greater than the plastic hinging capacity of the ductile component magnified by an overstrength factor. The overstrength factor shall account for the variations in material properties between adjacent components and the possibility that the actual strength of the ductile component may exceed its estimated plastic capacity.

The impact of global P-Δ effects on the capacity of all members subjected to combined bending and compression shall be considered. The impact of local second-order P-δ effects on steel structures, should also be considered. Components may require re-design if the P-Δ and P-δ effects are significant.

Effective Component Stiffness

The effective stiffness of ductile components modeled in linear elastic analyses shall represent the component's actual stiffness near yield. The effective stiffness of concrete components shall include the effects of cracking, longitudinal and transverse reinforcement, and axial load. The effective stiffness of steel components shall include the effects of residual stresses, out-of-straightness, and axial load. The effective stiffness of pile shafts shall include the restraining effects of the surrounding soil.

The detrimental effect on stiffness of known or anticipated future modifications, such as training walls, barriers, paving, channel lining, or scour, shall be included in the current seismic design.

Plastic Hinge Performance

The displacement ductility approach relies on a bridge's ability to undergo dependable deformation in plastic hinge regions without experiencing brittle failure. The rotation capacity of all plastic hinges shall be limited to a "safe" performance level. Plastic hinge capacity shall be based on the most probable material properties. Plastic hinge regions shall be designed and detailed to perform with minimal degradation in strength under sustained cyclic loading.

Seismic Design Practice

The following collection of ideas, observations and concepts are considered good seismic design practice based on laboratory testing and structural performance observed during past earthquakes. Project constraints will likely not allow the designer to employ all of these concepts on any particular project. The challenge for the designer is to provide a structural system that performs satisfactorily under all load combinations while conforming to the site topography and the restrictions imposed by existing facilities, project budget, the District, and other agencies.

Proportioning

It is often difficult to proportion a bridge for optimal seismic performance because of constraints beyond the control of the structural designer. However, a bridge shall be proportioned to reduce the ARS demands to the greatest extent possible and distribute them evenly throughout the structure.

The issues identified in this Memo affect seismic performance and have a large impact on bridge type, component selection, member dimensions, and aesthetics. Sufficient preliminary investigations into the impact of these issues shall be conducted during the initial phases of design to minimize significant changes to the structural system after the bridge type has been selected and approved through the Type Selection process. Aesthetics should not be the primary reason for producing undesirable frame and component geometry. However, the designer must combine the aesthetic and structural considerations to create reliable and pleasing bridges.

Analysis

The sophistication of the analysis and level of detail of the structural model should match the performance and design requirements specified for the bridge. Simplistic models should be used for the initial assessment of structural behavior. The results of more sophisticated models shall be checked for consistency with the results from the simplistic models.

Important bridges usually require more sophisticated analytical techniques to assess the demands generated by the design earthquake.

Performance Requirements

The estimated displacement demands generated by the design earthquake shall not exceed the structure's global displacement capacity or the local displacement capacity of any of its individual components. The overall performance of the structural system shall meet the performance criteria outlined in Table 1.

Frame Interaction

Global models including all bridge frames shall be used in the seismic demand analysis where possible. Drastic differences in stiffness between frames shall be avoided. The differences in the fundamental periods, and skew angle between adjacent frames shall be minimized.

Frame Design

Adjacent frames shall not be relied on to resist the demands generated by individual frames. All bridge frames must meet the strength and ductility requirements in a stand-alone condition. Stand-alone assessments must include appropriate boundary conditions.

Redundancy shall be utilized whenever possible. A well defined load path with pre-determined locations for plastic hinging shall be provided. Controlled damage shall be distributed as equally as possible to all plastic hinge locations within a frame. Drastic differences to the stiffness and mass distribution within a frame shall be avoided. Global frame rotation shall be avoided by minimizing the eccentricity between a frame's center of rigidity and center of gravity. The differences in skew angles between bents. within a frame shall be minimized. Each frame shall have a realistic level of lateral strength consistent with its period and lateral displacement demand.

Concrete Superstructure Design

All Ordinary bridges shall be proportioned to direct inelastic damage into the columns, pier walls, and abutments.

The superstructure shall have sufficient overstrength to remain essentially elastic when the bent reaches its most probable plastic moment capacity. The superstructure-to-substructure connection for non-integral caps may be designed to fuse prior to generating inelastic response in the superstructure.

The girders, bent caps, and columns shall be proportioned to minimize joint stresses. Moment resisting connections shall have sufficient joint shear capacity to transfer the maximum moments and shears. including overstrength demands without causing joint distress.

Steel Superstructure Design

Ordinary bridges shall be generally designed to ensure that inelastic deformation only occur in the specially detailed ductile substructure elements. 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. The inertial forces generated by the deck must be transferred to the substructure through girders, trusses, flanges, webs, cross frames, lateral bracings, end diaphragms, shear keys and bearings. As an alternative, specially designed ductile end-diaphragms may be used as structural fuses to prevent damage in other parts of structure [Sarraf and Bruneau, 1998a, 1998b, Zahrai and Bruneau 1998].

