

SUMMARY OF NCHRP RESEARCH ON DEVELOPMENT OF A PRECAST BENT CAP SYSTEM FOR SEISMIC REGIONS

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Abstract

This paper summarizes the findings of the research conducted under NCHRP Project 12-74 to (1) develop and validate design methodologies; (2) recommend design and construction specifications; and (3) provide design examples and example connection details for precast bent cap systems using emulative and hybrid connections for integral and nonintegral systems for all seismic regions throughout the United States.

Introduction

Precast bent cap systems are of increasing utility in highway construction. Precasting eliminates on-site concrete forming, placement, and curing operations making bridge construction safer and more environmentally friendly. It also removes bent cap construction from the critical path, thus accelerating the construction process. Precasting also improves quality and durability because the work is performed in a controlled environment. These benefits of precast bent cap systems support the philosophy of "get in, get out, stay out." Successful use of precast bent caps relies on proper design, constructability, and performance of the connections. Early uses of precast bent caps were limited to applications where minimal moment and shear transfer were required at connections. In seismic regions, provisions normally must be made to transfer greater forces through connections and to ensure girder continuity in the longitudinal direction.

Precast bent cap systems can be classified as either integral or nonintegral depending on superstructure-to-substructure connectivity. Integral bent cap systems develop longitudinal continuity through girder-to-bent cap connections. In contrast, nonintegral bent cap systems use bent cap-to-column connections to provide transverse moment continuity. However, integral precast bent cap systems require the use of precast cap-to-column and superstructure-to-cap connections.

Additionally, precast connections are typically categorized as being either emulative or hybrid. Emulative connections are designed to produce a system performance that is similar to (or "emulates") that achieved by traditional monolithic, cast-in-place (CIP) construction. Bridges using emulative precast bent cap connections are expected to form plastic hinges in the columns and redistribute forces to other members like CIP systems. The lateral force-displacement response of an emulative system is characterized by full hysteresis loops and stable energy dissipation. This

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response results from considerable damage and potential residual deformations--the underlying assumption of seismic design philosophy for CIP bridges. Hybrid systems are designed to provide sufficient energy dissipation through controlled rocking about specially detailed joints at the column ends. In addition, hybrid systems provide a significant reduction in damage and residual offsets as compared to cast-in-place and emulative systems.

NCHRP Project 12-74 was conducted to (1) develop and validate design methodologies, (2) recommend design and construction specifications, and (3) provide design examples and example connection details for precast bent cap systems using emulative and hybrid connections for integral and nonintegral systems for all seismic regions throughout the United States.

In this paper, the research efforts conducted under this NCHRP project related to nonintegral systems are summarized. The efforts summarized herein are: (1) experimental test program; (2) testing protocol and instrumentation; and (3) test results and key findings, extracted from the project’s final report authored by the principal investigator Dr. Jose I. Restrepo, professor at University of California, San Diego (UCSD); and the co-principal investigator Dr. Eric E. Matsumoto, professor at California State University, Sacramento (CSUS).

Experimental Test Program

In this research program, a number of promising precast bent cap details were investigated though experimental testing. These specimens were developed to meet a variety of performance objectives for locations throughout the nation’s seismic regions; descriptions are provided in Table 1.

Table 1 Summary of Experimental Specimens

Code	Specimen Name	Specimen Type	Specimen Purpose
CIP	Cast-in-place control specimen	Beam-to-column emulative	Control specimen detailed in accordance with Recommended AASHTO LRFD Seismic Guide Specification for high seismic applications.
GD	Grouted duct specimen	Beam-to-column emulative	Grouted duct specimen designed to provide high ductility response with similar response as CIP specimen

