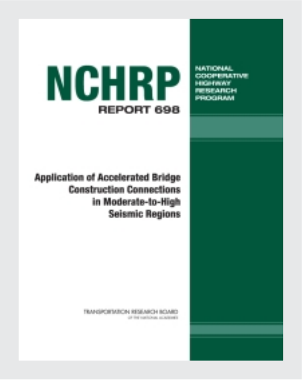

Application of Accelerated Bridge Construction Connections in Moderate-to-High Seismic Regions

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 698

Application of Accelerated Bridge Construction Connections in Moderate-to-High Seismic Regions

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

By Waseem Dekelbab
Staff Officer
Transportation Research Board

This report identifies promising details to be used for connections of bridge members in accelerated bridge construction in medium to high seismic regions and gives recommendations for further research. Existing connection details were gathered from state departments of transportation (DOTs), industry, and academia and were evaluated for their performance in terms of readiness for use, construction risk, durability, and seismic performance. The material in this report will be of immediate interest to bridge engineers.

The Federal Highway Administration (FHWA) and many state departments of transportation (DOTs) are actively promoting accelerated bridge construction (ABC) to minimize construction-related impacts to the traveling public and to enhance work-zone safety. Many successful applications of ABC techniques have been recently realized, largely in regions of low seismic activity. A number of these ABC applications are documented in *FHWA Connection Details for Prefabricated Elements and Systems* published in 2009.

However, use of ABC techniques has been more limited in seismic regions of the country. A key factor in successful implementation of this initiative lies in the connections between prefabricated elements. Providing reliable connections to ensure ductile performance is essential to developing designs capable of performing to the specifications required in seismic-prone areas. Several prefabricated connection details used for recent ABC projects in seismic regions hold significant promise for more widespread application, but they have not been fully tested for seismic loading. To develop an improved understanding of their ultimate performance, recommendations for further testing were needed

Research was performed under NCHRP Project 12-88 by BergerABAM and the Department of Civil and Environmental Engineering at the University of Washington. The research presented herein synthesizes the available information related to connection details recently used or under development for potential use on ABC bridges and gives suggestions for future research.

A number of deliverables are provided as appendices. These are not published herein but are available on the TRB website. These appendices are titled as follows:

- Appendix A—Summary Sheets of Bar Coupler Connections
- Appendix B—Summary Sheets of Grouted Duct Connections
- Appendix C—Summary Sheets of Pocket Connections
- Appendix D—Summary Sheets of Member Socket Connections
- Appendix E—Summary Sheets of Hybrid Connections
- Appendix F—Summary Sheets of Integral Connections

- Appendix G—Summary Sheets of Emerging Technology and Deformable Element Connections
- Appendix H—Detailed Evaluation of Connection Types
- Appendix I—Questionnaires
- Appendix J—2012 Research Problem Statement

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 12-88 by BergerABAM and the Department of Civil and Environmental Engineering at the University of Washington. BergerABAM was the contractor for this study with the University of Washington as subcontractor.

Dr. M. Lee Marsh of BergerABAM was the principal investigator. Jim Guarre of BergerABAM was consulting as senior bridge engineer, and Dr. John F. Stanton and Dr. Marc O. Eberhard, both professors at the University of Washington, were consulting researchers and authors to the project. The other authors of this report were Dr. Markus Wernli and Brian E. Garrett from BergerABAM, and Michael D. Weinert, research assistant at the University of Washington. The work was done under the general supervision of Dr. M. Lee Marsh at BergerABAM and Dr. John F. Stanton at the University of Washington.

The project would not have been possible without the support of the FHWA and the departments of transportation (DOTs) of Alaska, Arkansas, California, Florida, Georgia, Idaho, Illinois, Indiana, Louisiana, Massachusetts, Minnesota, Missouri, Montana, Nevada, New York, North Carolina, Oregon, Rhode Island, South Carolina, Tennessee, Texas, Utah, and Washington, and researchers from University of California, San Diego; California State University, Sacramento; Multidisciplinary Center for Earthquake Engineering Research; University of California, Berkeley; Iowa State University; University of Texas, Austin; University of Nevada, Reno; Utah State University; University of Minnesota; University of Tennessee at Knoxville; Stanford University; and University of Washington—all of whom filled out a questionnaire or e-mailed responses and shared their ongoing research and design guidelines that were relevant to this project.

Thirteen international contacts included researchers from the University of Nottingham, University of Rome, University of Kyoto, Tokyo Tech, University of Canterbury, National Autonomous University of Mexico (UNAM), Technical University Frederico Santa Maria, University of Patras, and University of Pavia.

Contractors and precast producers who responded to the questionnaire or provided information by telephone included Concrete Technology, Inc., C.C. Myers, Inc., Encon United Companies, Flatiron Construction Corp., Mammoet USA South, Inc., Mowat Construction, Kiewit Construction, and PCL Construction. The Washington State DOT and Graham Construction provided valuable information at the Time Savings workshop.

SUMMARY

Application of Accelerated Bridge Construction Connections in Moderate-to-High Seismic Regions

Increasingly, state DOTs are supporting initiatives to study and apply Accelerated Bridge Construction (ABC) techniques to bridge projects. They offer the potential benefits of reduced construction time, minimum traffic disruptions, reduced life-cycle costs, and improved construction quality and safety. Prefabrication of components is a promising approach to ABC but, in seismic regions, the connections between the elements must not only be easy to construct, but also must be robust enough to maintain their integrity under seismic loading. Development of connections and systems that satisfy these criteria will constitute significant progress in achieving the goals of ABC.

This report presents results of a literature review of the connections and systems that are currently in use, or are being studied for use, in ABC in the United States and other countries. A survey questionnaire was developed to involve bridge owners such as the FHWA, state DOTs, domestic and international universities and organizations, contractors, precast producers, and vendors.

The ABC connections identified in the literature study and survey are analyzed and categorized by type, such as bar couplers, grouted ducts, pocket, socket, hybrid, or integral connections, and emerging technologies, such as shape memory alloys and elastomeric bearings. Note that seismic isolation may also be used with ABC techniques; however, seismic isolation is a relatively mature technology and is not evaluated herein. A primary objective of the project was to evaluate and rank the connections. This was done using three parallel metrics: technology readiness, performance, and time savings potential. The technology readiness level is a measure of the development of the connection or system technology, and depends on the extent to which it has been tested, analyzed, and deployed. The performance evaluation includes characteristics, such as expected seismic performance, constructability, durability, inspectability, and reparability. Time savings potential is measured relative to cast-in-place construction. Gaps in the development of each connection type were identified. These rankings identified the ABC connections and systems that most urgently warrant further research, such as grouted splice bar couplers and development of a bent system, as well as subsequent development of integral connections and emerging technologies.

An extensive testing program will eventually be necessary to support the use of the various types of ABC connections that could be deployed in medium-to-high seismic regions of the United States. In addition, definitive design and construction specifications, design examples, demonstration projects, and field experience will be needed for owners, contractors, and designers to have the confidence to deploy the technology.

CHAPTER 1

Background

Statement of the Problem

The FHWA and many state DOTs are actively promoting accelerated bridge construction (ABC) to minimize construction-related impacts to the traveling public and to enhance work-zone safety. Many successful applications of ABC techniques have been recently realized, largely in regions of low seismic activity. A number of these ABC applications are documented in *Connection Details for Prefabricated Elements and Systems,* published by FHWA in 2009.

However, use of ABC techniques has been more limited in moderate-to-high seismic regions of the country. A key factor in successful implementation of this initiative lies in the connections between prefabricated elements. Providing reliable connections to ensure ductile performance is essential to developing designs capable of performing to the specifications required in earthquake-prone areas. Several prefabricated connection details used for recent ABC projects in seismic regions hold significant promise for more widespread application, but they have not been fully tested for seismic loading. In addition, by testing these details and developing an improved understanding of their ultimate performance, these details could be used for potential ABC application throughout the country for other extreme event hazards.

The challenge of ABC construction in seismic regions affects at least 36 of the 50 U.S. states, according to the American Association of State Highway and Transportation Officials (AASHTO) seismic design methodology, which is a function of site soil conditions. For sites with the poorest soils, 36 states could have bridges that fall into the moderate-to-high seismic areas (Seismic Zone 2 or higher and Seismic Design Category of B or higher). Therefore, this is a national issue. The systems developed in this research will, of course, be usable in all 50 states. If the connections' constructability properties are outstanding, their use may be economically attractive, even if high connection ductility is not required. The use of ABC is a national initiative and expansion of the use of ABC to seismic zones is necessary to provide the benefits of ABC for all highway users.

Objectives of the Study

The scope of the study was generally determined by the tasks identified in the request for proposal (RFP). The following is the task description from the RFP:

> The objective of this research is to synthesize the available information related to connection details recently used or under development for potential use on ABC bridges with promise for more widespread application in seismic regions. The work should include the following connection categories, and associated components and systems:
>
> - Pile to pile cap connections
> - Foundation to substructure connections
> - Substructure to superstructure joints and connections
> - Connections between column segments
> - Connection between precast girders and pier diaphragms
> - Various connection devices and technologies
> - Superstructure to substructure connection from Self-Propelled Modular Transporters (SPMTs) (Roll-in) technology
>
> It is anticipated that the research will encompass at least the following tasks.
>
> **Task 1.** Review relevant literature, specifications, ongoing research findings, current practices and other information canvassing all engineering and material disciplines to determine the current state of knowledge on connections, and associated components and systems for potential research in each abovementioned connection category. This information shall be assembled from published and unpublished reports, contacts with academia, transportation agencies, industry organizations, and other domestic and foreign sources, bridge owners, precast fabricators, contractors, and others.
>
> **Task 2.** Summarize the various connections and joints identified on Task 1. Outline the perceived advantages and disadvantages of each respective detail based on constructability, seismic performance, inspectability, and durability. In addition each connection and joint should be assessed for its effect on system performance.
>
> **Task 3.** Identify gaps in validation of the findings in Task 2.

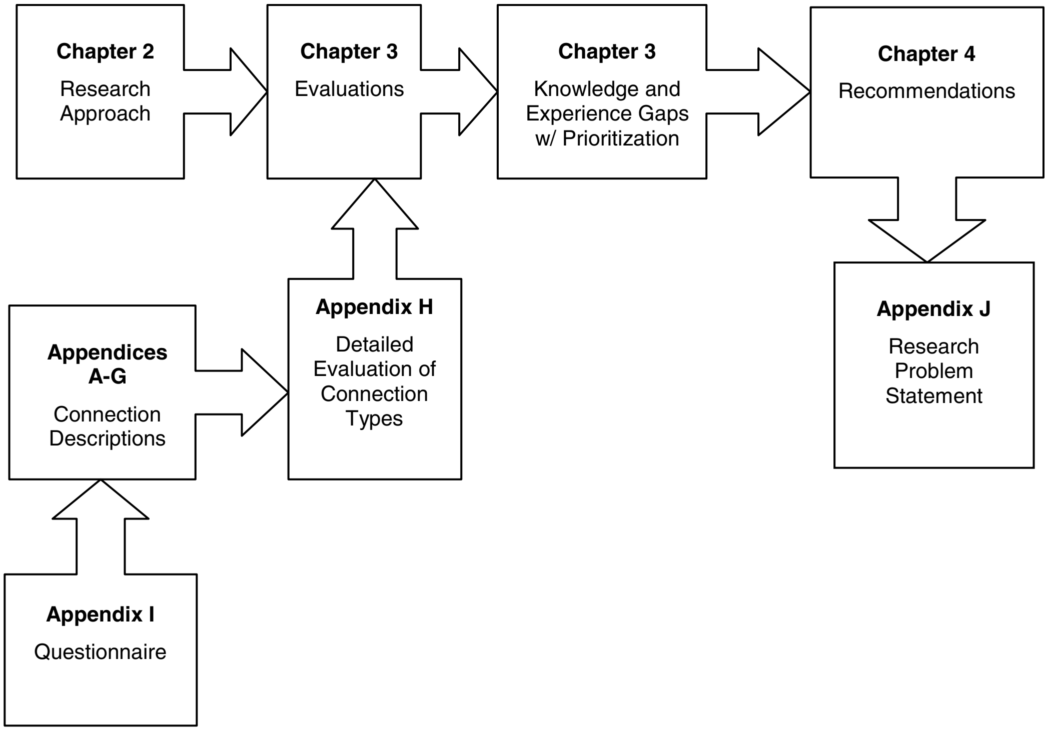


Figure 1. Report flow chart.

Task 4. Submit a final report describing the entire research project and making suggestions for future research needs. A draft final report is due one month before the contract end date.

Organization of the Research Report

The report is organized into four chapters. Chapter 1 gives the background for the research project. Chapter 2 summarizes the methodology used for information gathering and the approach for the evaluation of connections and bridge systems. The identified connections are characterized and evaluated individually according to the defined evaluation procedure and are presented in the form of separate cut sheets for each connection in Appendices A through G. Appendix H provides detailed summaries of connection types, and Appendix I includes the questionnaires that were sent out to support the information gathering.

Chapter 3 summarizes the characteristics and evaluations of connection types, expands the seismic performance evaluation to entire bridge systems, and presents the identified knowledge gaps. Chapter 4 presents the conclusions and gives suggestions for further research. A 2012 Research Problem Statement to address the identified research needs is given in Appendix J. The overall flow of the report is shown schematically in Figure 1.

CHAPTER 2

Research Approach

The research approach followed the task list given in the RFP by NCHRP. The work was split between the team members from BergerABAM and the University of Washington, the former focusing on the deployment and implementation side of ABC and the latter on the seismic performance substantiation side.

Literature and Practice Review

The literature and practice review started with the development of a list of bridge owners, researchers, organizations, contractors, and suppliers who might provide direct input or indirect leads to the state of the art of current ABC technologies. Parallel to this effort, a set of questionnaires was developed for each contact group. The questionnaires focused on the ABC work done by the institutions and they requested access to design specifications, design guidelines, reports, standard plans or details, special construction provisions, or design examples that relate to the use of ABC, seismic or non-seismic. For bridge designers and owners, the questionnaire was extended to obtain information on specific design procedures that are typically employed for seismic design for ABC and identification of the roadblocks to employing ABC. Copies of the questionnaires are provided in Appendix I. In total, 43 U.S. and 13 international organizations were contacted.

Twenty-three state DOTs were contacted, including Alaska, Arkansas, California, Florida, Georgia, Idaho, Illinois, Indiana, Louisiana, Massachusetts, Minnesota, Missouri, Montana, Nevada, New York, North Carolina, Oregon, Rhode Island, South Carolina, Tennessee, Texas, Utah, and Washington.

Research institutions that were contacted included University of California, San Diego; California State University, Sacramento; Multidisciplinary Center for Earthquake Engineering Research (MCEER); University of California, Berkeley; Iowa State University; University of Texas at Austin; University of Nevada, Reno; Utah State University; University of Minnesota; University of Tennessee at Knoxville; Stanford University; University of Washington; and the FHWA.

The 13 international contacts included researchers from the University of Nottingham, University of Rome, University of Kyoto, Tokyo Tech, University of Canterbury, National Autonomous University of Mexico (UNAM), Technical University Frederico Santa Maria, University of Patras, and University of Pavia.

From the construction side, eight contractors and precast producers were asked to share their experience on ABC work, including, Concrete Technology, Inc.; C.C. Myers, Inc.; Encon United Companies; Flatiron Construction Corp.; Mammoet USA South, Inc.; Mowat Construction; Kiewit Construction; and PCL Construction.

Information material on ABC was also gathered from libraries, research databases, and the internet. The material included standard guidelines or surveys from FHWA, AASHTO, the Precast/Prestressed Concrete Institute (PCI) Manual, as well as individual research papers and product information. The collected information was compiled and used by the research team for this project.

Definition of Seismic Connections and Performance Strategies

The use of precast element technology for bridges in moderate-to-high seismic regions must consider the location and seismic resistance function of the bridge elements being connected. In the United States, bridges are designed for seismic resistance by permitting some inelastic deformation of the structure. Such inelastic response is typically restricted to the substructure between the ground level and the soffit of the superstructure. An example of such behavior is a reinforced concrete column that may be designed to experience inelastic action in the form of plastic hinges that form at points of high moment, which are often at the bottom and top of the column depending on continuity of the connections between foundation and superstructure. In the recently adopted *AASHTO Guide Specification for LRFD Seismic Bridge Design* (2009), the overall concept of seismic behavior is related by identifying an earthquake resisting system (ERS), which is made up of earthquake resisting elements (ERE). In general, seismic forces are limited by the formation of a plastic mechanism within the structure when subjected to large infrequent earthquakes.

There are two seismic design procedures, a force-based procedure in the *AASHTO LRFD Bridge Design Specifications* (2010) and a displacement-based procedure in the *AASHTO Guide Specifications for LRFD Seismic Bridge Design* (2009). Both procedures are predicated on the use of inelastic action to resist large earthquakes. The design earthquake in both AASHTO specifications has approximately a 1,000-year recurrence interval. The use of inelastic action and, specifically, the formation of a plastic mechanism, limits the internal forces that the bridge will experience and provides energy dissipation to limit seismic response. However, the locations of inelastic action are typically at the areas of connection between two members (for example, column and cap beam) because these are the locations of maximum moment.

Figure 2 illustrates a pier of a bridge where ABC techniques have been used to connect both superstructure and substructure elements. The connections are shown as lines. Additionally, the plastic hinge locations for this bridge are indicated. It can be seen that some of the connection interfaces are adjacent to or in the plastic hinge zones and some are away from such zones. This is an important distinction for the use of ABC techniques in seismic regions of the country. If a connection is made in a plastic hinging location, then the connection must be capable of sustaining inelastic deformations and dissipating kinetic energy input to the bridge system by an earthquake. Such connections are energy-dissipating (ED) connections. Connections that are not located where inelastic action is expected would typically be designed using capacity protection principles where the element and adjacent connection are not permitted to experience inelastic action. Such elements and connections are termed capacity-protected (CP) connections.

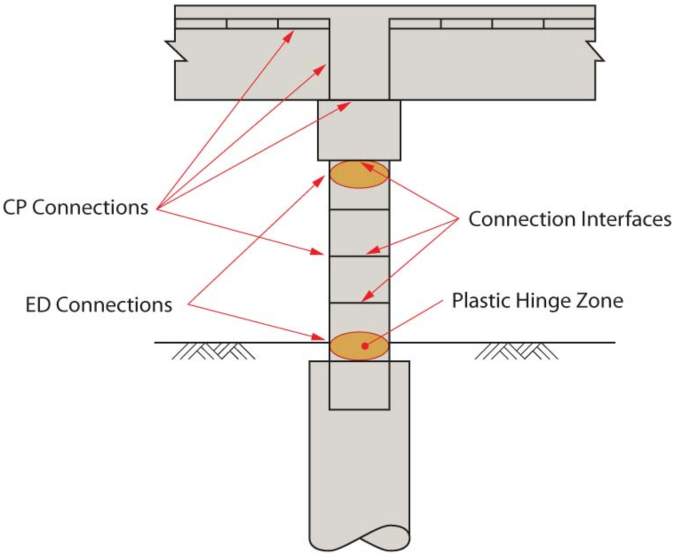


Figure 2. Potential precast element connection locations relative to plastic hinge locations.

Figure 3 illustrates two examples of locations of connections relative to the plastic hinging zones. The figure on the left has ED connections that are in the plastic hinging zones. These are commonly encountered because the preferred locations for connecting precast elements are also the preferred locations for plastic hinge zones. The preference for connections at the ends of members is related to the desire to transport elements that are compact and do not have pieces that protrude. The figure on the right shows an option where the precast connections are kept away for the plastic hinging zones and are, therefore, CP connections. This concept would be ideal for seismic use of ABC techniques, but is not consistent with the realities of handling and transporting heavy precast elements.

A third type of element and connection may be used, typically when seeking to provide internal articulation and permit displacements with minimal force induced. An example of this type of element would be an internal pin connection. Such connections are termed deformation elements (DE). Another type of DE element is the seismic isolation bearing. Such bearings provide both internal system articulation, typically between the super- and substructure, and they may also provide significant energy dissipation. Seismic isolation is a relatively mature technology and, thus, is not focused on in this report. That is not to imply that seismic isolation cannot be effective with ABC, it certainly can. The three types of seismic performance strategies are summarized in Table 1.

