Precast Columns with Mechanically Spliced Connections for Accelerated Bridge Construction in Seismic Zones

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Abstract

In recent years, a number of laboratory and analytical studies have been conducted to investigate the behavior of precast columns with mechanically spliced (MS) connections for accelerated bridge construction (ABC). These connections employ mechanical reinforcing bar splices as the primary jointing mechanism between precast columns and adjacent members. This paper provides insight on previous and current research on the seismic behavior of precast columns employing mechanically spliced connections. The paper is broken down into three parts. Part one presents key results from previous research conducted at the University of Nevada, Reno. Part two presents preliminary results from a parametric study that investigated the effect of splice size and location on precast column hinge behavior. Lastly, the third part provides an overview of a current research on MS connections being conducted at the University of Central Florida.

Introduction

Accelerated bridge construction (ABC) has become increasingly popular throughout the United States because of its numerous advantages. In many cases, ABC methodologies have been shown to decrease bridge construction time, reduce the overall project cost, and reduce the impact on the environment and traveling public. To effectively execute ABC projects, designers use prefabricated bridge elements that can be manufactured offsite in parallel with on-site construction. These members are then delivered to the site, and can be quickly assembled to form a functional structural system. Despite the numerous advantages, ABC has not been extensively used in areas subject to moderate and high seismic hazards for good reason. There has been a great deal of uncertainty about the seismic performance of the connections used to join precast elements. Of specific concern are substructure connections (column-footing, column-shaft, and column-bent-cap) because they must dissipate energy through cyclic nonlinear deformations under seismic loading while maintaining their capacity and the integrity of the structural system.

Traditionally, mechanical reinforcing bar splices have been used in cast-in-place concrete construction when long, continuous bars or reinforcement cages are required. A select group of mechanical splices commercially-available in the US are shown in Figure 1. Unlike lap splices, which can require lengths greater than $30d_b$, mechanical splices can

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be used to create structural continuity at discrete locations. US building design codes such as ACI 318 (2002) allow placement of mechanical splices in regions susceptible to inelastic deformations during seismic events as long as splices meet certain performance standards (ICC-AC133, 2010). Conversely, US bridge design codes such as the *AASHTO Guide Specifications for LRFD Seismic Bridge Design* (2011) and *Caltrans Seismic Design Criteria* (SDC) (2013) prohibit mechanical splices from being placed in plastic hinge zones. Despite current restrictions in design specifications, mechanical reinforcing bar splices have received considerable attention from both practitioners and researchers as a possible option for ABC column connections in seismic zones.

ABC column connections employing mechanical splices as the primary joining mechanism have been referenced to as mechanical spliced (MS) connections. One of the primary benefits of MS connections, compared with other precast column connections types, is that they can be detailed to closely resemble conventional cast-in-place (CIP) systems; this is illustrated in Figure 2. Thus, it was initially thought that these connections could be designed using an emulative design approach. The ultimate goal emulative design is to create a precast system that behaves identical to a conventional cast-in-place (CIP) system. Emulative design of precast columns with MS connections entails first designing an equivalent cast-in-place column that meets both strength and ductility requirements. The longitudinal reinforcement details would then be modified to incorporate mechanical splices within the column without violating spacing or cover requirements. The final set of reinforcement details would then be checked using an equivalent cast-in-place column to ensure strength and ductility requirements are still met.

This procedure assumes that the mechanical splices contribute very little to the local stiffness and deformation capacity of the plastic hinge region, which has been shown to be true in the elastic range (Haber et al., 2014b). Thus making emulative design produces effective for strength-based design of precast columns with MS connections. However, once yielding occurs, mechanical splices have been shown, in some cases, to significantly reduce the deformation capacity of spliced bars. This can cause redistribution of plastic hinging and reduced ductility capacity. Therefore, emulative design may not be appropriate for displacement-based design due to an inability to provide reasonable estimates of ductility capacity. Nevertheless, precast columns with MS connections are still a viable option for ABC projects in seismic zones, but a number of challenges must be met. Some of the challenges include lack of available guidance for designing these connections in regions of high seismicity, current code provision prohibiting the use of mechanical splices in hinge regions, and limited experimental data on the behavior of these connections.

The primary objective of this paper is to provide insight into the current state-of-knowledge on the use of MS connections for precast column seismic zones, and to provide some details about current research efforts. The paper is broken into three separate parts. The first part of the paper presents key results from previous studies conducted at the University of Nevada, Reno on precast columns with MS connections; focus is given to plastic hinge formation and behavior. The second part of the paper presents preliminary results from a limited parametric study that examines the effect of splice size and location on the hinge behavior and displacement ductility capacity of precast bridge columns. The third part of the paper summarizes research currently being conducted at the University of Central Florida focused on improving the seismic performance of MS connections.

PART 1 – Key Results from Tests at UNR

Column Details

The first series of tests on precast bridge columns with MS connections designed according to US standards were conducted at the University of Nevada, Reno (Haber et al., 2014a, and Tazarv and Saiidi, 2014). Prior to these tests, the majority of research on columns with MS connections was conducted in East Asia and predominately focused on precast concrete building columns. A total of six half-scale bridge column models were tested at UNR; one cast-in-place benchmark column and five precast columns with MS connections. All five precast columns were designed to be emulative of the cast-in-place baseline column. That is, the presence of mechanical splices was neglected in design calculations.