Code	Specimen Name	Specimen Type	Specimen Purpose
CPFD	Cap pocket full ductility specimen	Beam-to-column emulative	Cap pocket specimen designed to provide high ductility response with similar response as CIP specimen. Detail uses a corrugated metal pipe to provide stay-in-place form and joint shear reinforcement
CPLD	Cap pocket limited ductility specimen	Beam-to-column emulative	Cap pocket specimen design with alleviated seismic detailing intended to provide limited ductility for regions of low to moderate seismicity. Detail uses similar corrugated metal pipe detail as CPFD.
Hybrid 1	Conventional hybrid specimen	Beam-to-column hybrid	Hybrid specimen detailed with conventional spiral confinement reinforcement and full length mild reinforcement. Detail is intended to be a hybrid detail most similar to traditional CIP construction.
Hybrid 2	Concrete filled pipe hybrid specimen	Beam-to-column hybrid	Hybrid specimen using full length steel shell acting as confinement and shear reinforcement. Mild reinforcement utilized only at joint to provide energy dissipation and terminated into the column.
Hybrid 3	Dual steel shell hybrid specimen	Beam-to-column hybrid	Hybrid specimen using two full length shells (outer steel and inner corrugated metal pipe) acting as confinement and shear reinforcement. Mild reinforcement utilized only at joint. Dual shell detail intended to reduce weight of column section for precasting.

Testing Protocol and Instrumentation

In the following sections, the test setup, loading, and instrumentations for nonintegral emulative and hybrid specimens will be summarized.

Emulative Specimens

The specimen test setup, shown in Figure 1, included a simply supported bent cap with a column stub that allowed biaxial loading and accurate establishment of specimen forces. The specimen was tested in inverted position. Loads were applied using a vertical hydraulic actuator to apply scaled gravity load and the horizontal hydraulic actuator to induce seismic response. The test setup ensured accurate conditions at each end of the joint so that the force transfer mechanism in the joint could be investigated. Different axial force conditions in the bent cap were produced for the push and pull directions.

Force controlled and displacement controlled loadings were applied to all specimens. The force controlled loading was used for an approximate determination of first yield of column longitudinal bars in the push and pull directions, establishment of effective yield, and application of the displacement controlled sequence including quasi-static displacement in 3 cycles. Nominal displacement ductility (μ) demand, as multiples of system effective yield displacement, was applied at the $\mu 1$, $\mu 1.5$, $\mu 2$, $\mu 3$, $\mu 4$, $\mu 6$, $\mu 8$, and $\mu 10$ levels, or until the residual capacity of the specimen dropped below 30% of the maximum load.

External gages, including linear and string potentiometers and Linear Variable Differential Transformers (LVDT) were mounted on the column, joint, and bent cap. Internal strain gages were placed on bent cap, joint, and column reinforcing bars, as well as corrugated ducts or pipe. In addition to the approximately 100 sets of data, specimen response was also monitored using digital photos, crack markings and measurements, video recording, and notes.

Hybrid Specimens

The test setup for the hybrid specimens, shown in Figure 2, is similar to that used for the emulative specimens. The specimens were constructed in the upright condition and then inverted for installation in the test setup. The vertical actuator was set to apply a constant load during testing to simulate gravity loading. This force varied between hybrid specimens in order to match the lateral response of the three hybrid tests. The horizontal actuator was actively controlled to apply specified forces or displacements during testing.

The initial stage of loading consisted of force-controlled loading protocols in which positive and negative lateral forces of increasing magnitude were applied until first yield of the extreme mild reinforcing bar was reached. Each force loading cycle was repeated three times in both directions. Following the first yield of the system, the lateral

loading was applied to a specified lateral drift ratio. At each cycle to a given drift ratio, the column was subjected to two cycles in both directions followed by one cycle to the previous lateral drift. This protocol was developed to help accurately calibrate non-linear models of the system.

External instrumentation mounted on the specimens consisted of linear potentiometers and inclinometers for measuring and isolating various modes of deformation in the member. In addition, a significant number of internal strain gages were employed to capture the local response of materials.