The extent to which the connection possesses strength and deformation capabilities determines its usefulness for different types of seismic resistance and the seismic zone for which it could be considered. In many cases, the strength and deformability are associated with rotational behavior and, thus, refer to moment and rotation.

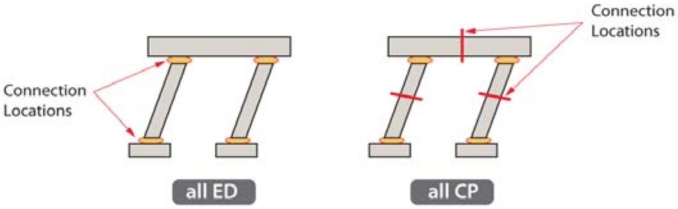


Figure 3. Energy-dissipating (ED) versus capacity-protected (CP) connections.

Table 1. Seismic performance strategies for connections.

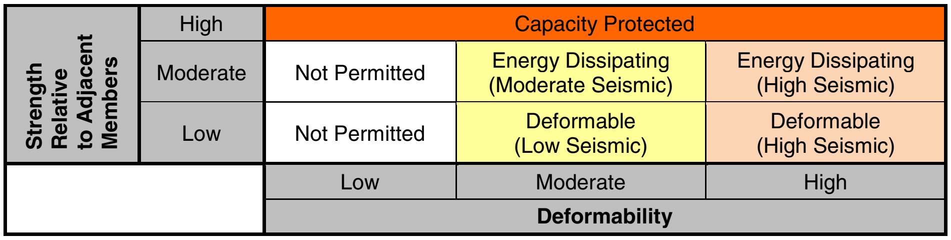
Seismic Performance Strategy	Performance Behavior
Capacity-Protected (CP) Connections	CP elements provide a cyclic strength that is higher than the strength of the adjacent bridge members, allowing the connection to remain essentially elastic with minimal or no damage. As a result, the inelastic deformations are forced to occur in the adjacent elements.
Energy-Dissipating (ED) Connections	ED elements provide a cyclic strength that is lower than that of the adjacent members, thereby causing the inelastic deformation to occur in the connection, but high enough to dissipate enough energy to contribute usefully to the system damping. The deformation capacity is high enough to satisfy the demands associated with the seismic zone in which the bridge is built. The connection may suffer damage, but the consequent strength loss must be acceptable in all degrees of freedom, including both the primary one in which the inelastic deformation occurs and others in which minimal deformation is expected.
Deformation Elements (DE)	DE have little or no strength in the degree of freedom in which the deformation occurs. The deformation capacity is high enough to satisfy the demands associated with the seismic zone in which the bridge is built. The connection protects the adjacent bridge members by concentrating seismic deformation within the connection region but typically provides negligible energy dissipation. The deformation may be free (e.g., a pin), elastic (e.g., an elastomeric pad), or inelastic. Seismic isolation bearings may provide both large deformation capabilities and significant energy dissipation.

Ideally, the strength would not degrade with cycling, although in reality some degradation is almost inevitable. The strength of the connection is evaluated relative to that of the adjacent members because their relative strengths control the location of the damage.

The cyclic deformation capacity measures the ability of the connection to undergo cycles of deformation without jeopardizing the strength or performance in some other degree of freedom. For example, a connection with good rotational deformability could undergo many cycles of rotation without loss of shear strength. The deformability is evaluated relative to the expected deformation demand in a high seismic zone, assuming rigid behavior in the connected elements.

Figure 4 presents the three seismic performance strategies from Table 1 in terms of their cyclic strength and deformation capabilities and how they are applicable to different seismic zones. A CP connection may be used in any seismic zone, including high seismic zones, as long as deformation capacity and energy dissipation are provided somewhere else within the bridge system. Note that such capacity protection may occur naturally by virtue of the dimensions of the members. For example, in a bridge bent that includes a dropped cap beam and cast-in-place (CIP) diaphragm, the combined cap beam-diaphragm is typically much larger than the column. Thus, the inelastic deformation is likely forced into the column. If the lower stage of the beam and the column are precast, and then connected by grouting bars into sleeves or ducts within the lower stage, the connection between the two stages of cap beam occurs in a beam-column joint region, which must be designed as capacity protected. For energy-dissipating and deformable connections, the required deformation capacity depends on the seismic zone. The distinction between an energy-dissipating connection and a deformable one is not precise, and depends on the level of energy dissipation that is considered necessary to limit peak displacements during an earthquake.

The word "connection" has been used numerous times, but it has not been defined. A clear definition is required to understand how a connection, particularly an ED or deformable-elements connection, relates to the seismic demands placed on the system of connected elements. Figure 5 illustrates the



Strength Relative to Adjacent Members	High	Capacity Protected		
	Moderate	Not Permitted	Energy Dissipating (Moderate Seismic)	Energy Dissipating (High Seismic)
	Low	Not Permitted	Deformable (Low Seismic)	Deformable (High Seismic)
		Low	Moderate	High
		Deformability		

Figure 4. Seismic performance of connection elements in relation to cyclic strength and deformability and their application for moderate and high seismic zones.

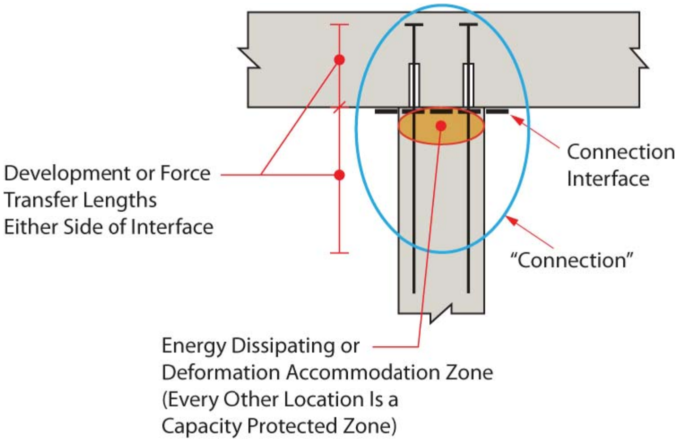


Figure 5. Connection definition.

various pieces of a connection that must be considered when evaluating its suitability for seismic use. The connection shown is between a column and a cap beam, and the seismic plastic hinging zone is indicated. The various reinforcing elements that constitute the connection are also indicated. On either side of the connection interface, or location where the members actually touch, the reinforcement must be developed or anchored to provide continuity of internal force flow for both seismic and permanent loads. Because the reinforcement may need to extend well away from the interface and plastic hinging zone, portions of an ED connection may actually be in capacity-protected zones. In fact, they must be because only selected portions of the connection will typically be capable of sustaining the inelastic demands without deterioration. This, of course, is highly dependent on the connection configuration and concept.

With respect to seismic performance, connections generally can be classified as "emulative" of CIP reinforced concrete or "non-emulative." The connection illustrated in Figure 5 might be an emulative connection because the configuration of connection hardware, shown as the white boxes above the interface, is kept away from the plastic hinging zone and only conventional reinforcement is used in the plastic hinging zone. The non-emulative types are typically unique to each concept. Emulative behavior is desirable on one level because confidence in the connection performance, be it seismic or durability, is generally high due to the vast experience that exists with CIP construction.

The use of ABC techniques with bridges designed for seismic loading (seismic accelerated building construction [SABC]) will generally follow a building-block approach. This means that various types of connections may be used to assemble a bridge that is completely or partially built with ABC techniques. The combination of connections, however, must result in a rational seismic load resisting system. This is generally a simple thing to achieve with emulative connections. However, with the more unusual non-emulative types, the connection technology's impact on the seismic system and performance must be considered by the designer and kept consistent throughout. The building-block approach does have the advantage of permitting several types of connections to be used in a structure to solve various constructability or other problems, so long as the overall ERS is rational. Rational in this sense means capable of providing the expected performance of the entire bridge.

Classification of Connection Types

The information materials provided in the questionnaire responses and obtained from other sources were screened for details of connection intended to transfer seismic forces between bridge members. These details were classified in terms of their location within the bridge structure, their force transfer mechanism, seismic performance, and method of installation. The classifications are explained in more detail in the following subsections.

Classification by Location

The connections were categorized according to the location for which they might be suitable. For the purpose of this project, only locations that are important for the seismic behavior of the bridge were considered. Starting from the ground up, the following location categories were defined:

- **Pile to Pile Cap Connections** are typically completely below grade and are very difficult to access for inspection or repair. The connection might join the pile cap to straight or batter piles, driven or drilled piles, and concrete or steel piles. During an earthquake, this location experiences a high shear, moment, tension, and compression demand.
- **Foundation to Substructure Connections** are at grade and may or may not be covered by overburden soil. The foundation may be a spread footing foundation, pile cap, or drilled shaft. One or more elements of the substructure can be connected to a foundation; typical elements include columns, piers, and walls. The location could be obscured by other structural elements, such as barriers, pavement, and buildings, or submerged in water, thereby making inspection difficult. The location could also be exposed to a harsh environment or be susceptible to damage from accidental impact. Under a seismic event, this location typically experiences a high moment and shear demand in multiple directions and may also be subjected to tension/compression in the case of multiple-column bents.
- **Connections between Column Segments** are generally splices of prefabricated columns, piers, or walls. The connections may be obscured in ways similar to those of the

foundation to substructure connections, but are generally more accessible for inspection and repair. Under a seismic event, these connections can experience loading that is similar in nature to, but less intense than, the loads experienced by the foundation to substructure connection. In some cases, connections between column segments may be specifically designed to accommodate earthquake displacements.

- **Substructure to Superstructure Connections** join piles, columns, piers, or walls to a cap beam or diaphragm. The location is relatively easily accessible and is typically protected from environmental exposure by the bridge superstructure above. In the longitudinal direction, this type of connection can experience high seismic demands for both moment and shear, and deformation demand may be high. Depending on how the connection is integrated with the bridge diaphragm, the girder moments can have a significant effect on the seismic behavior of the connection. In multiple-column bents, the moment and shear demands may also exist in the transverse direction.
- **Connections between Precast Girders and Pier Diaphragms** can be accessible in the same way as substructure to superstructure connections. Seismic loading can subject this connection to reversing moments and high shear loads. The deformation demand on these connections is typically small by virtue of the capacity protection provided by the system geometry.

Classification by Force Transfer Mechanism

The connections were classified according to their force transfer mechanisms, which range from highly localized, such as bar couplers, to more global mechanisms involving large volumes of site-cast concrete. The categories used for this project are as follows:

- **Bar Couplers** can be used to butt-splice reinforcing bars, allowing a continuous force flow in them across the interface between the adjacent members. The coupler type most commonly used in bridges is a steel sleeve that is filled with a high-strength grout after the members have been erected. Several proprietary versions are available. These couplers allow for some tolerance in field placement, but they are inevitably larger than the bar itself, especially if oversize couplers are selected to provide extra placement tolerance. Bar couplers allow the connection reinforcement details to resemble those of CIP construction as long as there is enough space to physically fit the coupler.
- **Grouted Ducts** do not directly splice reinforcement bars from adjacent bridge members, but rather allow individual reinforcement bars to be fully developed within the adjacent member. A separate duct is provided for each connection bar. The length of the duct is defined by the length needed to fully develop the capacity of the bar or the length needed to transfer the bar force to the adjacent bars in the segment. As the duct provides some confinement, the bar development length can be shorter than for typical CIP concrete design. However, the duct length can govern the size of a connection. Grouted ducts are nonproprietary and provide larger construction tolerances than bar couplers, but they require more space within the adjacent member's reinforcement cage. Nevertheless, the general joint reinforcement layout can still be similar to that of a CIP system.
- **Pocket Connections** involve forming a large opening, or pocket, in one bridge member, such as a cap beam. Reinforcement projecting from another member, such as a column, can be inserted into it, after which the pocket is filled with CIP concrete. The connection reinforcement is fully developed in the CIP concrete within the pocket. The connection allows for ample construction tolerances as long as the joint region is not heavily reinforced. The pocket requires that all or part of the joint reinforcement be cast into the precast member. For example, if the longitudinal cap beam reinforcement in a column-to-cap-beam connection penetrates the pocket, then the joint shear reinforcement must exist in the precast cap beam, as it cannot be post-installed with the longitudinal column reinforcement. On the other hand, if the column connection reinforcement includes longitudinal and spiral reinforcement, then the longitudinal cap beam reinforcement has to be placed outside the pocket. The relocation of reinforcement plus the requirement to provide full development length for the connection bars often leads to an increase of the member size compared with a CIP member.
- **Member Socket Connections** provide a socket in which an entire precast member can be inserted and grouted. A socket connection differs from a pocket connection in that no bare reinforcement crosses the interface between the two members; the connection bars are completely encased in the precast member. The inserted precast member is anchored by the bond provided by the grout and by prying action. Both interface surfaces are roughened to increase the bond resistance. The connection offers ample installation tolerances, particularly if the member with the socket is cast-in-place, as may be the case with a footing. If the member is precast, it needs to be large enough to accommodate the socket with enough strength to resist the expected prying action.
- **Hybrid Connections** are connections that contain unbonded post-tensioning through the joint, which remains elastic and renders the connection self-centering under lateral cyclic loading. The hybrid connections also contain bonded bar reinforcement that is either spliced by bar couplers or anchored in grouted ducts. It yields alternately in tension and compression to dissipate energy under cyclic loading.

- **Integral Connections** typically provide stay-in-place formwork in which two adjacent members can be monolithically connected. An example of an integral connection is a steel diaphragm/cap beam of a composite bridge that is filled with site-cast concrete to connect a concrete column. The integral connection requires the largest in-situ concrete pour of all connections previously described.
- **Emerging Technologies, Deformation Elements, and Miscellaneous Types** are in a class of connections that includes the various improvements proposed to either existing connection types, such as the hybrid type, or entirely new types of connections, that use new materials or advanced materials in new ways. Examples are the use of elastomeric bearings incorporated with columns and the use of shape-memory alloys (SMAs). The class also includes connections that might be used to relieve internal forces and, thus, primarily accommodate deformations. These types of connections are called deformation elements. They are included in the same type class as emerging technologies, because those connections are often used similarly to accommodate deformations.
- **Mechanical Connections** are bolted, welded, or provide mechanical devices to connect two adjacent members such as a bridge bearing.

In the connections that have been evaluated, proprietary hardware is commonly found. In some cases, there are multiple vendors of similar products so that sole source procurement of the hardware is not an issue. However, for some types of connection hardware, this is not the case. The user should be aware of this when considering a connection for potential use on a project. In this report, no effort has been made to identify the connection hardware by manufacturer, and in fact, the opposite is true. The report sought to avoid identification of specific manufacturers. In the categories above, the ones that typically have the potential for sole-source proprietary hardware that could affect the detailing are bar couplers, emerging technologies, and mechanical connections.

Evaluation Methodology

Connection details were assembled from the questionnaire responses and from other sources in the literature review phase. Each connection detail was evaluated to appraise its fitness for use and its potential performance during construction, service, and a seismic event. A set of evaluation criteria was developed that included the following: practical experience with an individual connection, measures for the evaluation of the technology, readiness of the connections for seismic application, the type of seismic performance, and the practical characteristics of the connections, such as constructability, durability, inspectability, and reparability. The characteristics, classification, and evaluation of each individual connection are presented in a standardized form and are summarized for each connection type in this report. The details for each connection are provided in the appendices. The three measures then indicate three different, but necessary, characteristics of the connection types:

- *Technology Readiness Level*—the level of development.
- *Performance Potential*—the potential merits and disadvantages in terms of performance.
- *Time Savings Potential*—the potential for accelerating the construction schedule.

Furthermore, an evaluation procedure was developed for the assessment of the performance of entire bridge systems composed of suitable combinations of the individual connection types analyzed. The following paragraphs explain the development of the various measures.

Technology Readiness

All the connections were assessed according to their readiness for implementation in accelerated bridge construction in seismic areas. In particular, if connections used newly developed technologies, the assessment provided insight into the requirements for complete deployment in the field or, failing that, described the activities required to move the technology to the next level.

The U.S. Department of Energy (DOE) provides a process for this type of evaluation and calls it Technology Readiness Assessment. The process was originally developed by the National Aeronautics and Space Administration (NASA) and has since found its application in the U.S. Departments of Defense and Energy, as well as in related industries. The process is defined by a scale of nine steps, referred to as technology readiness levels (TRL), that describe the readiness state of a new or newly applied technology, from TRL 1 (an observation) to TRL 9 (a fully implemented and functional technology). Typically, the process focuses on the assessment of a particular technology in a particular environment. A guideline can be found in the U.S. Department of Energy's *Technology Readiness Assessment Guide* (2009). The TRL levels defined by the DOE are given in Table 2.

An attempt was made to apply these nine levels of readiness directly to SABC. However, the DOE definitions were found to be a poor fit for the important characteristics of ABC, despite their apparent generality. Thus, a new scale, similar in intent but different in detail, was developed. The new scale is shown in Table 3.

A TRL value of 1 is applicable to all connection types in the database because their presence there indicates that a concept has at least been formulated.

Table 2. Original definition of technology readiness level (DOE).

Level	Definition per DOE
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or system validation in laboratory environment
5	Laboratory scale, similar system validation in relevant environment
6	Engineering/pilot-scale, similar (prototypical) system validation in a relevant environment
7	Full-scale, similar (prototypical) system demonstrated in a relevant environment
8	Actual system completed and qualified through test and demonstration
9	Actual system operated over the full range of expected conditions

In TRL 2, either analysis or testing is deemed acceptable for verification of static strength. Analysis is deemed acceptable for this purpose because member design for static response, such as bending of beams, is conducted without question using analysis alone.

TRL 3 provides a basic verification of constructability. If the connection concept is used in a seismic region, the bar congestion may be more severe and the connection may be less readily constructible than its non-seismic counterpart. However, a TRL of 3 indicates that there are no fundamental impediments to construction.

TRL 4 indicates that the connection type has been evaluated analytically for seismic loading. The analysis should include the effects of cyclic loading and inelasticity, including ductility demand and capacity. It is also deemed to satisfy the requirements of TRL 2.

TRL 5 demonstrates by test the viability of the critical components. For example, in a connection that depends on mechanical couplers to transfer tension between bars, TRL 5 might apply to an individual coupler. The testing must, of course, be successful for TRL 5 to apply.

TRL 6 refers to testing of a complete connection, such as a column-to-cap beam moment connection, rather than to a component, such as a bar coupler.

TRL 7 represents an important step towards field implementation. The existence of guidelines implies more than a single test and significant analysis, including studies of the influence of the important parameters in the design.

TRL 8 provides verification of constructability when seismic details are used. It is also deemed to satisfy the requirements of TRL 3.

TRL 9 provides verification that the connection satisfies the twin requirements of constructability and seismic performance. Few, if any, connections can be expected to achieve TRL 9 because ABC connections have been used in bridges only in recent years and have rarely been built in high-seismic regions. A full-scale dynamic shaking table test does not qualify as a TRL 9.

The technology readiness assessment procedure was applied to each identified ABC connection to evaluate its readiness for application in seismic regions. As part of the summary, the individual connection types were also evaluated for the extent the connections met the TRL in terms of percentage completed for each level. The evaluation table can be seen in Table 4. The evaluation allows identifying gaps in the current knowledge of a connection type. Ideally, a TRL is met 100% before the next level is started. However, in reality, some levels are skipped or deemed satisfactory after partial completion. A skipped or partially completed level does not necessarily mean that a knowledge gap exists, as later development steps might fill such gaps. But gaps in the TRL indicate risks that problems might show up later in the development that should have been addressed

Table 3. Definition of technology readiness level for seismic accelerated bridge construction (SABC).

Level	Definition for Accelerated Bridge Construction
1	A design concept has been formulated.
2	The connection type has been analyzed or tested for static strength.
3	The connection type has been successfully deployed in a low seismic region.
4	The connection type has been analyzed for response to inelastic cyclic loading.
5	The critical connection components have been tested under inelastic cyclic loading.
6	A connection subassembly has been tested under inelastic cyclic loading.
7	Seismic design guidelines for the connection type have been formulated and published.
8	The connection has been used in a bridge constructed in a high seismic region.
9	The connection type has performed adequately during a design-level seismic event in the field.

