EXPERIMENTAL AND NUMERICAL STUDIES ON PRECAST BRIDGE COLUMNS WITH SHIFTED PLASTIC HINGING

H. M. Al-Jelawy¹ and K. R. Mackie², Z. B. Haber³

ABSTRACT

Grouted sleeves (GSs) have received considerable attention from transportation agencies and contractors for use in accelerated bridge construction (ABC) connections in seismic zones because of their good construction tolerances and load transfer between precast concrete elements. This paper presents the experimental and numerical results of three large-scale precast column models with GS connections and one traditional cast-in-place (CIP) model. The GS columns were designed and tested using a shifted plastic hinge (SPH) mechanism that shifted the critical section above the sleeve region. The experimental program investigated the effect of splicing details and moment gradient on SPH formation and thus ductility. The columns were subjected to quasi-static cyclic loading in a cantilever configuration. A numerical modeling procedure using force-based beam column elements with fiber sections was developed for GS and CIP column models. Strain penetration of the bar into the footing and both ends of GS coupler was incorporated using rotational springs. The numerical model was calibrated with material tests and uniaxial tension tests on the GS assemblies. The numerical results showed good agreement with the experiments when comparing the hysteretic load-displacement, achieved ductility level, and energy dissipation.

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ABSTRACT

Grouted sleeves (GSs) have received considerable attention from transportation agencies and contractors for use in accelerated bridge construction (ABC) connections in seismic zones because of their good construction tolerances and load transfer between precast concrete elements. This paper presents the experimental and numerical results of three large-scale precast column models with GS connections and one traditional cast-in-place (CIP) model. The GS columns were designed and tested using a shifted plastic hinge (SPH) mechanism that shifted the critical section above the sleeve region. The experimental program investigated the effect of splicing details and moment gradient on SPH formation and thus ductility. The columns were subjected to quasi-static cyclic loading in a cantilever configuration. A numerical modeling procedure using force-based beam column elements with fiber sections was developed for GS and CIP column models. Strain penetration of the bar into the footing and both ends of GS coupler was incorporated using rotational springs. The numerical model was calibrated with material tests and uniaxial tension tests on the GS assemblies. The numerical results showed good agreement with the experiments when comparing the hysteretic load-displacement, achieved ductility level, and energy dissipation.

Introduction

Accelerated bridge construction (ABC) is gaining attention in the US due to many advantages compared with conventional cast-in-place (CIP) construction such as reduced construction time, improved product quality, reduced traffic interruptions, better work zone safety, and reduced cost. ABC methods commonly utilize precast concrete elements connected together using mechanical couplers. Grouted sleeve (GS) couplers are popular commercially available mechanical splices due to good construction tolerances and load transfer between the precast elements. Although ABC has been used in low seismic regions, use in moderate to high seismic regions is limited, especially for substructure connections due to lack of seismic performance data. Connection regions for precast substructure elements typically coincide with plastic hinge zones and are subject to high deformation demands.

Bridge columns with GS connections have only been subject to a limited number of

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investigations in the US [1-4]. Research thus far has indicated some performance issues related to this type of connection detail for seismic applications [1,3,4]. Although alternative connection details have shown improved results [2,3,4], they may create constructability issues. For example, a concrete pedestal needs more on-site construction time [2], and coupler placement inside the footing creates reinforcement congestion [3,4]. Furthermore, adequate debonded length may not be provided by bridge contractors [3,4]. Given the demand for ABC and popularity of GS coupler connections, there is a need to develop improved connections details.

A new connection detail for precast columns with GS couplers was recently proposed and validated [5]. The proposed connection detail uses the shifted plastic hinging (SPH) concept to relocate the critical column section above the sleeve region. SPH mechanism has been used previously for new building construction [6]. In bridge engineering applications, SPH has been mainly used for repair of earthquake-damaged columns [7-9]. The SPH was achieved using staggered bars (smaller bar diameter in the factory end) with high-strength bars in the capacity-protected element. Results of the experimental validation program showed improved performance compared with previously tested details.

The objective of this paper is to present a simplified numerical model that can describe the cyclic GS precast column behavior. The results presented herein include experimental testing and analysis of four large scale circular bridge column models: one CIP and three precast columns with GS connections from previous work [5]. The testing matrix was selected to perform experimental and numerical investigation on the effect of splicing details and moment gradient on SPH formation and thus ductility. All columns have a fixed aspect ratio (AR) of 4.0. The model is then used to study the response of a full-scale prototype column with GS sleeve and bar sizes typical of an actual bridge column.

