Bridge Resiliency to Extreme Events and Post-Earthquake Functionality Requirements

W. Phillip Yen, PhD, PE

Chair, International Association of Bridge Earthquake Engineering

wenhueiyen@hotmail.com

Bijan Khaleghi, PhD, PE, SE

Washington State Department of Transportation

Bridge and Structures Office

Olympia, Washington

Office: (360) 705-7181

Email: khalegb@wsdot.wa.gov

ABSTRACT

Washington State has a long record of major earthquakes and is considered to be one of the five states facing the greatest seismic hazards in the United States. Earthquakes can happen in Washington State at any time, and past history indicates there may be substantial shifting of land during a seismic event.

The highway system in Washington State is a vital economic resource. The Washington State Department of Transportation (WSDOT) manages approximately 18,500 highway lane miles and more than 3,600 bridges on the state's highway system. One of the agencies objectives is to ensure that state highways will be able to provide emergency responders access to damaged portions of the community quickly to provide essential life-saving services. State Highways will also need to provide the capability for the state economy and the movement of freight and goods to be re- stored as quickly as possible.

In an earthquake, damage to infrastructure bridges is more closely related to ground motion rather than magnitude. In addition, the ground type can significantly influence ground acceleration. Base on the geographic area and historical data geologists are able to create seismic hazard maps which show likely earth- quake ground motion zones. This paper discusses the seismic design requirements for WSDOT bridges and challenges to achieve these requirements for new and existing bridges.

INTRODUCTION

Bridge are designed based on "strong beam - weak column" proportioning principles. Plastic hinging shall be directed to Seismic Critical Members, allowing a mechanism to form and facilitates transverse and longitudinal movement of bridge bents and frames. Every bridge shall be designed with an Earthquake Resisting System that ensures a load path for gravity loads and provides sufficient strength and ductility to achieve the specified performance criteria.

The plastic hinge ductility or other means of energy dissipation/bridge damping shall be adequate to satisfy the deformation demands imposed by the "design seismic hazards" while minimizing the probability of bridge collapse.

Earthquake Resisting Systems shall consist of the following:

- Seismic critical members – ductile structural members that are intentionally designed to deform inelastic through several cycles without significant loss of strength, thereby limiting the forces transmitted to adjoining capacity protected members,
- Capacity protected members (CPMs) - structural members that remain essentially elastic after the adjoining members fuse or form plastic hinges,
- Earthquake resisting elements – bridge elements that undergo inelastic deformation, dissipate energy, or increase bridge damping, and
- Sacrificial elements – Bridge elements that are typically designed to disengage in order to limit forces transmitted to adjoining capacity-protected members.

Seismic design of new bridges and bridge widenings conform to AASHTO Guide Specifications for LRFD Seismic Bridge Design[1] per WSDOT Bridge Design Manual (BDM)[2]. For nonconventional bridges, bridges that are deemed critical or essential, or bridges that fall outside the scope of the Guide Specifications for any other reasons, project specific design requirements is developed and submitted for approval.

The importance classifications for all highway bridges in Washington State are classified as "Normal" except for special major bridges. Special major bridges fitting the classifications of either "Critical" or "Essential" will be so designated by the bridge owner.

Bridges are considered as Critical, Essential, or Normal for their operational classification as described below. Two-level performance criteria are required for design of Essential and Critical bridges. Essential and Critical bridges are designated by WSDOT Regions or Local Agencies, in consultation with WSDOT State Bridge and Structures Engineer and State Bridge Design Engineer.

- **Critical Bridges**
  Critical bridges are expected to provide immediate access to emergency and similar life-safety facilities after an earthquake. The Critical designation is typically reserved for high-cost projects where WSDOT intends to protect the investment or for projects that would be especially costly to repair if they were damaged during an earthquake.
- **Essential Bridges**

Essential bridges serve as vital links for rebuilding damaged areas and provide access to the public shortly after an earthquake.

- **Normal Bridges**
  All bridges not designated as either Critical or Essential are designated as Normal.

Expected Bridge Seismic Performance:

The seismic hazard evaluation level for designing Normal bridges is the Safety Evaluation Earthquake (SEE), and the seismic hazard evaluation level for designing Essential and Critical bridges is both the Safety Evaluation Earthquake and the Functional Evaluation Earthquake (FEE) as specified in Table 1.