The benchmark cast-in-place (CIP) column was designed using the California Department of Transportation (Caltrans) Seismic Design Criteria (SDC) (Caltrans, 2010) for a target design displacement ductility capacity of $\mu_C = 7.0$. Displacement ductility is defined as the ratio of ultimate displacement to effective yield displacement. The geometry and reinforcement details of CIP were selected to be representative of flexural-dominate columns commonly used in California with modern seismic detailing. The design details of CIP are listed in Table 1. CIP was designed to be a half-scale model assuming the prototype column had a 48-in (1.2-m) circular cross-section.

The remaining five models were precast and had the same geometric and reinforcement details as CIP. Two different connection details were developed using two of the mechanical reinforcing bar splices shown in Figure 1; the up-set headed splice (HC) and the grouted sleeve splice (GC). The HC and GC connection details are shown in Figure 3-a and 3-b, respectively. In the initial round of testing, two column models were tested for each connection detail for a total of four models. For each connection detail, one column was connected directly to a footing block, and the second was connected to the footing block atop a 12-in (305-mm) precast pedestal (Figure 1-c); the final column height was constant. The pedestal was used to reduce the moment demand over the connection region. Precast pedestals were detailed such that longitudinal reinforcing bar passed though the pedestal via grout-filled corrugated steel ducts. The fifth and final precast column was testing during a second round of testing, and employed a GC connection with a CIP pedestal (Figure 3-d), which was used to improve the performance. Column identification, splice types, and pedestal details are listed in the test matrix shown in Table 2.

Results

Each column model was tested under slow reversed cyclic loading until failure using a drift-based protocol. Columns were laterally loaded with a servo-hydraulic actuator in a single cantilever configuration. Axial load was applied using a spreader beam and two hydraulic rams. During each test, column tip displacement, plastic hinge curvatures, and internal reinforcing bar strains were digitally recorded.

In general, the force-displacement responses for precast models were similar to that of the CIP benchmark model. The elastic stiffness among CIP and precast models was comparable, and there was very little difference in the post-yield force-displacement behavior and ultimate load capacity. The primary difference amongst model performance was the ultimate drift and displacement ductility capacity. The measured ultimate drifts and displacement ductilities for each model are listed in Table 2. In the first round of testing, it was found that models with HC splices (HCNP and HCPP) had ultimate drift and ductilities capacities similar to that of the CIP benchmark column, while columns with GC splices (GCNP and GCPP) had much lower displacement capacities. The difference in ultimate displacement and ductility capacities amongst the columns was caused by the formation location and plastic rotation capacity of the plastic hinge.

The plastic hinge behavior of each model was evaluated using strain gages on longitudinal reinforcing bars and rotation measurements from displacement transducers mounted on the exterior of the columns. Figure 4 depicts the observed plastic hinge behavior of each column model. CIP exhibited well distributed plasticity in the longitudinal reinforcing bars, which resulted in a large plastic rotations and deformation capacity. Similar behavior was exhibited by models with HC splices even though the measured strain distributions in HCPP were not as uniform as those for CIP and HCNP; this was a result of added stiffness of the grout-filled steel ducts in the precast pedestal. The most significant difference in plastic hinge behavior compared with CIP was observed in columns with grouted splices, GCNP and GCPP. It was found that region incorporating the grouted splices had reduced the plastic rotation capacity compared with the other models. This caused the majority of plastic deformation to occur at the column-footing interface, which led to damage and bar fracture.

This behavior can be further illustrated by comparing the moment-rotation relationships for CIP, HCNP, and GCNP. This comparison is shown in Figure 5 up to 5.0%. Measurements were taken between 1-in (25-mm) and 15-in (381-mm) above the footing surface. Within the first half column diameter above the footing, CIP exhibited large plastic rotation, as would be expect, along with HCNP (Figure 5-a). In comparison, GCNP exhibited very little plastic rotation capacity up to the 5.0% drift as a result of grouted splices within the plastic hinge region.

In the second round of testing, redistributed plasticity and reduced ductility resulting from added stiffness of grouted splices was mitigated by using a CIP pedestal with debonded longitudinal bars; this column model was denoted GCDP. The ultimate drift and displacement ductility capacity of GCDP (shown in Table 2) were significantly increased compared with GCNP and GCPP as a result of the CIP pedestal and debonded bars. Strain and curvature measurements within the pedestal region indicated that well-distributed plasticity occurred compared with other GC models (Figure 4), which increased the rotational capacity of the hinge.

PART 2 – Effect of Splice Length and Location

The tests discussed in Part 1 suggested that splice length and the location of the splice within a plastic hinge region could significantly affect the seismic performance of a precast column with an MS connection. This part of the paper presents the preliminary results from a limited parametric study that investigated the effect of splice length and location on displacement ductility capacity. The study variables include splice length, splice location within the plastic hinge region, and column aspect ratio (AR), which is defined as the ratio of column length, L, to column diameter, D.

