STATE

Bridging Faults—

California's

Unique Engineering Challenges

by Raymond W. Wolfe and Michael D. Keever,
California Department of Transportation

Mission Valley Interchange, San Diego County (Multi-span box girders on single column bents).

The broad spectrum of landscape, from majestic mountain ranges to broad cultivated valleys and legendary coastline, defines the uniqueness of California. The state is situated at the junction of the Pacific and North American plates—two active tectonic crustal plates forming part of the "Rim of Fire." This is one of the most active volcanic and seismic regions in the world today. The constant shifting of the plates forms some of the most tantalizing landscape in the world, but also presents tremendous engineering challenges in one of the most heavily populated states. Geography, climate, and history have come together in California to produce dense population centers, with a high concentration of bridges in regions of high seismicity.

Adams Avenue Overcrossing, San Diego County (Three-span box girder bridge on pier columns).

Bridge designers in California face the somewhat unique challenge posed by the ever-present threat of earthquakes. A close inspection of fault maps reveals that the state is fragmented not unlike a textbook example of a shattered crystalline structure. Engineers and academicians continue studying earthquake damage and recorded seismic events to update design philosophies and details in an effort to mitigate damage. The basic underlying premise of bridge design in California is to prevent structural collapse. To ensure consistent behavior, the California Department of Transportation (Caltrans) has developed and continuously updates a seismic design manual—the Seismic Design Criteria (SDC). The SDC assumes that some structures or elements therein will require rehabilitation or replacement, but life preservation during the event is the primary consideration. However, California's most critical bridges have been designed to higher standards to provide some level of post-earthquake serviceability due to their importance in recovery activities and the economic impact of the closure.

The majority of bridge structures in California are cast-in-place, post-tensioned (CIP/PS) concrete box girders. The advantages afforded from precast construction are also realized in many instances, particularly when considering accelerated bridge construction. CIP/PS box girder structures have long held favor in California as they provide the following advantages:

- Monolithic connections, which are not susceptible to support loss due to ground motions;
- Excellent torsional resistance to seismic loading;
- Efficient designs for shear transfer and moment distribution;
- Historically, the most cost-effective structure type for many applications; and
- The preferred structure type of the local construction industry.

Ductile Design Detailing

Designing for purely elastic behavior in a seismic event is generally considered unnecessary as well-detailed concrete elements can resist loading through ductile response. Based on substantial research, Caltrans relies on ductile design detailing as a fundamental tenet of seismic bridge design. Ductile detailing in seismic zones is important because:

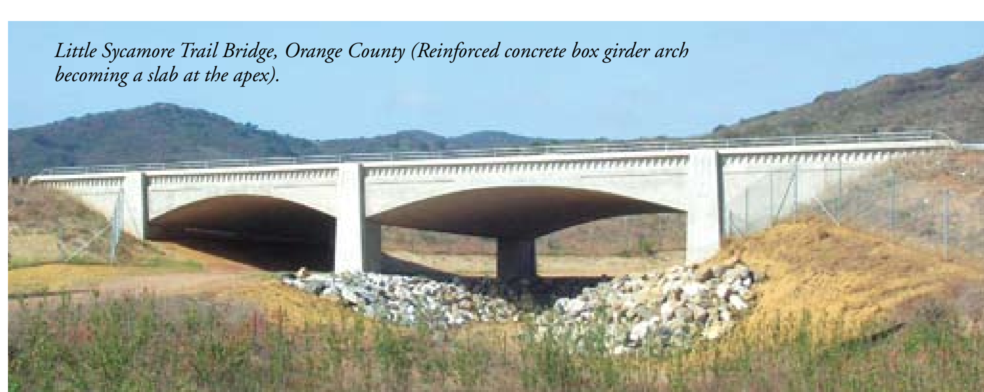
- It does not rely on highly accurate prediction of seismic demands;
- It ensures ductile response in predetermined plastic hinge zones resulting in an extended inelastic region with significant energy absorption;
- Ductility can be enhanced in a cost-effective manner through the addition of column confinement steel; and
- It yields a more cost effective foundation design by limiting the transmitted forces.

Elastic design produces stiffer bridges, which attract more seismic loads, increasing the cost of survivability and post-event serviceability.

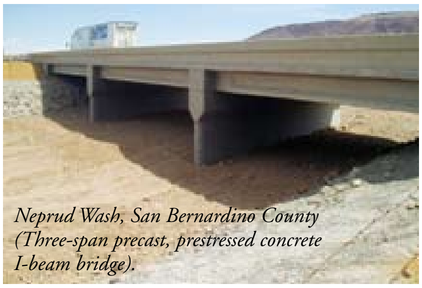
Substantial research in confined concrete sections has led to proven design details to limit damage and force plastic hinging to occur at predetermined locations in the columns. Poor detailing in columns leads to brittle failure. Caltrans design criteria establishes a minimum displacement ductility capacity of three. This ensures a level of post-elastic performance to address inherent seismic uncertainty, even in regions of low seismicity where seismic demands may not control the design.

Dynamic Design Considerations

Experience has highlighted the importance of balancing the overall structure to enhance its performance when subjected to seismic excitation. This is accomplished through providing a measure of "effective" stiffness



Little Sycamore Trail Bridge, Orange County (Reinforced concrete box girder arch becoming a slab at the apex).



Neprud Wash, San Bernardino County (Three-span precast, prestressed concrete I-beam bridge).

equity between adjacent bents in a frame and/or adjacent columns in a bent, and tuning the fundamental periods of vibration of adjacent frames. The above is analogous to an appealing aesthetic design wherein proportioning yields enhanced visual flow; seismic forces are better resisted through balanced geometries.