Table 4. Evaluation of technology readiness level of connection types and identification of knowledge gaps.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	Description	0-25	25-50	50-75	75-100
1	Concept exists				
2	Static strength predictable				
3	Low seismic deployment				
4	Analyzed for seismic loading				
5	Seismic testing of components				
6	Seismic testing of subassemblies				
7	Design and construction guidelines				
8	Deployment in high seismic area				
9	Adequate performance in earthquake				

in earlier stages. For example, for the development of a seismic connection, it is unlikely that a non-seismic deployment per TRL 3 is conducted. Hence, constructability issues in the field cannot be recognized until deployment of the connection in a seismic area at TRL 8. This seems to be a bearable risk. On the other hand, a risk might be perceived higher if a connection has been deployed to a seismic area without TRL 6, seismic testing.

Evaluation of Potential Time Savings and Performance of Connections

To identify connection systems that merit further investment in testing and analysis, two other measures were seen to be necessary. In this report, they are called the "time savings potential" and "performance potential." The first is a simple measure that indicates the time savings that appear possible if the connection is used. The real time savings depends on the construction system in which the connection is incorporated, so the evaluation is necessarily subjective and approximate. However, it is a measure of the possible time advantage relative to traditional CIP construction for the connection type. The scale is given in Table 5.

To establish the time savings for each connection type, the researchers convened a meeting attended by a bridge contractor, a Washington State DOT construction engineer, two Washington State DOT design engineers, and two researchers. A detailed description of this is included in Appendix H. The goal was to generate time estimates for each step of the construction of a CIP bridge bent, and then to do the same for four of the precast groups (socket, pocket, bar couplers, and grouted ducts) used to construct a typical bent. The predicted time savings were then computed as the difference between the time needed for the precast system in question and the CIP system. The connections were evaluated by connection type, rather than including every possible variant found in the appendices.

The estimates were necessarily subjective and were influenced by the prevailing building culture in the state (drop cap beams and precast, prestressed concrete girders). However, efforts were made to minimize the subjectivity, first by arranging the presence of both design and construction expertise at the meeting, and second by discussing each construction step in detail, including possible adverse circumstances, before assigning an approximate time. Despite those efforts, slight regional variations must be expected for the estimated time savings computed by this process.

The second measure is a composite measure of the performance potential of the connection type and is defined in terms of the connection's construction risk, seismic performance, durability, and post-earthquake inspectability. The scale is given in Table 6.

To show good performance potential, a connection must be expected to score at least adequately in all four categories. A "much worse" score in any one indicates a potentially unsatisfactory connection type. If connections have "slightly worse" scores in one or two categories, those scores could be offset by better performance in other categories. However, outstanding performance in one category would not necessarily make the connection type more attractive than performance that is merely satisfactory. Thus, the scales should saturate. For example, if most structures might be expected to experience 1.5 to 2% drift demand during a major seismic event and drift capacity of 5% was considered "adequate," then a connection drift capacity of 12% adds little to the value of the system because it is very unlikely to be used. This argument also applies to all four categories. The construction risk evaluates the possibility that something might go wrong during construction and

Table 5. Connection time savings potential.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	
+1	Slightly better	
0	Equal	
-1	Slightly worse	
-2	Much worse	

Table 6. Connection performance potential.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better				
+1	Slightly better				
0	Equal				
-1	Slightly worse				
-2	Much worse				

detract from the quality or schedule. However, it does not measure the potential time savings so it is also measured using a scale that saturates.

The performance evaluation is somewhat subjective, as it is based on the knowledge of the individual research team members in combination with the information gathered as part of this project. No additional studies or calculations have been performed to support any individual evaluation. However, where the need for such further studies is recognized, suggestions are given in the report. Because the performance potential is a qualitative measure, the scale was deliberately kept simple. Each characteristic was defined relative to the corresponding measure for CIP reinforced concrete construction.

In most cases, little information was provided by the respondents about durability and inspectability. Therefore, a default value of 0 (equal to CIP concrete) was used unless specific information was available.

It should be noted that some interaction exists between the TRL and the performance potential. If the connection type has already been developed to a high level, much will be known about its performance. The performance potential value can, therefore, be based on objective facts rather than subjective estimates.

The measures of potential time savings and performance could be combined to simplify the evaluation procedure. However, doing so would fail to display the relationship between risk and reward. For example, the same value might be assigned to one connection type that offered the potential for large time savings (if everything went right) but carried a high risk of something going wrong and to a second connection type with little potential time savings and little risk. To preserve this important distinction, the two characteristics were evaluated separately.

The individual performance evaluation criteria are defined in the following paragraphs.

Definition of Construction Risk Rating Criteria

The evaluation of the construction risks of a connection collectively assesses the difficulty to fabricate and install a connection and the associated quality, cost, and schedule risk for typical ABC practice. The ratings are presented in Table 7. The following issues are considered:

- Complexity of detailing and number of parts
- Required construction tolerances during component fabrication and field installation
- Handling, lifting, and shoring equipment needed for field installation
- Difficulty of labor access, work environment, and work condition
- Complexity of installation procedure and number of steps
- Vulnerability to construction mishaps, such as component damage during handling and noncompliant procedures, and availability of inspection and mitigation methods
- Sensitivity of installation schedule to individual operations, such as grouting and the time for grout to set
- Dependence on specialty trades or parts
- Repetitiveness of work and learning curve
- Risks associated with subcontracting part of the work

Definition of Seismic Performance Rating Criteria

The seismic performance rating evaluates how an ABC connection for a specific seismic performance strategy, per Table 1 (CP, ED, and DE), performs compared with a CIP connection for a specific seismic zone (low, moderate, and high). The criteria are defined in Table 8. The following issues are considered:

- Are there experimental data available and do they demonstrate a cyclic loading behavior that is comparable to CIP construction?
- Is the connection emulating CIP construction with proper seismic detailing?
- Is it possible to develop bar strength, as necessary, for cyclic loading?
- Is it possible to prevent excessive concrete spalling?
- Is it possible to prevent bar buckling?
- Does the connection allow strain penetration under inelastic loading?
- Are bars spliced outside the plastic hinge zone?

Table 7. Rating for construction risk.

Risk Potential	Definition Relative to CIP	Description of Field Work	Construction Risk
+2	Much Better	Detailing is simple and can be done by a reduced construction crew with minimum need for large construction equipment.	There is a very high likelihood that a connection will meet the required quality standard, cost, and installation schedule.
+1	Slightly Better	Detailing is simple and fabrication and installation of components can be performed by typically skilled construction workers under predictable conditions using conventional construction equipment.	There is a high likelihood that a connection will meet the required quality standard, cost, and installation schedule.
0	Equal	Detailing is simple but requires attention to fit-up and appropriate use of materials. Reasonably common supervision is required. Fabrication and installation of components might require a specialty contractor or specialized equipment. Most contractors will be able to successfully construct the project.	There is a high likelihood that a connection will meet the required quality standard, but there is a minimal risk for not meeting installation cost or schedule.
–1	Slightly Worse	Detailing is somewhat complex, but skilled construction workers can execute the construction. The work, while complex, is not out of the experience range of a skilled crew but might lead to a slow learning curve, with attendant mistakes, for an inexperienced one. The work might involve specialty contractors or specialized equipment. Close control will be needed to ensure appropriate quality and final acceptance.	There is a minimum likelihood that a connection will not meet the required quality standard without repairs after initial construction and there is a moderate risk for not meeting installation cost or schedule.
–2	Much Worse	Detailing is complex and skilled construction workers under close supervision will be required to properly execute the construction. Specialty contractors or specialized equipment will most likely be required for installation work. Tolerances may be close, materials may be difficult to use in the construction, and tight controls over the work must be worked out in advance and specifically for the particular project. Mock-ups would typically be beneficial and potentially required. Only the most experienced contractors will be successful with execution of the work.	There is a moderate likelihood that some repairs may be required after initial construction to satisfy the acceptance criteria for the work and there is a high likelihood that the connection will not meet the cost or installation schedule.

- Is it possible to retain axial and shear capacity during cyclic loading?
- Is the connection self-centering after cyclic loading?
- Can damage be contained to the plastic hinge region?
- Does the connection have a potential for energy dissipation similar to CIP?

Table 8. Definition of seismic performance potential.

Seismic Performance Potential	Definition Relative to CIP
+2	Much Better
+1	Slightly Better
0	Equal
–1	Slightly Worse
–2	Much Worse

- Does the connection provide adequate deformability and strength for its intended seismic performance strategy?

Definition of Inspectability Rating Criteria

The inspectability rating focuses on post-earthquake inspection of the seismic connection elements. It considers the ability to recognize damage by visual inspection and whether there are methods available for damage assessment of the critical structural components, such as reinforcement and post-tensioning. The rating directly compares to how difficult it would be to inspect and assess damage of the same connection built in CIP or CIP-emulative precast concrete. The rating is presented in Table 9. The following issues are considered:

- Can an inspector conclude that there is no damage if no damage is observed by visual inspection?

Table 9. Definition of inspectability evaluation criteria.

Potential	Definition Relative to CIP	Description
+2	Much Better	Damage of critical structural components is easily assessed by visual inspection or nondestructive testing.
+1	Slightly Better	
0	Equal	No cracking indicates no damage, large cracks indicate yielding of reinforcement, and spalling of concrete indicates excessive deformations and potential bar failure. Damage of critical structural components can typically be assessed with nondestructive testing.
–1	Slightly Worse	The absence of visual signs of damage might not necessarily guarantee the integrity of all the critical structural components. Damage assessment of critical structural components is difficult and cannot be done without dismantling a portion of the connection.
–2	Much Worse	

- Can visual inspection recognize that there is a failure of a critical structural component that needs immediate mitigation?
- Can damage be assessed with nondestructive evaluation tools?
- Can damage be assessed with minimum need of deconstruction?

Note that the inspectability during construction is evaluated as part of the construction risk rating and is not considered here.

Definition of Durability Rating Criteria

The durability rating evaluates how the durability of an ABC connection would compare with a connection built of CIP or CIP-emulative precast concrete under similar typical environmental exposure. The criteria are defined in Table 10. The following issues are considered:

- Does the connection provide adequate protection of its structural components?
- Does the connection avoid ingress paths for contaminants to structural components?
- Is the durability of the connection affected by the quality of construction?
- How easy is it to detect deterioration during routine bridge inspections?

Table 10. Definition of durability evaluation criteria.

Potential	Definition Relative to CIP
+2	Much Better
+1	Slightly Better
0	Equal
–1	Slightly Worse
–2	Much Worse

Bridge Systems

This report focuses primarily on individual connection or pier system technologies and not directly on full bridge systems. The nature of the ABC technologies, as they have been developed to date, lend themselves to consideration on the element (connection) or subsystem (column) levels. The seismic performance and efficacy of such elements or systems can be inferred through a building-block approach. Conceivably, different connection types could be used within a single bridge and the overall seismic performance could be made to conform to the objectives of the AASHTO design specifications. The performance and success of the design depends on where, within the bridge, ABC technology is used; specifically, whether the technology is used within a region where inelastic response is expected or within a region that is capacity protected.

Where ABC connections or systems are used in the columns where inelastic action is expected, then adequate seismic performance of the bridge will depend on the ability of the connections to tolerate cyclic inelastic deformations or on the ability to locate the connections where such inelastic action can be avoided. Where inelastic action is expected of the ABC connections, then proof testing must be conducted to demonstrate that sufficient toughness is incorporated into the connections. This type of connection is the focus of this report.

In other parts of a bridge system, (for example, the superstructure), ABC connections may be designed as capacity-protected elements; thus, they do not need to be designed to accommodate inelastic cyclic actions, and non-seismic connection technologies may be used. In abutments, typically the seismic loads are either carried elastically without damage or are transferred through shear keys or other fusible detailing to prevent damage to the superstructure and the abutment itself.

Technologies that lend themselves to inclusion of fusible elements between the superstructure and substructure may also find application in ABC projects. For example, seismic isolation may be used to provide such fusing, while also providing an interface for assembling large prefabricated systems, such as complete superstructures.

CHAPTER 3

Findings and Applications

Evaluation of Connection Types

The description of the findings and the evaluation of connection types in this section are organized by force transfer mechanism:

- Bar Couplers
- Grouted Ducts
- Pocket Connections
- Member Socket Connections
- Hybrid Connections
- Integral Connections
- Emerging Technologies

Descriptions of individual connections or systems are contained in Appendices A through G, and those descriptions are then used in the more general discussions and evaluations of the connection types listed above. Appendix H provides the detailed evaluations of the connection types, and this chapter summarizes the information in Appendix H. As described in Chapter 2, each connection type is evaluated on the basis of the following:

- Performance potential, which is a composite of construction risk, seismic performance, durability, and post-earthquake inspectability
- Time savings potential
- Technology readiness

The reader is referred to Appendix H for detailed information about each connection type. Additionally, the appendix provides information on material requirements, construction techniques, and detailed evaluation of laboratory testing of representative specimens of the connection type.

Bar Couplers

Description

A bar coupler is used to splice two bars together, end-to-end. It allows axial force to be transferred from one bar to the other and performs the same function as a welded butt splice. In most cases, compression can be resisted by end bearing, and the transfer of tension is the more critical matter. A typical arrangement is shown in Figure 6.

Several styles of coupler (described in the following list and illustrated in Figure 7) are commercially available. Each depends on a different mechanical principle.

- *Threaded sleeve.* The bars are equipped with male thread, and they screw into a sleeve with a female thread. The threads may be tapered to reduce the number of turns necessary for full engagement. Such couplers permit little alignment tolerance.
- *Headed bars with separate sleeves.* A head is formed on the end of each bar and a threaded coupling piece draws the two together. To ensure contact for transferring compression, a shim may be placed between the bar ends.
- *External clamping screws.* A steel sleeve fits over the bar ends. Set screws are driven radially through the sleeve into the bar. The tension force is transferred from bar to sleeve to bar through shear in the screws.
- *Grouted sleeves.* A steel sleeve fits over the bar ends and is filled with grout. Tension is transferred by bond from bar to grout, and grout to sleeve. A variant of the grouted sleeve uses a screw thread to connect one bar to the sleeve and grout to connect the other. This adaptation allows the sleeve to be shorter.

The bar coupler connection type can be used in the following locations:

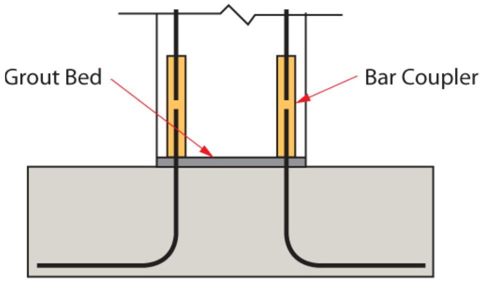


Figure 6. Bar coupler—typical application.

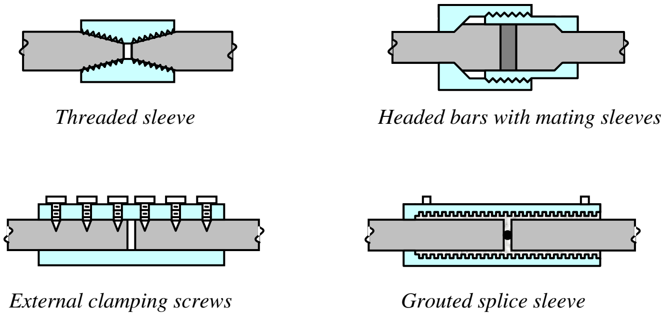


Figure 7. Bar coupler types.

- Footing to column
- Splices between column segments or cap beam segments
- Column to cap beam

Performance and Time Savings Evaluation

Performance scores were assigned for this connection type based on the comments outlined in Appendix H regarding construction risk, seismic performance, inspectability, and durability (see Table 11). In the table, the shaded cells indicate the composite performance expected as a group. Additionally, the numbers indicate the scores of individual connections, and the number corresponds to the identifying number for the connection in the appendix. For instance, the bar coupler type of connections include seven examples evaluated in Appendix A. In the appendix, the connections are denoted by BC-1 through BC-7, but in Table 11 only the connection number appears. The numbers are provided in the table simply to indicate the range of scores for the connection type. The numbers also indicate how a particular connection scored relative to other connections evaluated for the group.

The construction risk for bar coupler connections is less favorable than CIP construction because of the possibility that the bar and coupler might be misaligned relative to each other. The coupler might also not be correctly or fully engaged, for example, if a grouted splice sleeve was not filled properly. The seismic performance is rated lower than CIP construction because the test data for bar coupler connections is incomplete. The post-earthquake inspectability is similar to CIP; so a value of 0 is assigned. The durability is assigned a value of 0, because the potential for local voids during grouting is offset somewhat by the improvements in construction quality likely with precast elements.

The time savings for bar coupler connections was rated as +2 (much better than CIP) (see Table 12). The estimated savings is approximately 11 days for a bent in which the columns and cap beam are precast. The majority of that savings comes from using such connections at the cap beam.

Technology Readiness

Table 13 provides a summary of the TRL levels and of the estimated percentage of development that has been accomplished to date for the connection group. Because this rating applies to the entire group, it is a composite of the status of the individual couplers.

Summary

Bar coupler connections are being widely used in practice; however, their ability to sustain cyclic inelastic deformations is not well documented. Therefore, the connection type is considered constructible and promising for seismic use, but further experimental testing is suggested to verify its performance.

Table 11. Performance potential of bar coupler connections.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better				
+1	Slightly better				
0	Equal	6	6 7	1 2 3 4 5 6	1 2 3 4 6 7
–1	Slightly worse	1 2 3 4 5	1 2 3 4 5	7	5
–2	Much worse	7			

Table 12. Time savings potential of bar coupler connections.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	1 2 4 5
+1	Slightly better	3 6
0	Equal	
–1	Slightly worse	7
–2	Much worse	

Areas in which additional research is needed include the following:

- Inelastic cyclic performance—drift capacity
- Influence of coupler on bar strain distribution
- Influence of coupler location and orientation on inelastic performance

Grouted Ducts

Description

In grouted duct connections, reinforcing bars extending from one precast member are inserted into ducts cast into the second, and the ducts are then grouted. The hardened grout anchors the bar in the duct. The force from the bar is transferred into the surrounding concrete, and, possibly, to one or more bars lap-spliced to the outside of the duct. That load transfer mechanism contrasts with the one found in bar couplers, in which the load is transferred from one bar to another bar that is collinear with the first. A grouted duct connection can be configured in many different ways, examples of which are shown in Appendix B. Application of column to cap beam connections using grouted ducts are provided in Figure 8 and Figure 9, and a sample connection is shown in Figure 10.

Table 13. Technology readiness level evaluation of bar coupler connections.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	Description	0-25	25-50	50-75	75-100
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨	▨	▨	
3	Non-seismic deployment	▨	▨	▨	▨
4	Analyzed for seismic loading	▨			
5	Seismic testing of components				
6	Seismic testing of subassemblies	▨			
7	Design and construction guidelines	▨	▨	▨	
8	Deployment in seismic area	▨	▨	▨	▨
9	Adequate performance in earthquake				

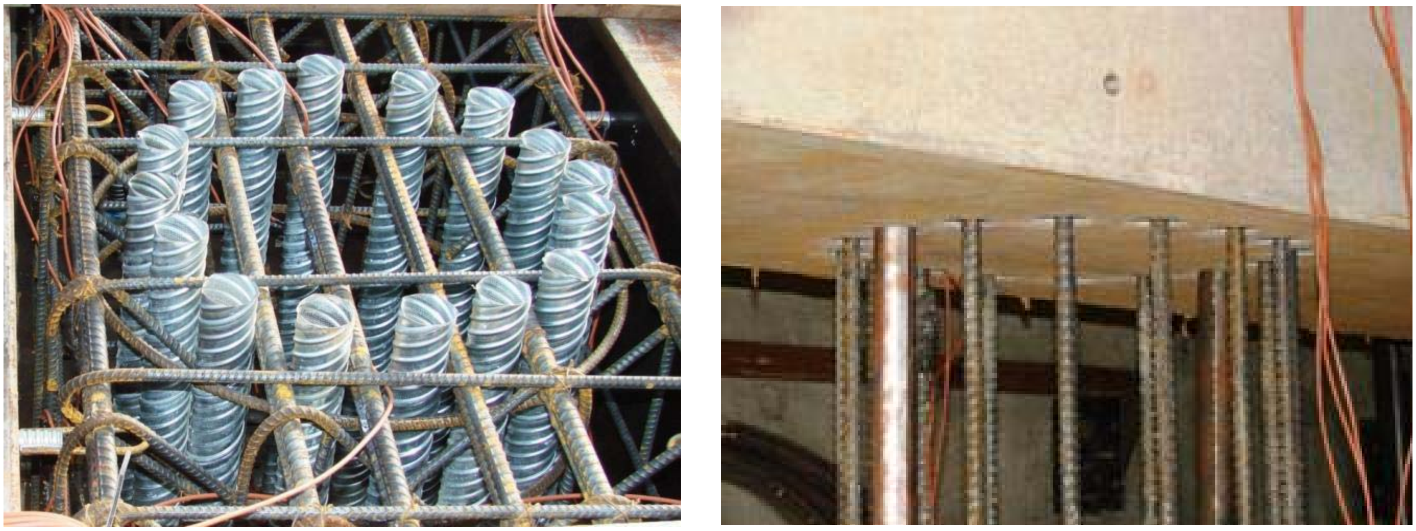


Figure 8. Grouted duct cap construction and cap placement (Matsumoto 2009b).