Parameters Details

Figure 6 illustrates column geometry, the typically cross-section and reinforcement details, and naming conventions. The cross-sectional geometry and reinforcing details were selected to be representative of the 48-in (1.2-m) diameter prototype column noted in Part 1; the longitudinal and transverse reinforcement ratios where approximately 2.0% and 1.0%, respectively. Each column was designed according to Caltrans' SDC (2013) for a displacement ductility capacity $\mu_C \approx 7.0$. The splice length parameter was defined using splice length-to-bar diameter ratio (L_{sp}/d_b). L_{sp}/d_b ratios were selected based on geometric properties of mechanical splices commercially-available in the US market for ASTM A706 / A615 Grade 60 reinforcing bars. The typical L_{sp}/d_b ratio ranges for different splice types are shown in Figure 1, and varied between 1.5 and 16. This study considered L_{sp}/d_b ratios of 4, 8, 12, 16, and 20. Although $L_{sp}/d_b = 20$ was not found in the literature, it was considered because a splice of this length could be designed in the future. Placement of splices within precast columns varied within the first column diameter, 1.0D, for columns with AR = 4.5 and 6, and within the first 0.67D for columns with AR = 3.0. The sections located below the splice were considered to behave as a CIP pedestal with bonded bars. The placement of splices within the column was defined by the distance between the surface of the footing and the base of the splice group, H_{ped}.

Analytical Models and Material Properties

Analytical models were created using the open-source finite-element software, OpenSEES. Columns were modeled using displacement-based beam-column frame elements with uniaxial fiber sections at the integration points. Bond-slip rotation at the column-footing interface was modeled using a rotational spring element with bilinear moment-rotation behavior. The bilinear behavior was calculated using the procedure presented by Wehbe et al. (1999). The global effect of shear deformation was included in the analytical models for columns with AR = 3.0 using a multi-linear rotational spring element; shear deformation was not included in columns with AR greater than 3.0. The properties of this element were calculated using the shear stiffness model proposed by Correal et al. (2007). Unconfined concrete was modeled using the Concrete01 material and confined concrete was modeled using the Concrete04 material. Confined concrete properties were determined using Mander's Model. Longitudinal steel reinforcement was modeled using the ReinforcingSteel material. The material properties for concrete and steel were based on expected deigns properties reported in Caltrans' SDC. Mechanical splices were modeled using an idealized model based on uniaxial tensile tests (Haber et al., 2014b) and implemented using the ReinforcingSteel material. The stress-strain behavior of the mechanical splice fibers was calibrated to be representative of a stiff splice with low ductility similar to the grout sleeve coupler (GC) device; these properties are more conservative for predicting reduction in column displacement ductility capacity. Models were subject to monotonic lateral push-over analysis using displacement control, and included P-Δ effects. Axial load was applied to the tip of each model such that ALI = 0.1. Lateral displacement was imposed until concrete core crushing occurred, which was defined at the failure point.

Results

Figure 7 shows the distribution of plastic hinge curvatures at the on-set of concrete core crushing for three different L_{sp}/d_b ratios when AR = 6.0 and the splice location $H_{ped} = 0.25D$. As a point of reference, the HC and GC splices used in previous tests had L_{sp}/d_b ratios approximately equal to 3.0 and 14.5, respectively. It can be observed that as the length of the splice increases, the length over which plastic rotation can occur decreases. Thus, the ductility capacity of the column is reduced. The effects of splice length and location (pedestal height) on ductility capacity are shown in Figure 8 for each aspect ratio; three of the five splice lengths are presented. The calculated displacement ductility capacity is shown as a function of pedestal height. A horizontal dashed line indicates the ductility for a corresponding conventional column ($\mu_C \approx 7.0$) without mechanical splices. As would be expected, that largest reductions in ductility occur when splices are placed at the footing surface ($H_{ped} = 0$); it should be noted that results presented for $H_{ped} = 0$ where extrapolated. When $H_{ped} = 0$, the displacement ductility capacity of precast models varied between 85% and 92% of that from corresponding baseline models depending on splice length and AR. Furthermore, it can be observed that splice length has a greater effect on columns that are dominated by flexural deformation. In general, splice lengths greater than $4d_b$ can have a significant effect on ductility capacity depending on placement with the hinge.

As expected, ductility capacity is shown to improve as the distance H_{ped} increases. However, after a certain point, lengthening the distance H_{ped} does not provide further enhancement of ductility capacity. Thus, there is a minimum distance H_{min} that needs to be provided such that columns with MS connections emulate the behavior and ductility capacity of a corresponding conventional column. The relationship between H_{min} and the splice-to-bar length ratio (L_{sp}/d_b) is shown in Figure 9-a for each aspect ratio. It can be observed that H_{min} is more dependent on AR than L_{sp}/d_b. Figure 9-b presents the same data as Figure 9-a, but H_{min} has been normalized by the analytical plastic hinge length, L_p, as defined by Caltrans' SDC. This plot indicates that for most parameter combinations used in this study, a pedestal length of L_p may be considered an upper bound for design purposes.