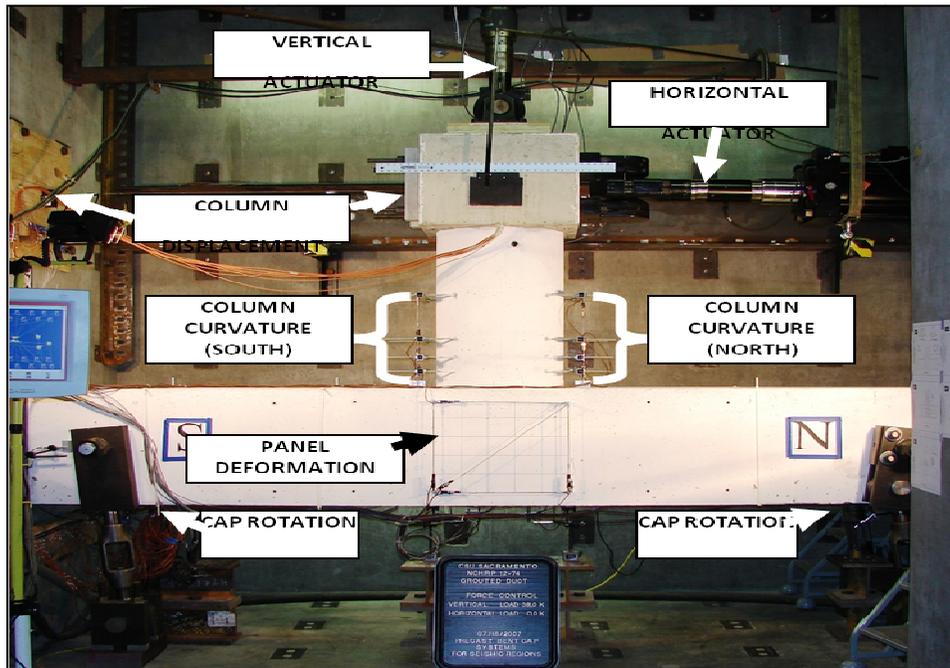


Figure 1 Test Setup for Emulative Specimens

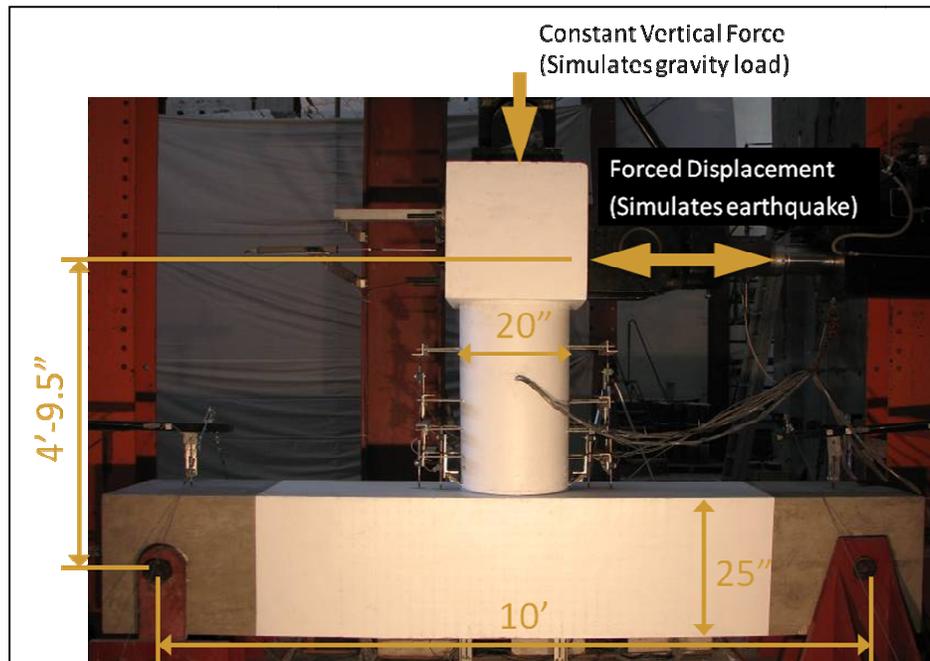


Figure 2 Test Setup for Hybrid Specimens

Test Results and Key Findings

This section summarizes the key aspects of specimen response for the emulative and hybrid experimental tests. In reporting specimen response, displacement ductility, μ , and drift ratio are both used. Drift ratio is defined as the column displacement divided by the column height, and is reported as a percent. It provides a more consistent basis for comparison of specimen response than displacement ductility. However, system ductility levels are also reported, although these values should be considered nominal (i.e., approximate) due to the approximate determination of first yield. The terms drift and drift ratio are used interchangeably.