Figure 9. Grouted duct lower stage cap erection (Washington State DOT SR 520/SR 202).

This connection type can be used in the following locations:

- Pile to pile cap
- Spread footing or pile cap to column
- Column to cap beam
- Splice between column segments or cap beam segments

Performance and Time Savings Evaluation

Performance grades were assigned based on the comments stated previously regarding construction risk, seismic performance, inspectability, and durability. The construction risk was rated as less favorable than CIP construction because of the possibility of difficulties with grouting the ducts. All other evaluations are similar to CIP, and they are shown in Table 14. The several −1 evaluations for inspectability reflect cases where the grouted connection is deep within the member and, thus, difficult to inspect.

The time savings potential was evaluated as much better than CIP concrete, especially if the cap beam is precast (see Table 15). The corresponding group score was +2.

Technology Readiness

Grouted ducts have been tested extensively under static loading, and a few tests have been conducted under cyclic loading (Matsumoto 2009b, Pang et al. 2010). Preliminary design guidelines have been formulated for seismic use (Restrepo et al. 2011; Matsumoto et al. 2001, 2008; *PCI Design Handbook* 2004) and are in the process of refinement. The connection type has been deployed in non-seismic regions and a few times in seismic regions (SR 520, Highways for LIFE). Thus, a TRL maximum value of 8 is assigned without any gaps (see Table 16).

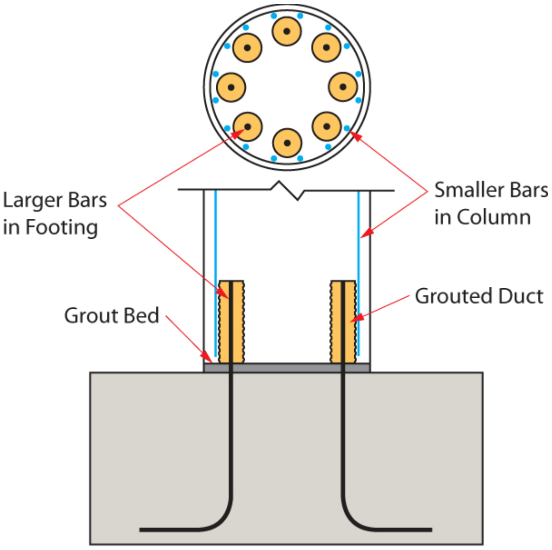


Figure 10. Typical grouted duct.

Summary

Grouted duct connections have been used on projects in both non-seismic and seismic regions. Additionally, significantly more research has been conducted on grouted ducts than on other connection types.

As noted in the seismic performance section, the use of fibers to reinforce the grout bedding layer needs to be confirmed. The question of strain distribution, which is affected by the relatively rigid ducts, is similar to the one raised in the grouted splice sleeve evaluation and also merits further investigation.

Areas in which additional research is needed include the following:

- Effect of duct size on anchorage length
- Influence of duct location on cyclic performance (e.g., in plastic hinge zone versus adjacent)

Table 14. Performance potential evaluation for grouted duct connections.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better				
+1	Slightly better				
0	Equal	2 3	1 2 3 4 5 6	1 2 3 4 5 6 7	2 3 5 6
−1	Slightly worse	1 4 5 6 7	7		1 4 7
−2	Much worse				

Table 15. Time savings potential evaluation for grouted duct connections.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	1 2 4 6
+1	Slightly better	5 7
0	Equal	3
–1	Slightly worse	
–2	Much worse	

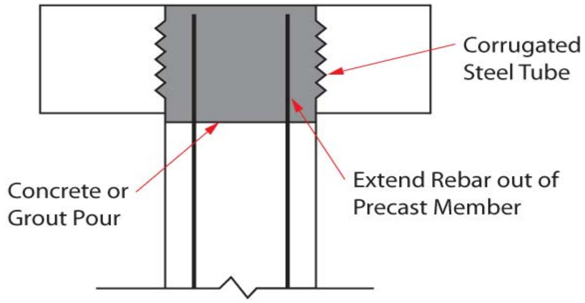


Figure 11. Pocket connection concept.

- Implications of lap splicing column bars to connection bars
- Impact of additional bars on plastic hinge region cyclic performance
- Influence of duct material, off-center bar, group pull-out effects, bedding layer reinforcement

Pocket Connections

Description

Pocket connections are constructed by extending reinforcing from the end of one precast structural member, typically a column or pile, and inserting it into a single preformed pocket inside another member. The connection is secured by using a grout or concrete closure pour in the pocket (Figure 11). A grout/concrete bedding joint can be used to provide adjustability. This connection differs from the member socket connection, in which the whole end of a member is embedded in the other. Pocket connection examples can be found in Appendix C.

Special consideration must be given to the detailing of the pocket and how it will be formed. The transfer of forces between the embedded member and the surrounding member occurs at the pocket perimeter. A steel duct can be used as a stay-in-place formwork that provides joint reinforcement and confinement to the pocket concrete. This duct should be placed between the cap beam top and bottom reinforcing bars. An additional piece of formwork, such as a cardboard concrete form tube, must be adhered to the top and bottom of the steel duct to extend the pocket form to the surface of the cap beam. The cardboard concrete form tube can be notched to fit over the reinforcing bars that cross through the pocket (Matsumoto 2009c).

This connection type can be used in the following locations:

- Column to cap beam
- Footing to column
- Pile to pile cap

Performance and Time Savings Evaluation

Performance grades were assigned based on the comments outlined in Appendix C regarding construction risk, seismic performance, inspectability, and durability (see Table 17). The scores lower than CIP generally reflect the increase in difficulty of constructing the connection and the potential for moisture intrusion into the joint, which potentially reduces durability. The much lower seismic performance value for two connections reflects designs not well-suited to seismic use.

The use of precast columns and cap beams connected with pockets is estimated to save 5.5 days, relative to CIP bridge bent construction (see the Time Savings section of Appendix H). This is an approximately 25% reduction in construction time. The majority of the savings was due to precasting the cap beam. Little, if any, time is saved by using a pocket at the column to

Table 16. Technology readiness level evaluation for grouted duct connections.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	Description	0-25	25-50	50-75	75-100
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨	▨		
3	Non-seismic deployment	▨	▨		
4	Analyzed for seismic loading	▨	▨	▨	
5	Seismic testing of components	▨	▨		
6	Seismic testing of subassemblies	▨	▨		
7	Design and construction guidelines	▨	▨	▨	
8	Deployment in seismic area	▨	▨	▨	
9	Adequate performance in earthquake				

Table 17. Performance potential evaluation for pocket connections.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better				
+1	Slightly better				
0	Equal		1 2 5		1 2 3 4 5
–1	Slightly worse	1 2 3 4 5		1 2 3 4 5	
–2	Much worse		3 4		

footing connection. Furthermore, if the pocket is formed in the footing, depositing the concrete into it would be difficult because the precast column would block access from above.

Out of all the precast connection types, the time savings associated with the pocket connection was the smallest, leading to a score of +1 (Table 18). Due to the large volume of material required to fill the pocket, concrete would typically be used instead of grout. This choice reduces speed of the pocket connection because concrete typically requires more time to gain strength than grout. A pocket connection also likely requires column jacks or other devices to support the cap beam's weight until the concrete has gained sufficient strength to transfer the loads by bond to the corrugated tube. By contrast, in a cap beam equipped with grouted ducts or sleeves, no column jacks are needed and the grout in the bed needs to gain only enough strength to carry the beam's weight through compression.

Table 18. Time savings potential for pocket connections.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	
+1	Slightly better	1 2 3 4 5
0	Equal	
–1	Slightly worse	
–2	Much worse	

Technology Readiness

Based on the level of seismic research, available design guidance, and use in practice, the evaluated pocket connections achieved TRL scores as shown in Table 19. The absence of testing of seismic components (Level 5) is not regarded as negative because there are essentially no components, such as individual couplers or grouted ducts, to test. Individual TRL values are given in Appendix C for different versions of the connection.

Summary

Given their good performance potential, pocket connections are promising for use in high seismic regions, if sufficient joint reinforcement is provided. However, the additional curing time of concrete relative to grouted connections makes the pocket less attractive for accelerated construction. This shortcoming could be mitigated by using grout or concrete with high early strength. To avoid the material's shrinking away from the corrugated steel tube, grout with non-shrink properties would be the better choice.

Additional experimental and analytical efforts are necessary to develop full design specifications for pocket connections.

Table 19. Technology readiness level evaluation for pocket connections.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	Description	0-25	25-50	50-75	75-100
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨	▨		
3	Non-seismic deployment	▨	▨	▨	
4	Analyzed for seismic loading	▨	▨		
5	Seismic testing of components				
6	Seismic testing of subassemblies	▨	▨		
7	Design and construction guidelines	▨	▨		
8	Deployment in seismic area	▨			
9	Adequate performance in earthquake				

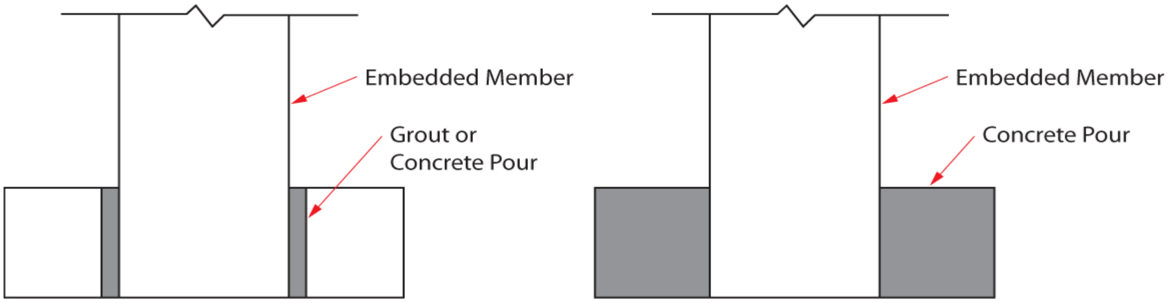


Figure 12. Member socket connection concepts.

Other areas that need to be further explored are the joint behavior and joint performance limit states.

Member Socket Connections

Description

Member socket connections are constructed by embedding a precast structural member inside another member. An example is shown in Figure 12. The connection is secured by either casting the second member around the first or using a grout or concrete closure pour in a preformed socket. The major types described are connections involving precast concrete columns or concrete-filled steel tubes (CFST). Additional discussion is provided on concrete filled fiber-reinforced plastic tubes (CFFT) and on topics for which information was available. Socket connections have been used occasionally in the building industry, but few examples of their use in bridges were found. Connection examples are provided in Appendix D.

This connection type can be used in the following locations:

- Footing to column
- Column to cap beam
- Pile to pile cap

Performance and Time Savings Evaluation

Performance scores were assigned based on the comments listed in Appendix D regarding construction risk, seismic performance, inspectability, and durability and are given in Table 20. Note that the range of evaluations is particularly wide for this connection owing to complexity of the connection detailing and whether the connection's design considered seismic loading.

Table 21 provides the time saving potential for socket connections. The use of precast columns and cap beams connected with sockets is estimated to save 10.5 days, relative to CIP bridge bent construction (see the Time Savings section of Appendix H). This is an approximately 50% reduction in construction time. The majority of the savings was due to precasting the cap beam. For a column with a footing cast around it, time savings is limited by the strength required of the concrete before construction may proceed.

Technology Readiness

Based on the level of seismic research, available design guidance, and use in practice, the evaluated socket connections achieved TRL scores as shown in Table 22. Individual TRL values are given in Appendix D for different versions of the connection type.

Summary

Given their good performance potential and time savings, member socket connections are promising for use in ABC in high seismic regions.

For precast concrete column member sockets, the connection needs to be tested for use with precast cap beams. A cap

Table 20. Performance potential evaluation for socket connections.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better	2	4		
+1	Slightly better	1		1 2 4	4
0	Equal	4	1 2 3	3 5 6	1 2 3 5 6
–1	Slightly worse	3 5 6			
–2	Much worse		5 6		

Table 21. Time savings potential for socket connections.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	1 2 4 5 6
+1	Slightly better	3
0	Equal	
–1	Slightly worse	
–2	Much worse	

beam is much narrower than a footing, and the effect of the reduced strength and stiffness on the connection has not been determined. The effect of different member surface roughnesses on required embedment, bond, and connection performance should be explored. Also, models and design equations for transfer of forces in the joint region are needed, including the required embedment of column and required footing depth.

Additional experimental and analytical efforts are necessary to develop design equations for CFST columns and foundation connections. Areas that need to be addressed are the ratio of diameter (*D*) to thickness (*t*) of the tube (*D*/*t* ratio), steel strength, and models for the transfer of forces in the joint. Those models are likely to be different from the ones for precast columns because CFSTs are typically embedded to a smaller depth and are anchored by means of a flange on the bottom of the tube.

The monotonic loading tests of embedded CFFT connections are a good start to understanding the connection behavior. Additional research is necessary to determine the cyclic performance of embedded fiber-reinforced polymer (FRP) connections. However, CFSTs are not considered a good candidate for seismic zones because the cost is higher than steel and FRP tubes are more susceptible to impact damage, more difficult to repair, and non-ductile. CFFTs are most beneficial for corrosive environments, where steel tubes could suffer from corrosion.

Hybrid Connections

Description

Hybrid systems and connections contain an unbonded prestressing tendon and mild steel reinforcement or other energy-dissipating material in the plastic hinge region. The term "hybrid" denotes the use of two reinforcing materials, prestressing, and mild steel, where each provides a benefit for seismic performance, as described below. The joints between precast members open when the seismic moment becomes large enough, and essentially all the member displacement is accommodated by the concentrated rotation at the joint. The body of the member undergoes no plastic deformation and damage to the member is thus minimized. Furthermore, because the tendon is unbonded and able to elongate evenly along its full length, joint opening causes only a small increase in strain in the tendon, which therefore remains elastic. Consequently, the tendon provides an elastic restoring force to the system that minimizes residual drift after a seismic event. That system produces a nonlinear elastic response with no energy dissipation. When it is coupled with yielding reinforcing bars, which do dissipate energy, it leads to hysteresis loops that are "flag-shaped," as shown in Figure 13. Ideally, the hysteresis loop passes through the origin at each cycle thereby resulting in no displacement when the load is removed.

Some building structures have been constructed using the hybrid concept, but as yet no bridges. Examples of proposed systems and summaries of laboratory tests on these systems are given in Appendix E. In most cases, the column is post-tensioned, although pretensioned systems are being developed.

Performance and Time Savings Evaluation

Performance scores were assigned based on the foregoing discussion regarding construction risk, seismic performance, inspectability, and durability (see Table 23). The values should be taken as indicative rather than definitive

Table 22. Technology readiness level evaluation for socket connections.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	Description	0-25	25-50	50-75	75-100
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨	▨	▨	
3	Non-seismic deployment	▨	▨	▨	▨
4	Analyzed for seismic loading	▨	▨	▨	
5	Seismic testing of components	▨	▨	▨	
6	Seismic testing of subassemblies	▨	▨	▨	
7	Design and construction guidelines	▨	▨		
8	Deployment in seismic area	▨			
9	Adequate performance in earthquake				

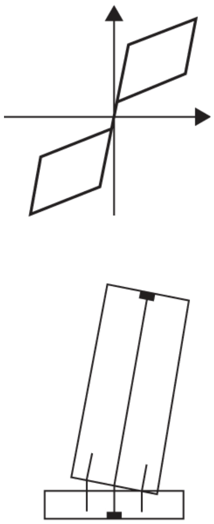


Figure 13. Hybrid connection—diagram and generalized hysteresis (Restrepo et al. 2011).

because of the many possible ways to implement a hybrid system. The construction risk is rated as less favorable than for a CIP system largely because of the additional site activities needed for post-tensioning and grouting. However, those are not necessary in a pretensioned system. The seismic performance is rated as potentially much better because of the reduced residual drift, and the consequently high probability of being able to use the structure directly after an earthquake. The durability and post-earthquake inspectability are slightly worse than CIP due to concerns about the post-tensioning tendons corroding and about verification of remaining post-tensioning force after an earthquake.

The time savings for hybrid connections was rated as 0 (equal to CIP) (see Table 24), due to the range of time savings estimated during the evaluations. As with the performance estimates, the expected time savings depend heavily on the details of the implementation. Use of precasting will reduce the time required, but post-tensioning will add to it, most likely resulting in a modest net gain. A pretensioned system, connected to both the foundation and cap beam using socket connections, would be expected to offer the same time savings as a non-prestressed socket system, a type of connection that represents the greatest time savings of all the systems considered.

Table 24. Time savings potential of hybrid connections.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	8
+1	Slightly better	3 4
0	Equal	1 5
–1	Slightly worse	6 7
–2	Much worse	2

Technology Readiness

The TRL evaluation is given in Table 25. Non-seismic field deployment is unlikely to occur because the unbonded tendon system offers no advantage there. The analysis for seismic loading, seismic testing of components and subassemblies, and the design guidelines all take into account the extensive work that has been conducted on the system for buildings, much of which concerns the basic hybrid concept, rather than the implementation in a particular structural type (bridges). This has not been done for the "deployment in seismic area" category because that depends on particular details of construction. However, it should be noted that a number of buildings, including the 39-story Paramount Building in San Francisco, California, (Englekirk 2002), have been constructed using the hybrid system.

Summary

Hybrid systems have been shown to have seismic performance that is potentially better than that of conventional construction because of the hybrid's re-centering properties. They have been used in buildings in high seismic zones in California, but have not yet been used for bridges. One hybrid building in Santiago went through the recent Chile earthquake with no damage (Stanton personal communication with Patricio Bonelli, the building's designer, October 26, 2010).

Use of the technology in bridges differs from that in buildings because the columns, rather than the beams, are prestressed. This is an advantage because, in building frames, the "beam elongation" associated with rocking of the beams

Table 23. Performance potential of hybrid connections.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better		5		
+1	Slightly better	4	1 2 3 6 7 8	8	
0	Equal	8		4	4 8
–1	Slightly worse	1 3 5 6 7	4	1 2 3 5 6 7	1 2 3 5 6 7
–2	Much worse	2			

Table 25. Technology readiness level evaluation of hybrid connections.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	**Description**	**0-25**	**25-50**	**50-75**	**75-100**
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨	▨	▨	
3	Non-seismic deployment				
4	Analyzed for seismic loading	▨	▨	▨	
5	Seismic testing of components	▨	▨	▨	
6	Seismic testing of subassemblies	▨	▨		
7	Design and construction guidelines	▨			
8	Deployment in seismic area				
9	Adequate performance in earthquake				

against the columns creates detailing problems in the floor system. In a bridge, the column elongates slightly as it rocks, and it may do so freely, without concern about its attachment to adjacent members, if the bridge is designed for this effect.

While the seismic performance benefits are not in doubt, connection details for bridges that allow good constructability and durability are still being developed. The primary concerns expressed by bridge engineers include the potential for higher cost to be weighed against the benefits of re-centering, the additional time on site needed for post-tensioning, corrosion of post-tensioning tendons, anchorage details, and ease of inspection and repair.