PART 3 – On-Going Research Efforts

This part of the paper provides an overview of research currently being conducted at the University of Central Florida (UCF) focused on behavior of precast bridge columns with MS connections employing GC splices. Although previous studies with GC connections showed that emulative behavior and ductility can be realized using a CIP pedestal below the spliced region, this detail may not be the most practical for ABC projects. Construction of pedestals may require added on-site labor, materials and formwork, which could reduce time savings and increase cost. Furthermore, when pedestals aren't used with GC connections, damage tends to occur in adjacent members, which are typically capacity-protected, as a result of plasticity redistribution. The goal of this research project is to develop alternative details for MS connections employing GC splices that provide improved displacement ductility capacity compared with previous designs, and reduce damage in capacity-protected elements.

The full study will incorporate experimental testing of six scaled bridge column models, tensile testing of grouted splice assemblies, numerical analysis and parametric study, and development of more well-defined design methods for MS connections with GC splices. The first round of experimental testing includes four bridge column models (two precast and two CIP), which are currently under construction, and investigates the use plastic hinge shifting for improving ductility capacity of precast columns with GC connections. Furthermore, two different column aspect ratios will be used, AR = 2.5 and AR = 4.0, to investigate the effect of shear intensity on column behavior.

The concept of plastic hinge shifting has been used in the past for post-earthquake bridge column repair (Lehman et al., 2001; Park et al., 2014), but has not been typically used in new construction. Figure 10 presents a comparison of the plastic hinge locations for previously tested GC connections and the proposed detail that would promote hinge formation above the GC splice region. To shift the plastic hinge zone, the plastic moment capacity of the section at the column-footing interface must be increased relative to the section located above the grouted splices. To achieve this objective using currently available grouted splice technology, a transition splice detail can be employed along with high-strength reinforcing bars in the footing. Transition splicing refers to using a smaller bar in one end of the splice and a larger bar in the other. That is, for example, if the section above the grouted splices was designed using ASTM A706 Gr. 60 #10 bars then the section at the interface of the capacity-protected member would employ ASTM Gr. 1035 Gr. 100 (or Gr. 120) #11 bars. A #11 grouted splice would be used to join the two different bar types. Although the moment demand is higher at the base of the column, larger, higher-strength bars significantly increase the yield moment such that the critical section exists above the grouted splices. The design objective of this detail is to prevent damage in the capacity-protected member and allow a well-distributed plastic hinging to form above the grouted splice region.

Overall Summary and Concluding Remarks

This paper provided insight into previous and current research on mechanically spliced connections for precast columns in seismic zones. Three different, but related topics were discussed: previous research conducted at the University of Nevada, Reno, current analytical work investigating the effects of splice length and location, and an overview of current experimental work being conducted at the University of Central Florida.

Column tests at UNR indicated that mechanical bar splices are a viable option for use in ABC substructures in seismic zones. However, emulative design procedures may not be appropriate for all splice types. Placement of mechanical splices within the plastic hinge zone can affect formation and behavior of the plastic hinge mechanism, which can result in lower displacement ductility capacity. Shorter splices, such as the upset headed (HC) splice, may not have a significant effect on where plastic rotation occurs whereas larger splices, such as the grouted sleeve splice (GC), are likely to change the plastic hinge behavior. Lastly, depending on detailing and splice type, pedestals may or may not improve the seismic performance of precast columns. Precast pedestals with grout-filled corrugated steel ducts in the pedestal increase section rigidity thus inhibiting well-distributed plastic rotation. Cast-in-place pedestals provide better distribution of plasticity and may allow for emulative design practices.

The effect of splice length and splice location within the plastic hinge region was further investigated analytically using OpenSEES. Relationships were generated to correlate ductility capacity with splice length, location, and column geometry. Results indicate that the pre- and post-yield stiffness of mechanical splices should be considered in ductility calculations when the L_{sp}/d_b ratio is greater than 4.0. Results also provide insight into minimum CIP pedestal length, H_{min}, required such that precast columns with MS connections behavior emulative of conventional columns.

The proposed “Shifted Hinge Design” method, which is being investigated at UCF, may provide a solution to some of the previous issues identified with MS connections employing GC splices. This detail could minimize damage in adjacent capacity-protected elements through the use of high-strength reinforcing bars, and improve ductility compared to previously tested details without using a CIP pedestal below the spliced connection.

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Disclaimer

The publication of this paper does not necessarily indicate approval or endorsement of the findings, opinions, conclusions, or recommendations either inferred or specifically expressed herein by the California Department of Transportation, Federal Highway Administration, or the United States Government.