Table 1 Seismic Hazard Evaluation Levels and Expected Performance

Bridge Operational Importance Category	Seismic Hazard Evaluation Level	Expected Post Earthquake Damage State	Expected Post Earthquake Service Level
Normal	SEE	Significant	No Service
Essential	SEE	Moderate	Limited Service
	FEE	Minimal	Full Service
Critical	SEE	Minimal to Moderate	Limited Service
	FEE	None to Minimal	Full Service

Expected Post-earthquake Service Levels

- **No Service** – Bridge is closed for repair or replacement.
- **Limited Service** – Bridge is open for emergency vehicle traffic: A reduced number of lanes for normal traffic is available within three months of the earthquake; Vehicle weight restriction may be imposed until repairs are completed. It is expected that within three months (Essential Bridges) or within three days (Critical Bridges) of the earthquake, repair works on a damaged bridge would have reached the stage that would permit normal traffic on at least some portion of the bridge.
- **Full Service** – Full access to normal traffic is available almost immediately after the earthquake. The expected post-earthquake damage states and service levels of Critical bridges are included in Table 2 to provide an indication of their expected performance relative to other bridge categories.

Table 2 Displacement Ductility Demand Values, μ_D

Seismic Critical Member	Displacement Ductility Demand Limits				
	Normal Bridges	Essential Bridges		Critical Bridges	
		SEE	FEE	SEE	FEE
Wall Type Pier in Weak Direction	5.0	2.5	1.5	1.5	1.0
Wall Type Pier in Strong Direction	1.0	1.0	1.0	1.0	1.0
Single Column Bent	5.0	2.5	1.5	1.5	1.0
Multiple Column Bent	6.0	3.5	2.0	1.5	1.0
Pile Column with Plastic Hinge at Top of Column	5.0	3.5	2.0	1.5	1.0
Pile Column with Plastic Hinge Below Ground	4.0	2.5	1.5	1.5	1.0
Superstructure	1.0	1.0	1.0	1.0	1.0

EXPECTED POST-EARTHQUAKE DAMAGE STATES

- **Significant** – "imminent failure," i.e., onset of compressive failure of core concrete. Bridge replacement is likely. All plastic hinges within the structure have formed with ductility demand values approaching the limits specified in Table 4.1-2.
- **Moderate** – "extensive cracks and spalling, and visible lateral and/or longitudinal reinforcing bars". Bridge repair is likely but bridge replacement is unlikely
- **Minimal** – "flexural cracks and minor spalling and possible shear cracks". Essentially elastic performance
- **None** – No damage

The Design Spectrum for Safety Evaluation Earthquake (SEE) is taken as a spectrum based on a 7% probability of exceedance in 75 years (or 975-year return period). BDM Section 4.2.3 provides the ground motion software tool SPECTRA to develop spectral response parameters.

The Design Spectrum for Functional Evaluation Earthquake (FEE) is taken as a spectrum based on a 30% probability of exceedance in 75 years (or 210-year return period). The Geotechnical Engineer is provide final design spectrum recommendations. The FEE may be obtained using the USGS Interactive website (https://earthquake.usgs.gov/hazards/interactive).

Normal and Essential bridges subjected to the seismic hazard levels specified in Table 1 satisfy the displacement criteria specified in LRFD-SGS as applicable and the maximum displacement ductility demand, μ_D values as specified in Table 2.

SEISMIC DESIGN REQUIREMENTS BRIDGE WIDENING PROJECTS

The Seismic Design requirements for Bridge Modifications and Widening are as follows and as illustrated in BDM Figure 3:

1. Normal bridge modification or widening projects classified as Minor Modification or Widening do not require either a seismic evaluation or a retrofit of the structure. If the conditions for Minor Modification or Widening project are met, it is anticipated that the modified or widened structure will not draw enough additional seismic demand to significantly affect the existing sub-structure elements.
2. Seismic analysis is required for all Major Modifications and Widening projects at project scoping level in accordance with Section 4.1. A complete seismic analysis is required for Normal bridges in Seismic Design Category (SDC) B, C, and D for major modifications and widening projects as described below. A project geotechnical report (including any unstable soil or liquefaction issues) is available to the structural engineer for seismic analysis. Seismic analysis is performed for both existing and widened structures. Capacity/Demand (C/D) ratios are required for existing bridge elements including foundation.
3. The widening portion of the structure is designed for liquefiable soils condition in accordance to the AASHTO Seismic, and
4. Procedure for Normal Bridges: Seismic improvement of existing columns and crossbeams to C/D > 1.0 is required. The cost of seismic improvement is paid for with widening project funding (not from the Retrofit Program). The seismic retrofit of the existing Normal structure conform to the BDM, while the newly widened portions of the bridge comply with the AASHTO Seismic, except for balanced stiffness criteria, which may be difficult to meet due to the existing bridge configuration. However, the designer should strive for the best balanced frame stiffness for the entire widened structure that is attainable in a cost effective manner.
5. Major Modification and Widening Projects require the designer to determine the seismic C/D ratios of the existing bridge elements in the final widened condition. If the C/D ratios of columns and crossbeam of existing structure are less than 1.0, the improvement of seismically deficient elements is mandatory and the widening project is included the improvement of existing seismically deficient bridge elements to C/D ratio of above 1.0. The C/D ratio of 1.0 is required to prevent the collapse of the bridge during the seismic event as required for life safety. Seismic improvement of the existing foundation elements (footings, pile caps, piles, and shafts to C/D ratios could be deferred to the Bridge Seismic Retrofit Program.

6. Procedure for Essential/Critical Bridges: The initial goal is to conduct the seismic design effort so the composite structure (existing bridge and widening) meet requirements of the two-level seismic design (FEE and SEE) de-scribed in BDM Section 4.1. This includes the superstructure, substructure and foundation elements of the composite structure. Retrofitting or strengthening of the existing structure may be necessary to achieve this. Depending on the year the bridge was constructed, type of foundation and capacity of the soils during a seismic event, it may become expensive to meet this goal. If the Engineer determines it is cost prohibitive to meet the two-level design criteria, the Bridge Design Engineer may approve deviations.

Examples of potential deviations include:

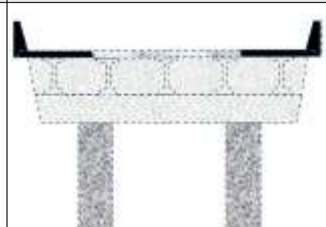
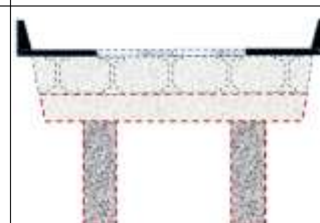
a. Meeting two-level design criteria for the widened portion, but only achieving Normal bridge criteria for the existing bridge.

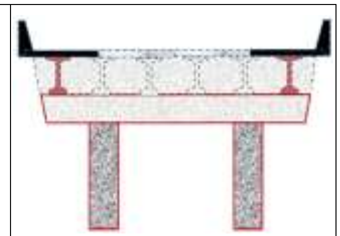
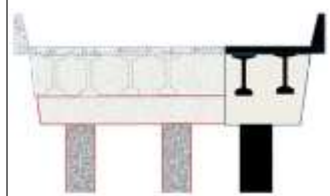
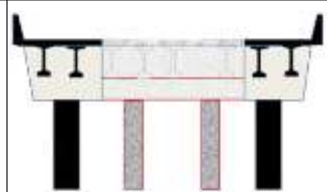
b. Meeting two-level design criteria for the above-ground portions of the composite structure, but not achieving this for the below-ground portions (foundations).

c. Performing a two-level design, but requiring deviations from the displacement ductility demand limits identified in BDM Section 4.1.

d. Only achieving Normal (no collapse) criteria for the composite structure.

Table 3 Seismic Design Criteria for Bridge Modifications and Widening

Modifications or Widening	Alterations	Seismic Design Guidance	Illustration
Minor Modifications • Deck Rehabilitations • Traffic Barrier Replacements • sidewalk addition/rehabilitation • No change in LL use	• Superstructure mass increase is less than 10% • Fixity conditions are not changed	• Do not Require seismic evaluation • Do not require retrofit of the structure	
Major Modifications Minor Modifications PLUS • Replacing/adding girder and slab • Change in LL use	• Superstructure mass increase between 10% to 20% and/or • Fixity conditions are changed	• Seismic evaluation of the structure is required. • Do-No-Harm is required for substructure. • Do-No-Harm is required for foundation.	