Non-integral Emulative Connections

This section summarizes the primary aspects of specimen response for all specimens: Cast-in-Place (CIP), Grouted Duct (GD), Cap Pocket Full Ductility (CPFD), and Cap Pocket Limited Ductility (CPLD). The joint response is summarized in Tables 2 and 3. Comparisons are made between the CIP and precast connections, as well as between the full and limited ductility specimens. GD as well as CPFD joint distress was limited and joint behavior compared very favorably with that of the CIP specimen. In contrast, the joint region for the CPLD specimen exhibited a significant level of distress that increased throughout the test. Figure 3 shows the joint shear stress-strain response envelopes, and Figure 4 shows the load-displacement envelopes for all specimens. The figures reveal a very similar overall load-displacement response for the GD, CPFD, CPLD and CIP specimens. The dominance of ductile plastic hinging in the column and

minimal damage in the capacity-protected joint and bent cap satisfied the performance goal for the GD emulative specimen.

Table 2 Maximum Joint Response

Parameter	CIP	GD	CPFD	CPLD
Joint Shear Stress (psi)	328 ($4.86\sqrt{f'_c}$)	312 ($4.62\sqrt{f'_c}$)	323 ($4.31\sqrt{f'_c}$)	371 ($6.32\sqrt{f'_c}$)
Principal Tensile Stress (psi)	363 ($5.38\sqrt{f'_c}$)	343 ($5.09\sqrt{f'_c}$)	356 ($4.75\sqrt{f'_c}$)	411 ($6.99\sqrt{f'_c}$)
Principal Compressive Stress (psi)	401 ($0.088f'_c$)	370 ($0.081f'_c$)	398 ($0.071f'_c$)	460 ($0.13f'_c$)
Angle of Principal Plane (deg)	45.0	45.0	44.2	44.8
Joint Rotation (rad)	1.95×10^{-3}	2.25×10^{-3}	1.73×10^{-3}	2.87×10^{-3}
Change in Panel Area (%)	0.16	0.19	0.13	0.46

Table 3 Maximum Joint Response – Comparison Ratios

Parameter	GD/CIP	CPFD/CIP	CPLD/CIP	CPLD/CPFD
Joint Shear Stress	0.95	0.89	1.30	1.47
Principal Tensile Stress	0.94	0.88	1.30	1.47
Principal Compressive Stress	0.92	0.81	1.48	1.86
Angle of Principal Plane	1.00	0.98	1.00	1.01
Joint Rotation	1.15	0.89	1.47	1.66
Change in Panel Area	1.19	0.81	2.82	3.26