**Experimental Program**

**Design Concept**

In the conventional CIP column, well-distributed plasticity occurs at the column base producing adequate displacement ductility capacity. In the typical GS connection detail, plasticity is concentrated at the interface between the column and the adjacent capacity-protected member. This concentration limits plastic rotation and ductility capacities. In the proposed SPH detailing, the plastic hinge zone is shifted above the sleeve region by increasing the plastic moment capacity of the section at the column-footing (or column-cap) interface relative to the section located above the GSs. To achieve this using GS technology, a transition splice detail can be employed along with high-strength reinforcing bars in the capacity-protected element. Transition splicing refers to using a smaller bar in the factory end of the splice sleeve and a larger bar in the field end. That is, for instance, if the section above the grouted sleeves was designed using Gr. 60 #7 bars then the section at the interface of the capacity-protected member would employ Gr. 100 #8 bars, and the connection is spliced with sleeve size designed for #8 bars.

**Specimen Details**

A total of four columns were used from previous work [5]: one CIP and three precast columns. The precast columns were designed using the proposed SPH detailing in which the plastic hinge
zone is shifted above the sleeve region. Three column models were approximately 0.42-scale and one model was 0.33-scale assuming a full-scale bridge column has a diameter of 48 in. The testing matrix is shown in Table 1 and detailed specimen design is shown for one precast column in Fig. 1a. The first letter of the column ID, “C” or “G”, denotes if the column was CIP or precast with GS connections, respectively. The second identifier indicates the column AR. Herein the AR is defined as the ratio between cantilever height (distance between the footing surface and loading point) and the column diameter. The first set of columns (C-40-1 and G-40-1) were tested to examine proof of concept. The CIP column model (C-40-1) was designed using the elasto-plastic analysis procedure outlined in Caltrans Seismic Design Criteria (SDC) [10] to have a target displacement ductility of $\mu \approx 7.0$, while G-40-1 was designed to achieve the same approximate plastic lateral load capacity of C-40-1, assuming the plastic hinge forms above the sleeve region. The second set of columns (G-40-2 and G-40-3) was designed using a simplified DBD procedure [5] that accounts for the sleeve region to achieve a target displacement ductility of $\mu \approx 7.0$. The columns were tested to examine the effect of splicing detail (G-40-2) and moment gradient (G-40-3) on SPH formation.

Table 1. Testing matrix

<table>
<thead>
<tr>
<th>Column ID</th>
<th>Construction Method</th>
<th>Diameter (in)</th>
<th>Aspect Ratio</th>
<th>Reinforcing Ratios</th>
<th>Longitudinal Bar Sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Long.</td>
<td>Trans.</td>
</tr>
<tr>
<td>C-40-1</td>
<td>CIP</td>
<td>20</td>
<td>4.0</td>
<td>1.95%</td>
<td>0.74%</td>
</tr>
<tr>
<td>G-40-1</td>
<td>Precast</td>
<td>20</td>
<td>4.0</td>
<td>1.43%</td>
<td>0.74%</td>
</tr>
<tr>
<td>G-40-2</td>
<td>Precast</td>
<td>20</td>
<td>4.0</td>
<td>1.43%</td>
<td>1.11%</td>
</tr>
<tr>
<td>G-40-3</td>
<td>Precast</td>
<td>16</td>
<td>4.0</td>
<td>1.59%</td>
<td>1.13%</td>
</tr>
</tbody>
</table>

- $^a$ Denotes reinforcement ratio within the column shaft
- $^b$ High-strength steel - ASTM A1035 Grade 100
- $^c$ Normal-strength steel - ASTM A615 Grade 60

The columns were tested at the Structures Laboratory at the University of Central Florida in a single cantilever configuration. A 100-kip actuator was used to apply a drift-based displacement control protocol. The testing setup is shown in Fig. 1b. Drift levels of 0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 6, 8 and 10%, each contained two full cycles, were applied in succession or until failure, which was characterized by a 20% loss of lateral load capacity. The applied axial load corresponded to an axial load index (ALI) of 0.08; ALI is defined as the ratio of axial load divided by the product of column cross sectional area and concrete compressive strength. Strain gauges were installed on the reinforcement cage of the column shaft and the footing at different layers ranging from below the footing surface and through the plastic hinge region. The column models were instrumented externally with linear variable displacement transducers (LVDTs) to measure bond-slip, curvatures, and shear deformations within the expected plastic hinge zone.