Major Widening – Case 1 Minor Modifications PLUS • Superstructure or Bent Widening	• Superstructure mass increase is more than > 20% and/or • Substructure/bents modified and/or • Fixity conditions are changed	• Seismic evaluation of the structure is required. • C/D ratio of equal or greater than 1.0 is required for substructure. • Do-No-Harm could be used for Foundation.	
Major Widening – Case 2 • widening on one side	• Substructure or bents are modified. Columns are added on one side.	• Seismic evaluation of the structure is required. • C/D ratio of equal or greater than 1.0 is required for substructure. • Do-No-Harm could be used for Foundation.	
Major Widening – Case 3 • widening on both sides	• Substructure or bents are modified. Columns are added on both sides.	• Seismic evaluation of the structure is required. • C/D ratio of equal or greater than 1.0 is required for substructure. • Do-No-Harm could be used for Foundation.	

SEISMIC RETROFITTING OF EXISTING BRIDGES

Seismic retrofitting of existing bridges is performed in accordance with FHWA publication FHWA-HRT-06-032, Seismic Retrofitting Manual for Highway Structures. When combining the response of two or three orthogonal directions the design of any quantity of interest (displacement, bending moment, shear or axial force) be obtained by the 100-30 percent combination rule as described in AASHTO Specifications.

SEISMIC ANALYSIS REQUIREMENTS

The first step in retrofitting a bridge is to analyze the existing structure to identify seismically deficient elements. The initial analysis consists of generating capacity/demand ratios for all relevant bridge components. Seismic displacement force demands is determined using the multi-mode spectral analysis of Retrofitting Manual as a minimum. Prescriptive requirements, as support length, is considered mandatory and is included in the Seismic capacities is determined in accordance with the requirements Seismic Retrofitting Manual. Displacement capacities is determined by Method D2 – Structure Capacity/Demand (Pushover) Method of Seismic Retrofitting Manual Section 5.6. The seismic analysis need only be performed for the upper (1,000 year return period) ground motions with a life safety seismic performance level.

SEISMIC RETROFIT DESIGN

Once seismically deficient bridge elements have been identified, appropriate measures is selected and designed. Table 1-11, Chapters 8, 9, 10, 11, and Appendices D thru F of the Seismic Retrofitting Manual is used in selecting designing the seismic retrofit measures. The WSDOT Bridge and Structure Office Seismic Specialist will be consulted in the selection and design of the retrofit measures.

The seismic retrofit of Essential and Critical bridges is in accordance with the requirements of the WSDOT BDM with consultation of Bridge Design Engineer and Geotechnical with regard to practicability and cost.

INNOVATIVE BRIDGE CONSTRUCTION

Innovative Bridge Construction is simply an idea that encourages outside the box thinking encouraging engineers to consider principles that will enhance bridge performance, speed up construction, or add any other benefit to the industry. There is no single or handful of ideas that can contain or describe Innovative Bridge Construction. It's simply a mentality that new ideas ought to be explored. Innovation might be defined as any contribution to the bridge industry that takes bridge construction past the current standard practice of bridge construction. Some items produced recently are described in the following sections.

SELF-CENTERING COLUMNS

Self-centering columns are columns designed restore much of their original shape after a seismic event. They're intended to improve the serviceability of a bridge after an earthquake.

Self-centering columns are constructed with a precast concrete column segment with a duct running through it longitudinally. They rest on footings with post-tensioning (PT) strand developed into them. Once the precast column piece is set on the footing, the PT strand threads through the duct and gets anchored into the crossbeam above the column. The PT strand is unbonded to the column segment. As a column experiences a lateral load, the PT strand elastically stretches to absorb the seismic energy and returns to its original tension load after the seismic event. The expectation is the column would rotate as a rigid body and the PT strand would almost spring the column back to its original orientation. A depiction of the self-centering concept is shown in Figure 1.