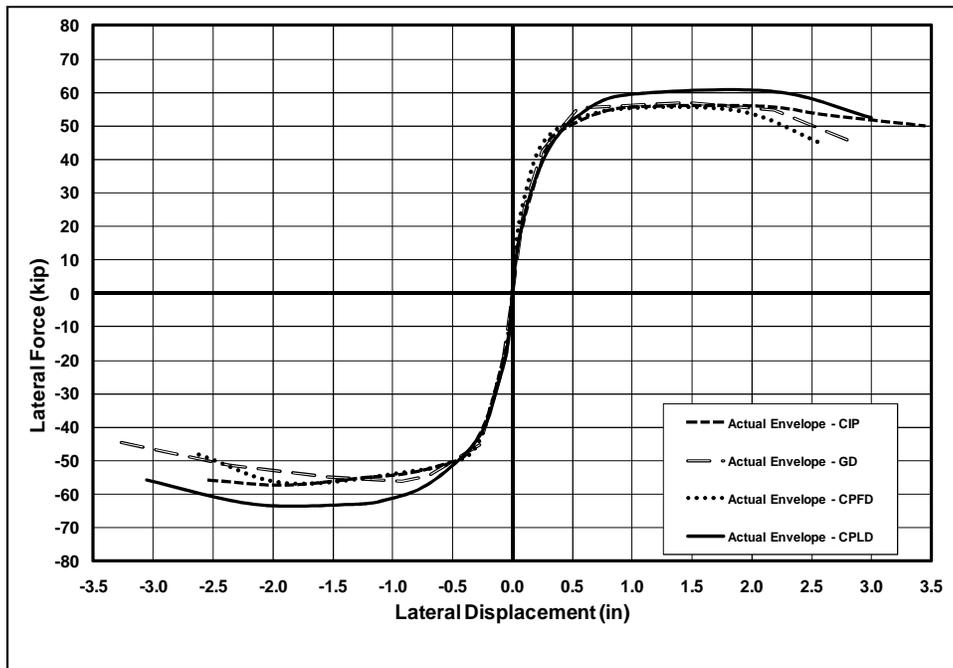


Figure 3 Joint Shear Stress vs. Joint Shear Strain Envelopes

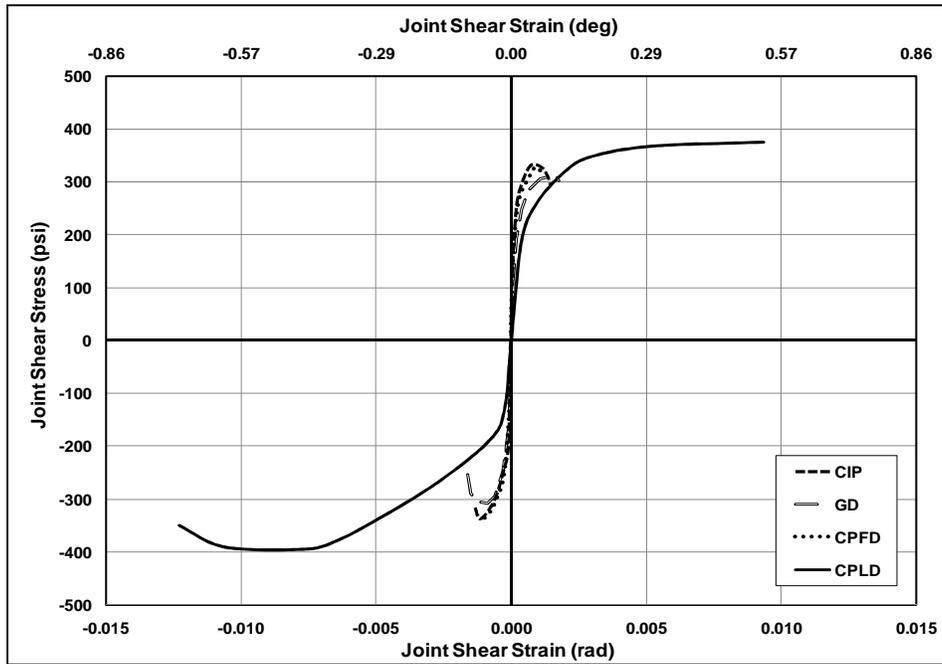


Figure 4 Applied Lateral Force vs. Lateral Displacement Envelopes

Non-integral Hybrid Connections

This section summarizes the primary aspects of specimen response including column hysteretic response (lateral force-displacement), joint response, and residual drift. Comparisons are made between the CIP and hybrid connections (Hybrid 1—conventional hybrid specimen, Hybrid 2—concrete filled pipe hybrid specimen, and Hybrid 3—dual steel shell hybrid specimen). The force-displacement envelopes for all three hybrid specimens along with the cast-in-place specimen are shown in Figure 5. It is apparent that all hybrid specimens have greater lateral capacity than the cast-in-place control. The higher lateral capacity resulted from the larger than anticipated effective post-tensioning force in the conventional specimen and that the other hybrid specimens were designed to be similar to the conventional hybrid specimen. Regarding joint response, only minor damage occurred within the joint during the entire testing of all hybrid specimens. Diagonal cracking patterns were observed indicating joint shear cracking, but the joint reinforcement was adequate to resist extensive crack growth and subsequent joint damage.

One of the major aims of hybrid bridge systems is the reduction of residual displacements. Figure 6 shows the ratio of recorded residual drift to the maximum drift during the first cycle for the three hybrid and the cast-in-place control specimens. However, the second cycle exhibited slightly greater residual drifts. In general, for the conventional hybrid specimen the residual drift ratio increases with the applied lateral drift. However, the recorded residual drift was significantly less than for the cast-in-place specimen indicating an expected improved post-earthquake performance.