Concrete Bents

The initial sizing of concrete bents shall be based on the slenderness ratio (KL/r), bent cap depth, compressive stress ratio, and service loads. Columns must demonstrate dependable post yield displacement capacity without an appreciable loss of strength. Moment-curvature relationships that incorporate the effects of axial load should be used to optimize a column's performance under service loads and seismic loads. Columns shall be well proportioned, moderately reinforced and easily constructed.

Abrupt changes in the cross section and the capacity of columns shall be avoided. Columns must have sufficient rotation capacity to achieve the target displacement ductility requirements and withstand P-Δ demands. Force demands on pile caps and footings shall be based on the most probable plastic moment capacity of the column and the associated amount of overstrength.

In the case of column/pile shaft combinations, the designer may choose to accept inelastic behavior in the pile shaft. Alternatively, enlarged pile shafts supporting columns with smaller cross sections can be utilized to provide a well-defined location for the formation of the plastic hinge at the base of the column. Enlarged pile shafts shall be designed to remain essentially elastic when resisting the overstrength capacity of the column.

Pier walls shall be designed to perform in a ductile manner longitudinally (about the weak axis), and to remain essentially elastic in the transverse direction (about the strong axis).

Steel Bents and Towers

Steel multi-column bents or towers shall be designed as ductile Moments-Resisting Frames (MRF) or ductile braced frames such as Concentrically Braced Frames (CBF) and Eccentrically Braced Frames (EBF). For components expected to behave inelastically, elastic buckling (local compression, global flexural, and lateral torsion buckling) and fracture failure modes shall be avoided. All connections and joints shall be designed to remain essentially elastic.

For Moment-Resisting Frames, the primary inelastic deformation shall occur in the columns. For Concentrically Braced Frames, diagonal members shall be designed to yield when the members are in tension and to buckle inelastically when they are in compression. For Eccentrically Braced Frames, a short beam segment designated as a *"link"* shall be designed and detailed in a ductile manner.

Abutments

The effects of abutment flexibility shall be considered in the seismic analysis and design of all bridges. An abutment's ability to resist bridge inertial forces shall be based on its structural capacity and the soil resistance that can be reliably mobilized.

Skewed abutments are highly vulnerable to damage. Skew angles at abutments shall be reduced, even at the expense of increasing the bridge length.

The energy dissipation capacity of the abutments should be considered for bridges whose response is dominated by the abutments.

Foundations

Foundation components for Ordinary Standard bridges, except pile shafts and pier wall foundations in the weak direction, shall be designed to remain essentially elastic when resisting the plastic hinging moments, associated shears and axial force at the base of columns and pier walls in the strong direction. Pile shaft foundations are permitted to respond inelastically if they are designed and detailed in a ductile manner. Typically, it is not economical to design pier wall pile foundations to resist the transverse seismic shear elastically. However, the designer should attempt to minimize the inelastic response in pier wall foundations, and shall verify global stability is maintained under the anticipated seismic demand.

The effects of foundation flexibility shall be considered in the seismic design and analysis of all bridges. The rotational and translational foundation stiffness modeled in the demand analysis must be compatible with the foundation's structural and geotechnical capacity.

The lateral design of foundations for seismic demands shall consider the relative stiffness between the foundation and the surrounding soil.

The effects of anticipated degradation or deposition of material shall be considered in the seismic design of bridges spanning streambeds.

Restraint at Joints

Necessary hinge restrainers, keys, and sufficient seat width shall be provided between adjacent frames at all intermediate expansion joints, and at seat-type abutments to eliminate unseating and to control differential transverse displacement during a seismic event.

Energy dissipation and isolation devices may be inserted at joints to reduce the seismic demands. The purpose of these devices is to increase the effective damping of the structure or to change the fundamental mode of vibration of the structure respectively.

Energy dissipation and isolation devices must be selected carefully to meet their performance objectives as well as meet reliability, serviceability, constructability and maintainability requirements. The performance and design criteria for dissipation and isolation devices shall be developed on a job specific basis and meet Caltrans' minimum requirements. These devices shall only be considered with approval from OSD management.

References

Housner, G.W. *The Continuing Challenge - The Northridge Earthquake of January 17, 1994*, (Report to Director, California Department of Transportation), Sacramento, California, 1994.

Saffar, M. and Bruneau, M., Ductile Seismic Retrofit of Steel Deck-Truss Bridges. I: Strategy and Modeling, *Journal of Structural Engineering*, ASCE, Vol. 124, No. 11, 1998. pp. 1253-1262.

Saffar, M. and Bruneau, M., Ductile Seismic Retrofit of Steel Deck-Truss Bridges. II: Design Application, *Journal of Structural Engineering*, ASCE, Vol. 124, No. 11, 1998. pp. 1263-1271.

Zahrai, S. M. and Bruneau, M., Impact of Diaphragms on Seismic Response of Straight Slab-on-Girder Steel Bridges, *Journal of Structural Engineering*, Vol. 124, No. 8, 1998, pp. 938-947.

TO/RL: pal