The concept of balanced "effective" column stiffness precludes the danger of substantial damage to stiffer elements from localized shear demand. An example of this is unbalanced inelastic response or increased column torsion demand due to rigid body rotation in the superstructure. Empirical data has led to target column "effective" stiffness ratios of $k_i^e / k_j^e \geq 0.75$, where k_i^e is defined as the smaller "effective" bent or column stiffness, and k_j^e is the larger bent or column stiffness. The calculated "effective" stiffness should consider column heights and diameters, framing effects, end conditions, longitudinal and transverse steel ratios, and foundation flexibility.

Long concrete bridges in California often incorporate in-span hinges to accommodate superstructure thermal movement without substantially increasing column stresses. Design of structures containing in-span hinges requires careful attention to the potential for out-of-phase response between adjacent frames. Neglecting this leads to increased probabilities of localized failure due to unintended collisions between adjacent elements excited by seismic events at different fundamental periods. Unseating of in-span hinges, an event leading to partial or total collapse mechanisms, was first identified after the 1971 San Fernando Earthquake. Modern designs incorporate a minimum hinge seat of 2 ft. Retrofit strategies for narrower seats primarily employ double extra-strong steel pipe seat extenders to accommodate larger longitudinal displacement excursions under extreme seismic events. Restrainer cables attached to concrete bolsters were employed in California's Phase I seismic retrofit program, with pipe seat extenders gaining favor later.

Another innovation developed to address this vulnerability is the "seatless" hinge. It consists of cantilever end spans, emanating from adjacent frames, butted together without restraint as in typical seated hinge configurations.

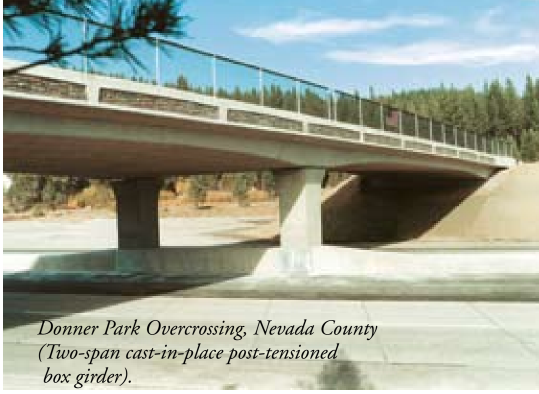
It is also important to limit the ratio of longitudinal and transverse fundamental periods of vibration between adjacent frames. Based on analytical studies, the SDC caps the ratio of the natural period of the less flexible frame to that of the more flexible frame at a minimum of 0.7. Effective strategies to accomplish this include adjusting "effective" column lengths, modifying end fixities, reducing/redistributing superstructure mass, modifying column reinforcement ratios, etc. Column length adjustments are typically the most easily incorporated, and involve simple footing depth modifications or isolation casings. The latter employs steel casings designed to provide a gap between the column and the surrounding soil mass to effectively lengthen the column.

Seismic Response

Russian River Bridge, Sonoma County (Precast, prestressed and post-tensioned double-tee superstructure used as an emergency replacement).

Modification Devices

Isolation from extreme event forces such as earthquakes is a proven means of cost-efficient design. This strategy has been employed in civil infrastructure design worldwide, from Japan to Italy and California. Rather than relying solely on ductile behavior, the premise is to limit the forces transmitted into the structure by isolating portions from ground motions, or reducing the input magnitude. Numerous devices exist today to accomplish this goal, from large self-centering bearings to viscous dampers, hysteretic damping mechanisms, and lock-up devices. These are particularly useful when considering retrofitting existing structures not previously detailed to respond in a ductile fashion to large displacement demands. As primary reinforcement confinement is crucial to ductile behavior, it may be difficult to incorporate into existing structures, particularly on large-scale structures, and thus isolation strategies become more enticing for retrofits. Most of the major long-span toll structures have some type of seismic response modification device to enhance performance and limit damage. However, because of their cost and long-term maintenance needs, these devices are not typically used on "standard" structures designed with today's criteria, or those that can be retrofitted with simpler solutions.



Donner Park Overcrossing, Nevada County (Two-span cast-in-place post-tensioned box girder).

Future Innovation

Accelerated bridge construction has received much attention in recent years, largely through a concerted effort by the Federal Highway Administration and public demand for less interruption from highway construction projects. Research projects contemplating substantial diversions from historical design norms such as re-centering precast column/bent elements may prove viable for future bridges. The long-term vision for transportation projects across the Golden State includes incorporation of design features leading to rapid on-site construction. Increased structure durability and enhanced post-earthquake serviceability must be provided to effectively meet the motoring public's demands, maintain California's prominence in the global economy, and promote good environmental stewardship.

Conclusion

California has and continues to expend tremendous resources developing design criteria and pursuing research in an effort to counter seismic effects on bridges. The SDC is performance-based. In simple terms, the element and system capacities are selected to exceed the imposed demands. The strong beam-weak column approach focuses the damage at predefined locations, otherwise known as plastic hinge zones, in column elements. System redundancy is required to provide alternate load paths and prevent local failure from resulting in collapse. Targeting a minimum ductility prevents brittle failure modes, which are often sudden and catastrophic. Some solutions employ seismic response modification devices to isolate or limit exciting forces from specific areas of structures. The goal is to prevent collapse, while localizing damage to accommodate repairs.