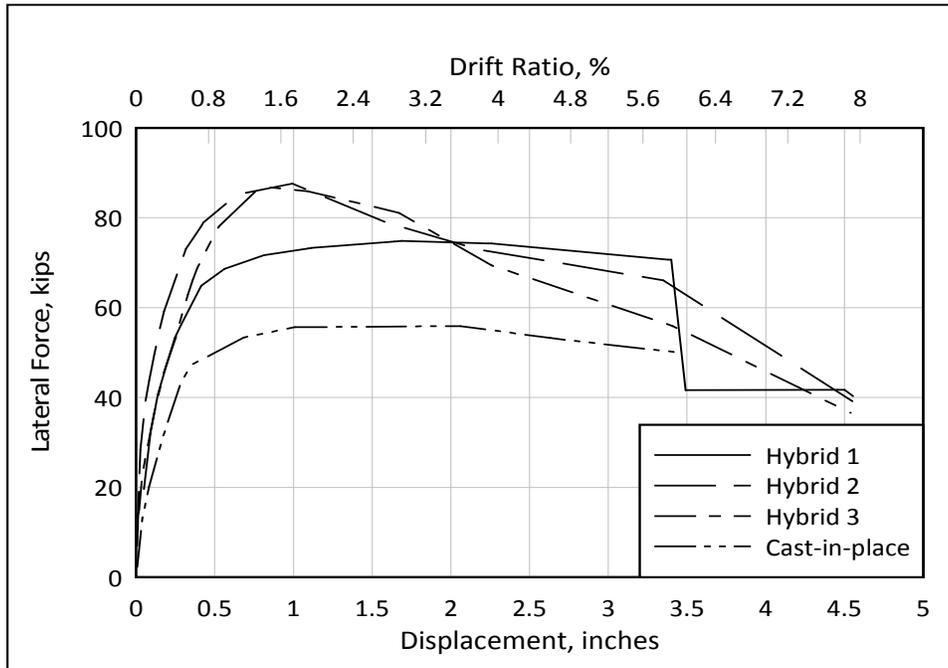


Figure 5 Lateral Force vs. Lateral Displacement Envelopes for Hybrid Connections

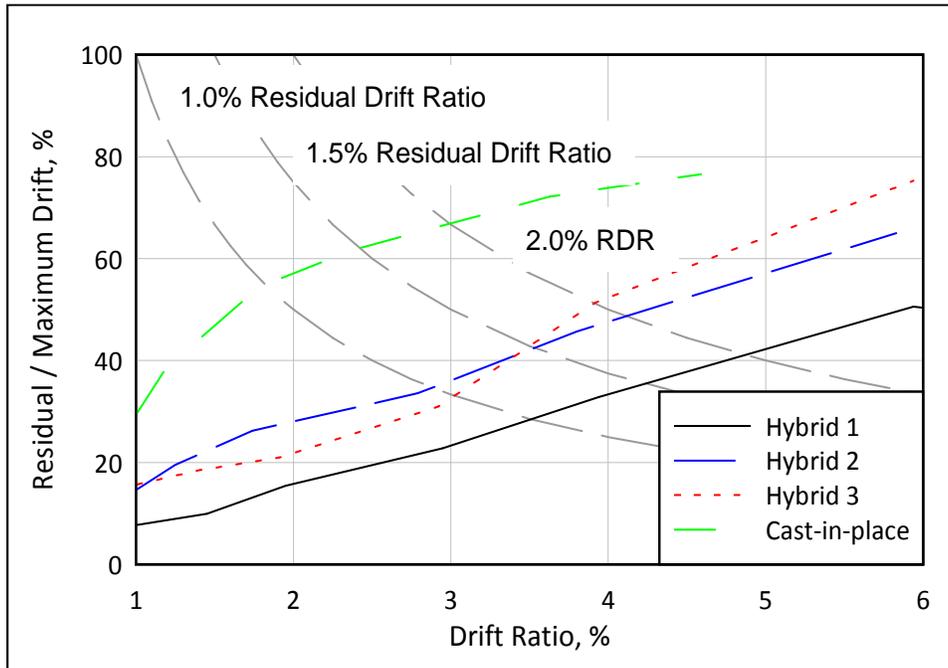


Figure 6 Residual Drift Ratio vs. Applied Drift Ratio for Hybrid Connections

Key Findings

Based on a review of the experimental efforts conducted under NCHRP 12-74, the research team provided the following key findings:

- The current joint shear design methodology contained in the 2009 LRFD Seismic Guide Specification, with minor modifications, is appropriate for the design of emulative and hybrid, integral and nonintegral precast bent cap systems.
 - For Seismic Design Categories (SDCs) B, C and D, the level of joint shear reinforcement should be based on the calculated principal tensile stress, and if the stress exceeds $0.11\sqrt{f'_c}$, ksi, joint shear reinforcement should be specifically designed.
 - Minimum joint shear reinforcement should be provided for all SDCs.
 - Design methodologies and detailing for hybrid systems should be employed to facilitate the implementation of these systems for improving the post-earthquake functionality of the bridge structure.
 - Properly designed and detailed hybrid systems can produce substantially less residual deformation and damage than cast-in-place and emulative systems.
 - In hybrid systems, the contribution of flexural reinforcement should be limited to produce its intended response. In addition, the neutral axis depth should be limited to minimize the magnitude of compressive strains within the section.
 - Design and detailing of the unbonded post-tensioning and longitudinal reinforcement in a hybrid system should be such as to ensure premature fracture does not occur.
 - Provisions of the 2009 LRFD Seismic Guide Specification for the design of multi-column integral connections should be updated for consistency with the design of multi-column nonintegral connections.
 - For the cap pocket connections, the use of a supplementary hoop at the top and bottom of the corrugated pipe should be employed.
 - Proposed equations for anchorage of reinforcement within grouted ducts and the cap pocket connection should be implemented.
 - Future provisions of seismic design and detailing requirements should be developed for knee joints for both cast-in-place and precast bent caps.
 - Alternate connection details are provided for structures located in SDC A with S_{DI} less than 0.10. However, minimum vertical stirrups in the joint are recommended, as well as the extension of column longitudinal reinforcement as close as practical to the top of the bent cap.
 - Grouted joints for use in seismic applications should be limited to 3 inches in thickness and should be reinforced with hoops to maintain the spacing of lateral reinforcement within the plastic hinge region.
 - For hybrid columns and integral closure joints, grouted connections should employ a 3 pound per cubic yard fraction of polypropylene fibers to enhance the integrity of the joint.

Conclusions

In addition to the contractors' final report that will be published as *NCHRP Report 681, Development of A Precast Bent Cap System for Seismic Regions*, a series of recommended updates to the *AASHTO LRFD Bridge Design Specifications, Guide Specification for LRFD Seismic Bridge Design* and *Bridge Construction Specifications* were developed.

Design specifications SDCs C and D, SDC B, and SDC A were developed in appropriate format for incorporation into a future edition of the *AASHTO Guide Specifications for LRFD Seismic Bridge Design* (LRFD SGS). A major proposed change is to revise Article 8.13—Joint Design for SDCs C and D of the *2009 LRFD SGS* to include precast bent cap connections (grouted duct and cap pocket). Also, to address all seismic design categories, two new articles were required and recommended to be added: an article on Joint Design for SDC A and an article on Joint Design for SDC B.

Design flow charts and design examples were developed to illustrate the use of design specifications for both grouted duct and cap pocket connections at all SDC levels. Construction specifications, Special Requirements for Precast Bent Cap Connections, were provided and proposed for inclusion in the *AASHTO LRFD Bridge Construction Specifications* (LRFD BCS).

Acknowledgements

The work summarized herein was performed under NCHRP Project 12-74 and was guided by NCHRP Project Panel C12-74, chaired by Mr. Richard A. Pratt, with members Dr. Xiaohua Hannah Cheng, Mr. Carl J. Fuselier, Mr. Jim Ma, Mr. Richard Marchione, Mr. Chuck Prussack, Ms. Holly Winston, and Mr. Lloyd M. Wolf. Mr. Derrell A. Manceaux and Mr. Stephen F. Maher provided liaison with the FHWA and TRB, respectively. Dr. Waseem Dekelbab served as the responsible NCHRP staff officer. The final report was prepared by the principal investigator Dr. Jose I. Restrepo, professor of structural engineering at the University of California, San Diego (UCSD), and the co-principal investigator Dr. Eric E. Matsumoto, Professor at California State University, Sacramento (CSUS). The other author of this report is Dr. Matthew J. Tobolski, President of Tobolski Watkins Engineering, Inc. and former graduate researcher at UCSD.

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.705	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)