Further research is needed on connection detailing that will address the concerns of practicing bridge engineers. Engaging practitioners and contractors in such work would lead to benefits. The pretensioned system presently under development appears to hold particular promise because it effectively addresses many of the major practical concerns.

Integral Connections

Description

Integral connections form joints between bridge elements that provide no articulation and transfer moment across the connection interface. The most typical application of integral connections is the integral cap beam/diaphragm to girder connection for a steel/concrete composite bridge. Such connections have historically been constructed with CIP methods, but with ABC, these may use a steel or precast concrete stay-in-place formwork that is filled with reinforced concrete to integrate the bridge components in the joint area.

An example of a CIP integral cap beam that supports concrete girders with a lower stage cap beam is illustrated in Figure 14. The lower stage is constructed first then infilled to create the integral connection after the superstructure is erected. This provides longitudinal positive and negative moment continuity for seismic and other lateral loads. With ABC, the lower stage of the cap beam may be precast and set on the column using any of several connections described in previous sections. The erection of the girders and completion of the integral connection would proceed as with CIP techniques. The girders can be built with stay-in-place forms attached for the upper stage of the cap beam, or forms could be built on site. An example of a precast lower stage cap is shown in Figure 15 for the San Mateo (California) bridge project. This application used upper-stage forms that were built on site.

Integrating the columns directly into a combined cap beam/diaphragm, whose soffit is flush with the superstructure, allows for a shallower construction height of the assembly and provides for both positive and negative moment resistance in the longitudinal direction, with potential benefits to seismic performance. The stay-in-place formwork can be part of the

Figure 14. Two-stage cap beam with prestressed girders.

Figure 15. Integral precast lower stage cap with precast girders* (Restrepo, Matsumoto, and Tobolski 2011)*.

load-carrying system and can be equipped with dowels to integrate the structural formwork with the CIP concrete. A structural formwork can be designed robust enough to allow carrying construction loads to enable the erection of the superstructure to continue before the CIP concrete is cured. Typically, the stay-in-place formwork is already fully reinforced before erection. Alternatively, the stay-in-place formwork could be filled with fiber-reinforced concrete as the formwork provides confinement.

Integral connections must develop the joint shear force transfer mechanism that is required to "turn" the longitudinal girder moments into the column moments. In the confined space between girders and the column, adequate force transfer can be difficult to achieve.

Development of both positive and negative longitudinal bending capacities of the girders must be provided. Development of negative bending is usually simple because the deck slab provides space for reinforcement. Positive (tension on bottom) bending capacity is more difficult to provide. Strand may be extended from the bottoms of the girders and may be terminated with strand chucks or other positive anchorage devices. Older methods include bending the strand up into the cap beam, but this detail provides questionable anchorage. Alternatively, deformed bars may be extended from the girders and spliced, as shown in Figure 15. However, this requires that sufficient room in the girder lower flange exists for the bars. Often, this is not the case where straight strands have been used.

Longitudinal post-tensioning can be used to improve the transfer of forces, and the post-tensioning force can potentially be used to compress vertical shear interfaces, simplifying the fit-up of the girders to the cap for a flush-soffit arrangement. Restrepo et al. (2011) have investigated one such configuration for ABC methods as part of the *NCHRP Report 681*.

In the case of a composite steel and concrete bridge, the stay-in-place formwork may be steel and can provide flanges to which the steel girders can be bolted, as in Figure 16. Similarly, a stay-in-place formwork for concrete girders provides cut-outs through which the girders can be inserted and monolithically connected within the CIP concrete. The concrete column is integrated by either inserting the entire concrete column with exposed connection reinforcement into a bottom opening of the steel form or by only extending connection steel through the bottom steel form and providing dowels for shear transfer. This principle is illustrated in Figure 15, although the form there is precast concrete rather than steel. Examples of integral connections can be found in Appendix F.

This connection type can also be used in the following locations:

- Pile to pile cap
- Spread footing or pile cap to column

Performance and Time Savings Evaluation

The performance ratings of integral connections are provided in Table 26. The construction risk is seen generally as slightly lower than or equal to CIP connections because of the need to fit the girders to prefabricated cap beam elements. The seismic performance is seen as the same, because in both cases the connection should be designed as capacity protected and should respond elastically. Several connections not well-suited for seismic response scored poorly. Durability is, on average, the same, but is probably slightly better for precast concrete systems because of the higher quality control available in a plant and slightly worse for steel systems because of the risks of water intrusion. Inspectability can be slightly worse, but, in many cases, is equal to CIP. No damage should occur because of the expected elastic response but, if it does, detection of interior problems in a steel system would be very difficult because the steel formwork masks the concrete inside.

The time savings potential for integral connections is shown in Table 27. The high time savings potential is related to the use of precast cap beam elements or prefabricated steel sections. Both types can be filled with concrete after erection of the key components of the connection. The use of precast or prefabricated beam sections has the potential for excellent time savings because the construction of forms in the air and the time of curing for the cap beam concrete are removed from the schedule. However, depending on the scheme for erecting the cap beam, the time savings may be nil, particularly if shoring is required. For conventional girder bridge systems with either single- or multi-column bents, the use of

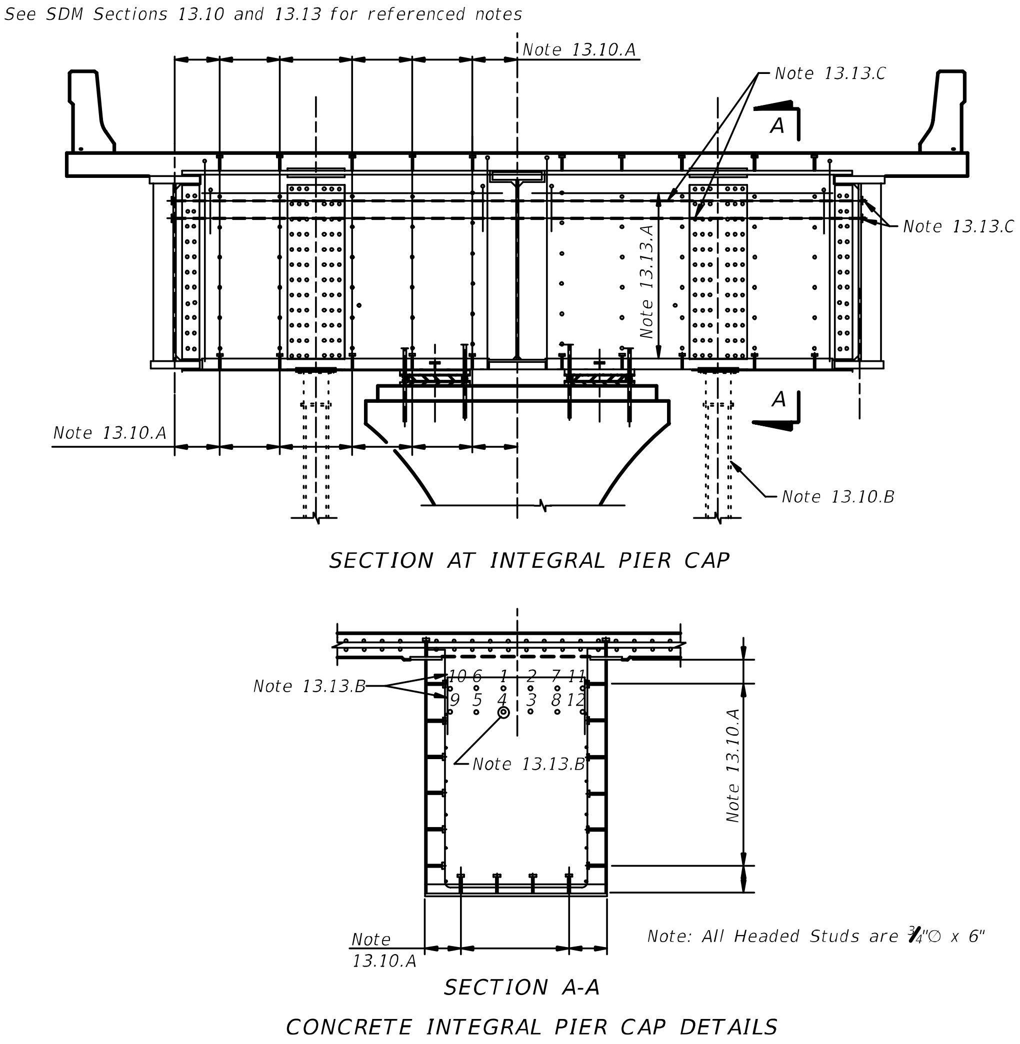


Figure 16. Example for an integral connection, a pier cap on bearings made as a steel/concrete composite (Florida DOT).

ABC techniques for the cap beam is the single most effective item in producing time savings.

Technology Readiness

The TRL and the completeness of development for integral connections are given in Table 28.

Summary

Integral connections represent a promising detail that for connections of columns, cap beam, and bridge superstructure provide a high TRL for seismic applications and have a significant history of construction experience. Among the individual connections investigated, three have been tested under seismic loading at a large scale (at least one-third of full

Table 26. Performance potential evaluation for integral connections.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better	5			
+1	Slightly better		3	3	
0	Equal	3 4 6 8 9	1 2 4 5 6 8 9 11	1 2 4 5 6 7 8 9 11	3 5 6 7 8 9 10 11
–1	Slightly worse	1 2 7 10 11	7	10	1 2 4
–2	Much worse		10		

Table 27. Time savings potential for integral connections.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	1 2 4 10
+1	Slightly better	7 8 9
0	Equal	3 5 6 11
–1	Slightly worse	
–2	Much worse	

scale). Limited design information is also available for the following connections:

- Integral connection of a steel superstructure with a steel/concrete composite cap beam and concrete pier per *NCHRP Report 527* (2004)
- Precast spliced-girder bridge with integral concrete column (Holombo et al. 1998)
- Integral connection of a steel superstructure with a post-tensioned concrete cap beam and concrete pier (Patty et al. 2001)

These connections were not specifically designed for ABC and would have to be re-detailed in that regard. However, their testing conclusions and design examples are applicable to ABC because the philosophy for seismic design would be to avoid damage within the integral cap beam.

Emerging Technologies

This section describes connections that use emerging materials and technologies in combination with prefabricated bridge elements. The category is intended to contain connection types that are at an early stage of development but offer promise, on the basis of some novel feature, if they can be developed further. Two connection types are included, as follows:

- Rotational Elastomeric Bearing
- Special Energy-Dissipating Bar Systems

Both have been proposed for use in the context of a hybrid connection. However, they are not evaluated in the hybrid section of the report because their behavior is expected to be characterized more by their special features than by the post-tensioning. Because they differ significantly, they are described and evaluated separately here.

Rotational Elastomeric Bearing

Description. An elastomeric bearing can be used to provide a region of concentrated deformability at a structural joint. A possible use for such a connection might be to reduce the moment entering the foundation for a given column drift. The California DOT (Caltrans) already uses a moment-reducing detail that has the same goal, although it is achieved by forming a concrete hinge rather than an elastomeric one.

This connection type can be used in the following locations:

- Foundation to column
- Column to cap beam

An example is shown in Appendix G, where the connection is shown as a footing to column connection. This connection is illustrated here in Figure 17 and Figure 18. Figure 19 shows photographs of the test specimen during construction.

A steel reinforced elastomeric bearing assembly is cast into both the top of a footing and a short segment of column above. Precast column segments complete the column above, with no mild steel reinforcement to connect the segments.

Table 28. Technology readiness level evaluation for integral connections.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	Description	0-25	25-50	50-75	75-100
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨			
3	Non-seismic deployment	▨	▨	▨	▨
4	Analyzed for seismic loading	▨	▨		
5	Seismic testing of components	▨			
6	Seismic testing of subassemblies	▨	▨		
7	Design and construction guidelines	▨	▨		
8	Deployment in seismic area	▨	▨	▨	
9	Adequate performance in earthquake				

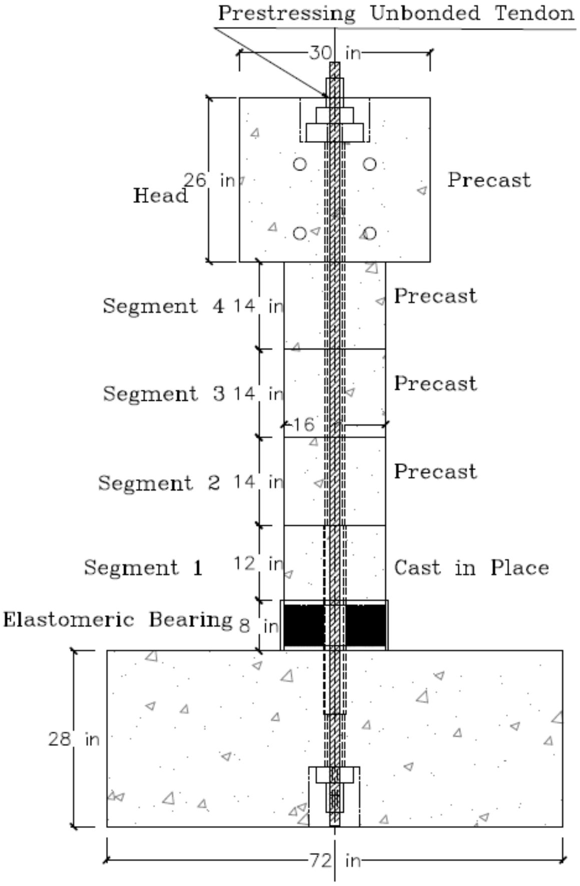


Figure 17. Rotational elastomeric bearing connection test specimen (Motaref et al. 2010).

Studs welded to the outer plates of the bearing connect the assembly to the adjacent concrete. Longitudinal bars are cast into the footing and extend through holes in the bearing into the first cast-in-place column segment above the bearing. The whole column is post-tensioned vertically by an unbonded post-tensioned bar anchored at the footing and cap beam. Shear deformation of the bearing is restrained by a steel pipe around the post-tensioned bar at the center of the bearing.

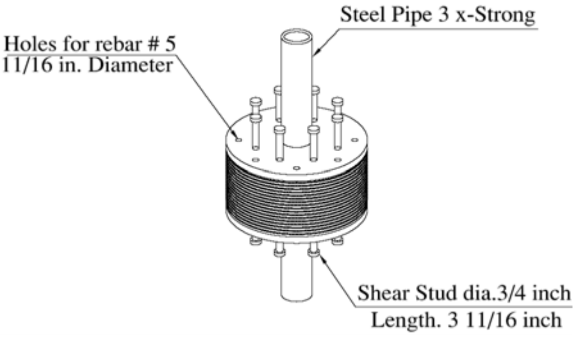


Figure 18. Rotational elastomeric bearing (Motaref et al. 2010).

Figure 19. Elastomeric bearing energy-dissipating bars at column base (Motaref et al. 2010).

Performance and time savings evaluation. This connection, identified as connection 1, is given a –2 for construction risk due to the complexity of embedding a prefabricated element in the footing and for the additional complexity of the construction of the bearing element and assembly (see Table 29). It is likely that the construction risk would be lowered (and the score would be higher) if such construction were to become commonplace. The seismic performance is given a +2, because the displacement capacity of this connection type is outstanding relative to other considered connections. The durability of the connection is given a –1 due to the incorporated joints between the concrete and the elastomeric bearing. Such a joint can permit deleterious materials to intrude, leading to corrosion problems.

The times savings rating for this elastomeric bearing connection is given a –2 due to the complexity of construction and the fact that the assembly must be cast into the foundation (see Table 30). This could cause alignment problems if the placement of the lower segment is not controlled very carefully.

Technology readiness. The TRL and the completeness of development for the elastomeric bearing connection is shown

Table 29. Performance potential evaluation for emerging technology connections.

Performance Potential	Definition Relative to CIP	Construction Risk Value	Seismic Performance Value	Durability Value	Inspectability Value
+2	Much better		1		
+1	Slightly better		2		
0	Equal				
–1	Slightly worse			1 2	1 2
–2	Much worse	1 2			

Table 30. Time savings potential for elastomeric bearing connections.

Time Savings Potential	Definition Relative to CIP	Value
+2	Much better	
+1	Slightly better	
0	Equal	
–1	Slightly worse	
–2	Much worse	1 2

in Table 31. The concept of installing an elastomeric bearing to provide local rotational flexibility has been developed and initial, proof-of-concept, testing has been conducted. The system has not been deployed in the field, for either non-seismic or seismic applications. Many details require further development, particularly with regard to constructability. It is also important to consider the system aspects of such a connection. For example, it is unlikely that it would be a suitable choice for a single-column bent or other statically determinate structure.

Special Energy-Dissipating Bar Systems

Description. Nickel-titanium alloy bars have been explored for use in earthquake engineering applications. This and other SMAs have the unusual properties of superelasticity (stress-related) and shape memory (temperature-related). Both of these behaviors are related to phase transformations of the material between austenite and martensite. A superelastic material can undergo very large inelastic strains and recover them after the removal of the applied stress. The superelastic behavior shown in Figure 20 is described in Youssef et al. (2008). Structural engineering researchers are interested in leveraging the superelastic properties of SMA bars to create low residual drift lateral systems.

One example of these connections is shown in Appendix G. The details are not fully represented and the construction procedure is not described by the researchers, but an attempt has been made to describe a possible method of assembly. The connection is part of a hybrid system that uses unbonded SMA bars for energy dissipation and unbonded post-tensioning strands for re-centering. The column consists of precast concrete segments with clamped steel plates at the joint to prevent joint opening. Threaded studs and a post-tensioned tendon anchorage are cast into a concrete footing. Unbonded SMA bars are screwed into the threaded studs and extend to the height of the first column segment. The first column segment is placed over the SMA bars. The top of each SMA bar is secured to the top of the first concrete segment or clamped to steel plates with a nut.

Table 31. Technology readiness level evaluation for elastomeric bearing connections.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	Description	0-25	25-50	50-75	75-100
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨			
3	Non-seismic deployment				
4	Analyzed for seismic loading	▨	▨		
5	Seismic testing of components	▨	▨		
6	Seismic testing of subassemblies	▨	▨		
7	Design and construction guidelines				
8	Deployment in seismic area				
9	Adequate performance in earthquake				

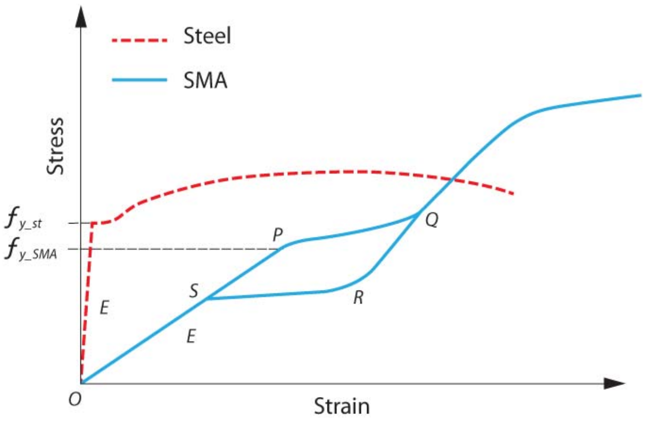


Figure 20. Stress-strain behavior of SMA and steel.

Performance and time savings evaluation. At this point in their development, SMA bars have worse performance and take more construction time than conventional CIP construction with mild steel. From the seismic performance perspective, the material behavior is very attractive: energy dissipation with minimal residual strains, high strain capacity, high corrosion resistance, and good low and high cycle fatigue properties. However, the difficulties with constructability, the high material cost, and the additional time required to splice SMA bars suggest that the technology is not ready for use in ABC. The scores for this connection type are shown in Table 29 and Table 30 as connection 2.

Technology readiness. SMA bars are a relatively new technology in structural engineering. Only a handful of studies and tests have examined the material's advantages and disadvantages for use in lateral force resisting systems. SMA bars have not been experimentally tested for use in precast bridge elements. Experimental testing of a constructible SMA connection detail with prefabricated bridge substructure elements needs to be completed before considering SMA technology for use in ABC. TRL values are given in Table 32.