**Description of The Numerical Model**

The proposed numerical model was developed in OpenSees framework using force-based (FB) beam and rotational zero-length elements. For the CIP column, one FB element with five integration points was used. For GS precast columns, one FB element with three integration
points was used in the sleeve region, and a second FB element with five integration points was used in the shaft region. The Gauss-Lobatto integration scheme was used both CIP and precast columns. Fiber sections with uniaxial material models were assigned to the integration points. The Concrete01 material was used for both the concrete cover (unconfined concrete) and the core (confined concrete) fibers. For the confined concrete, Mander’s model [11] was used to define the parameter values. The Steel02 material was used with tensile testing results to model longitudinal steel bar fibers.

![Figure 1. Design details of precast column G-40-1 and test setup](image)

A modified stress-strain behavior using the ReinforcingSteel material was used for the GS fibers in the sleeve region. The tensile behavior of the GS splices was similar in trend to the steel bar behavior but stiffer. Two parameters, $SR_E$ and $SR_I$, express the ratio of the stress-strain behavior of the coupler region in GS splices and the steel bar in the elastic region and inelastic region, respectively. The parameter $SR_E$ was always 1.0 and $SR_I$ was less than 1.0. The parameter $SR_I$ for GS splices in this paper are 0.54, 0.4, and 0.5 for G-40-1, G-40-2, and G-40-3 columns, respectively. Details of the modified stress-strain material model can be found in Reference [12]. The Fatigue material was used to capture bar fracture due to low-cycle fatigue, and the parameters of this material were taken from Hawileh et al. [13].

The rotational zero-length elements were used at locations where bar strain penetration (bond-slip) would occur. That is; they were used at the column–footing interface of CIP and GS precast columns and above the sleeve region of GS precast columns. A bilinear moment-rotation relationship was assigned to the springs to account for bond-slip rotation following the method proposed by Wehbe et al. [14] for column-footing interface and reused afterwards to account for bond slip rotation above sleeves [15]. Moment-curvature analysis was performed for the sections at which bond-slip rotation occurs. Then slip of the extreme longitudinal bar was determined,
after which rotation could be obtained.

Results

Observed Damage

Damage of the column models was observed to examine the SPH mechanism. Figs. 2 and 3 depict the damage state for all columns at 4% drift and failure, respectively. Before 4% drift cycles, each column exhibited hairline flexural cracking that widened with increased drift levels. Also, inclined shear cracks began to form gradually. Localization of flexural cracks occurred near the column-footing interface for C-40-1 (CIP), since high tensile strains developed near the column base.

Flexural cracks localization for precast columns occurred above the sleeve region, as expected, due to high tensile strains and strain penetration of the column bars into the GSs. Also, the precast columns utilized a rubber cap on the top of GSs preventing column concrete from entering the sleeve during casting. This cap effectively debonds the longitudinal bars over a very short length, approximately 2.5 in., resulting in increased rotations for a given applied load. At 4% drift level (Fig. 2), columns C-40-1 and G-40-1 exhibited minor spalling at the base (Fig. 2a and 2b), while G-40-2 and G-40-3 showed more extensive spalling and exposed transverse reinforcement (Fig. 2c and 2d).

At failure (Fig. 3), all columns exhibited extensive spalling, fractured spirals and buckled and/or fractured longitudinal bars. However, two primary failure locations were observed: near the column base for C-40-1 and above the sleeve region for all GS precast columns. Also, significant delamination of footing concrete was observed for C-40-1 due to strain penetration of longitudinal bars (Fig. 3a). GS precast columns had minor spalling in the sleeve region and it was least observed in G-40-2 column (Fig. 3c) which had higher transition index and employed larger, stiffer coupler sleeve. Lastly, GS precast columns showed very little damage to the footings, which indicates minimal strain penetration into the footing as a result of the enlarged HS bars.

![Figure 2. Damage conditions at 4% drift – north side.](image-url)
Figure 3. Damage conditions at failure – east and west sides

Load-displacement Relationship

The measured and predicted hysteresis loops for all column models are shown in Fig. 4. The measured ductility capacity is also plotted for pull and push directions. Also, a summary of key results is listed in Table 2. All columns exhibited stable hysteresis behavior with wide hysteresis loops. All columns achieved very good average displacement ductility $\mu_{\text{avg}}$, which is the average of ductilities in the push and pull directions, compared with the target design ductility (refer to Table 2).

The measured plastic load for columns was comparable to the design plastic load except for G-40-1 column model. This was caused by a slight construction error that led G-40-1 to be constructed with 29% more cover concrete above the sleeve region. The predicted behavior from the numerical modeling showed a good agreement with the measured hysteresis loops and point of longitudinal bar fracture due to low-cycle fatigue. Note that for C-40-1 model, low-cycle fatigue parameters were not used in the modeling because the column failed by bar buckling. The hysteresis behavior and displacement ductility showed that the selected design parameters ($I_T$ and moment gradient) did not have an influence on the hysteresis behavior of GS precast columns.