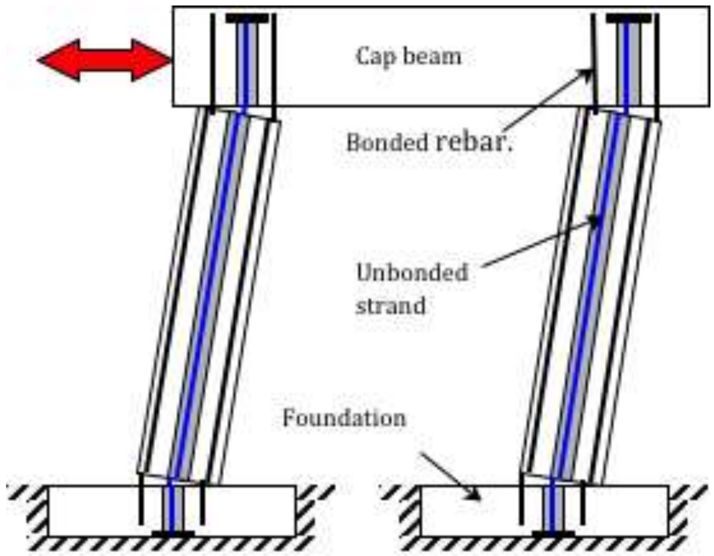


Figure 1 Self-Centering Column Concept

SHAPE MEMORY ALLOY

Like self-centering columns, Shape Memory Alloy (SMA) and Engineered Cementitious Composite (ECC) products are introduced into bridge design as a means to improve ductility, seismic resilience, and serviceability of a bridge after an earthquake.

SMA is a class of alloys that are manufactured from either a combination of nickel and titanium or copper, magnesium and aluminum. The alloy is shaped into round bars in sizes similar to conventional steel reinforcement. When stressed, the SMA can undergo large deformations and return to original shape. The SR 99 Alaskan Way Viaduct Replacement – South Access project demonstrated that yield strengths of 55 ksi can be achieved with an initial modulus of elasticity of approximately 5400 ksi. Under service and strength limit states the SMA in the column is designed similarly to traditional mild reinforcement, the stress in the bar is limited to the yield strength. During a seismic event, when the yield stress is exceeded, the bars deform trilinearly and restore to the undeformed state as the stress dissipates.