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Tables

Table 1. Column Design Details

Design Parameter	
Cross-section:	Circular–24in [610 mm] Dia.
Longitudinal Reinforcement:	11–No. 8 Bars [25.4 mm Dia.]
Longitudinal Reinforcement Ratio:	1.92%
Transverse Reinforcement:	No. 3 Spiral with 3" Pitch [9.5 mm Dia. Bar with 51mm Pitch]
Transverse Reinforcement Ratio:	1.05%
Aspect Ratio:	4.5
Design Axial Load, P_{axial}:	226 kip [1005 kN]
ALI -P_{axial} / (f'_c * A_g):	0.10

Table 2. Test Matrix and Results

Model ID	**Splice Type**	**Pedestal Details**	**Ultimate Drift (%)**	**Displacement Ductility Capacity, μ_c**
CIP	None	No pedestal	9.93	7.36
HCNP	Up-Set Headed (HC)	No pedestal	9.85	6.49
HCPP	Up-Set Headed (HC)	Precast	10.3	7.07
GCNP	Grouted Sleeve (GC)	No pedestal	5.95	4.52
GCPP	Grouted Sleeve (GC)	Precast	5.93	4.53
GCDP	Grouted Sleeve (GC)	Cast-in-place with debonded Bars	7.90	6.32

Figures

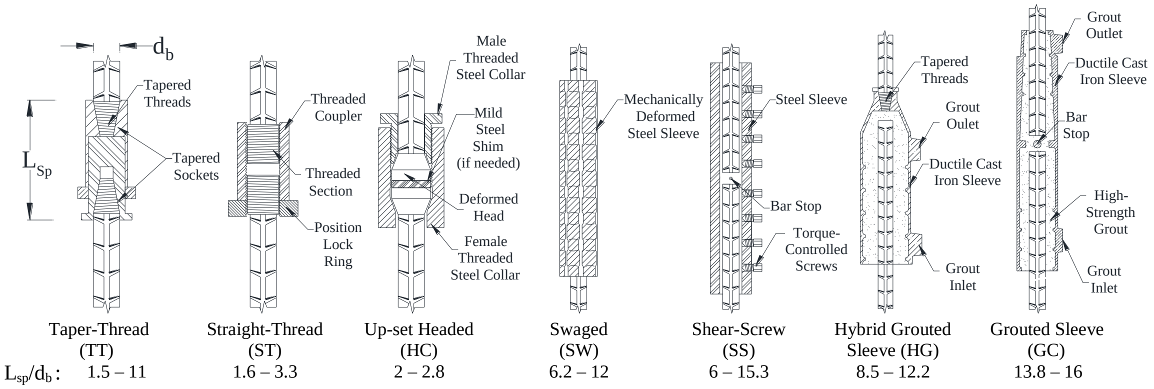
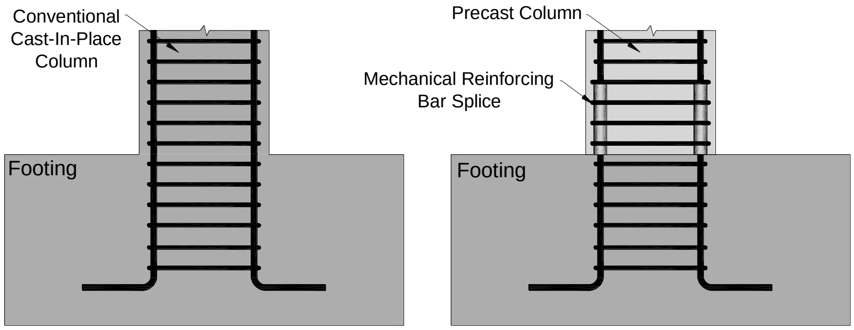


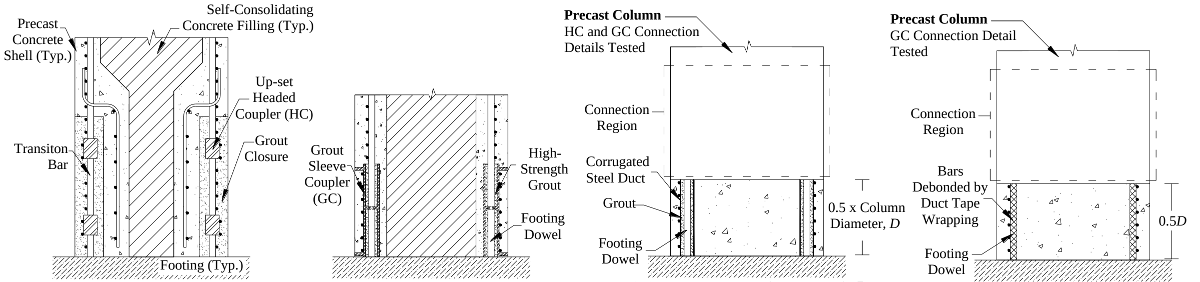
Figure 1. Commercially-Available Mechanical Reinforcing Bar Splices



Conventional System

Precast Column System with a Mechanically-Spliced Connection

Figure 2. Comparison Between Conventional Bridge Column Connections and Mechanically Spliced Precast Column Connections