![Load-displacement Relationship](image)
Table 2. Summary of lateral load and ductility results

<table>
<thead>
<tr>
<th>ID</th>
<th>Plastic Shear, $V_p$ (kip)</th>
<th>Displacement Ductility, $\mu$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.</td>
<td>Design</td>
<td>Model</td>
<td>Exp.</td>
</tr>
<tr>
<td>C-40-1</td>
<td>44.8</td>
<td>44.7</td>
<td>44.6</td>
<td>7.75</td>
</tr>
<tr>
<td>G-40-1</td>
<td>37</td>
<td>41.75</td>
<td>37.3</td>
<td>7.0</td>
</tr>
<tr>
<td>G-40-2</td>
<td>44.1</td>
<td>44.4</td>
<td>44.5</td>
<td>6.3</td>
</tr>
<tr>
<td>G-40-3</td>
<td>30.3</td>
<td>28.9</td>
<td>29.6</td>
<td>6.6</td>
</tr>
</tbody>
</table>

*Calculated using measured material properties

*Calculated according to DBD procedure in Caltrans [11]

Energy Dissipation

The equivalent damping ratio, $\zeta_{eq}$, is used to compare the energy dissipation between column models. The damping ratio normalizes the energy dissipation with respect to the effective stiffness. Fig. 5 presents the damping ratio for all four columns up to 6% drift. The average of the two full cycles at each drift level is shown in the plot. Prior to yielding (1% drift), $\zeta_{eq}$ is low, after which it starts to increase as the longitudinal steel yielding initiates and propagates. All four columns showed good energy dissipation capacity after the onset of yielding. The precast columns showed comparable energy dissipation to the CIP column.

To better compare the hysteresis behavior of the 2-D modeling procedure with the measured response, the predicted energy dissipation was calculated using the enclosed areas of the hysteresis loops and shown in Fig. 6 for cycles 1 and 2 for all columns up to a reliable drift level. It can be seen generally that the predicted energy dissipation from the simplified modeling approach is comparable to the measured response.
Figure 5. Equivalent damping ratio for the column models

Figure 6. Measured and predicted energy dissipation for the column models
Prototype Column Modeling

The simplified 2-D numerical model was used to analyze a full-scale GS precast column. A bridge column geometry representative of single-column bents commonly found in California was selected for analysis. The column has a diameter of 48 in, cantilever length of 288 in (AR = 6.0), 20 # 11 Gr. 60 ASTM A615 longitudinal steel bars (longitudinal reinforcement ratio of 1.72%), and double #5 hoops spaced at 5 in (transverse reinforcement ratio of 1.14%). The longitudinal steel bars in the column shaft were spliced with #14 Gr. 100 ASTM A1035 steel dowels in the capacity-protected element using a #14 sleeve size. The ALI was selected to be 0.08 (724 kip). The parameter $S_{RE}$ and $S_{RI}$ for GS couplers splicing #11 Gr. 60 to #14 Gr. 100 bars were determined from tensile testing to be 1.0 and 0.376.

![Figure 7. Predicted hysteresis loops of a full-scale bridge column](image1)

![Figure 8. Stress-strain hysteresis of the longitudinal bars above and below sleeve region](image2)

The predicted hysteresis loops are depicted in Fig. 7 along with the predicted bar fracture due to low-cycle fatigue. The column shows a stable and wide hysteresis behavior with a ductility of 7.25 before failure. The hysteretic stress-strain behaviors of the extreme longitudinal bars at locations directly above and below sleeve region are plotted in Fig. 8. The normal strength bar (Gr. 60) in the critical section above the sleeve region showed good energy dissipation. The high strength bar (Gr. 100) showed almost linear behavior due to the enlarged bar size (#14) and the use of SPH mechanism. The maximum recorded stress was 92.1 ksi, which is below the minimum specified tensile strength of the sleeve.

Conclusions

The main goal of this study was to present a simplified numerical model to predict the behavior of grouted sleeve (GS) precast columns. Four large-scale column models were used from previous work to validate the numerical modeling. Experimental results showed that SPH mechanism can be used for flexure and flexure-shear precast columns to achieve a significantly improved ductility capacity. Different design details such as higher transition index and moment gradient did not affect SPH formation. Furthermore, the proposed numerical model was very simple and produced acceptable behavior of GS precast columns. The numerical model showed...
that GS precast columns with SPH mechanism can be used in full-scale bridge columns.

Acknowledgments

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