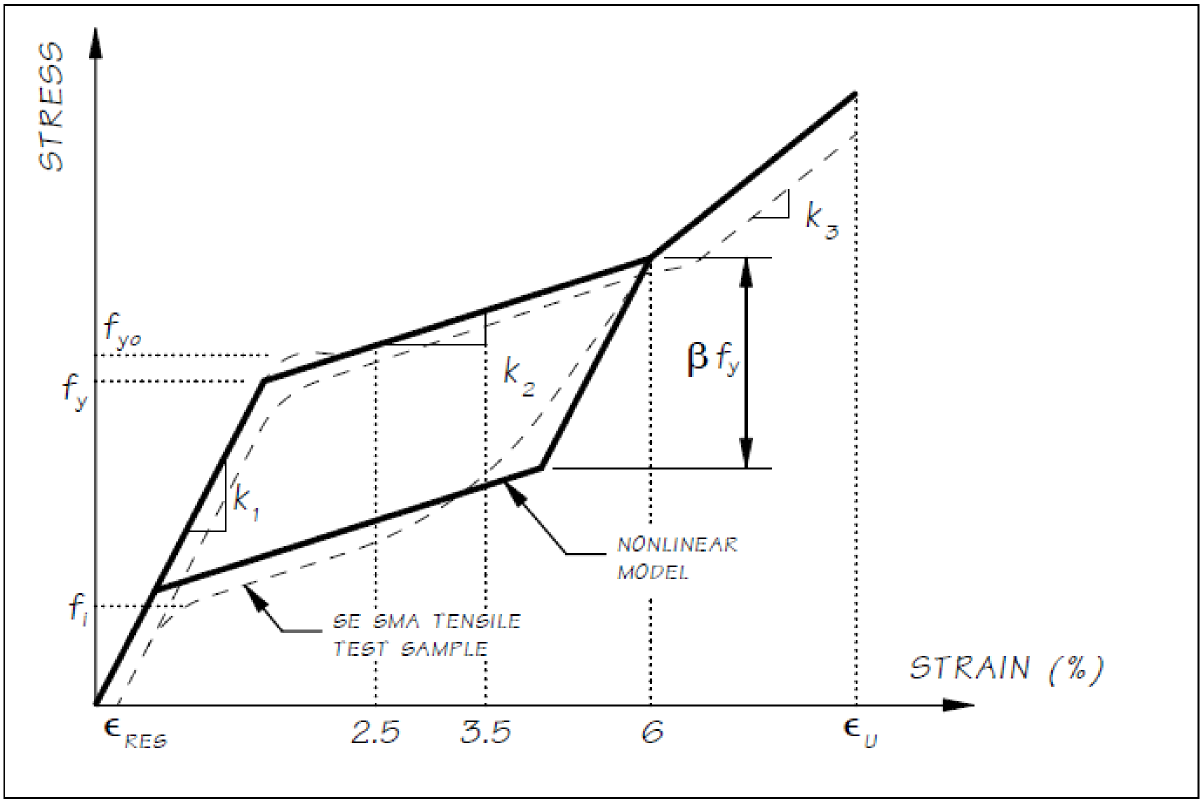


Figure 2 Shape Memory Alloy Stress-Strain Model

ECC is in the family of High Performance Fiber Reinforced Cementitious Composites and is similar to traditional concrete mixes, except that the mix includes a polyvinyl alcohol fiber and omits the course aggregate. ECC replaces conventional concrete in columns to provide a moderate tensile strength and increase ductility to accommodate the large deformations of the SMA. The use of ECC eliminates the spalling expected of conventional concretes in the hinge region. Figure 3 shows the stress-strain profile comparison of confined and unconfined ECC (f`c = 5 ksi) and conventional concrete (f`c = 4 ksi)(Li 2007 and Xu 2010)[4, 5].

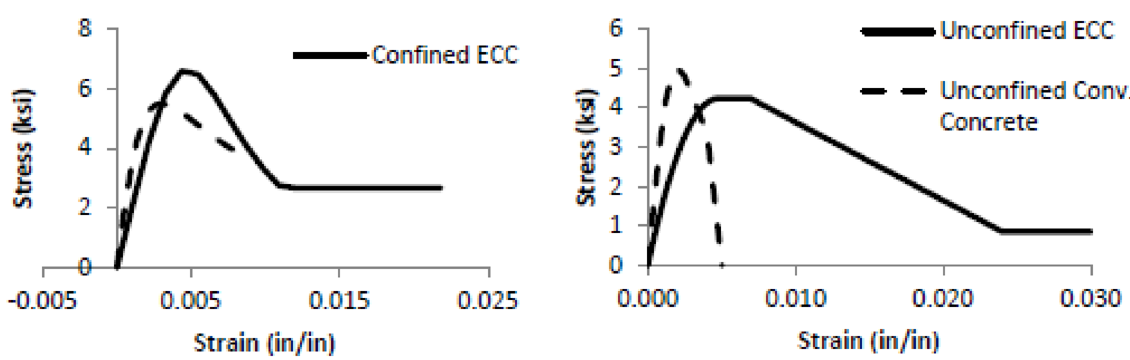


Figure 3 Engineered Cementitious Concrete Stress-Strain Model

When combined in the plastic hinge zones of bridge columns, the SMA and ECC materials are designed to provide high levels of strain with a super-elastic performance to allow for large deflections with negligible permanent deformation and minimal damage. This combination of materials provides the ductility a bridge column needs to perform well in a seismic event while providing enough elasticity to restore the bridge closer to its original shape than conventional concrete and rebar, even with proper detailing.

Bars fabricated with SMA are coupled with conventional steel reinforcing located outside the plastic hinge region to reduce the amount of SMA used in the bridge column. The engineered cementitious material can be poured within the plastic hinge region separately from the rest of the column concrete. An example of a column with ECC and SMA reinforcing in the plastic hinge regions is shown in Figure 4.