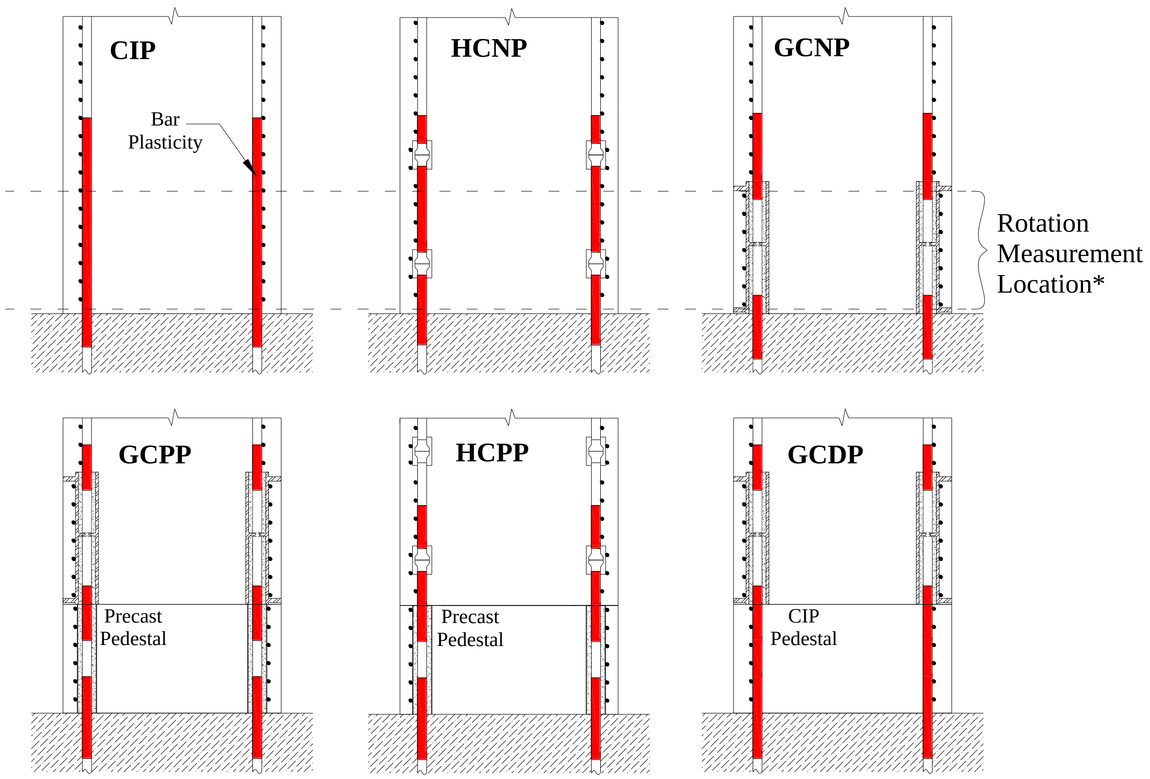
(a) HC Connection Detail

(b) GC Connection Detail

(c) Connection With Precast Pedestal

(d) Connection With CIP Pedestal

Figure 3. Connection Details Tested at the University of Nevada, Reno: Details (a) – (c) Tested by Haber et al., 2014a, and Detail (d) tested by Tazarv and Saiidi, 2014



* Rotation measurement data shown in Figure 5

Figure 4. Observed Plastic Hinge Formation

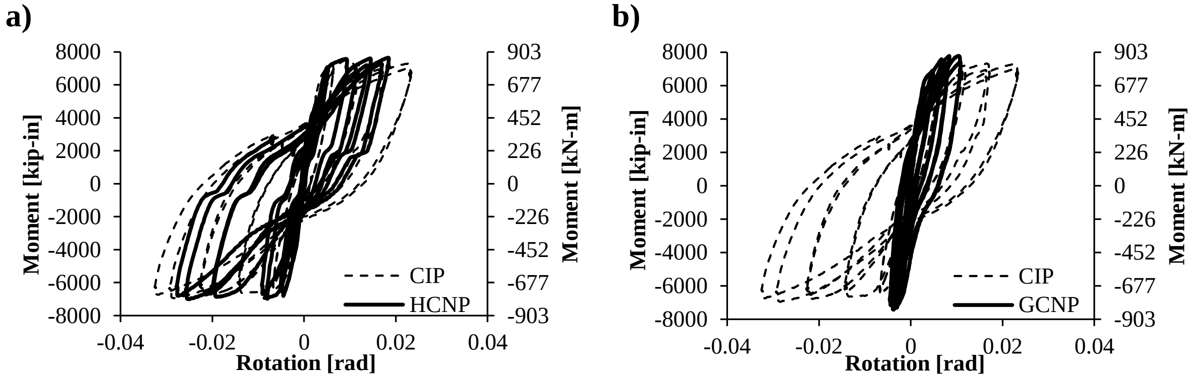


Figure 5. Measured Moment-Rotation Relationships: (a) Comparison of CIP and HCNP, and (b) Comparison of CIP and GCNP.