Self-Propelled Modular Transporters

SPMTs are computer-controlled platform vehicles that can move prefabricated bridge superstructures weighing up to several thousand tons with precision to within a fraction of an inch. They consist of a load-bearing platform with many pairs of steered wheels, each pair with its own hydraulic jack. The platform may be raised or lowered as necessary to follow a certain travel path. This technology is used to lift and transport existing bridge superstructures from bridges requiring replacement. The technology can also be used to transport new bridge superstructures from temporary substructures at a bridge staging area along a designated travel path to be placed in the final bridge position, minimizing road closure time (Figure 21). SPMTs provide large amounts of flexibility, can move loads in multiple directions with a high degree of accuracy, all within a span of hours rather than months required by conventional bridge construction methods.

The Utah DOT used SPMTs for their "Innovate 80" project to replace 13 bridge structures. UDOT is endeavoring to make ABC the standard for bridge construction, so SPMTs are being employed to assist in accomplishing that goal. See the UDOT website for the *ABC SPMT Process Manual and Design Guide* (2009a) for more information regarding engineering and construction using SPMTs.

When SPMTs are used for rapid installation of bridge replacement projects, the traveling public experiences fewer hours interrupted by construction and spends less time in work zones. In addition, workers have less exposure to traffic hazards. Typically bridges requiring transport using SPMTs are simply supported beam and slab spans. Constructing the entire bridge superstructure away from the bridge site can allow longer cure times prior to loading for all concrete com-

Table 32. Technology readiness level evaluation for emerging technologies.

Technology Readiness Level (TRL)		% of Development Complete			
TRL	**Description**	**0-25**	**25-50**	**50-75**	**75-100**
1	Concept exists	▨	▨	▨	▨
2	Static strength predictable	▨			
3	Non-seismic deployment				
4	Analyzed for seismic loading	▨			
5	Seismic testing of components	▨			
6	Seismic testing of subassemblies	▨	▨		
7	Design and construction guidelines				
8	Deployment in seismic area				
9	Adequate performance in earthquake				

Figure 21. Prefabricated superstructure installed using SPMTs (Utah DOT).

ponents (because these are no longer on the critical path). Other advantages of SPMTs include better control by the contractor over the environment at the work site, lower life-cycle costs, and public favor for fewer disruptions to traffic. Constructing the entire span in a controlled environment adds benefits of reduced maintenance and improved quality. The technology should be considered for all bridge replacement projects where reduced onsite construction time is a priority and a nearby space is available for constructing the bridge.

The SPMT process requires considerable coordination between the engineer of record, the contractor, a heavy lift contractor, and multiple disciplines, including traffic control, roadway and geotechnical engineering, as well as utilities and right of way.

SPMTs are versatile devices that can be used to transport either a complete bridge or parts of one, depending on which approach is the most efficient and what equipment is available. For example, the interior bridge piers and end abutments can be constructed at the final bridge site, without blocking traffic, while the superstructure is constructed off site at the bridge staging area and brought in on SPMTs when the supporting structure is ready.

Seismic isolation techniques can be integrated fairly simply with bridges where the entire superstructure is moved into place. Isolation bearings may be used to support the superstructure, thereby providing a place to attach the superstructure, although connections that are appropriate to the ABC construction would need to be developed for each application.

SPMTs provide additional means for handling large weights of precast and/or preassembled bridge elements. This advantage has great potential for SABC because seismic connectivity requirements lead to larger and heavier elements. For more information regarding SPMTs, refer to the FHWA *Manual on Use of Self-Propelled Modular Transporters to Remove and Replace Bridges* (2007).

Note that simpler means than SPMTs can be used to transport whole spans where space and conditions permit. These include sliding, skidding, launching, and crane placement. Such schemes have been used in a number of applications, including bridges in Utah, Washington State, and California. These approaches work best with a partnering arrangement between the designer and contractor to ensure that the system is designed to handle the erection stresses and deformations. The same design considerations apply for SPMT use (Park 2011, Khaleghi 2011).

Time Savings

The distinguishing characteristic of the bridge bent systems considered in this study is speed of construction, so some way of measuring it was necessary to evaluate the systems. Because of the wide variety of systems reviewed, a sophisticated method for evaluating the required construction time was deemed impractical. The method chosen is described in Chapter 2, and consisted of comparing the construction time of the precast system with that needed for a conventional CIP system. A mini-workshop was arranged to obtain estimates of construction time from professional design and construction personnel.

As the project developed, it became clear that most of the connection technologies could be applied in several locations within the bridge. Thus, the decision was made to base the evaluations of performance, TRL, and so forth on connection technology rather than on connection location.

A test bed structure was needed to make comparisons between the connection technologies. For that purpose, a bridge bent was selected that had dimensions typical of a freeway overpass in Washington State. The bent is shown in Figure 22. The results of the time savings workshop are presented in Appendix H.

The major conclusions from the time savings study are as follows:

- The required curing time before construction may progress has an important influence on the total construction time.
- In the precast systems, the majority of the time savings arises from precasting the cap beam, leading to 9 to 10 days savings for bar coupler, grouted duct, and socket-type connections used to facilitate the placement of a cap beam. Pocket-type connections saved about half that time due to the curing time of concrete in the pocket.
- Precast columns provide significant time savings only under special circumstances, such as a bridge with a large number of columns.

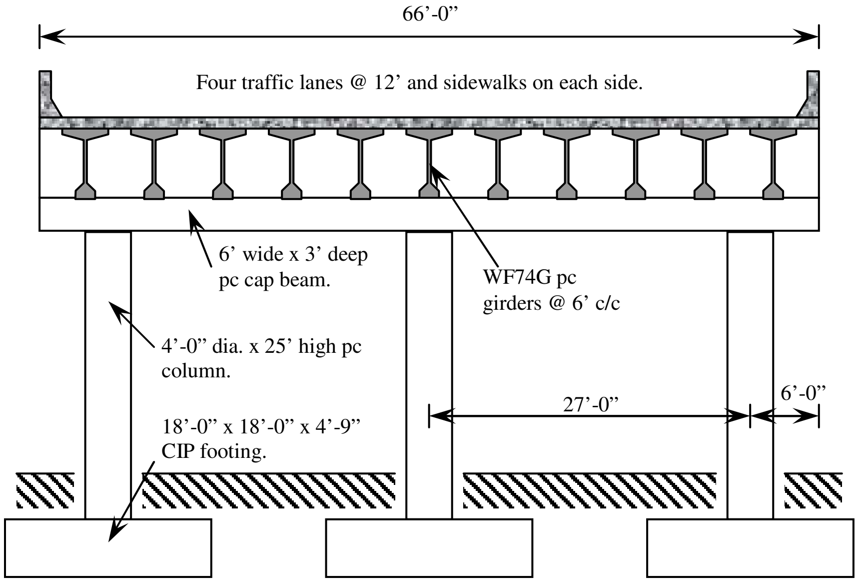


Figure 22. Bridge bent considered for time savings evaluation.

- Most precast connection types have the potential to reduce bridge bent construction time by 50% relative to CIP, although pocket connections only provided about a 25% time savings.

The discussion at the workshop on time requirements showed that the potential time savings were more closely related to the characteristics of the bridge bent system as a whole rather than to any particular connection technology. In particular, the choice of precasting the cap beam rather than casting it in place made the dominant contribution to time savings.

Evaluation of ABC Bent and Bridge Systems

The connections summarized above each may be used to construct a bridge system. Overall the bridge system includes superstructure, deck, piers or bents, foundations, and abutments. Almost any of the bridge elements may be made up of precast or steel members connected with various forms of connection technologies. These are called Prefabricated Bridge Elements and Systems (PBES). Not all the connections used to connect such elements require the same ability to tolerate inelastic deformations in moderate or high seismic zones, and accordingly connection types have been categorized as energy-dissipating, capacity-protected, or deformation elements. The connections requiring the most rigorous seismic testing and the most thorough understanding of their behavior are the energy-dissipating and deformation elements connections. These connections typically occur in the substructure at pier locations. Thus, pier or bent systems are a primary focus for seismic use of ABC.

Seismic Design

A key point to understanding ABC in seismic regions is that it is essential that the designer understand and control the seismic design to ensure appropriate seismic behavior. This statement applies even more to ABC than it does to the more conventional construction types, because the seismic bridge design codes for conventional construction are set up to ensure appropriate behavior, even if the designer does not fully understand how all the provisions actually work. Such is not the case with ABC, in part because the connection technologies vary widely and because specifications for design of such systems have not progressed to the same point as for conventional bridges.

As has been pointed out several times, energy-dissipating and deformation elements connections must be able to endure multiple inelastic or large deformation cycles without losing their integrity. In contrast, capacity-protected connections only need to be capable of developing adequate elastic resistance, although such resistance is required under cyclic loading. This classification tool then is useful for focusing the designer's attention on the elements and connections that require the most attention in seismic design.

Bent Systems

The approach for considering ABC in seismic regions has been one using "building blocks" of connection types. To a great extent, systems (for example, pier or bent systems) can be constructed using one or more of the connection types previously reviewed. Ultimately, different DOTs or regions of the country might prefer different connection technologies for any of a number of reasons. It is certainly clear that different bridge construction technologies have been adopted for reasons of regional preference, success with systems, or other reasons. For instance, precast, prestressed girder bridges are often preferred in the Pacific Northwest while other types, such as steel girder bridges or CIP concrete boxes, may dominate the market in other states, each being considered the most cost-effective in its own region. A typical prestressed girder bridge is shown in Figure 23. In this bridge, only the girders are precast; however, research sponsored by the Highways for LIFE program is under way to produce a precast bent system for these bridges that can be used in high seismic regions.

As ABC technologies develop, it would be expected that regional preferences might still prevail. This trend can be seen in the emergence of several ABC bent technologies that have been conceived or even deployed to date. For example, the Utah DOT has probably constructed more full ABC bridges in seismic zones than any other agency. An example of one of the bents used along the Interstate-15 corridor near Salt Lake City is shown in Figure 24, where precast columns are connected to foundations and cap beams using grout-filled bar couplers (splice sleeves). Other types of PBES substructure systems or elements are shown below.

Figure 24 illustrates a bent system constructed using grouted splice bar couplers between the base of the column and footing and between the top of the column and cap beam (Culmo 2009). Such connections have been widely used in the non-seismic applications of ABC, but as indicated in the bar coupler summaries, such connections may require special constraints for use in seismic regions.

Figure 25 illustrates the construction of two column pile bents where steel pipe piles passed through sockets formed by corrugated metal pipe similar to that used for the “pocket connections” described previously. The pipes had steel rings

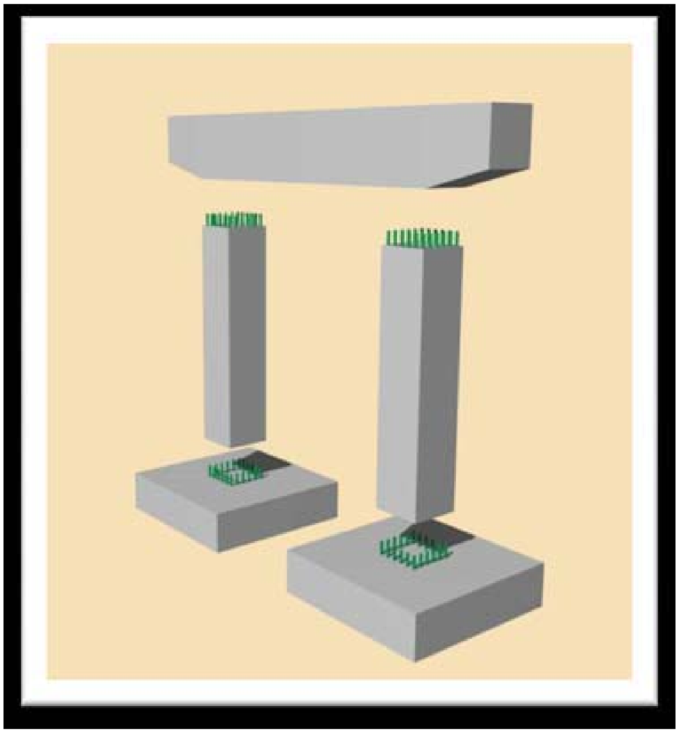


Figure 24. Utah DOT bridge bent system (Culmo 2009).

Figure 23. Typical precast, prestressed girder bridge in Washington State.

Figure 25. Steel pipe pile bent with socket connections (BergerABAM).

welded to them to create roughness that would improve vertical shear transfer, then the precast cap was lowered over the pipe piles and the annular space was grouted to form a full socket connection. The tops of the piles extended into the upper stage cap. Only the lower stage, as shown in the photo, was precast. Pile or trestle bents are common construction types used in many parts of the United States, and this marine application illustrates a viable configuration for use in seismic zones. The use of precast piling is also prevalent in pile bent construction, and marine applications of grouted duct connections to cap beams can be adapted for ABC use in land-based environments as well.

Figure 26 illustrates another form of making the pier to superstructure connection using a precast pier segment of a spliced girder bridge. The bridge pictured used a CIP lower stage cap beam; however, a precast cap could have been made to work in this application. The longitudinal force transfer is made via interface shear/torsion similar to connection IC-9 of Appendix F.

Figure 27 illustrates the concept under development in Washington State to develop PBES bent systems for ABC use in high seismic regions. This project is supported by the FHWA's Highways for LIFE Technology Transfer Program and a demonstration project is currently under contract to construct this system. Precast columns along with precast lower-stage cap beams are used in this project, thus, making use of grouted duct, member socket, and integral connection types. The demonstration project also uses precast, prestressed decked-bulb tees as superstructure. These will be delivered to the site with "ears" at the ends to form stay-in-place forms for the upper stage of the CIP diaphragm. The objective is to use as many precast elements as is reasonable.

The examples described above serve to illustrate the range of ABC connections and PBES that have been used previously in bridge bent construction. Much of the research work to date has focused on this type of bent system. PBES elements have also been constructed in the field, and the experience serves to provide data on constructability, durability, and time savings. Often the use of precast elements arises out of value engineering or contractor-proposed alternatives. A side benefit of such proposals is that, when a contractor chooses to use ABC technologies, the problems of tolerances and complex erection procedures can largely disappear, because the contractor "owns" the tight tolerances and can develop a casting and erection procedure that will work well. For low-bid work conditions, this may not be so positive. Much depends on the contractor's attitude and willingness to work with unusual substructure configurations or connections, and much depends on the spirit of collaboration between the contractor, engineer, and owner.

Figure 26. Spliced girder bridge with precast pier segment (BergerABAM).

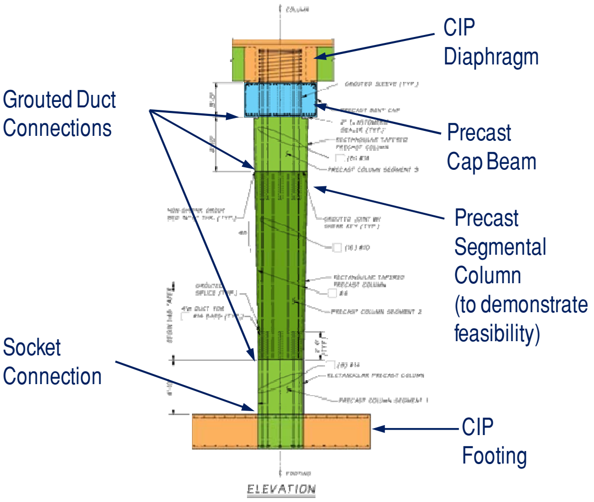


Figure 27. Highways for LIFE precast bent for seismic regions.

As described in the Time Savings section, the time savings expected for a bent system may not be directly attributable to a certain type of connection, but rather to the elements that are used. For example, it has been demonstrated that more time is saved by precasting the cap beams than by precasting columns, even if the connections at the base and top of the columns are the same. This illustrates a point that time savings are primarily a system attribute and not a connection attribute. This also means that savings may be bridge- or job-dependent.

Other bent systems have been proposed that make use of ABC technologies. For example, the hybrid systems, containing either a basic combination of prestressed and deformed bar steel, or more elaborate systems that provide further enhanced performance, were discussed earlier in this chapter and in the appendices. Such systems have been developed to the same point as the bent systems using the individual connection technologies. The hybrid systems are just that, a system for the entire bent, rather than a single connection. Various versions of hybrid systems have the potential for providing significantly enhanced seismic performance, as well as potentially providing benefits for ABC. However, the two attributes may not always go together. Some systems may be more complex and take longer to construct than ABC systems optimized just to save construction time. Additionally, the hybrid systems are more appropriate for high seismic zones than for the lower to moderate zones. In a high seismic zone, the additional performance may be judged worthwhile despite possibly higher costs or construction times longer than those for the basic ABC bent systems.

One system that has been considered by MCEER (Aref 2010) that could potentially have use in lower seismic regions is a pier that uses isolation bearings between the superstructure and substructure with precast column segments stacked without reinforcement between the segments. This type of system has features in common with the use of isolation to protect older masonry piers. A high confidence in the response of the system would need to be developed, through analytical and shake table testing, before such a system could be deployed.

In summary, the non-prestressed bent systems have, in general, progressed to a more complete development than the hybrid systems. Design specifications have been developed for some connection systems and are under development for others. Field experience with construction of the basic connection systems also provides a higher comfort level both for constructability and durability of the basic connection systems. While hybrid systems and some of the emerging technologies may ultimately provide greater seismic performance, they are not currently at the same level of development as are the more basic systems, particularly with respect to their implementation details and their ease of construction.

Bridge Systems

At the full bridge level, many of the connections that can be used to produce a complete bridge system are capacity-protected type connections, and therefore, if reliable methods can be developed for predicting their cyclic first-yield strength, they may be deployed. Examples of such connections are precast deck panel connections, internal diaphragm connections, connections used to assemble abutments from smaller pieces, and connections for attaching barriers.

Connections that are still very much capacity-protected types but are adjacent to energy-dissipating regions, such as the integral class of connections summarized, represent a bit more complexity. Due to the proximity of the energy-dissipating regions and the local force-distribution attributes of these connections, more scrutiny of these connections is required. This is evident from the work that has been ongoing over the last 10 years to quantify the efficacy of integral connections. Such work includes consideration of both deformed bar and post-tensioning force transfer mechanisms from columns into the superstructure. To some extent, the work underway on integral connections seeks to fill in gaps in knowledge that may exist for non-ABC or partial-ABC applications, for example, precast girder superstructures with CIP substructure. Nonetheless, quantification of performance levels for integral connections is, and will continue to be, an important area of research for ABC in seismic regions.

An interesting emerging area of full bridge response that shows some promise is the use of the flexibility of partial opening of segmental or splice-girder superstructures under lateral loading (Aref 2009). When coupled with a hybrid-type substructure, such response, which provides deformability more than energy dissipation, may provide a viable seismic earthquake-resisting system in the future.

Seismic isolation systems may also be used to facilitate ABC in bridge systems. Such systems may be particularly useful where large subassemblages of superstructure can be built and moved into place using such methods as the SMPTs. Isolation bearings could be used both to reduce the seismic demands that the bridge would experience in a design earthquake and to provide an interface between the substructure and superstructure that would permit rapid erection. The reduced inertial force demands inherent in isolation systems could permit lighter connections between PBES, thereby simplifying design and potentially reducing costs. The associated improvements in seismic performance would also be a benefit of using isolation systems. While not discussed in detail in this report, seismic isolation is another tool or building block that can be used with ABC construction.

Shear keys for abutments represent another location in a bridge system that may not be entirely rationalized with capacity-protected connections alone. Fusible shear keys are used by Caltrans and represent a rational means to limit internal seismic forces in superstructures. Often shear keys at abutments are designed to be very strong such that they perform elastically under the design earthquake. Such behavior may be acceptable in the design event, provided that all induced forces can be handled. But, there is no fusing mechanism to limit and control forces. Thus, adding fusible shear keys does provide a force-limiting feature that can be beneficial for bridge performance. The fusible shear keys developed for Caltrans by University of California, San Diego (Megally et al. 2002, Bozorgzadeh et al. 2007) could be used in combination with PBES abutment elements.

Identification of Knowledge Gaps and Research Priorities for Connections for Seismic Performance

Introduction

Two of the primary goals of the study were to identify gaps in validation of the findings in the properties of each ABC system and to rank them in such a way as to facilitate selection for funding future research. The evaluations of connections were organized primarily according to the operational principle, rather than to the location of the connection, because it was found that many of the technologies could be used in several places in the bridge. Hence, a "building blocks" approach would be the most effective way of covering the range of possible ABC developments. For the same reasons, the identification of knowledge gaps and the ranking of the relative status of the connections considered are presented here using the same organizational structure. Prior to addressing each connection group, certain overarching observations are made.