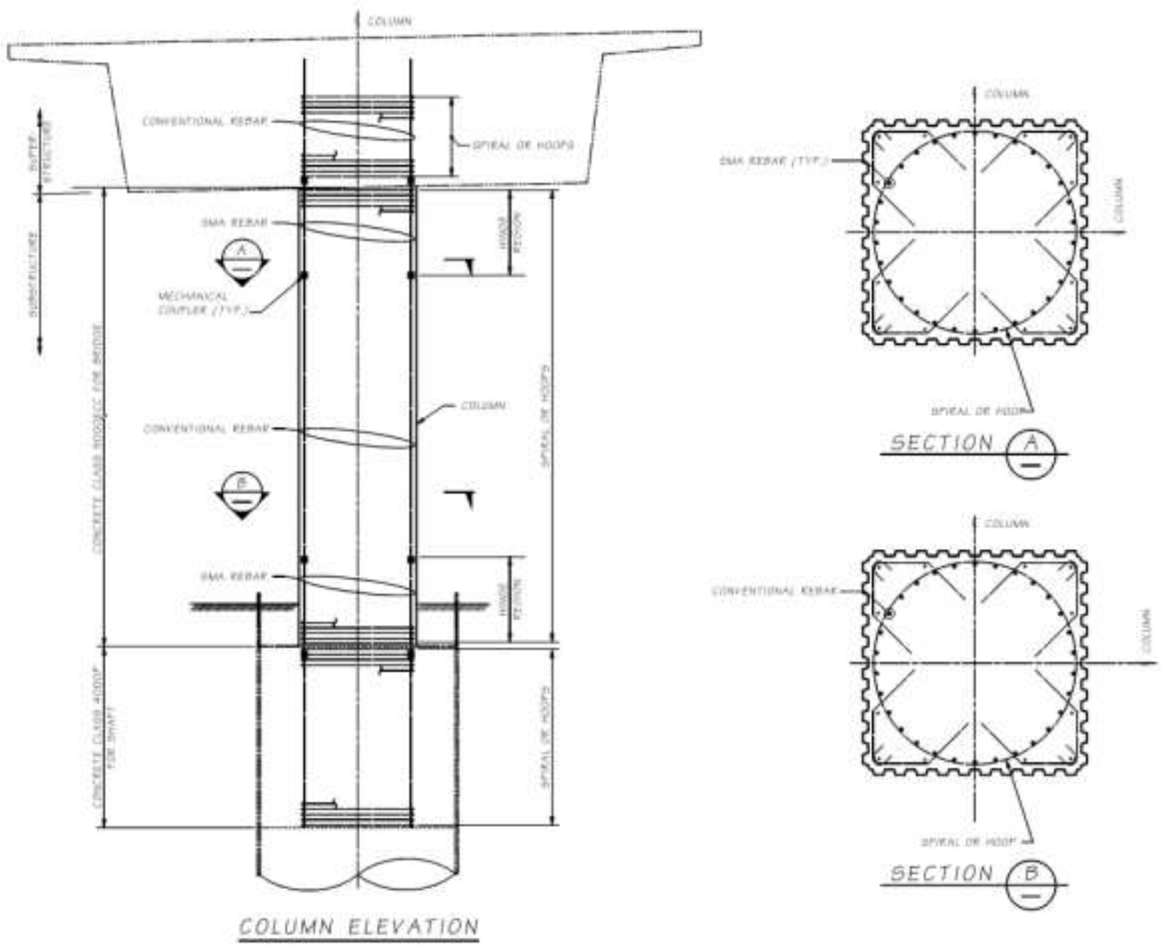


Figure 4 Shape Memory Alloy and Engineered Cementitious Column (Elevation and Sections)

CONCLUSION

This paper described the WSDOT seismic design requirements and innovative design and construction features used in designing and constructing bridges. The conclusions summarize principal concepts and highlights from the design, research, and lessons learned. WSDOT's objectives is to ensure that state highways will be able to provide emergency responders access to damaged portions of the community quickly to provide essential life-saving services. State Highways will also need to provide the capability for the state economy and the movement of freight and goods to be re- stored as quickly as possible.

REFERENCES

1. AASHTO Guide Specifications for LRFD Seismic Bridge Design. AASHTO, Washington, D.C., 2009.
2. Washington State Department of Transportation. Bridge Design Manual (LRFD). Publication No. M23-50. Olympia, Washington. 2019.
3. Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges, Publication NO. FHWA-HRT-06-032 January 2006
4. Li, Victor C., 2007, Engineered Cementitious Composites (ECC) – Material, Structural, and Durability Performance. In Nawy, E. (ed), Concrete Construction Engineering Handbook, CRC Press, Boca Raton, Chapter 24.
5. Xu, Shi-Lang and Xiang-Rong Cai, 2010, Experimental Study and Theoretical Models on Compressive Properties of Ultrahigh Toughness Cruz, C., and M. Saiidi, 2012, Shake Table Studies