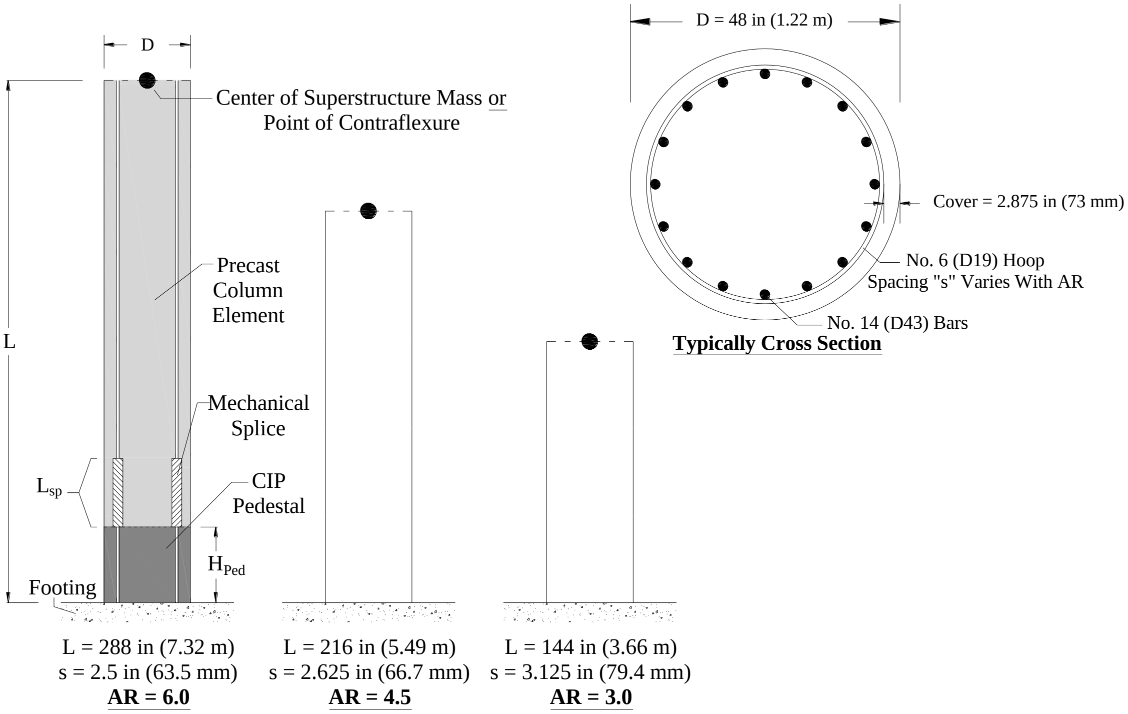
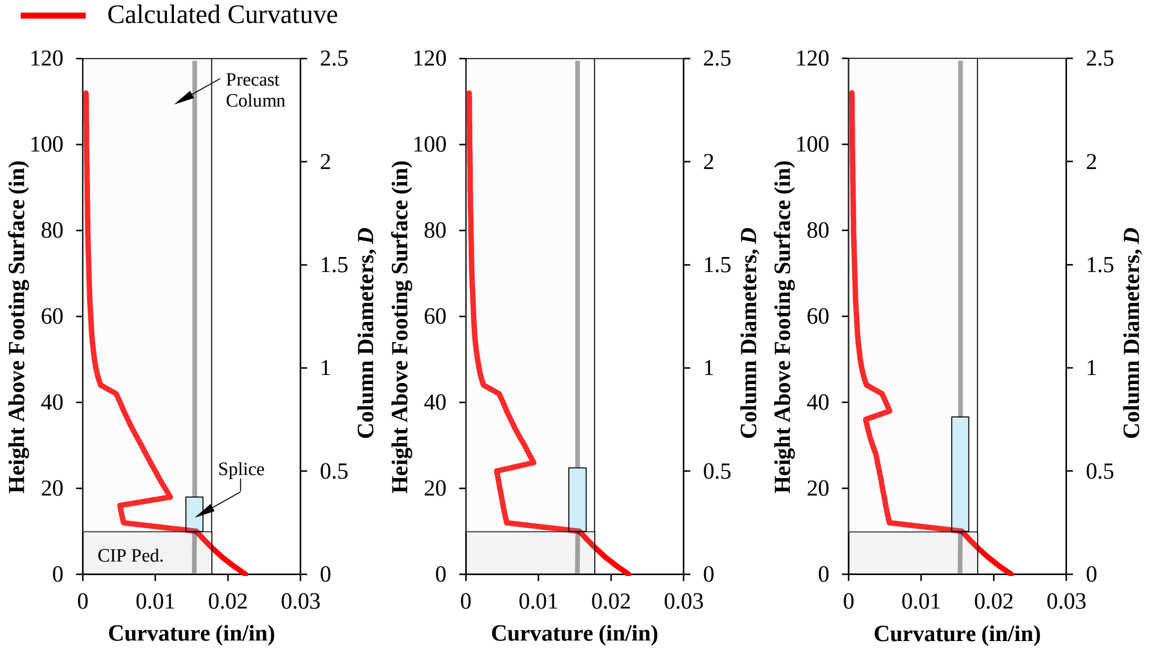
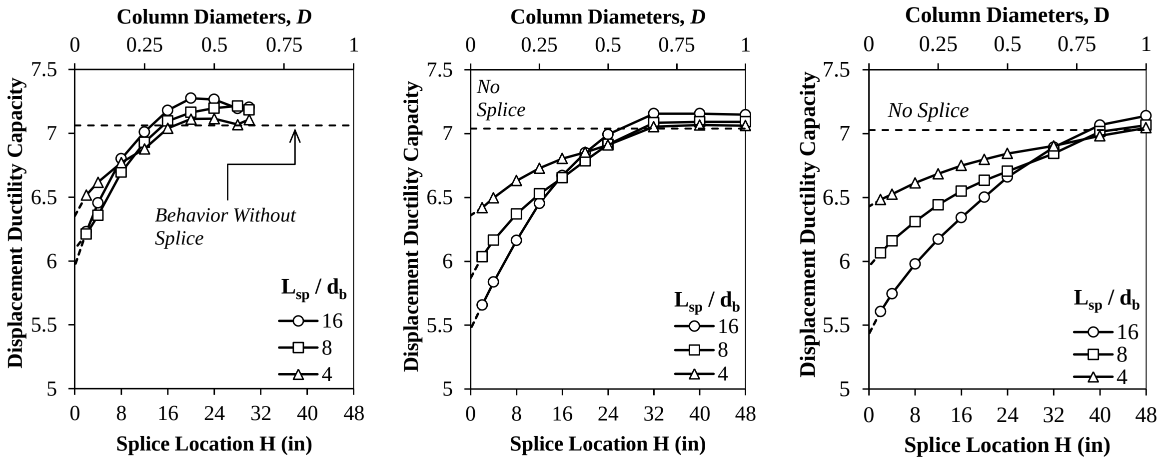