First, it is emphasized that the most important feature of each technology under evaluation should be its contribution to speed of construction. Thus, a system with seismic performance that is, or has the potential to be, better than that of conventional seismic designs was not considered unless it offered the possibility of accelerating construction. Furthermore, performance (i.e., seismic performance, durability, etc.) was judged according to whether it was good enough. No more was required. By contrast, the speed of construction was judged against an unlimited scale. This approach was adopted because it reflected the focus of the project, and because many other research programs have the goal of improving the other characteristics, such as seismic resistance.

Second, connections that have the potential to be used in the context of energy dissipation or deformability were viewed more favorably than those that would have to be restricted to capacity-protected roles. This was done because such connections are more versatile and offer more possibilities for use in the building blocks approach. One of the findings of the study was that large variations exist in approaches to design and construction, both due to regional differences in construction culture and to variations among contractors' preferences within a region. Consequently, provision of a range of versatile technologies would allow the designer and contractor the greatest freedom in selecting the system best suited to the circumstances. It should be noted that any connection that will perform well in an energy-dissipating context will also perform well in a capacity-protected one; capacity-protected elements are a subset of energy-dissipating elements in which the ductility demands are low.

Third, some construction approaches, such as use of SPMTs, do not fit well into this building blocks approach. They clearly offer huge advantages in terms of site erection time, but they are also subject to certain restrictions, such as the need for space close to the site for prefabrication of the structure. They are highly project-specific and, thus, considered separately.

Fourth, some time advantages were found that accrue to the system, rather than the local connection technology. The most important finding was that the greatest potential for time savings in the construction of a bridge bent is generally associated with precasting the cap beam. This was found to be true almost regardless of the nature of the individual connections used because of the time needed in a CIP system to erect shoring, formwork, and a reinforcing cage, and then to wait for the concrete to gain strength before girders could be set. Precasting the columns can offer significant advantages, primarily when some special circumstances exist or when the local building culture has embraced the technology and contractors are comfortable with it. In the cases where special circumstances prevailed, it was noteworthy that the option of precasting the columns was proposed by the contractor, who had detected a schedule advantage in so doing.

Bar Coupler Connection Systems

Bar coupling systems permit adjacent elements to be joined by connecting the reinforcing bars to create a continuous load path. The role of the couplers is typically to transfer tension forces, because the compression component of a coupler can readily be transferred by concrete-to-concrete bearing. Therefore, bar couplers function in much the same way as a welded butt splice between two bars, but they are faster to complete and avoid the material disadvantages of welding, such as loss of ductility. Bar couplers can be further subdivided into "hard" and "soft" couplers; in the former, the bars are joined using steel threads or locking devices, whereas the latter use a grouted sleeve to transfer the tension force. The sleeves are more forgiving of slight misalignment of the bars, but are typically more bulky, heavier, and create a relatively rigid region along the tension load path.

Bar couplers are quite widely used already, largely because of their convenience and the fact that they open the door to precasting.

The major finding with respect to bar couplers is the paucity of comprehensive test data available to support their use in high seismic zones. It contrasts with their relatively widespread deployment in the field. For example, grouted splice sleeves have been adopted for wide use in Utah, but only one study, conducted in Japan in the 1970s, could be found that addressed inelastic cyclic loading of a connection that contained sleeves. (Other studies were found in which the sleeves had been tested, but they typically contained only a small number of tests and were used to compare various technologies rather than focusing on splice sleeves).

Both the AASHTO LRFD design specifications and ACI 318-08 contain requirements for mechanical splices, but they address only strength. Acceptance is based on a static test criterion.

Comprehensive test data is urgently needed for these couplers. Some of the questions or needs that should be addressed are as follows. These are organized in terms of priority—ranked from 1 to 3—as shown.

Priority 1—Fundamental to Successful Seismic Application

Cyclic performance. Is the performance of the coupler satisfactory under cyclic loading with bar stresses in the inelastic range?

Cyclic strain concentrations within the coupler. Does the coupler cause strain concentrations at hard contact points that could lead to low-cycle fatigue? Again, this question applies most readily to hard coupling systems.

Buckling. Do certain types of couplers promote bar buckling by virtue of the discontinuity in the bar? This is more likely to affect hard couplers versus grouted couplers and may be sensitive to how well the coupler is tightened. It is worth noting that bar buckling is an important milestone on the road to bar failure by tension fracture, so premature buckling would be a serious shortcoming.

Strain distribution in the bar. Does the presence of a coupler adversely affect the distribution of strain along the bar by creating strain concentrations? This question applies most urgently to grouted sleeve couplers because they are large and rigid and, consequently, force the inelastic deformations into the regions of the bar outside the coupler. For example, if a coupler is placed in the bottom of a precast column, the moment gradient in the column may be such that the bar does not yield in the column above the coupler. Little inelastic deformation may occur in the coupler region, so most of the necessary deformation must occur in the footing. However, the footing is typically bulky and, therefore, confines the bar well, leading to a short anchorage length and potentially high strains. This is a deformation problem, but attention has mostly been focused on strength of bar couplers. Related questions include the selection of bar size. Small bars have shorter anchorage lengths and, if the system deformation is concentrated at a single crack, small bars are likely to suffer higher strain concentrations than big bars. This exacerbates the strain concentration effect of the coupler. What limits, if any, should be applied? Should such bars be locally debonded to reduce the strain concentrations?

Priority 2—Highly Desirable Refinement for Seismic Use

Strength details. Can the coupler develop the full strength of any bar that may legally be used with it? For example, AASHTO requires that a mechanical splice develop 125% of the specified yield strength of the bar. An ASTM A706 bar has a specified (minimum) yield strength of 60 ksi, but f_y may legally be as much as 78 ksi. Thus, the strength of the coupler may satisfy the formal requirement, but may, in fact, not even develop the yield strength, much less the ultimate strength of the bar. In most bars, the tensile strength is at least 1.25 times the yield strength, in which case the real tensile strength of the bar could be 1.25* 78 ksi, or close to 100 ksi.

Location of splice. Should the coupler be placed in the column or the adjoining element (typically footing or cap beam)? Many arguments can be applied and should include consideration of both seismic performance (including deformation capacity) and ease and reliability of assembly. The seismic performance of connections using couplers that may alter the strain distribution over long lengths may also be more sensitive to coupler location (for example, grouted-sleeve couplers).

Priority 3—Further Refinement

Role of surrounding concrete. In one test series, a grouted sleeve fractured before the bar broke. The test was conducted in air. Does the concrete that normally surrounds the bar have a beneficial effect? If so, how much is the benefit, and should designers rely on it? This effect may only be relevant to grouted sleeve couplers, and not to the other types of bar couplers. However, due to the widespread use of grouted sleeve couplers by some owners, the impact of surrounding concrete on coupler efficacy should be clearly understood.

Other questions are also relevant, but are less amenable to solution through research. They involve such matters as the reliability with which a contractor will completely fill a grout sleeve, the ease with which a threaded coupler can be assembled and tightened even when the bars are not perfectly aligned, and so forth.

In addition to physical testing, work also needs to be done to develop formal guidelines for use of bar couplers and suitable specification language to regulate design of not only the coupler itself but also the connection region immediately surrounding it. Examples are included in the Required Design Specifications section that follows the individual connection knowledge gap summaries.

Grouted Duct Connection Systems

Grouted ducts share some characteristics with grouted splice sleeve bar couplers, but their use differs. A grouted duct is generally used to transfer tension force in a bar to the surrounding concrete, rather than to another collinear bar. For example, they have been considered for connecting bars projecting from a column to a cap beam, but they can be used anywhere in the structure.

In a grouted duct, the variety of available duct sizes allows the possibility of generous tolerances on bar location, provided that the space is available. Thus, they offer a versatile means of connecting bars to concrete.

More studies have been conducted on grouted ducts than on grouted splice sleeves, perhaps because splice sleeves are generally proprietary products. Thus, the behavior of grouted ducts is, in general, better understood. Several studies have demonstrated that the anchorage length of the bar in the ducts is much shorter than the development length required in concrete without a duct.

Further testing is desirable because several features of behavior are not yet fully understood. Examples include the following.

Priority 1—Fundamental to Successful Seismic Application

Transfer of force into the surrounding concrete and bars. What are the anchorage requirements for the duct in the concrete? In some tests, especially with groups of ducts, the duct pulled out of the concrete. What are the requirements for lap splicing bars to the outside of the duct, for example, in a column? How does the amount of concrete and/or spiral reinforcement surrounding the duct affect the seismic performance?

Priority 2—Highly Desirable Refinement for Seismic Use

Strain distribution. Does the presence of a grouted duct adversely affect the distribution of strain along the bar by creating strain concentrations? The questions are similar to those for grouted splice sleeves.

Shear strength of interface. Are shear keys required and what shape should they be? Should the grout contain fiber reinforcement to prevent loss of material from the joint after large cyclic forces are applied? What grout properties are best?

Priority 3—Further Refinement

Grout properties. Can the pullout strength of the bar be related to the cube strength of the grout alone or are other parameters, such as age, also important? This is important for determining when load can be placed on a grouted duct connection.

Eccentricity of the bar in the duct. Does bar eccentricity in the duct detract from the anchorage strength? A small sample of information is available, but a more comprehensive study is desirable.

Role of surrounding concrete. Does the mass or amount of surrounding concrete affect the efficacy of the grouted duct connection? Is a specific amount of confinement transverse steel required to ensure proper performance?

Shear strength of interface. Are keys required? How thick can the grout be? Should local/fiber reinforcement be used? What are the limits for grout material properties?

Design guidance and specification requirements are included in the Required Design Specifications section.

Pocket Connection Systems

Pocket details are likely to be restricted to connections between a column and precast cap beam because the geometry of the connection at a footing makes casting the pocket concrete difficult. However, precast cap beams are an important element in saving onsite construction time, so the connection is likely to be useful.

The cap beam should be as narrow as possible, to minimize its weight. However the presence of a pocket reduces the local bending and shear strength of the cap beam, so stresses during handling need to be checked on a case-by-case basis.

The major outstanding issues requiring testing are associated with the mechanics of force and moment transfer from the column to the cap beam. Specific questions include the following.

Priority—Fundamental to Successful Seismic Application

Pocket form material. What material, shape, and thickness of pocket form is required?

Joint shear. What is the mechanism of joint shear transfer, and how do the steel pocket former and the stirrups contribute to joint shear strength?

Priority 2—Highly Desirable Refinement for Seismic Use

Stirrups outside pocket. What are the shear strength requirements in the parts of the cap beam that lie on either side of the pocket? What stirrups or other reinforcement are needed outside the pocket?

Priority 3—Further Refinement

Bar size. Can large column bars (and, therefore, a small number of them) be used in a pocket connection? Does the pocket provide enough confinement that the anchorage length of such large column bars would be reduced substantially below the length required for unconfined bars cast directly in concrete? If reduced development or anchorage lengths are used, how does this relate to joint shear performance?

Design guidance and specification requirements are included in the Required Design Specifications section.

Member Socket Connection Systems

Member socket connections offer simplicity of construction and generous tolerances. They appear to be best suited for footing to column connections; tests on socket connections to spread footings have proved successful and connections to drilled shafts are in process. The simplest approach seems to be to cast the footing in place around the precast column. This approach is less likely to be used at the top of the column, because it would mean casting the cap beam in place. The socket connection has the added advantage that it provides a simple way of connecting a pretensioned column to the footing and cap beam. (In those tests, the column diameter was stepped down just below the cap beam to minimize the size of the opening).

The tests to date have established that the socket concept works. Further experimental research is needed to determine design details. Examples include the following.

Priority 1—Fundamental to Successful Seismic Application

Joint shear. What is the mechanism of force and moment transfer in the joint region?

Column surface roughness. What surface roughness is needed to transfer the vertical/gravity shear stresses across the interface?

Priority 2—Highly Desirable Refinement for Seismic Use

Use with drilled shafts. Can the detail be used to connect a column to a drilled shaft so the connection zone remains elastic?

Priority 3—Further Refinement

Element size ratio. What limits the ratio of column diameter to footing or cap beam depth?

Footing and cap beam transverse steel (ties). What are the tie requirements in the footing (and to a lesser extent, the cap beam)? Note that straight, headed, longitudinal column bars have been used to date in place of bars bent out into the footing.

Design guidance and specification requirements are included in the Required Design Specifications section.

Hybrid Connection Systems

Hybrid connections hold the promise of superior seismic performance, but are not inherently rapid to construct. Thus, it is their ABC features, rather than their seismic performance, that needs attention in the present context. Furthermore, while hybrid systems could be used in low-to-moderate seismic zones, they are unlikely to provide a significant advantage there because the displacements are small enough that nonprestressed systems already offer a modicum of re-centering.

In this report, attention was focused on solid hybrid columns suitable for a typical freeway overpass, on the basis that large hollow columns would be used for large structures with special features. Such columns would be feasible, but would require custom designs.

The tests conducted for bridge columns, as well as those previously conducted for the building industry, show that the hybrid concept works. However, further studies are needed to develop details that are readily and rapidly constructible. The primary impediments lie with the prestressing tendon. If it is post-tensioned, it constitutes an extra operation to be conducted on site, probably by a separate subcontractor. This inevitably slows down construction. It also raises questions about installing the anchorages, especially at the footing, and about corrosion protection. Although a number of tests have been conducted by several researchers, these matters have not yet been resolved. Possible solutions lie in using a U-shaped tendon, with two post-tensioning anchors at the top, or in pretensioning the tendon. Both designs solve the corrosion and the bottom anchorage questions. Pretensioning would also eliminate the need to post-tension on site.

Further experimental research is needed to develop appropriate design details. Examples include the following.

Priority 1—Fundamental to Successful Seismic Application

Corrosion protection. How can a post-tensioned system be protected against corrosion? Stainless steel, epoxy-coated, or greased and sheathed strand? Is corrosion really a problem?

Priority 2—Highly Desirable Refinement for Seismic Use

Anchorage details. Development is needed of constructible post-tensioning anchorage details, especially at the footing.

Anchorage slip-back. What procedures should be used to avoid loss of prestress through slip-back at the post-tensioning anchor? The tendon length might be on the order of 25 feet, in which case slip-back, which can be especially large with epoxy-coated strands, could lead to the loss of a substantial and somewhat variable proportion of the jacking stress. What details are best suited for past earthquake assessment of remaining post-tensioning force?

Priority 3—Further Refinement

Damage at the rocking interface. What details are needed to minimize crushing at the rocking interface?

Hybrid systems have force-displacement relationships that differ significantly from those of conventional, yielding, reinforced concrete systems. This is true for both bending and shear. Some modeling needs, therefore, exist in addition to the experimental ones outlined. The primary design and specification guidance that is needed is included in the Required Design Specifications section.

Integral Connection Systems

Integral systems represent whole bent cap systems rather than individual connections. Thus, any laboratory experiments are likely to be larger, more complex, and more expensive than those conducted for other connection types.

The primary needs are for improved understanding of the behavior under earthquake loading parallel to the longitudinal axis of the bridge, or longitudinal loading. Then, the end moments from the girders must be transferred to the cap beam, which carries them in torsion to the columns, where they are resisted by bending and shear. That complete load path needs to be studied, preferably in a test of a complete bent system. Several different bent cap systems are in use in different parts of the country (drop caps, flush caps, etc.) and each presents its own detailed questions in addition to the more global ones.

Further experimental research on integral connection systems should be undertaken to answer the following questions.

Priority 1—Fundamental to Successful Seismic Application

Positive moment capacity of precast, prestressed girders anchored to cap beams. What anchorage details of deformed bar and extended strand provide acceptable positive moment capacities?

Priority 2—Highly Desirable Refinement for Seismic Use

Joint shear. What joint shear geometry/requirements are necessary for two-stage cap beam construction? What are the analytical or effective limits of the joint? What strut-and-tie models are recommended for quantifying strength?

Anchorage requirements of column steel into two-stage cap beams. How are the column forces distributed to the joint area in the upper stage of a two-stage cap beam?

Priority 3—Further Refinement

Torsional stiffness and strength of two-stage cap beams. How are superstructure longitudinal moments transferred to the columns through the cap beam? What is the effective width of superstructure? What torsional steel requirements are necessary in addition to shear steel? Where interruptions in stirrups occur to permit girders to be placed, what details will provide adequate performance?

For the commonly used drop cap bents, the primary outstanding design guidance and specification requirements are included in the Required Design Specifications section.

Emerging Technology Connection Systems

The two systems classed as emerging technologies are both based on the hybrid concept, but they are not grouped with the other hybrid connections because they include an additional component. In one case, the column contains an elastomeric bearing that is intended to provide rotational flexibility and to reduce damage in the highly strained region. In the other, the mild steel energy-dissipating bars are replaced by SMA bars, which have special load-displacement properties that produce flag-shaped hysteresis loops. The development of these components is less advanced than for other connection types, so they are categorized separately. Both offer the possibility of superior seismic performance, but both would likely be slower to construct than a conventional CIP concrete system.

The elastomeric bearing system could be used at the bottom of the column to reduce the end moments, thereby reducing the size of the footing. However, that design requires the top connection to carry more moment if the design base shear is to remain unchanged. Placing a bearing at both top and bottom would likely lead to a long period and excessive drift. As shown in Appendix G, the bearing is built integrally into the column system and replacement would likely be difficult. Because the bearing is the critical element that accommodates most of the deformation, the ability to replace it would be desirable.

The hybrid system with SMA bars was not tested physically, but was studied analytically. Yet many of the problems with implementation of SMAs are practical ones: the material is expensive, not widely available, and hard to machine. Forming upset ends on the bars and then threading them is likely to be difficult. Aligning the threads on site with those on the bars embedded in the column and foundation might also be difficult and cost time. Furthermore, because the system contains a post-tensioning tendon, flag-shaped hysteresis loops can already be generated by combining the tendon with mild steel bars. Thus, the benefits of using the SMA are unclear.

In each case, considerable development would be necessary to bring a system to a buildable stage, particularly to meet the demands of ABC. The needed design guidance, at both the connection and system level, should be addressed through the requirements outlined in the next section.

Table 33. Design guidance required.

Design Guidance Required	Seismic Guide Specification Section	Bar Couplers	Grouted Ducts	Pocket Connections	Socket Connections	Hybrid Connections	Integral Connections	Emerging Technologies
Earthquake resisting element definitions	3	X	X	X	X	X	X	X
Restrictions on location in structure	3	X	X	X	X	X	X	X
Modification or confirmation of displacement capacity calculation methodology	4	X	X	X	X	X		X
Plastic hinge length guidance	4	X	X	X	X			
Ductility limits	4	X	X	X	X			
System-specific displacement capacity calculation methodology	4					X		X
Dynamic demand analysis methodology for 3-D structures	5					X		
Material property guidance for modeling	5, 8					X		X
Strut-and-tie modeling guidance for force transfer	5, 8			X	X			
Guidance for systems deforming biaxially, including skews and curves	5					X		X
Load distribution to girders	5						X	
Torsion modeling of cap beams	5						X	
Interface shear design for reinforced concrete columns, steel piles, and steel columns	7, 8	X	X	X	X	X		X
Guidance for development of moment-curvature relationship	8	X	X	X	X			X
Reinforcing bar and strand strain limits	8	X	X	X	X	X		X
Development length of bars in ducts, pockets, or sockets	8		X	X	X	X		
Lap splice requirements for adjacent bars transferring force to ducts	8		X					
Limitations on duct size relative to bar size	8		X					
Permissible materials and interface shape for pocket/socket forms	8			X	X			
Proportioning of pocket/socket form relative to adjacent member for force transfer and confinement	8			X	X			
Local detailing to avoid spalling near high force locations	8				X	X		X
Shear capacity protection design for hybrid columns	8					X		X
Post-tensioning or pre-tensioning guidance, including installation force and debonding lengths, if any (note that these have been worked out for buildings, but similar requirements need to be developed for bridges)	5, 8					X		X
Joint shear design requirements similar to those for T and knee joints	8			X	X	X	X	
Anchorage detailing for development of precast girder strength in longitudinal direction	8						X	
Torsional steel detailing for cap beams, both flush soffit and two-stage cap beams	8						X	

Required Design Specifications

For each of the connection types that have been summarized, design specifications need to be developed that address the specific performance, material, and configuration of the connection. Many of the required design specification provisions are similar to one another and, for that reason, the specification requirements are summarized in this section for all connections. This permits one to review the requirements for all connections at one time. The design specification requirements are focused on the AASHTO *Guide Specifications for LRFD Seismic Bridge Design* (2009) because this document, with its displacement design approach, has a framework that can support all the different connection types, including the hybrid connections and emerging technologies. The suggested design specification additions or modifications are listed in Table 33. These are listed in order of the specification section that requires modification.