Figure 6. Column Details for Parametric Study



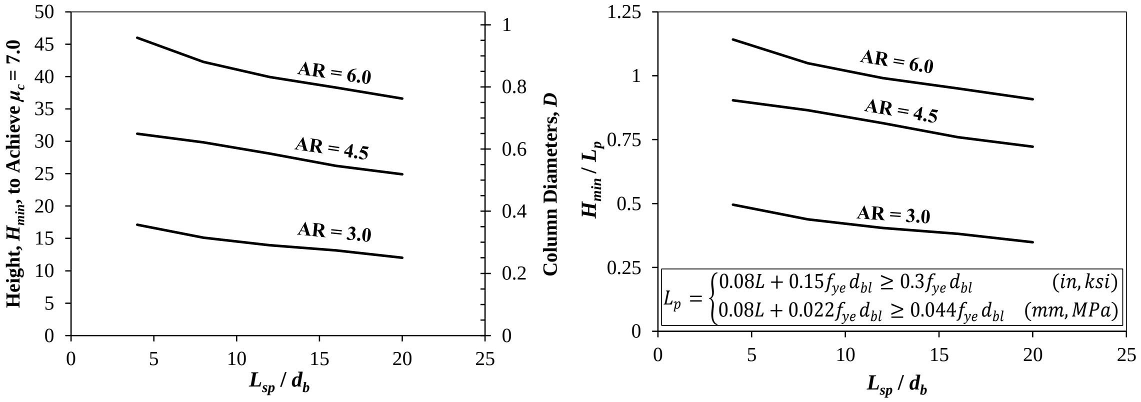
(a) $L_{sp} / d_b = 4$ (b) $L_{sp} / d_b = 8$ (c) $L_{sp} / d_b = 16$

Figure 7. Example of Plastic Hinge Behavior with Different Size Splices



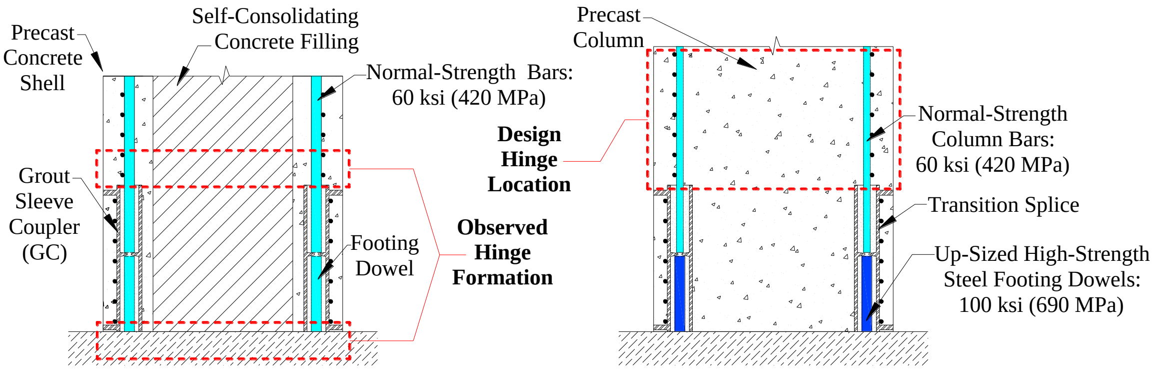
(a) AR = 3.0 (b) AR = 4.5 (c) AR = 6.0

Figure 8. Effect of Splice Length and Location on Displacement Ductility Capacity



(a) (b)

Figure 9. Splice Length and Placement Requirements to Achieve Emulative Behavior



GC Detail Tested By Haber et al., 2014

GC Shifted-Hinge Detail to be Tested by Haider Al-Jelawy et al., 2014

Figure 10. Comparison of Hinge Formation Locations