Knowledge Gaps for Bridge Systems

There are several knowledge gaps that exist for bridge systems and they include, but are not limited to, the following:

- Adequate design and construction specifications for bent systems addressing:
  - Design of column bottom, top, and intermediate connections
  - Design of capacity-protected connections with superstructure elements

Laboratory testing will be necessary to fill these knowledge gaps. Suggested testing includes the following:

- Subassemblage test for flush-soffit integral connections with precast cap beams
- Subassemblage testing of commonly used integral connections with two-stage cap beams (dropped cap beams)
- Shake table concept validation testing of large-scale bent systems

Much experience remains to be gained before owners and engineers will be satisfied with the actual field performance of ABC bridge systems. Significant experience gaps that exist for bridge systems include the following:

- Durability experience for unbonded, post-tensioned, hybrid systems
- Durability of grouted bed joints for connections in energy-dissipating and hybrid regions, both environmentally and under cyclic loading
- Performance of systems in design level earthquakes
- Performance of systems in skew or curved bridges
- Demonstration projects for all types of ABC bridge systems in high seismic regions

These knowledge and experience gaps serve to identify the development activities that should be undertaken in the near future to advance the use of ABC in seismic regions. The development of all information that will be needed for use of ABC in seismic regions will likely take a number of years. To that end, the first priority should be to ensure deployment as soon as reasonably possible of those bent systems that are presently at the most advanced stage of development. This would be the easiest route to implementing ABC substructures in seismic regions and would also serve the greatest number of bridges. The second priority would be further development of those hybrid and emerging technology systems that have the potential for not only significantly enhancing seismic performance but also serving the ABC needs of the country.

CHAPTER 4

Conclusions and Suggested Research

This report has reviewed recent advancements in ABC techniques that are either being used currently or show promise for use in regions of the United States that are subject to moderate-to-high seismic hazards. ABC techniques have been applied on many projects, primarily in regions of low seismic activity. However, their use in moderate-to-high seismic regions of the country has been limited, because the conventional, linear, precast elements used with ABC cause the connections to be located at the intersections of framing elements, and those locations are typically the regions expected to experience the highest demands under earthquake loading. Accordingly, significant work is under way and more is needed to ensure that ABC connections can meet the required seismic performance, in addition to having the necessary non-seismic properties of constructability, cost effectiveness, durability, and inspectability.

Conclusions

The use of precast or prefabricated elements in bridges located in seismic areas can be characterized into two categories, energy-dissipating and capacity-protected, and this separation is useful in focusing the development of SABC. Bridge systems are designed such that the inelastic response that is unavoidably induced by the ground motion is concentrated in a few predetermined components. These components are typically the columns, which act like fuses. Other components are thereby protected from the heavy loading demands and do not need to be designed for the more rigorous conditions experienced by the columns. Many of the connections that were reviewed participate in the dissipation of earthquake-induced energy. These elements are termed energy dissipating and they significantly influence the overall seismic performance of the bridge. The components and connections of a bridge that are protected by the fuse-like behavior of the columns are designed with capacities that are large enough to prevent damage from occurring in them. Such elements are denoted as capacity-protected connections between components and comprise the integral connection type that has been considered here.

In some cases, emerging nontraditional concepts seek not to dissipate energy so much as act compliantly and accommodate seismically induced displacements with minimal damage. Such connections are called deformable, and are used in lieu of energy-dissipating connections at locations where inelastic deformations are expected. They may allow the bridge designer to improve the seismic response of the system by selecting an optimal distribution of moments within it.

Significant knowledge gaps remain to be closed for energy-dissipating connections, so a focus of additional research should be on energy-dissipating and deformable connections. The reason for this is that capacity-protected connections may be designed largely with data that supports the use of these same elements in non-seismic areas. Typically, such design data exists. Gaps in the experience and knowledge base for these capacity-protected components must eventually be closed, but the energy-dissipating work is a more pressing impediment to implementation.

Long-Range Needs

The status of the existing state-of-knowledge and practice for SABC, coupled with the wide range of construction preferences by owners and engineers around the country, suggests that a broad and extensive testing program will ultimately be necessary to fully support the use of SABC in the United States. Such a program should eventually include large-scale subassemblage (full pier) tests, as well as field demonstration projects to build confidence in the use of SABC. Experience suggests that a single technology will not fit the needs of all the states with moderate-to-high seismic areas, especially in view of the fact that SABC technologies are a significant departure from conventional CIP systems. A realistic estimate of the total time to develop the required knowledge could be in the range of 20 years. Therefore, this section summarizes the broader, long-term needs and proposes the first, but significant, step of a journey that will likely last a number of years. This assessment of duration is supported by recalling the time taken for the lessons learned in the 1971 San Fernando (California) earthquake to be formally adopted into bridge design practice in 1990. Compared with conventional bridge technology (e.g., CIP), SABC elements are somewhat more complex and include a wide range of possible behaviors, which suggests that time will be required to fully develop the technology. Nevertheless, such a research undertaking is crucial for the implementation of ABC in seismic areas and is an important step for the states, the traveling public, and work-zone safety.

Many ABC systems have been proposed for seismic use and limited testing has vastly improved the knowledge base and reduced the gaps in it. However, for owners and designers to have the confidence to deploy SABC technology, it is necessary to develop definitive design and construction specifications, design examples, demonstration projects and field experience. Future efforts should fill the remaining gaps in this knowledge in a systematic way. The objective is to provide the user with a palette of connections that can be constructed easily and that will accommodate inelastic deformations expected at intermediate piers—an essential "toolbox" for bridge designers in moderate-to-high seismic regions.

An ancillary benefit of development work on SABC systems is that such systems may address other extreme events, such as vessel impact, blast, or other loadings that may load a bridge beyond its elastic limits in ways not addressed by design for gravity load alone. The design principles used for seismic loading require continuity of load path, reserve inelastic strength, and a high level of structural integrity, and such attributes directly benefit the structure for other extreme events with strong lateral effects.

Previous NCHRP and state DOT-funded research to develop workable solutions to meet seismic performance requirements for ABC applications has produced a good start, and the suggested additional effort represents the next logical step on a longer journey.

Leveraging existing knowledge and experience is necessary to prevent redundant research. An example of such leverage is the use of existing data for the design of capacity-protected connections. Deferring consideration of capacity-protected connections focuses the next stage of SABC work on a smaller universe of connections that are affected by the seismic demands placed on energy-dissipating and deformable-element connections.

The overall strategy for the implementation of SABC should also account for owner preference in deployment of technology. There is a distinct preference apparent in the survey results for technologies that emulate CIP construction performance, and this is a manifestation of comfort level with the known. It is also apparent that there are emerging technologies that may provide seismic performance that is superior to that available from present designs, but the effort required to get those technologies both to a level of maturity that will instill high confidence in owners and designers and to imbue them with characteristics of rapid constructability will take longer than that needed for CIP-emulative types. Thus, the recommended strategy is to give higher priority to development of the technologies that align with current preferences and to take them to a deployable level.

The review of existing technologies undertaken in this project led to the generalization of connections into seven types, which are listed in Table 34. The use of connection types in a bridge follows a building-block approach, where the overall bridge system is built of SABC connections, along with more conventional connections in non-seismic critical locations. For each of the seven connection types, the available information is insufficient to justify implementation as an SABC system in the field.

The concept of TRL has been adapted for the use of SABC, providing rankings within nine categories that range from initial concept development to the system having successfully performed in the intended environment (in this case, a design earthquake). In addition to the ranking of TRLs, a judgment of the level of completeness at each TRL has been used and this helps identify three ways in which connection or system development may be deficient. The deficiencies fall into one of the three broad classifications defined above by the degree of completion of the steps in the TRL. The generalizations of the deficiencies are meant to represent a composite status for the type of connection under consideration.

- The *catch-up* classification indicates that a step along the connection's development is missing altogether and must be provided to justify the connection's use at the highest level at which other information is available. In some cases, the connection may be in use today, despite the lack of information in one previous step.
- The *infill* classification indicates that in one or more steps, the needed information has been partially, but not fully, developed. In some cases, the partial knowledge may justify use of the technology in moderate seismic areas where

Table 34. Work remaining by SABC connection type.

Connection Type	Catch-up	Infill	Advancement
Bar couplers	▨		
Grouted ducts		▨	
Pocket		▨	
Socket		▨	
Hybrid			▨
Integral	▨		
Emerging			▨

demands are somewhat lower, but not in higher seismic regions.
- The *advancement* classification indicates that all the information up to and including a given step is available and the remaining developments are those needed to push the technology to a higher level of readiness.

In an ideal world, all TRLs would be completed before moving on to the next level. In the real world of bridge engineering, this has not been done.

The reasons for the foregoing classifications are as follows.

Bar Couplers refer to devices that connect reinforcing bars for tension or compression using grouted sleeves or various types of mechanical connections. A wide range of tension capacities are available, but only a limited set of such couplers are potentially suitable for seismic applications. Of these, the grouted sleeves have been used in a number of applications, and several versions are commercially available. A primary shortcoming is that a comprehensive test series on grouted-types of bar couplers is lacking. Partial information is available (tests on couplers in air under high strain rates; isolated tests on members connected using particular couplers, [e.g., Splice Sleeve Japan Ltd., undated, Riva 2006]), but tests covering the full range of behaviors under seismic loading have not been conducted. Open questions include not only the cyclic response of the couplers themselves, but also system effects, such as the influence of the coupler stiffness on the strain distribution in the plastic hinge zone and its effects on the strain penetration in the opposing connected element and on the overall deformation capacity of a coupled-bar system. Because grouted sleeve bar couplers have already been deployed in seismic regions, the paucity of cyclic performance data for that type of bar coupler represents a serious shortcoming, so they are placed in the "catch-up" category.

Grouted Ducts refer to the anchorage of bars from one element into another by means of grouting the projecting bars into ducts. The load is then transferred from the duct into the surrounding concrete by bond. A number of test programs have demonstrated the high anchorage capacity of grouted ducts under monotonic loading, but only a few tests have been conducted using inelastic cyclic loading. Other areas where more information is needed include the effects of the size of duct, the type of duct (particularly the nature and roughness of the corrugations), the location of the bar in the duct (eccentric or otherwise), group pullout failure, and transfer of the load from the duct wall through the concrete to neighboring reinforcement. Grouted ducts have been deployed in non-seismic applications, on the basis of the available static strength data. The connection is therefore placed in the "infill" category.

In a **Pocket Connection,** bars projecting from the top of a column are fitted into a single void, or pocket, in the cap beam, which is subsequently filled with concrete. The primary information was developed in NCHRP Project 12-74. The system provides considerable promise, but mechanics-based design procedures are needed for the joint region and more extensive testing is needed to advance their development. The joint region includes not only the confined pocket itself, but also the surrounding region in the cap beam. The dimensions of that region are limited by the width of the cap beam and the size of the pocket, so it may be quite small and, therefore, highly stressed. In particular, the required quantity of tie and other confining reinforcement and procedures for computing it need to be established. The connection is placed in the "infill" category.

In a **Socket Connection,** the footing or cap beam is CIP around a precast column, from which no reinforcement projects. These are simple to fabricate and transport and offer excellent onsite constructability characteristics. Some cyclic testing has been conducted on both precast concrete and steel columns embedded in footings that are typical of bridge construction. Other studies have investigated footings suitable for buildings, but those results appear to translate poorly to bridge construction. A more extensive study is needed to define the relationships between the embedded length of the column, the column diameter, surface roughness, and confining reinforcement. Clear, mechanics-based design guidelines are needed for the design of the critical connection region. The connection is placed in the "infill" category.

Hybrid Systems typically contain unbonded prestressing tendons that remain elastic at all times during an earthquake and re-center the bridge system when the lateral load is removed—a highly advantageous characteristic for post-earthquake use. Hybrid systems differ from many of the others discussed here in that their primary purpose is to provide superior seismic performance, with rapid erection seen as a desirable, but not essential, additional feature. This ranking of priorities is the opposite of most of the other systems presented here. The principles of hybrid structures have now been well established in the vertical building industry and a number of such structures have been built. This level of development in a parallel industry, coupled with their demonstrated potential for improved performance, justifies their being treated differently from other emerging technologies. However, details suitable for bridge construction have not yet been fully worked out. This is the case partly because many variants on the configuration are possible. The primary questions include the choice between pre- and post-tensioning, use of bars or strand, corrosion protection, anchorage details in the footing and pier cap, confinement needed at the rocking interface, and so forth. Hybrid systems are, thus, classified as "advancement" in terms of needed work to advance to deployment.

Integral Connections are taken here to mean the connection between girders, cap beam, and columns that resists longitudinal load at a pier. The girders may be steel or concrete, and the cap beam may be completely or partially precast. Such connections are likely to be designed as capacity-protected, so that any inelastic deformations are forced to occur in the top of the column, below the connection. Their expected capacity-protected behavior renders them different from most of the other connections described here. Many configurations are possible, and they tend to follow the dictates of the local bridge-building culture. The internal forces must be transferred from bending in the girders to torsion in the cap beam and back to bending and shear in the columns. That load path is complex and its integrity can only be investigated with a large-scale test set-up. Consequently, very few such tests have been completed and those that have were on specialized systems. Integral connections have been used in many bridges, with the connection details determined using conventional principles of structural design. However, such principles are least reliable when load is transferred between many elements and the geometry of those elements is complex. The system performance must be understood clearly to ensure that such connections really can behave as capacity-protected elements. The shortage of system information, combined with extensive field deployment, place the connection type in the "catch-up" category.

Emerging Technologies are a number of technologies that offer promise of excellent seismic performance, but most are not particularly suited to ABC. Examples include specialized materials, such as SMAs and engineered cementitious composites (ECCs) to improve toughness and or damping, elastomeric bearings to increase deformability, and so forth. Most of the technologies have not yet been sufficiently developed to permit evaluation of their promise for ABC, and only a few preliminary tests have been conducted to investigate their inelastic response to cyclic loading. Therefore, they are classified here in the "advancement" category. The emerging technologies show considerable promise for excellent seismic performance, but the concepts will require significant additional effort to bring them to a high TRL and to deployment in the field. This category of technology will likely affect bridge seismic design practice some years in the future. Such systems should be nurtured by continued development effort, but immediate SABC deployment will come from the other technologies that have been developed more completely and, in many cases, already tried in the field either in non-seismic regions or in specialized innovative projects.

Suggested Research

The objectives of future research for SABC are first, to address immediate needs for use of ABC in moderate-to-high seismic regions, then second, to address more promising areas. This project has identified and prioritized these needs, and those that will provide the quickest and most widespread value are suggested for near-term efforts.

In the spirit of addressing the most urgent next steps first, the suggested work for immediate research should provide substantiation of seismic performance and further develop design and construction guidance for the following:

- Bar coupler systems that have already been deployed in high seismic regions (i.e., grouted sleeves)
- Connections for a complete pier or bent system, inclusive of top, bottom, and splice column connections using either grouted ducts or pocket-type connections at the top and socket-type connections for the bottom.

By addressing the infill effort judged to be remaining for grouted duct, pocket, and socket connections, the suggested work will enable a complete pier system to be deployed with confidence in moderate-to-high seismic areas. Of these, the grouted duct and pocket connections are particularly well suited for the column to cap beam connection, and the grouted duct and socket connection types are suited to the foundation connection. Bar couplers, once verified, could be applied anywhere in the structure.

Quasi-static, statically determinate tests are preferred for most of the testing because these permit, without ambiguity, the relationships of internal force and displacement to be quantified. Such data is necessary to support the development of design procedures compatible with the AASHTO Guide Specifications, which use displacement-based methodologies. Beyond such simple testing, eventual proof-of-concept tests should be performed on large-scale subassemblages using shake tables. This provides additional confidence in the technologies under near-actual dynamic conditions. Because we cannot control the occurrence of large damaging earthquakes, which would provide actual field proof-of-concept, such dynamic testing is the next best thing to boost confidence in TRL toward the highest level.

The next phase of work that is suggested, potentially several years in the future, is comprehensive evaluation and development of integral connections that form part of the load path for longitudinal seismic loading in common with prestressed girder bridges including the following:

- Two-stage cap beams with a precast lower drop cap without prestress in the connection region
- Flush-soffit cap beam types where longitudinal post-tensioning may or may not be used
- Innovative connecting approaches beyond those currently in use for cap beams

Overall, testing and development of such integral systems is no less important than development of pier systems. Pier system development was prioritized ahead of integral connection development, in part, because such systems have been deployed, they are common throughout the country, and testing is somewhat less expensive due to specimen size. However, ultimately, both pier and integral testing should be undertaken.

It is apparent that there is other infill work and much remaining advancement work that falls beyond the scope of the near-term suggestions. The reasons for not suggesting any of that work for immediate priority are as follows:

- Adequate development work for even one emerging system would consume the entire likely budgets available in the near term.
- There is a higher likelihood of achieving the highest readiness level in the shortest time for conventional bridges with the catch-up and infill work that has been recommended.

Accordingly, an underlying assumption to the recommendations made herein is that the best approach in the near term is to focus on bringing the technology with the highest potential to benefit the most users to a deployment-ready stage as fast as possible. This, in the research team's judgment, is to bring a bent system to market that can be used with widely used precast girder conventional bridges.

Beyond these near-term goals and to the extent possible, development should continue on technologies that will provide enhanced seismic performance, in addition to enhancing ABC, and that will benefit more specialized bridge types that are used in smaller numbers.

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ABC	accelerated bridge construction
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
Caltrans	California Department of Transportation
CFFT	concrete filled fiber-reinforced plastic tube
CFST	concrete filled steel tube
CIP	cast-in-place
CP	capacity-protected
CPFD	cap pocket full ductility
CPLD	cap pocket limited ductility
DE	deformation elements
DOE	U.S. Department of Energy
DOF	degree of freedom
DOT	Department of Transportation
ECC	engineered cementitious composites
ED	energy-dissipating
ERE	earthquake resisting elements
ERS	earthquake resisting system
FHWA	Federal Highway Administration
FRP	fiberglass-reinforced polyester
GRFP	glass fiber reinforced plastic
LRFD	Load and Resistance Factor Design
MCEER	Multidisciplinary Center for Earthquake Engineering Research
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NIST	National Institute of Standards and Technology
PBES	prefabricated bridge elements and systems
PCI	Precast Prestressed Concrete Institute
PRESSS	Precast Seismic Structural Systems

RFP	request for proposal
SABC	seismic accelerated bridge construction
SCC	self-consolidating concrete
SMA	shape-memory alloy
SPMT	self-propelled modular transporter
TRB	Transportation Research Board
TRL	Technology Readiness Level
UDOT	Utah Department of Transportation
UNAM	Universidad Nacional Autónoma de México (Spanish: National Autonomous University of Mexico; Mexico City, Mexico)
UTA	University of Texas at Arlington
WSDOT	Washington State Department of Transportation

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APPENDICES A THROUGH J

The following appendices are available as PDFs on the TRB website under NCHRP Project 12-88.

Appendix A	Summary Sheets of Bar Coupler Connections
Appendix B	Summary Sheets of Grouted Duct Connections
Appendix C	Summary Sheets of Pocket Connections
Appendix D	Summary Sheets of Member Socket Connections
Appendix E	Summary Sheets of Hybrid Connections
Appendix F	Summary Sheets of Integral Connections
Appendix G	Summary Sheets of Emerging Technology and Deformable Element Connections
Appendix H	Detailed Evaluation of Connection Types
Appendix I	Questionnaires
Appendix J	2012 Research Problem Statement

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation