DEVELOPMENT OF PRELIMINARY STRUT-TIE MODELS
FOR PRECAST BENT CAP CONNECTIONS
(CAST-IN-PLACE AND GROUTED DUCT)

A Project

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by
David Van Zanen

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Department of Civil Engineering
Abstract

DEVELOPMENT OF PRELIMINARY STRUT-TIE MODELS FOR PRECAST BENT CAP CONNECTIONS (CAST-IN-PLACE AND GROUTED DUCT)

by

David Van Zanen

This report, Development of Preliminary Strut-Tie Models for Precast Bent Cap Connections (Cast-in-place and Grouted Duct), develops strut-tie models (STM) for precast bent cap-column connections using the NCHRP 12-74 Grouted Duct (GD) and Cast-in-Place (CIP) specimens. In development of these STM’s, the bent cap bar strains from the specimens were compared against three theoretical models: beam theory, 2D strut-tie models, and 3D strut-tie models.

The beam theory analysis used statics, moment-curvature analysis, and actual material properties of the specimens to determine the theoretical bent cap bar strains. The 2D STM, based on the modified external strut force transfer model (EFTM) proposed in the literature, was established using the computer aided strut-and-tie (CAST) program. Through an iterative process, a refined 2D STM was developed for both the push and pull test directions by comparing specimen strain data to CAST output. An
important modification to the EFTM-based STM was the addition of a tension tie at the bottom cap face (as tested) for the pull direction. This corresponded to tension strain present in test data and made the CAST model stable. Based on the 2D STM, the 3D STM was created in the SAP 2000 structural analysis program. The 3D STM incorporates out-of-plane effects related to actual column bar positions and allows a more accurate representation of the two primary mechanisms assumed in anchoring column tension forces: clamping mechanism and splice transfer mechanism.

The beam theory results included limited comparisons of actual-to-theoretical flexural strains for two locations adjacent to the joint, top vs. bottom bars, and CIP vs. GD specimens. The average percent differences of the actual to the theoretical strains for the CIP was 49 and 146 for the compression bar, 12 inches away from the cap face and at the cap face, respectively. Over the entire range of loading stages, differences in actual-to-theoretical strains were generally larger for locations closer to the joint, indicating a more pronounced local disturbance compared to locations further away from the joint. Bars that were in compression for most of the loading sequences exhibited a much closer match to theoretical strains than bars that were primarily subjected to tension. Local cracking and other effects are believed to have influenced gage readings. CIP and GD strains for the same locations generally displayed similar trends and values, especially for bars in compression.

Compared to beam theory, results of the 2D STM analysis indicated a closer correlation between actual and theoretical strain. The difference between actual and theoretical strains for the CIP specimen were limited to 28 percent and averaged
approximately 16 percent for both push and pull directions. For the GD specimen, the differences were as large as 44 percent except for one location, which reached a 98 percent difference. On average, the differences averaged 27 percent in the push direction and the 45 percent in the pull direction. This increased accuracy reflects the more realistic representation of the flow of forces within a joint and their effects.

The 3D STM showed the closest correlation between the test data and theoretical analysis. Actual to theoretical strains for the 3D STM’s differed by no more than 42 percent and only 14 percent on average. These values were smaller than for any other analytical method. The reason is because the 3D mechanisms associated with anchoring the column tension force were more accurately detailed and accounted for in the 3D model.

Conclusions from these analyses include: 1) beam theory does not accurately represent strains that develop in longitudinal reinforcement at the face of CIP and precast bent cap joints; 2) the limit of the disturbed (D) region appears to extend a distance of approximately half of the bent cap depth (h_b/2) from the face of the joint; 3) the developed 2D STM, including the additional tension tie, provides a reasonably simple and accurate model for the flow of forces through a bent cap joint using CIP or GD connections; 4) the modified EFTM requires an additional tension tie in the pull direction to accurately represent tension that develops in the exterior face of bent caps; 5) the developed 3D STM is the most complicated yet accurate model for analyzing joint forces and associated reinforcement strain in a CIP or precast bent cap joint; 6) the presence of ducts in the GD specimen did not noticeably affect specimen strain values compared to
the CIP specimen nor affect the development or results of the 2D or 3D STM’s; and 7) analytical results from this study do not indicate the need for any changes to existing NCHRP 12-74 recommendations for non-integral precast bent caps using CIP or GD connections.

Based on results of this analysis, the following are recommended for future study: 1) perform finite element analysis (FEA) of the CIP and GD specimens in the pull direction to confirm the need for the additional tension tie; 2) further develop the 2D STM, with special focus on determination of strains in the joint hoops and joint stirrups (interior and exterior) and comparison to test data; 3) perform FEA for CIP and GD precast bent caps to validate the three splice transfer mechanisms and their impact on joint behavior; and 4) incorporate data from the CSUS Preliminary Grouted Duct specimen to supplement these analytical results.

_____________________, Committee Chair

Eric E. Matsumoto, Ph.D., P.E.

_____________________

Date
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Disclaimer

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Chapter 1

INTRODUCTION

1.1. Background

1.1.1. Overview

Currently in the United States there are thousands of bridges in use that have been classified as structurally deficient or obsolete. [2] According to the American Society of Civil Engineers (ASCE) website, out of all the bridges in California 12% are considered structurally deficient and an additional 16.8% are considered functionally obsolete. [3] Typical bridge construction projects can take several months and potentially years to complete and can disrupt traffic causing delays. The Federal Highway Administration (FHWA) has been promoting the philosophy of accelerated bridge construction (ABC), and since 2008 the practice of ABC has been adopted by Caltrans. The goal of ABC is to complete bridge construction at a fast pace, reduce traffic delays and hazards during construction, and provide economic savings not only in potential construction costs but to the regional economy as a whole and the traveling public. [4] With this in mind, new construction methods need to be employed to speed up construction.

Precast concrete has been used for years and has proven to speed up bridge construction time and lower overall construction costs. Constructing a precast structural element away from the site can provide reliable quality control by ensuring that the concrete cures in a controlled environment. [2] With the concrete curing ahead of time and being delivered to the site there is a significant savings in cost and construction time.
The use of precast can reduce the need to construct falsework and having to wait for the concrete to cure before removal of the falsework.

Precast bent caps have been used for non-integral bridges in regions of the United States that have little to no seismicity. Figure 1-1 shows the use of a precast bent cap being used in the state of Texas. However, to be able to adopt the use of precast bent caps in regions with high seismicity, testing and analysis are required to demonstrate their effectiveness with seismic forces.

1.1.2. Testing at CSUS

"To address the uncertainties associated with seismic behavior of precast bent cap systems and the lack of specifications, the National Cooperative Highway Research Program (NCHRP) funded Project 12-74, Development of Precast Bent Cap Systems for Seismic Regions, to develop design methodologies, design and construction specifications, design examples, and semi-standard details for seismic precast bent cap systems using emulative and hybrid connections for non-integral and integral systems." [2, p. 3] Emulative connections are meant to behave (or "emulate") a typical cast-in-place connection so that there will be plastic hinging and energy dissipation of a seismic loading. This type of performance is desired for areas with high seismic activity. [2] The testing for NCHRP 12-74 included 4 specimens at California State University, Sacramento (CSUS) and four specimens at University of California, San Diego (UCSD). See Table 1-1 for a list of the CSUS NCHRP 12-74 specimens. In addition to the specimens listed in Table 1-1, a specimen not officially part of the NCHRP 12-74 testing program called the Preliminary Grouted Duct Specimen (PGD) (Unit 5) was also tested.
This report will focus on the Cast-in-Place specimen and the Grouted Duct specimen that were tested at CSUS. Figure 1-2 shows the Grouted Duct specimen being lowered in to position before grouting. Figure 1-3 shows the Cast-in-Place Specimen being constructed at Clark Pacific.

1.1.3. Strut-Tie Method used in Joints

One of the more recent theories used in analyzing the beam-column joint region are strut-tie models. Strut-tie models or methods (STM), also known as strut-and-tie models or methods, were first proposed by Ritter [5] and Morsch [6] over a hundred years ago. As technology has progressed, the means to test STM have developed into a more sophisticated theory where it has been used to determine several code provisions in reinforced concrete design. It has proven to be a rational, unified and safe approach to designing concrete structures. [7]

The first step in using STM is to identify where the B-regions are, where traditional beam theory applies, and where D-regions are, also known as discontinuity regions. D-regions occur near regions of concentrated loads, corbels, joints or any other places were abrupt changes may occur in the structure. In these D-regions forces are carried by the in-plane forces of concrete compression struts or steel reinforcement tension ties. [8, p. 753] Generally in the past, the orientation of the struts and ties, or topology, of a strut-tie model has been designed by "rules of thumb" or engineering judgment. [9] However, in more complex cases, such as beam-column joints, a more refined analysis for the design of these structures is warranted.
Prior to the San Fernando earthquake in 1971, beam-column connections were detailed without any thought to shear reinforcement which resulted in significant damages to bridges. After 1971 and prior to the Loma Prieta Earthquake in 1989 the common practice was to simply extend the beam and column shear reinforcement into the joint region. [1] After the 1989 Loma Prieta earthquake a survey of the damaged bridges in the bay area revealed many failures in the beam-column region, and it was believed that many of the failures of the San Fernando earthquake were misdiagnosed as column failures. [10] After the Loma Prieta earthquake a more concerted effort has been made to research and to prevent damage in the joint region during a seismic event and to avoid a collapse failure by allowing the energy to dissipate in a ductile column in order to ensure life safety criteria.

1.2. Research Objective

The objective of this report is to develop a preliminary strut-tie model for the emulative precast bent cap connection and a further understanding of strut-tie methods being used in column-joint regions in general. This will be done by using theoretical analytical computer models and comparing them against actual data collected from the Cast-in-Place and Grouted Duct specimens.

1.3. Significance of Research

The overall goal of this research is to pave the way for further research into precast bent cap systems being used in areas of high seismicity in order to gain greater acceptance within the engineering community. With the adaptation of precast bent caps being used in seismic regions this will help lower construction costs, decrease
construction times and provide cost savings benefit to the community and to the traveling public.

1.4. Literature Review

1.4.1. Literature Review Overview

The development of an appropriate strut-tie model for a particular structure is an iterative process based on trial and error, but also requires engineering judgment and experience. Once the D-region has been established, Yun [11] [9] outlined a process of developing a strut-tie model that can be summarized in the following steps: (1) develop a preliminary topology of strut-tie model using past research and common sense guidelines; (2a) calculate the force vectors within the STM frame; (2b) determine if the thickness of the struts and ties fall within the geometry constraints of the structure and if not re-evaluate the geometry of the STM frame; (3) once a suitable strut-and-tie model is created then it is evaluated using a finite element analysis (FEA) model and checked to see if the results are similar to the strut-and-tie model. If the FEA model does not verify the results of the STM then the FEA model or the STM model will need to be evaluated.

1.4.2. Determining the Strut-Tie Topology

Determining a proper geometry of a strut-tie model in the preliminary phase can greatly reduce the time and effort spent on developing a working strut-tie model. As mentioned before, engineering judgment and past experience can play a role, but also more standardized methods have been developed. The performance-based optimization (PBO) technique algorithm was proposed by Liang et al. [7] as a method of finding a truss model within structure. The PBO itself is an iterative process that uses the finite
element analysis results of a structure. Once the model is run, the designer removes
regions of concrete that are deemed ineffective in carrying loads, thus reducing the
weight of unnecessary concrete. [12]

A similar method called the evolutionary optimization (ESO) mentioned by Kwak
and Noh [13] is an alternative method that uses several brick elements, each composed of
six truss elements. After a preliminary analysis is run, a systematic removal of the brick
elements that have the least amount of strain energy will reveal a strut-tie model. Kwak
and Noh state that "the ESO is a simple and straightforward, because the use of a fixed
finite element model to represent the initial design domain avoids the necessity of
remeshing" the finite element model. [13] Leu et al. [12] expand on the ESO model and
use a refined ESO (RESO) model for a three-dimensional strut-tie topology refinement.
However, the analysis done by Leu et al. is limited to linear analysis and does not take
into account nonlinear effects.

1.4.3. Strut-Tie Analysis Tools

Since the development of a strut-tie model can involve several iterations which
can be time consuming and labor intensive. This is particularly true for a very complex
computer graphics program called NL-STM as a method to evaluate and perform a linear
or nonlinear strut and tie analysis. The computer-aided strut-and-tie (CAST) design tool
is also proposed by Tjhin and Kuchma [14] as an effective means to analyze strut-and-tie
models linearly or nonlinearly. Both programs operate in a 2D environment and assume
a uniform thickness of the D-region being analyzed.
As mentioned earlier, a finite-element analysis is often used to verify any strut-and-tie modeling that may be done. To further simplify and speed up the analysis of the FEA verification process, Tjhin and Kuchma [15] and Park et al. [16] discussed an enhanced version of CAST currently being developed called CAST2FEA. In CAST2FEA a suitable finite element mesh to be used in a nonlinear FEA program called Plane NL will be built automatically off of an existing CAST model. This integrated platform will speed up the time that a designer can create a strut-and-tie model in CAST and then verify it in a FEA analysis.

1.4.4. Strut-Tie Development for Beam-Column Joints

The most recent and extensive research in beam-column joint design has been presented in two companion papers by Sritharan [1] [17] as well as a doctoral dissertation [10]. The external strut force transfer method has been used to design and analyze beam-columns in bridge joints. Sritharan proposes a modified version of the strut-and-tie model called the external strut force transfer method (EFTM). The modified EFTM is derived from two main mechanisms that develop from two tension ties that come from the tension forces in the column rebar at the ultimate limit state of when the column experiences plastic hinging: (1) the clamping mechanism and; (2) the splice mechanism. Both mechanisms exert approximately 50% of the total column tension force into the joints and are anchored by concrete struts. Sritharan [17] proposes a modified EFTM based on research of tested specimens where: (1) the external strut of the clamping mechanism (See strut C2 in Figure 1-4) was shown to act over a distance $h_b/2$ at an angle of $45^\circ$ where $h_b$ is the total depth of the column; and (2) the adaptation of a splice
mechanism that extends to the top of the cap. Sritharan [17] concluded that the longitudinal reinforcement should be increased when there is no prestressing and the joint shear reinforcement outside of the joint region should be spread out over a distance of 1.0 times the cap depth on both sides of centerline of column.

1.4.5. Finite Element Analysis of Concrete Structures

There are many different types of nonlinear finite element analysis programs currently in use with each using different modeling approaches. In an analysis of column displacement responses, Mosttafæi et al. [18] compared two different FEA software programs, VecTor2 and UC-win/WCOMD. Each program used different concrete material properties with: (1) VecTor2 using a smeared rotating cracks and; (2) UC-win/WCOMD using smeared fixed cracks. Both programs showed to be useful for analysis up to the ultimate load state, but the VecTor2 software proved highly reliable for shear-critical problems and provided reliable results for even post-peak response.

Much of the ideas behind the modified EFTM were built on the nonlinear finite element analysis as presented by Sritharan et al. [19] [10]. For the finite element analysis software the authors primarily relied on ABAQUS with ANAMAT material interface. The analysis performed indicated the importance of modeling the bond slip that results from the strain penetration into the cap beam from the column longitudinal reinforcement which was modeled using a rebar force transfer (RFT) element in the joint region. Sritharan et al. [19] concluded that without proper modeling of the bond slip in the column reinforcing into the cap, the stress and strain contours were not accurately modeled. Bond slip can happen by two different methods: (1) due to inadequate
anchorage of the column reinforcement and; (2) due to strain penetration into the joint. [10, pp. 65,66] The finite element analysis also provided the nature of the splice mechanism as it is shown in the modified EFTM.

Hansra [20] performed research on a finite element analysis on the Cast-in-Place specimen that was tested at CSUS and compared it to actual data collected. The modeling only focused on the push sequence of the testing where the actual specimen was subjected to reverse cyclical loading. The finite element analysis was performed using the LS-DYNA finite element program using the Kazagozian & Case Damaged Concrete model for the concrete material. The steel rebar used a plastic kinematic model. Strain-hardening effects were not considered in this analysis. The conclusion of the report was that the finite element analysis accurately captured the nonlinear behavior of the beam-column connection.

1.5. Scope of Report

This report will provide a basis of a preliminary strut-tie model that can be used for a precast bent cap joint. This effort will use actual strain gauge test data from the NCHRP 12-74 specimens: the Cast-In-Place (CIP) specimen and the Grouted Duct (GD) specimens. This actual data, primarily the bent cap flexural bars, will be compared against different theoretical models, namely flexure theory, two-dimensional strut-tie models, and a three-dimensional strut and tie model. Computer models will be used to calculate the theoretical values that the actual data will be compared against. This report will include the following chapters:

1.0 Introduction
2.0  Flexure Theory Applied to Joint Region
3.0  Development of a 2D Strut-Tie Model
4.0  Development of a 3D Strut-Tie Model
5.0  Summary, Conclusions and Recommendations
1.6. Tables

Table 1-1. CSUS Component Test Matrix for Bent Cap-Column Connections [2]

<table>
<thead>
<tr>
<th>Test Unit</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cast-in-place (CIP)</td>
<td>Control specimen for comparison to precast connections, with bent cap and column detailing intended to achieve full ductility</td>
</tr>
<tr>
<td>2. Grouted Duct Connection (GD)</td>
<td>Individual ducts cast in bent cap to connect each column bar, with bent cap and column detailing intended to achieve full ductility</td>
</tr>
<tr>
<td>3. Cap Pocket Full Ductility (CPFD)</td>
<td>Single pipe cast in bent cap to connect all column bars, with bent cap and column detailing intended to achieve full ductility</td>
</tr>
<tr>
<td>4. Cap Pocket Limited Ductility (CPLD)</td>
<td>Single pipe cast in bent cap to connect all column bars, with bent cap and column detailing intended to achieve limited ductility</td>
</tr>
<tr>
<td>5. Preliminary Grouted Duct (PGD)</td>
<td>The PGD was built with similar details to the GD specimen except with larger column rebar size and a thicker bedding layer.</td>
</tr>
</tbody>
</table>
1.7. Figures

Figure 1. Precast Bent Cap System Used in Crossing of State Highway 36 Over Lake Belton, Texas [21]

Figure 2. Grouted Duct Bent Cap Being Lowered in to Position Prior to Being Grouted
Figure 1-3. Cast-in-Place Specimen Being Constructed on Site at Clark Pacific

Figure 1-4. Partial Diagram of Modified External Strut Force Transfer Method [17]
Chapter 2

BENT CAP LONGITUDINAL REINFORCING STRAINS - BEAM THEORY VS. TEST DATA

This chapter presents the results of a comparison of actual data from the longitudinal bent cap bar strains from the CIP and the GD specimens to a theoretical analysis using beam theory applied to the bent cap. The theoretical analysis uses moment-curvature to provide theoretical strains at sections of the bent cap where the bent cap bars strain gages are located.

2.1 Specimen Design Background

The specimens were based on a prototype bridge that consists of two 100 foot spans (See Figure 2-1) with a precast girder supported deck with a nonintegral bent supporting the spans at the middle of the bridge (see Figure 2-2 thru Figure 2-5). A bridge like the prototype bridge is based on a typical overpass bridge that could be used in an urban environment. The design of the test specimens are based on a 42% scale of the middle column bent T-joint of the prototype bridge bent. This scale factor came from the scaling of the 48 inch column in the prototype bridge to a scaled 20 inch column of the specimen \((20/48 = 0.42)\). The as-built construction drawings for the specimens are provided in Figures 2-6 thru 2-8 and Figures 2-9 thru 2-13 for the Cast-in-Place and the Grouted Duct specimen respectively. The prototype and specimen design calculations are shown in a report previously submitted to the NCHRP Panel. [22] Since the focus of this research is to examine the behavior of the joint region much of the instrumentation was placed in this region. The specimen instrumentation drawings are shown in Figures
2-14 to 2-17 and Figures 2-18 to 2-22 for the Cast-in-Place and Grouted Duct specimen respectively.

As stated in the introduction there are two regions that a concrete structure can be divided into, the D-region which can be analyzed by the strut-tie method and the B-region where the beam theory analysis is traditionally used. As proposed by in Sritharan [1] the disturbed region of the joint expands to a distance of $h_b/2$, where $h_b$ is defined as the depth of the cap, from the face of the column. As a preliminary analysis of the bent cap, the longitudinal bent cap bar strains recorded during testing were checked against the theoretical analysis of the bent cap using traditional beam flexure theory. The main purposes for this initial analysis was to assess the accuracy of beam theory at the joint face within approximately $h_b/2$ of the column face. Additionally, the moment curvature analysis will establish the boundary conditions of the joint region for the strut-tie analysis discussed in this report.

2.2 Specimen Testing

After construction, the specimen was placed into the inverted position for testing with a vertical actuator used to simulate dead load. A horizontal actuator was used to simulate the seismic load, loading the column, quasi-statically, in a push (pushing the column stub towards the south) and pull (pulling the column stub towards the north). The loading occurred in 2 stages, the force control stage and the displacement control stage. In the force control stage the horizontal actuator pushed and pulled the column stub to a specified load in order to locate first yield moment of the column ($M_Y$).
Once the initial yield of the column was established, the idealized yield
displacement of the column (\( \Delta_Y \)) was calculated. In the displacement controlled stage the
horizontal actuator displaced the column stub to a specified push or pull displacement
with the intent that it be displaced based on a multiples of \( \Delta_Y \) (\( \mu_1 = 1 \times \Delta_Y \), \( \mu_{1.5} = 1.5 \times \Delta_Y \),
etc.) Figures 2-23 shows the column force-displacement hysteresis for the Grouted Duct
specimen and an envelope showing the maximum push (positive) and pull (negative)
forces. For the purposes of this report however, only the peak forces that occur during
each cycle along the envelope are of interest. The reason for this is because the
displacement and ductility of the column have no bearing on how the joint is analyzed in
this report.

Table 2-1 and Table 2-2 show the peak forces for the push and pull cycles for the
Cast-In-Place and Grouted Duct specimen respectively. For the Cast-in-Place specimen
the tables reflect only when the push or pull increased in force level. Meaning that if the
peak force of a displacement controlled cycle was less than the peak force of a preceding
cycle it was not included in the table. For the Grouted Duct specimen no displacement
control cycles presented a load greater than what was experienced during force control
with the maximum load being experienced during the 55 kip cycle. Since the 55 kip
cycle is also the cycle where the GD specimen reaches and surpasses its plastic moment,
more data points along the 55 kip cycle were plotted. To show a more complete profile
of the bar strains for the 55 kip cycle, force levels within the 55 kip cycle were added as
data points. Force levels at 48.5 kip and 52.3 kip for the push direction and at 48.7 kip
and 52.6 kip for the pull direction were also included.
2.3 Moment-Curvature Analysis of Bent Cap

In order to find the theoretical strains using flexure theory, the bent cap was modeled in moment-curvature software called XTRACT. In XTRACT a reinforced concrete section is created and meshed into small elements with each element assigned a material property of unconfined concrete, confined concrete or steel reinforcement. In a step-by-step analysis, XTRACT can determine the moment to a given reinforced concrete section and numerous results including the theoretical stress-strain of the individual mesh elements (i.e. concrete or rebar).

In order to establish an accurate XTRACT model, actual material properties were modeled in the program based on the testing of concrete cylinders collected during construction and rebar tested from the same batch as the rebar used in construction. For the actual concrete material properties used, see Table 2-3 and Table 2-4 for the CIP specimen and the GD specimen respectively. Confined concrete properties were modeled as explained by Mander and Priestley. The properties used for the steel reinforcing bars are shown on Table 2-5 and Table 2-6 for the CIP specimen and the GD specimen respectively. As shown by the actual data for the CIP and GD, the longitudinal bent cap bars never reached the yield strain of approximately 2224 microstrain based the yield stress and an assumed modulus of elasticity of 29000 ksi.

2.4 Flexure Theory Applied to the Joint

Important to all moment-curvature analysis of any reinforced concrete section is knowing what the axial force is on the section being analyzed. As shown in the free body diagram in Figure 2-24, the specimen can accurately be modeled as being supported on a
roller-pin connection with the north side of the cap being the pin. Therefore, the horizontal force on the column stub will generate tension or compression in the cap, north of the column, while there is no axial loading on the cap on the south end.

2.4.1 Theoretical Analysis of Bent Cap (South)

Since there is no axial load present, the analysis on the south side of the cap is much simpler than the north. As shown in Figure 2-15 and Figure 2-19, there are two sets of strain gauges on the bent cap bars (LB gauges), right at the column face and 12 inches from the column face. The process of analyzing the theoretical strains at both these locations along the cap can be summarized as follows: (1) analyze a moment curvature model of the cap and; (2) use statics to back calculate the horizontal force on the column stub for the S1 and S2 location.

Prior to running a moment-curvature analysis the solution method in XTRACT was set so there would be several data points being captured in the analysis. The output of the analysis captured the moment of the section and what the strains were in the top and bottom longitudinal bars at each increment of moment on the section. With the moment and equivalent bar strains entered in a spreadsheet, the reaction in the south end of the column was calculated with the following equation:

$$ R_{South} = \frac{M}{L_{gage}} \quad (2.1) $$

where:

$ R_{South} =$ support reaction at the south end

$ M =$ output moment from XTRACT
Knowing the reaction of the south support and based on the free body diagram shown in Figure 2-24, using basic statics the horizontal force on the column stub was solved for, using the following equation:

\[ PH = \left( R_{South} - \frac{PV}{2} \right) \frac{L_{SUP}}{L_{COL}} \]  

where:

- \( PV \) = vertical downward force on the column stub (38 kip)
- \( PH \) = horizontal force on the column stub (push is positive; pull is negative)
- \( L_{COL} \) = distance from PH application to the center of the bent cap
- \( L_{SUP} \) = distance between the supports of the bent cap

Because the specimen was already in the test position and supporting its own weight prior to the strain gage data being recorded, the data did not capture the initial strain present in the bent cap bars due to the self-weight of the specimen. Therefore, the self-weight of the specimen was ignored in the static analysis of the specimen.

2.4.2 Theoretical Analysis of Bent Cap (North)

Since the north side of the bent cap experiences constantly changing axial forces, the same method that was used on the south side of the column could not be used. Although the principles remain same, the process of relating the horizontal force to the theoretical bar strains is reversed. The process of determining the theoretical strain in the bent cap bars on the north side of the cap can be summarized as follows: (1) for each peak horizontal force the bending moment in the cap was calculated at the N1 and N2
strain gage locations; (2) moment-curvature analysis was run with an axial load equivalent for each maximum push or pull cycle as shown in Table 2-1 and 2-2; (3) use the interactive output in XTRACT to find the theoretical bar strain that coincides with the moment calculated in step 1.

Using the free body diagram in Figure 2-24 the vertical reaction at the north end of the cap was solved using the following equation:

\[ R_{North} = \frac{PV}{2} + \frac{-PH \times L_{COL}}{L_{SUP}} \]  

(2.3)

The equation uses the same sign convention as the south side of the bent cap. However, the negative sign (-) associated with the PH is used since the reaction is on the opposite side of the cap. Once the north reaction was calculated for a particular PH, the moment was then calculated at the strain gauge locations LB-N1 and LB-N2 with the following equation:

\[ M = R_{North} \times L_{Gage} \]  

(2.4)

With the moment calculated for each push and pull cycle shown on Table 2-1 and Table 2-2, an XTRACT model was created and run with the corresponding axial compression (pull cycle) or tension (push cycle) in the section equal to the horizontal force on the column stub. By modifying the solver options in XTRACT, several data points were created in the moment-curvature analysis. Using the interactive output module in XTRACT, the user can step through the analysis of the section to see the material strains of the section mesh associated with the moment of the section. Once the correct moment was located, the bar strain was found by selecting the top and bottom longitudinal bar in the graphic interface. The appropriate bar strain was determined using
the interactive output by finding the moment in the analysis associated with the horizontal force and selecting the longitudinal bar in the graphic of the bent cap section. Figure 2-25 shows the interactive output module for XTRACT and how the bar strains were collected.

2.5 Determination of Actual Bent Cap Bar Strain

As mentioned in Section 2.2, only the peak forces that occur along the force-displacement envelope are of interest. For the force control sequence, once the horizontal force was reached it was then held in that position for a number of minutes during which the marking and measuring of cracks on the specimen was done. During that time strain gages readings would change almost invariably. This effect was more pronounced when a particular gage was in tension. This “drift” in strain gage output does not represent the true nature of the relationship between the bar strains and the horizontal push or pull. The strain gage drift is more likely due to cracks in the column, joint cracks opening up and the concrete degrading. As a result the reinforcing bars would often end up being subjected to more tension. To demonstrate this Figure 2-26 shows a force-displacement response single force controlled loading cycle. The point labeled the “maximum effective push” indicates the moment when the maximum push cycle force (in this case 48 kips) was reached and then held. To remain as accurate as possible and discount any effects of concrete degradation, only the corresponding strain gage data was used at the moment that this maximum effective push or pull had been reached.

For the displacement controlled sequence in the CIP, after a targeted displacement was reached the horizontal load on the specimen, along with the tension strain on the
longitudinal bars, decreased during the marking and measuring of cracks. The relaxing in
the strain and the horizontal load also is due to the degradation of the concrete. Because
of the instantaneous drop in the reaction force in the actuator, once the targeted
displacement was reached the peak force was always located on the envelope.

This drift effect was comparatively non-existent when the longitudinal bent cap
bars were in compression. This effect cannot be predicted in any theoretical model as its
nature is unpredictable.

2.6 Longitudinal Bent Cap Bar Strain Profile

It should be noted that the locations of the longitudinal rebar of the Grouted Duct
specimen were not placed as originally intended. The bars for the Grouted Duct
specimen were placed in reverse with the north gages actually on the south and vice
versa. However, based on the strain profiles it was easily detected and the actual strains
were plotted against the correct strain gage “locations”. These locations are indicated in
the instrumentation plans in Figure 2-15 and 2-19.

Figures 2-27 through 2-30 and Figures 2-31 thru 2-34 show the strain profiles of
the longitudinal reinforcement (top and bottom bars) for the Cast-in-Place specimen and
the Grouted Duct specimen respectively. The strain gages LB13-N2 on the CIP specimen
and the LB10-S1 strain gauge for the GD specimen were lost prior to any testing. The
strain gage LB13-CL for the CIP specimen was lost for the displacement sequence. No
usable data was recorded for the entire LB7 bar for both the CIP and GD and the LB16
bar for the CIP specimen.
The overall trend of the strain data follows an expected pattern with the highest strains occurring as expected at the joint region (S1, CL and N1 positions) and the bottom bar (LB10) showing much more tension strain than the top bar (LB13). As shown in Figure 2-28 and 2-32, the bottom bar strain at the joint face (S1) showed slightly higher strains than the centerline (CL) bar for the push direction but overall the strains were fairly close. In the pull directions this relationship is not present for the centerline gage and the north gage at the joint face (N1). The tension in the cap is the most probable reason for the added tension in the CL gage in the push direction in comparison to the push direction.

2.7 Comparison of Actual Data to Theory

Figures 2-35 thru 2-44 show Force vs. Strain plots for the recorded longitudinal bar strain against the theoretical strain based on moment-curvature results that were calculated as described in the Section 2.5.

The CL strain gages were not plotted against any theoretical prediction. Since the CL gages are directly under the column, flexure theory does not directly apply to the CL gage. Although shown with the rest of the Force vs. Strain plots CL strain plots in this chapter, the strain gage data will be more significant in later chapters of this report. The actual strain and theoretical strain are compared to yield strain as shown in Tables 2-7 thru 2-10 for the CIP and 2-11 thru 2-14 for the GD.

For average percent differences of actual-to-theoretical flexural strains, see Table 2-15. The beam theory results included limited comparisons of actual-to-theoretical flexural strains for two locations adjacent to the joint, top vs. bottom bars, and CIP vs.
GD specimens. Over the entire range of loading stages, differences in actual-to-theoretical strains were generally larger for locations closer to the joint, indicating a more pronounced local disturbance compared to locations further away from the joint. Bars that were in compression for most of the loading sequences exhibited a much closer match to theoretical strains than bars that were primarily subjected to tension. Local cracking and other effects are believed to have influenced gage readings. CIP and GD strains for the same locations generally displayed similar trends and values, especially for bars in compression.

2.7.1 Localized Column Shear Effects

In the top bar strain gages near the column face showed a deviation in the predicted Force vs. Strain as well. Figure 2-36 and Figure 2-41 both show an increase in tension in the LB13-N1 position, where compression is predicted. As the specimen is being pushed there likely some drag forces across the top face of the bent cap due to the shear forces from the column in this direction. This trend is evident only at the higher levels of the horizontal force.

In the pull direction, this was shown conversely at LB13-N1 for the CIP specimen. In this case there was an increase in compression in the pull direction, as shown in Figure 2-38. This showed a jump in the increase of compression strain at this location. The GD specimen showed an exact opposite behavior by showing an increase in tension strain in the pull at the LB13-N1 location, see Figure 2-43. One would expect to find compression at this location similar to the CIP based not only from sectional
analysis from cap, but also from compression from the axial stress in the cap due to the horizontal load.

For the pull direction, however, this display of tension strain only exists on the 55 kip cycle. In looking the LB 13-N1 hysteresis for the GD specimen in Figure 2-45, the 55 kip cycle is shown to be in tension in the pull direction while other cycles show an expected trend. There is no definitive reason for this anomaly. It is possible that cracking in the cap near this location caused a tension reading in the strain gage when a compression was expected. See Figure 2-46 for a picture that illustrates the cracking at the top bar N1 location.

2.7.2 Grouted Duct Bottom Bar Behavior

Figure 2-40 and Figure 2-41 show the Grouted Duct Force vs. Strain at the S2 an S1 location respectively (labeled N2 and N1). In the push direction both gages show close correlation with the predicted tension strain. In the pull direction however both gages show compression, with the more pronounced compression occurring at the LB10-S2 location. The slope of the actual data on the compression strain side of the plot is almost the same as it is on the tension side. This would indicate that compressive stress is not being redistributed to the surrounding concrete as would be expected in sectional analysis. Because of this drastic increase in strain it is possible that there is a localized disturbance at this gage location.

One possibility is that some existing cracks before testing occurred and opened up even more so near the strain gage early on in the test caused some error in the reading of the strain gage. See Figure 2-47 of a photo of the bent cap at the LB10-S1 and S2 region.
It is possible some delamination between the concrete and the rebar, caused the rebar to take more compressive stresses than expected. However, this is not possible to determine with the available testing data.

2.7.3 CIP Displacement Control Offset

Comparing plots of the actual data to the theoretical, there are varying offsets in the actual data trend between the force control and the displacement control sequence. Although the cause is not completely understood; this offset did not change the overall results and conclusions gathered from this data.

2.8 Conclusions for Beam Theory

Based on the actual to theoretical ratios at the point of maximum discrepancy the behavior of the specimen would appear to have not compared very closely to the specimen. However, based on the observed trends the strain gages, the gages at the S2 location agreed more closely to the theoretical analysis than at S1. Due to loss of gages on the north side of the cap, a relative comparison could not be made.
2.9 Tables

Table 2-1. Peak Horizontal Forces — Cast-in-Place Specimen

<table>
<thead>
<tr>
<th>Push Direction</th>
<th>Max Push</th>
<th>Pull Direction</th>
<th>Max Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 kip</td>
<td>13.0 kip</td>
<td>13 kip</td>
<td>-13.3 kip</td>
</tr>
<tr>
<td>20 kip</td>
<td>20.0 kip</td>
<td>20 kip</td>
<td>-20.3 kip</td>
</tr>
<tr>
<td>30 kip</td>
<td>30.1 kip</td>
<td>30 kip</td>
<td>-30.4 kip</td>
</tr>
<tr>
<td>48 kip</td>
<td>48.2 kip</td>
<td>48 kip</td>
<td>-48.5 kip</td>
</tr>
<tr>
<td>µ1.5</td>
<td>49.4 kip</td>
<td>µ2</td>
<td>-50.6 kip</td>
</tr>
<tr>
<td>µ2</td>
<td>53.3 kip</td>
<td>µ3</td>
<td>-53.6 kip</td>
</tr>
<tr>
<td>µ3</td>
<td>55.6 kip</td>
<td>µ4</td>
<td>-54.9 kip</td>
</tr>
<tr>
<td>µ6</td>
<td>55.9 kip</td>
<td>µ6</td>
<td>-57.2 kip</td>
</tr>
</tbody>
</table>

(Negative sign indicates Pull direction)

Table 2-2 Peak Horizontal Forces — Grouted Duct Specimen

<table>
<thead>
<tr>
<th>Push Direction</th>
<th>Max Push</th>
<th>Push Direction</th>
<th>Max Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 kip</td>
<td>13.1 kip</td>
<td>13 kip</td>
<td>-13.1 kip</td>
</tr>
<tr>
<td>20 kip</td>
<td>20.1 kip</td>
<td>20 kip</td>
<td>-20.2 kip</td>
</tr>
<tr>
<td>30 kip</td>
<td>30.2 kip</td>
<td>30 kip</td>
<td>-30.3 kip</td>
</tr>
<tr>
<td>45 kip</td>
<td>45.2 kip</td>
<td>45 kip</td>
<td>-45.5 kip</td>
</tr>
<tr>
<td>55 kip</td>
<td>48.5 kip</td>
<td>55 kip</td>
<td>-48.7 kip</td>
</tr>
<tr>
<td>55 kip</td>
<td>52.3 kip</td>
<td>55 kip</td>
<td>-52.6 kip</td>
</tr>
<tr>
<td>55 kip</td>
<td>55.9 kip</td>
<td>55 kip</td>
<td>-55.41 kip</td>
</tr>
</tbody>
</table>

(Negative sign indicates Pull direction)
Table 2-3. Cast-in-Place Specimen Concrete Material Properties [2]

<table>
<thead>
<tr>
<th>Concrete Parameter</th>
<th>Property</th>
</tr>
</thead>
</table>
| Compressive Strength | Cap: 4553 psi (137 days)  
                        Column: 6178 psi (194 days) |
| Tensile Strength (Split Cylinder) | Cap: 361 psi (5.35 $\sqrt{f'_{c}}$, 138 days)  
                                  Column: 452 psi (5.75 $\sqrt{f'_{c}}$, 195 days) |
| Modulus of Elasticity | Cap: 3811 ksi (137 days)  
                        Column: 4033 ksi (194 days) |

Table 2-4. Grouted Duct Specimen Concrete & Grout Material Properties [25]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>Cap and Column: 4557 psi (194 days)</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>Cap and Column: 3400 ksi (194 days)</td>
</tr>
<tr>
<td>Grout Compressive Strength (Bedding Layer and ducts)</td>
<td>8026 psi (6421 psi, equivalent cylinder strength)</td>
</tr>
</tbody>
</table>

Table 2-5. Cast-in-Place Specimen Rebar Material Properties [2]

<table>
<thead>
<tr>
<th>Rebar Size</th>
<th>Type</th>
<th>Yield Strength (ksi)</th>
<th>Tensile Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#3</td>
<td>Bent cap stirrups; Column hoops</td>
<td>68.2</td>
<td>95.5</td>
</tr>
<tr>
<td>#5</td>
<td>Bent cap longitudinal; Column longitudinal</td>
<td>64.5</td>
<td>90.0</td>
</tr>
</tbody>
</table>
Table 2-6. Grouted Duct Specimen Rebar Material Properties [25]

<table>
<thead>
<tr>
<th>Rebar Size</th>
<th>Type</th>
<th>Yield Strength (ksi)</th>
<th>Tensile Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#3</td>
<td>Bent cap stirrups; Column hoops</td>
<td>64.1</td>
<td>99.0</td>
</tr>
<tr>
<td>#5</td>
<td>Bent cap longitudinal; Column longitudinal</td>
<td>64.5</td>
<td>95.2</td>
</tr>
</tbody>
</table>

Table 2-7. Theoretical vs. Actual Longitudinal Bar Strain — CIP Push LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-S2</th>
<th>LB10-S1</th>
<th>LB10-N1</th>
<th>LB10-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>1169</td>
<td>1345</td>
<td>837</td>
<td>336</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>0.53</td>
<td>0.60</td>
<td>0.38</td>
<td>0.15</td>
</tr>
<tr>
<td>Theoretical</td>
<td>769</td>
<td>1009</td>
<td>74</td>
<td>114</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>0.35</td>
<td>0.45</td>
<td>0.03</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 2-8. Theoretical vs. Actual Longitudinal Bar Strain — CIP Pull LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-S2</th>
<th>LB10-S1</th>
<th>LB10-N1</th>
<th>LB10-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>131</td>
<td>496</td>
<td>1386</td>
<td>961</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>0.06</td>
<td>0.22</td>
<td>0.62</td>
<td>0.43</td>
</tr>
<tr>
<td>Theoretical</td>
<td>-33</td>
<td>-43</td>
<td>758</td>
<td>518</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>-0.015</td>
<td>0.019</td>
<td>0.34</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 2-9. Theoretical vs. Actual Longitudinal Bar Strain — CIP Push LB13

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-S2</th>
<th>LB13-S1</th>
<th>LB13-N1</th>
<th>LB13-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>-163</td>
<td>80</td>
<td>298</td>
<td>N/A</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>-0.07</td>
<td>0.04</td>
<td>0.13</td>
<td>N/A</td>
</tr>
<tr>
<td>Theoretical</td>
<td>-178</td>
<td>-235</td>
<td>418</td>
<td>374</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>-0.08</td>
<td>-0.11</td>
<td>0.19</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 2-10. Theoretical vs. Actual Longitudinal Bar Strain — CIP Pull LB13

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-S2</th>
<th>LB13-S1</th>
<th>LB13-N1</th>
<th>LB13-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>131</td>
<td>342</td>
<td>-493</td>
<td>N/A</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>0.06</td>
<td>0.15</td>
<td>0.22</td>
<td>N/A</td>
</tr>
<tr>
<td>Theoretical</td>
<td>140</td>
<td>168</td>
<td>-238</td>
<td>-187</td>
</tr>
<tr>
<td>$\epsilon/\epsilon_y$</td>
<td>0.06</td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
</tr>
</tbody>
</table>
### Table 2-11. Theoretical vs. Actual Longitudinal Bar Strain — GD Push LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-N2</th>
<th>LB10-N1</th>
<th>LB10-S1</th>
<th>LB10-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>765</td>
<td>1229</td>
<td>N/A</td>
<td>40</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.34</td>
<td>0.55</td>
<td>N/A</td>
<td>0.018</td>
</tr>
<tr>
<td>Theoretical</td>
<td>770</td>
<td>1013</td>
<td>79</td>
<td>347</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.35</td>
<td>0.46</td>
<td>0.04</td>
<td>0.16</td>
</tr>
</tbody>
</table>

### Table 2-12. Theoretical vs. Actual Longitudinal Bar Strain — GD Pull LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-N2</th>
<th>LB10-N1</th>
<th>LB10-S1</th>
<th>LB10-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>-600</td>
<td>-129</td>
<td>N/A</td>
<td>734</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>-0.27</td>
<td>0.58</td>
<td>N/A</td>
<td>0.33</td>
</tr>
<tr>
<td>Theoretical</td>
<td>-31</td>
<td>-260</td>
<td>745</td>
<td>-198</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>-0.01</td>
<td>0.12</td>
<td>0.33</td>
<td>0.09</td>
</tr>
</tbody>
</table>

### Table 2-13. Theoretical vs. Actual Longitudinal Bar Strain — GD Push LB13

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-N2</th>
<th>LB13-N1</th>
<th>LB13-S1</th>
<th>LB13-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>-144</td>
<td>70</td>
<td>719</td>
<td>21</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.065</td>
<td>0.03</td>
<td>0.32</td>
<td>0.01</td>
</tr>
<tr>
<td>Theoretical</td>
<td>-191</td>
<td>-41</td>
<td>416</td>
<td>121</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>-0.09</td>
<td>-0.02</td>
<td>0.19</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### Table 2-14. Theoretical vs. Actual Longitudinal Bar Strain — GD Pull LB13

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-N2</th>
<th>LB13-N1</th>
<th>LB13-S1</th>
<th>LB13-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>110</td>
<td>375</td>
<td>217</td>
<td>-234</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.05</td>
<td>0.17</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>Theoretical</td>
<td>127</td>
<td>167</td>
<td>-252</td>
<td>516</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.06</td>
<td>0.08</td>
<td>-0.11</td>
<td>0.23</td>
</tr>
</tbody>
</table>

### Table 2-15. Average Percent Difference of Actual Strain

<table>
<thead>
<tr>
<th>Gage Location</th>
<th>LB10-S2 (Bottom Bar)</th>
<th>LB10-S1 (Bottom Bar)</th>
<th>LB13-S2 (Top Bar)</th>
<th>LB13-S1 (Top Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIP</td>
<td>303</td>
<td>467</td>
<td>49</td>
<td>146</td>
</tr>
<tr>
<td>GD</td>
<td>718</td>
<td>85</td>
<td>37</td>
<td>141</td>
</tr>
</tbody>
</table>
2.10 Figures

Figure 2-1. Prototype Bridge Plans — Profile Elevation [21]
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Figure 2-30. LB13 Displacement Control Strain Profile — CIP Specimen
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Figure 2-32. LB10 55 Kip Cycle Strain Profile — GD Specimen
Figure 2-33. LB13 Force Control Strain Profile — GD Specimen

Figure 2-34. LB13 55 Kip Cycle Strain Profile — GD Specimen
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Figure 2-36. Force vs. Strain at S1 — CIP Specimen
Figure 2-37. Force vs. Strain at CL — CIP Specimen

Figure 2-38. Force vs. Strain at N1 — CIP Specimen
Figure 2-39. Force vs. Strain at N2 — CIP Specimen

Figure 2-40. Force vs. Strain at S2 (Labeled N2) — GD Specimen
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Chapter 3

DEVELOPMENT OF A PRELIMINARY 2D STRUT-TIE MODEL

This chapter presents the results of a comparison of actual data from the longitudinal bent cap bar strains of the CIP and the GD specimens to a theoretical analysis using a 2D strut-tie model. This chapter also presents a revision to the strut-tie model called the modified external strut force transfer model (EFTM) a presented by Sritharan. [1]

3.1 Strut-Tie Modeling Overview

As mentioned previously strut-tie modeling (STM) is based on the idea that there are areas of discontinuity (D-regions) where beam theory (B-regions) does not apply. In 2D, D-regions the stresses are modeled as in-plane forces like the axial forces in a truss with the tension forces being carried by reinforcing bars and the compressive struts being carried by the concrete. While the idea behind STM is a concept that is easily understood, the difficulty often lies in the creation of the strut-tie model geometry. For a particular concrete element more than one viable truss model can be created. This often requires testing and verification of a model.

The basis of the strut-tie model that is used in this report comes from the modified external strut force transfer model (EFTM) as defined by Sritharan from experimental studies of beam-column connections. [10] The modified EFTM assumes that the total column force, Tc, resulting from the column reinforcement at the column plastic moment. This force can be divided into 2 forces, Tc1 and Tc2, which are anchored into the cap by 2 mechanisms: 1) the clamping mechanism, and 2) the splice transfer as shown in Figure
3-1. The clamping mechanism mainly consists of two concrete struts that anchor TC1 into the cap. The splice transfer mechanism is more complex, transferring TC2 to the top bent cap longitudinal bars, and anchors it primarily with strut joint CDF.

Sritharan proposes three different models for the splice mechanism: the conventional splice model (CSM), the single strut splice model (SSSM), and the symmetric out-of-plane splice model (SOSM) for the splice mechanism, as shown in Figure 3-2. [1] From experimental data Sritharan concluded that individual mechanisms could not be established to have occurred during testing, but it was assumed that all three models were engaged during the final stages of testing. When performing a 2D strut-tie analysis it generally accepted that compression strut trajectories should not cross each other (as shown with struts CGF and CGE). This would indicate a multidirectional stress field in the concrete at the same location would have to develop. It is assumed, however, the splicing mechanism and the clamping mechanism occur out-of-plane from each other where the clamping mechanism occurs closer to the center of the joint, while the splicing mechanism occurs closer to the outside face of the joint. Figure 3-3 shows a column section, indicating which bars are responsible for the clamping and splice transfer mechanisms. Therefore, in this instance a 2D analysis with the struts crossing is assumed to be valid, but requiring a 3D analysis to justify this.

3.2 Computer Aided Strut-and-Tie (CAST) Program

To assist with the STM analysis the computer aided strut-and-tie (CAST) computer program was used to analyze various strut-tie models of the joint region. As mentioned previously, one of the difficulties in developing strut-tie models is the
variability in a potential truss model. CAST can speed up the process of analyzing
different truss models and enable the designer to explore a variety of different modeling
scenarios.

The CAST analysis provides compression and tension forces for the struts and
ties, as well as the reactions for a statically determinate or indeterminate truss system. If
a truss is indeterminate, CAST will use material properties to solve for the truss forces. It
performs a 2D analysis of the truss that assumes a uniform thickness across the entire
member. Once the forces for the struts have been calculated, the depth of the strut can be
calculated by entering allowable stress criteria for the concrete. There is still much
debate on the effective strength of the concrete within a strut as reflected in several codes,
but there is general agreement within the structural engineering community that effective
strength is less than what would be reported by concrete cylinder tests. [14]

3.3 Strut-Tie Model Development

With the aid of CAST and the guidance of the modified EFTM, revised STM
models were developed for the CIP and GD specimens. The new push and pull models
are slightly different from one another due to the presence of an axial force on the north
side of the column. However, for the push and pull directions the same general approach
was used. The strut-tie analysis reflects only the maximum push or pull that was
experienced by the specimen as the modified EFTM was developed for forces consistent
with plastic hinging.

3.3.1 Establishing a Strut-Tie Model Geometry
A procedure similar to what was used by Sritharan to set up the modified EFTM was used in the development of the strut-tie models for the CIP and GD specimens. [1] The steps in determining the model are shown below. Figure 3-4 and Figure 3-5 show a schematic of the truss model for the push and pull respectively.

1. Sectional analysis using moment-curvature of the column was performed to determine the appropriate forces and the horizontal location of TC1, TC2 and C1.

2. Node C was assumed to act at the middle of the effective development length from the end of the column bars. The effective development length for the CIP specimen was based on the following equation.

\[
l_{a,eff} \geq \frac{0.012d_{pl}f_{ye}}{\sqrt{f'_{ce}}} \quad (3.1)
\]

where:

- \(l_{a,eff}\) = minimum anchored length into column (in)
- \(d_{pl}\) = diameter of longitudinal column reinforcement (in)
- \(f_{ye}\) = expected yield stress of longitudinal column reinforcement (psi)
- \(f'_{ce}\) = expected compressive strength of bent cap (psi)

Equation 3.1 is a converted version of the equation that was defined by Sritharan that uses assumes a maximum bond stress between concrete and rebar. [10, p. 92]

From Node C, the strut CAC was assumed to be inclined at an angle of 45° towards Node A. Node A occurs where the CAC intersects the top reinforcing bars. Node A and the corresponding Node B mark the limit of the joint on the tension side of the column.
3. Extent of the joint region on the compression side was assumed, as described by Sritharan, to be at a distance of $h_b$ (total height of the cap) from the centerline of the column which gave Nodes H and I their horizontal location. [1]

4. The same splice mechanism that was used by Sritharan was also used to locate Node D, where the column force $T_{C2}$ intersects with the bottom bars.

5. Node G, supporting the splicing mechanism, is located horizontally in line with the column compression force and vertically with Node C.

6. Node E was logically determined to be the intersection of the top reinforcing bar and the compression force from the column.

7. Sectional analysis using moment-curvature of the cap was used to determine the forces on the north and south boundary of the joint at the maximum push and pull, as well as the vertical location of the tension forces ($T_{B1}$, $T_{B2}$ and $T_{B3}$) and the compression force ($C_{B2}$). The compression force was assumed to act through the centroid of the compression block.

8. All shear forces at the column and cap face were applied as a compression force inclined at a 45° angle. The force of the shear compression strut was determined by multiplying the shear force by a factor of $\sqrt{2}$ to account for the inclined angle. To maintain equilibrium the accompanying boundary force from sectional analysis at the same node had to account for the vertical and horizontal component of the shear force at the column and cap face respectively.

9. The location of Node F, a crucial and iterative step, was determined by trial and error. Various coordinates were tried and compared to the actual strain gage data.
When the closest correlation possible was found, it was assumed that location of Node F had been determined.

The boundary conditions that were calculated in steps 1 and 7 are shown in Table 3-1 and Table 3-2 for the Cast-In-Place specimen and Grouted Duct specimen respectively for the maximum push and pull. Because CAST requires at least 3 reactions for a stable truss model, three of the boundary condition forces were replaced with reactions and labeled R1, R2 and R3. However, due to equilibrium, the reactions forces matched the calculated forces of the boundary conditions exactly.

3.3.2 Push STM Model Development

See Figure 3-6 for push STM truss overlaid with the strain gages. As mentioned in step 9, Node F was located based on the actual strains that were experienced at the peak push. For both specimens the longitudinal cap bars provided the best measure to compare against the STM model and locate Node F. Not having yielded, the cap bars remained linear elastic during the test and provided the most reliable data during the test. The strain in the cap bars were related to the STM tension forces based on the following equation.

\[
T = 12 \text{ bars} \times 0.31in^2 \times 29000ksi \times \frac{\varepsilon}{10^6} \quad (3.2)
\]

where:

\[
T = \text{tension tie force in the bent cap (kip)}
\]

\[
\varepsilon = \text{actual longitudinal cap bar strain (microstrain)}
\]

As mentioned in Chapter 2, there were some gages that didn’t report any usable data or the data that was reported was assumed to have been influenced by possible cracking or
delamination of the bar from the surrounding concrete. To account for this, some assumptions were made on what the strain would likely have been based on behavior from the other specimen and neighboring gages that reported useable strain.

In the push direction tie $T_{AE}$ was assumed to be represented by LB13-CL and tie $T_{DI}$ and $T_{BD}$ were assumed to be represented by gages LB10-S1 and LB10-N1 respectively. Since LB13-CL is closest to Node E it makes sense that this strain gage would represent the tie force coming from Node E. LB10-N1 and LB10-S1 lie closest to the center of their respective struts and it was determined that they would represent their respective struts.

3.3.3 Pull Model Development

In order to solve for the forces in any truss system the model must first be a stable model. Truss stability can be determined by the formula.

$$M - (2 \times j - R) \geq 0 \quad (3.3)$$

where:

- $M =$ number of members in a truss
- $j =$ number of joints in the truss
- $R =$ number of reactions

If the result of the equation is less than zero, then the truss system is unstable and cannot be solved. If the result is equal to zero, then the system is stable and statically determinate. If the result is 1 or greater, the system is stable but statically indeterminate and the member forces will need to be solved by a more advanced structural analysis.
When applying this test to the modified EFTM, the push model shows it is stable and determinate while the pull model is unstable. Figure 3-7 and Figure 3-8 show the push and pull models respectively with their members and joints labeled. The outer members and joints are not labeled since they only deliver a load or reaction to frame and their exclusion does not change the result. In the pull model the tie between Nodes B and D is not shown, whereas, in the pull it is shown. This missing member in the pull is the reason for the instability when compared to the push model.

Based on the stability equation the push model can be made determinate by a) adding a reaction or b) adding an element to the truss. As mentioned earlier in 3.3.1 the reactions of the truss (R1, R2 and R3) matched the calculated reactions exactly. Adding an additional reaction, while making the truss stable, would create an entirely new support system for the truss and cause the reactions to be vastly different from the calculated boundary condition forces. The only option is to add a tension tie from Node B to Node D for the push model.

The modified EFTM, developed by Sritharan, shows this region between Nodes B and D to be only in compression as shown in Figure 3-9. This is understandable since the section analysis of the cap would indicate compression in this area. But based on Figure 2-27, tension is shown to be present in the area between Node B and D at the maximum push. In fact, previous research done by Sritharan, which served as the basis for the modified EFTM, showed that “the bottom beam reinforcement was never subjected to any compression, which was not expected from the section analysis of the beam.” [10, p. 186] This indicates that placing a tie between Node B and D not only will make the
model stable but is validated by actual test data. This tie is assumed as an important tie for the analysis in this report.

Because the pull STM truss is a mirror of the push model, the same strain gages were used to develop the truss model in the pull direction. $T_{AE}$ was assumed to be represented by LB13-CL and tie $T_{DI}$ and $T_{BD}$ were assumed to be represented by gages LB10- N1 and LB10-S1 respectively. Figure 3-10 shows the pull STM truss overlaid with the longitudinal strain gages.

3.4 Rebar Embedment into Cap

Equation 3.1 that was used to calculate the effective rebar length that was proposed by Sritharan assumes the maximum bond stress between the concrete and rebar. [10, p. 92] By comparison, the minimum development length proposed by Priestley et al. is shown in the following equation 3.4. [26, p. 395]

$$l_{dc} \geq \frac{0.025d_{bl}f_{ye}}{\sqrt{f_c'}} \quad (3.4)$$

where:

$l_{dc}$ = minimum anchored length into column (in)

$d_{bl}$ = diameter of longitudinal column reinforcement (in)

$f_{ye}$ = expected yield stress of longitudinal column reinforcement (psi)

$f_c'$ = nominal compressive strength of bent cap (psi)

However, equation 3.4 is for design purposes and therefore is conservative and does not reflect the true development length and does not provide a good guideline on where to anchor the clamping mechanism. Equation 3.4 would provide a development
length double the length of what would be calculated in equation 3.1 which has a more realistic approach in determining the correct location for Node C.

Based on experimental results, the columns for the CIP specimen proved to be well anchored into the cap. The use of this smaller effective development length is validated by Figure 3-11. After the 30 kip cycle, however, the strain gage at mid-depth into the cap was lost, but the remaining data shows that yield strain was reached and that strain penetration went deep into the joint, thus validating the use of equation 3.1.

For the Grouted Duct specimen, prior research done by Matsumoto [27] [28] and Mislinski [29] show that the development length of a bar in the Grouted Duct specimen can be calculated with the equation below.

\[
l_{ac} \geq \frac{2d_{bl}f_{ye}}{f'_{cg}} \quad (3.5)
\]

where:

\(d_{bl}\) = diameter of longitudinal column reinforcement (in)

\(f_{ye}\) = expected yield stress of longitudinal column reinforcement (psi)

\(f'_{cg}\) = the nominal compressive strength of the grout (cube strength) (psi)

However, as mentioned by Matsumoto the grout strength should not be assumed greater than 7000 psi. [21] This equation is also conservative as it incorporates a factor of safety of at least 2.0. [21] Equation 3.5 was divided by the 2.0 safety factor that was incorporated into the equation in order to find a more appropriate effective development length for the Grouted Duct specimen. This effective embedment length was used to find Node C for the Grouted Duct specimen. As shown in Figures 3-12 and 3-13, the Grouted
Duct rebar showed to perform well under loading and showed behavior similar to that of the CIP specimen. Yielding of the bar took place and the column was able to reach its plastic moment. Using the effective embedment length for the Grouted Duct specimen, the vertical location for Node C was essentially the same as the CIP.

3.5 Strut-Tie Model Results

The actual strain gage data for the bent cap bars is shown in Table 3-3 and 3-4 for the CIP and the GD respectively. The actual strains of LB13-CL, LB10-S1 and LB10-S2 were assumed to correspond to the tie force T_{AE}, T_{DI} and T_{BD} in the STM as indicated in 3-6 and 3-7. In the iterative process of locating Node F as mentioned in step 9, the actual strain gage value was divided by the theoretical value from the CAST model. When the three ratio reached as close to 1.0 as possible, Node F was assumed to have been located.

3.5.1 CIP Push Results

The coordinate system of the specimens set up for the CAST model located the X-axis along the bottom face of the cap and the Y-axis thru the centerline of the column. The closest correlation to the actual data was found when Node F was at X=-11.375 in and Y=16.5 in as shown in Figure 3-14. The theoretical tie strains compared relatively well to the actual strains, as shown in Table 3-5, when compared against a yield strain (2224 microstrain) of the bent cap bar.

Because the LB13-CL did not produce any viable results for the maximum push, a value of approximately 680 micorstrain was assumed to occur at the max push. This assumption is close to what was experienced by the GD specimen, showing a similar strain level. In Figure 2-37, the strain is shown to end at the maximum force control at
approximately 500 microstrain. Based on the trend, it is possible that a strain similar to the one assumed of 680.

Despite having to assume a strain at the LB13-CL location, the final coordinates of Node F would not have changed significantly. Based on the truss model, the position of Node F has little effect on the resulting force in the $T_{AE}$ tie. The force in $T_{AE}$ is mainly affected by the force in the clamping mechanism struts.

3.5.2 Cast-In-Place Model Pull Results

For the pull model, the best correlation between actual and theoretical occurred when the Node F was located at $X=14\text{in}$ and $Y = 14.25 \text{ in}$ as shown in Figure 3-15. The theoretical tie strains compared relatively well to the actual strains, as shown in Table 3-5, when compared against a yield strain (2224 microstrain) of the bent cap bar.

Again, in the pull direction at strain was assumed at LB13-CL. Although the last strain recorded at this location was in the push direction and was in compression, the observed trend in the GD, see Figure 2-42 shows that this gage will trend towards a positive strain. If the trend similar to the GD is assumed in the CIP, then the strain in the bottom bar would increase approximately 330 micorstrain. This is based on the increase in strain observed in the GD during the 55 kip cycle. Applying this same difference to the CIP would increase the LB13-CL to approximately 260 microstrain. For lack of better data this is the best assumption that can be made to compare to theoretical data.

As mentioned previously however, the Node F location has little influence over the force that is reported in the $T_{AE}$ tie.

3.5.3 Grouted Duct Model Push Results
For the push model of the GD, the best correlation between actual and theoretical
occurred when Node F was located at X=-10 in and Y = 18.25 in as shown in Figure 3-
16. The theoretical strains compared relatively well to the actual strut-tie model as
shown in Table 3-6 when compared against a yield strain of 2224 microstrain. For this
model the strain at LB10-S1 did not report any data and therefore a reasonable
assumption had to be made. If we assume that the gage in the same position behaves
similarly in the CIP specimen, then a scaled version of that strain can be used as the best
way to approximate the data. Using the LB10-CL data for both the CIP and the GD data,
a scaling factor (1138/1262 = 0.90) was used to multiply the LB10-N1 gage in the CIP.
This established a presumed strain of 755 microstrain.

3.5.4 Grouted Duct Model Pull Results

For the Grouted Duct pull model the most probable coordinates for Node F are at
X = 14.75 in and Y =13.38 in as shown in Figure 3-17. These coordinates are similar to
the Node F coordinates for the CIP. As mentioned in Chapter 2, the data for the LB10-
N1 was believed to be in error due to cracking or possible delamination of the bars, while
the gage at LB10-S1 did not record any data. Based on this, assumed strains were
interpolated from the CIP specimen in an attempt to find a model for the GD pull.

The strain at LB10-CL reported a strain of 747 microstrain and 826 microstrain
for the CIP and the GD specimen respectively. Based on this, the strains in the CIP were
scaled up by a factor (826/747 = 1.11) determined by the CL strains from the CIP and GD
specimen and assumed to be an approximate representation of the strains in the GD.
Even though there is no viable data for the GD specimen to compare to the theoretical, it is believed that this method is the best solution with the available data.

As mentioned in section 2.8.2 there was an anomalous reading of tension strain at the LB13-S1 (N1 location) in the maximum pull direction. The results of the CIP specimen show compression in this region as one would expect and indeed the hysteresis (see Figure 2-45) of the gage also show this with the 55 kip cycle being the exception. Figure 3-9 shows the modified EFTM in the pull direction with the gage in question located between nodes E and H. It is possible that at the relative high pull force, a tension tie was induce between Nodes E and H, with $C_{EF}$ and $C_{FH}$ providing demand load on the bent cap bar at this location. However, as this effect was not observed in the CIP specimen and is therefore only a possibility.

3.6 Joint Shear Behavior

This STM model doesn't explicitly address the analysis of the hoops and the stirrups and how they are affected by the column tension forces. However, actual stirrup strain profiles are provided in Figures 3-18 to 3-21 for the CIP specimen and Figures 3-24 to 3-27 for the GD specimen. Figures 3-22 and 3-23 illustrate where the stirrup strain gages are located with respect to the strut-tie model.

3.7 Conclusions

The actual to theoretical ratios of the bent cap bar strains are provided in Tables 3-5 and 3-6. For the CIP specimen the actual strain data fell within 28 percent of the theoretical data with some actual data being less than 2 percent of the theoretical data. For the GD the actual to theoretical ratios fell within 36 percent with the exception of
LB10-S1 in the push direction and LB13-CL in the pull direction. LB10-S1, however, is an assumed strain based on observed trends from other strain gages.

Overall the actual strain gage data for the CIP agrees well with the theoretical as indicated by the ratios in Table 3-5. The GD specimen, with a few exceptions, also agrees well with the theoretical data. This indicates that within the joint region, STM is a better predictive model than flexure beam theory.
3.8 Tables

Table 3-1. Boundary Condition Forces — CIP Specimen

<table>
<thead>
<tr>
<th>Boundary Condition</th>
<th>Maximum Push</th>
<th>Boundary Condition</th>
<th>Maximum Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force (kip)</td>
<td></td>
<td>Force (kip)</td>
</tr>
<tr>
<td>$C_{C1}$</td>
<td>166.95</td>
<td>$C_{C1}$</td>
<td>173.33</td>
</tr>
<tr>
<td>$C_{C2}$</td>
<td>79.07</td>
<td>$C_{C2}$</td>
<td>80.87</td>
</tr>
<tr>
<td>$C_{B1}$</td>
<td>11.02</td>
<td>$C_{B1}$</td>
<td>6.16</td>
</tr>
<tr>
<td>$C_{B2}$</td>
<td>31.70</td>
<td>$C_{B2}$</td>
<td>11.88</td>
</tr>
<tr>
<td>$C_{B3}$</td>
<td>64.76</td>
<td>$C_{B3}$</td>
<td>63.01</td>
</tr>
<tr>
<td>$T_{C1}$</td>
<td>98.95</td>
<td>$C_{B4}$</td>
<td>65.62</td>
</tr>
<tr>
<td>$T_{C2}$</td>
<td>85.91</td>
<td>$T_{C1}$</td>
<td>98.95</td>
</tr>
<tr>
<td>$T_{B1}$</td>
<td>14.56</td>
<td>$T_{C2}$</td>
<td>93.57</td>
</tr>
<tr>
<td>$T_{B2}$</td>
<td>22.16</td>
<td>$T_{B1}$</td>
<td>14.56</td>
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<tr>
<td>$T_{B3}$</td>
<td>77.49</td>
<td>$T_{B2}$</td>
<td>52.22</td>
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Table 3-2. Boundary Condition Forces — GD Specimen

<table>
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<th>Boundary Condition</th>
<th>Maximum Pull</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Force (kip)</td>
<td></td>
<td>Force (kip)</td>
</tr>
<tr>
<td>$C_{C1}$</td>
<td>173.06</td>
<td>$C_{C1}$</td>
<td>170.40</td>
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<tr>
<td>$C_{C2}$</td>
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<td>88.86</td>
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<td>$T_{B1}$</td>
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<tr>
<td>$T_{B3}$</td>
<td>77.69</td>
<td>$T_{B2}$</td>
<td>51.94</td>
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Table 3-3. Actual Bar Strain and Max Push and Pull — CIP

<table>
<thead>
<tr>
<th>Push or Pull</th>
<th>LB13-S2</th>
<th>LB13-S1</th>
<th>LB13-CL</th>
<th>LB13-N1</th>
<th>LB13-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.91 kip</td>
<td>-163</td>
<td>80</td>
<td>N/A</td>
<td>298</td>
<td>N/A</td>
</tr>
<tr>
<td>-57.19 kip</td>
<td>131</td>
<td>342</td>
<td>N/A</td>
<td>-493</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Push or Pull</th>
<th>LB10-S2</th>
<th>LB10-S1</th>
<th>LB10-CL</th>
<th>LB10-N1</th>
<th>LB10-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.91 kip</td>
<td>1169</td>
<td>1345</td>
<td>1262</td>
<td>837</td>
<td>336</td>
</tr>
<tr>
<td>-57.19 kip</td>
<td>131</td>
<td>496</td>
<td>747</td>
<td>1386</td>
<td>961</td>
</tr>
</tbody>
</table>

(Negative indicates Pull for Force and Compression for strain)

Table 3-4. Actual Bar Strain and Max Push and Pull — GD

<table>
<thead>
<tr>
<th>Push or Pull</th>
<th>LB13-N2</th>
<th>LB13-N1</th>
<th>LB13-CL</th>
<th>LB13-S1</th>
<th>LB13-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.85 kip</td>
<td>-144</td>
<td>70</td>
<td>683</td>
<td>719</td>
<td>21</td>
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<tr>
<td>-55.41 kip</td>
<td>110</td>
<td>375</td>
<td>587</td>
<td>217*</td>
<td>-234</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Push or Pull</th>
<th>LB10-N2</th>
<th>LB10-N1</th>
<th>LB10-CL</th>
<th>LB10-S1</th>
<th>LB10-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.85 kip</td>
<td>765</td>
<td>1229</td>
<td>1138</td>
<td>N/A</td>
<td>40</td>
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<tr>
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<td>-600*</td>
<td>-129*</td>
<td>826</td>
<td>N/A</td>
<td>734</td>
</tr>
</tbody>
</table>

(Negative indicates Pull for Force and Compression for strain)

*Indicates assumed data, see section 3.4

Table 3-5. Theoretical vs. Actual Longitudinal Bar Tie Comparison — CIP

<table>
<thead>
<tr>
<th>Bar</th>
<th>Push Direction</th>
<th>Pull Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LB13-CL</td>
<td>LB10-S1</td>
</tr>
<tr>
<td>Actual</td>
<td>680*</td>
<td>1345</td>
</tr>
<tr>
<td>$\varepsilon/ \varepsilon_y$</td>
<td>0.33</td>
<td>0.60</td>
</tr>
<tr>
<td>Theoretical</td>
<td>552</td>
<td>1367</td>
</tr>
<tr>
<td>$\varepsilon/ \varepsilon_y$</td>
<td>0.27</td>
<td>0.66</td>
</tr>
<tr>
<td>Actual/Theor.</td>
<td>1.23</td>
<td>0.98</td>
</tr>
</tbody>
</table>

*Indicates assumed data, see section 3.4
### Table 3-6. Theoretical vs. Actual Longitudinal Bar Tie Comparison — GD

<table>
<thead>
<tr>
<th></th>
<th>Push Direction</th>
<th></th>
<th></th>
<th>Pull Direction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LB13-CL</td>
<td>LB10-N1</td>
<td>LB10-S1</td>
<td>LB13-CL</td>
<td>LB10-N1</td>
</tr>
<tr>
<td>Actual</td>
<td>683</td>
<td>1229</td>
<td>755*</td>
<td>587</td>
<td>550*</td>
</tr>
<tr>
<td>(\varepsilon/\varepsilon_y)</td>
<td>0.31</td>
<td>0.59</td>
<td>0.36</td>
<td>0.28</td>
<td>0.27</td>
</tr>
<tr>
<td>Theoretical</td>
<td>535</td>
<td>1332</td>
<td>523</td>
<td>296</td>
<td>405</td>
</tr>
<tr>
<td>(\varepsilon/\varepsilon_y)</td>
<td>0.26</td>
<td>0.60</td>
<td>0.25</td>
<td>0.13</td>
<td>0.18</td>
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<tr>
<td>Actual/Theor.</td>
<td>1.28</td>
<td>0.92</td>
<td>1.44</td>
<td>1.98</td>
<td>1.36</td>
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</tbody>
</table>

*Indicates assumed data, see section 3.4
3.9 Figures

Figure 3-1. Splice and Clamping Mechanism [1]
Figure 3-2. Conceptual Models of Splice Mechanisms [1]
Figure 3-3. Clamping and Splice Mechanism Bars

Figure 3-4. Strut-Tie Model in Push Direction
Figure 3-5. Strut-Tie Model in Pull Direction

Figure 3-6. Push Direction Strut-Tie Diagram with LB Strain Gages
Figure 3-7. Push Model Truss Members and Joints (Struts Dashed)

Figure 3-8. Pull Model Truss Members and Joints (Struts Dashed)
Figure 3-9. Modified EFTM in Push Direction [10, p. 182]

Figure 3-10. Pull Direction Strut-Tie Diagram with LB Strain Gages
Figure 3-11. Strain Profile of LC8 Bar — CIP [21]

Figure 3-12. Strain Profile of LC8 Bar — GD [21]
Figure 3-13. Strain Profile of LC16 Bar — GD [21]

Figure 3-14. Push Strut-Tie Model — CIP
Figure 3-15. Pull Strut-Tie Model — CIP

Figure 3-16. Push Strut-Tie Model — GD
Figure 3-17. Pull Strut-Tie Model — GD

Figure 3-18. Strain Profile Top Stirrup Strain Gages FC — CIP [21]
Figure 3-19. Strain Profile Bottom Stirrup Strain Gages FC — CIP [21]

Figure 3-20. Strain Profile Top Stirrup Strain Gages DC — CIP [21]
Figure 3-21. Strain Profile Bottom Stirrup Strain Gages DC — CIP [21]

Figure 3-22. Stirrup Strain Gages Overlaid on Push STM
Figure 3-23. Stirrup Strain Gages Overlaid on Pull STM

Figure 3-24. Strain Profile Top Stirrup Strain Gages FC — GD [21]
Figure 3-25. Strain Profile Bottom Stirrup Strain Gages FC — GD [21]

Figure 3-26. Strain Profile Top Stirrup Strain Gages 55 kip Cycle — GD [21]
Figure 3-27. Strain Profile Bottom Stirrup Strain Gages 55 kip Cycle — GD [21]

Figure 3-28. Strain Profile of Duct 8
Figure 3-29. Strain Profile of Duct 16
Chapter 4

DEVELOPMENT OF A PRELIMINARY 3D STRUT-TIE MODEL

This chapter presents the results of a comparison of actual data from the longitudinal bent cap bar strains of the CIP and the GD specimens to a theoretical analysis using a 3D strut-tie model. This 3D model uses the 2D model mentioned in Chapter 2 as a basis for the model geometry. It also incorporates the use to the single strut splice model (SSSM) and the symmetric out-of-plane model (SOSM) as presented by Sritharan. [1]

4.1 3D STM Modeling Overview

As mentioned in Chapter 3, strut-tie modeling is generally a 2D analysis that assumes compression and tie forces exist in plane and are uniform through out of plane depth of the structure under consideration. This assumption however does not capture the out-of-plane effects that occur for in structures that are not uniform in the out-of-plane direction as in a beam-column joint with a circular column connecting to a rectangular cap.

As mentioned in Chapter 3, the modified EFTM shows two concrete struts that cross over each other, seemingly unaffected by each other. However, in a traditional 2D STM analysis where the forces are carried in plane trajectories, these struts would impact each other and influence the forces in each other. However, as shown in Figure 3-2 the clamping and splicing mechanism are occurring out-of-plane from each other and therefore can potentially co-exist with in the same plane as seen from a 2D perspective.
Therefore, it is a necessity in this case to consider a three-dimensional (3D) analysis of the beam-column joint and compare it to the 2D analysis as well as the actual data. Typically, 3D verification of a STM has been done by a finite element analysis (FEA), however, for this analysis, the structural analysis program SAP 2000 version 15 is used to represent the 3D analysis.

4.2 SAP 2000 Software

SAP 2000 is a structural analysis program that is widely used throughout industry that can use assigned material properties to solve for forces determinate and indeterminate forces. In the program, concrete struts and tension ties are represented as structural frame elements within a 3D space in the program.

SAP also has the ability to create models of solid structures that constitute several small rectangular elements. However, SAP does not have the ability to assign non-isotropic material properties to the solid elements, which would be required when assigning a concrete material. Also, a solid model would not be very useful in examining the potential stresses that would occur inside of the beam column joint. It was decided using frame elements to represent the compressive struts and tension ties would be preferable. This would also correlate more directly with the geometry 2D strut-tie model as seen in from an elevation view as seen in Figure 4-1.

4.3 3D Strut-Tie Model Development

4.3.1 Basic Model Geometry

The basis of the 3D strut-tie model is the 2D modified EFTM as mentioned in Chapter 3. The locations of the nodes in the 3D model were extrapolated from the node
locations from the 2D representation, with each node located at the same vertical and horizontal lactation as seen from the 2D perspective. In SAP, the model was constructed in the 3D space where the coordinate system of the X-Axis (out of plane direction), Y-Axis (longitudinal direction) and Z-Axis (vertical direction). See Figure 4-1 for elevation view of model with clamping and splicing mechanism indicated.

4.3.2 Tension Ties

Each column bar was represented with a single tie based on where they were located in the specimen drawings. Also, the bent cap bars were located in their out-of-plane location with a single tie representing the each 2-bar bundle. The stirrups that were located within the joint region were represented as separate ties as they assist with the splicing mechanism. The vertical ties were located horizontally at the same location as in the 2D STM. The hoops that are represented as T_{DG} in the 2D model are represented as multiple frame elements that connect the column bars in tension for T_{C2}, similar to an actual hoop. See Figure 4-2 for steel reinforcement labeled on the elevation view.

4.3.3 Adaptation of the Clamping Mechanism

T_{C1} and T_{C2} account for the total column tension force that is achieved during the column plastic moment as seen in the modified EFTM. Since T_{C1} and T_{C2} each consist of about half of the total column tension, the 5 column bars closest to the column tension face account for the T_{C1} tie and the remaining 6 bars in tension (3 bars on each side of the column) near the center of the column account for the force from T_{C2} see Figure 3-3. This is verified through moment-curvature of the column. The clamping mechanism is
represented as compression truss elements, anchored at the end of the $T_{C1}$ tie bars to Node A and Node E, similarly as the 2D model indicates.

Because of model stability reasons and also to ensure a uniform spreading of the compression load, multiple struts had to be placed in each direction from the end of the $T_{C1}$ ties.

4.3.4 Adaptation of the Splice Transfer Mechanism

As stated by Sritharan, it was assumed that all three splicing mechanisms that are shown in Figure 3-2 were simultaneously active at during the plastic hinging of the column. [1] This assumption was also applied to the 3D model by applying all viable splicing mechanisms to the 3D model as they were deemed applicable.

The conventional splice model (CSM) shows a force transfer of the column tension through small struts to an adjacent stirrup. To reconcile the forces from the struts, a tension is assumed to develop my means of the concrete tension capacity. As indicated by Figure 3-2 and the use of concrete tension capacity, this model would seem to rely upon the close proximity of the column bar to a stirrup for this model to occur. As shown in the specimen construction drawings, due to congestion in the joint, there are no vertical stirrup legs inside the confined region or at the side face of the joint. The only stirrups inside the joint are set 4.5 in offset form the center of the column. Based on this, the CSM seems unlikely to occur for the CIP and GD specimens.

See Figure 4-3 for a representation of the SSSM in used in the model. By comparison the single strut splice model (SSSM) shows a similar force transfer to the adjacent stirrup but with a single strut. The strut force is then reconciled by the tension
ties form the bottom rebar (top bar for in the inverted specimen) and by hoops or side
face reinforcement towards the end of the rebar. Because this model depends less upon
the proximity of the stirrups, this splice model is assumed to be present.

See Figure 4-4 for a representation of the SOSM in the model. The symmetric
out-of-plane splice model (SOSM) is anchored by compression struts towards the center
of the confined joint region. These struts are supported by a tie spanning between the
two longitudinal column bars, which would be in place of a joint hoop. A vertical stirrup
would anchor the two the struts towards the top of the cap (bottom for in the inverted
specimen).

It was decided that this mechanism was valid to include in the model after
comparing different models to the actual strain, one model with the SOSM and one
without it. The model with the SOSM performed much closer to the actual data as
indicated in the results; see section 4.4.

4.4 3D Model Results

4.3.1 Bent Cap Bar Results

Because the material properties of the concrete and longitudinal steel are
essentially identical as well as the Node F location on the 2D analysis, the CIP and GD
data were compared to one unique push and pull model. To compare the model results of
the bent cap bar forces were then calculated in to microstrain. The forces in the bent cap
bars from the model were added together and then averaged to find the average force in
the bent cap bars. The force in the ties varied little with the outer bars showing less force.
However it is believed that the force is evenly distributed across the section. The results
were then compared to the expected yield strain of the rebar of 2224 microstrain. Because some of the actual data, as mentioned in Chapter 3, was not viable, the same assumed values were used to compare to the theoretical data as mentioned in Chapter 3. The results are shown in Tables 4.1 thru 4.4 and compared to the yield strain.

Tables 4.5 and Tables 4.6 compare the strain to yield ratios for the actual and theoretical data as a comparison. The result is that the ratios for the most part were very close to each other. In the cases where the actual data from a specimen wasn’t present or gave unexpected results, the other specimen gave results at the corresponding gage location and gave results that compared well with the theoretical data.

Modeling the specimen in 3D has also enabled the CL gage on the bottom bar to be compared to theoretical data. As seen in bent cap bar profiles in Figures 2-28 and 2-32, the CL gage of the bent cap bar shows a fairly flat relationship between the CL gage and the Gage at the S1 location in the push. However, in the pull direction the same gages show a drop in strain across the bar. By analyzing the structure in 3D, it allowed the opportunity to place two $C_{DG}$ struts and two $C_{DF}$ struts at the base of the two column bars as shown in the elevation view Figure 4-5 (4 each when considering the opposite face). With this orientation of struts, the model was able to accurately predict the strain in the LB10-CL bar where this wasn’t possible in a 2D model.

4.3.2 Stirrup Observations

The stirrups in this model were represented as ties along the side of the bent cap, similar to how they are sown in the specimen drawings. Based on how they are oriented in the model, the upper portion of the strut was treated as a zero force member and
received no tension force in the model. However, this analysis of the 3D STM model
doesn't explicitly address the analysis of the stirrups.

4.3.3 Hoop Observations

See Figure 4-12 for the location of the hoops in the joint of the 3D model
highlighted. The actual hoop strain profiles are shown in Figures 4-8 thru 4-11 for the
CIP and GD specimen. The hoop strain gages in the cap recorded a fairly low strain at
the low strain in the hoops near the middle of the cap while the lower hoop recorded
higher strain. This trend agrees with the 3D modeling approach that showed a lower
tension in the hoops closer to the center of the joint region. However, due to the
complexity of the actual confined joint region and the simplifications made by the model,
a direct comparison would not be a realistic and are not specifically addressed in this
report.

4.4 Conclusions

Based on the Tables 4-1 to 4-6, there is a close correlation between the theoretical
3D STM model and the actual data. For both the CIP and the GD specimen, all the
ratios, accept one, were within a 32 percent difference than the theoretical data. And the
one ratio that exceeded this 32 difference was based on an assumed strain and not based
on any actual data. Half of the total ratios reported showed the actual data has a
difference of less than 10 percent from the theoretical.

Overall the actual strain gage data compare closely with the 3D model. In
inclusion of the SOSM and the SSSM splice transfer mechanisms in the 3D model give
credibility to the assumption that they are both occurring at the plastic moment. This
indicates that the 3D model is an improvement on the 2D model. This agrees with Sritharan's hypothesis that more than one splice transfer model is present at the plastic or overstrength moment. [1]
### 4.5 Tables

#### Table 4-1. Theoretical vs. Actual Longitudinal Bar Strain Comparison Push — CIP

<table>
<thead>
<tr>
<th>Bar (Tie)</th>
<th>LB13-CL (TAE)</th>
<th>LB10-S1 (TDI)</th>
<th>LB10-CL (Node D)</th>
<th>LB10-N1 (TBD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>680*</td>
<td>1345</td>
<td>1262</td>
<td>837</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.31*</td>
<td>0.60</td>
<td>0.57</td>
<td>0.37</td>
</tr>
<tr>
<td>Theoretical</td>
<td>576</td>
<td>1324</td>
<td>1247</td>
<td>731</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.26</td>
<td>0.60</td>
<td>0.56</td>
<td>0.33</td>
</tr>
<tr>
<td>Actual/Theor.</td>
<td>1.18</td>
<td>1.02</td>
<td>1.01</td>
<td>1.15</td>
</tr>
</tbody>
</table>

*Indicates assumed strain, see section 3.4

#### Table 4-2. Theoretical vs. Actual Longitudinal Bar Strain Comparison Pull — CIP

<table>
<thead>
<tr>
<th>Bar (Tie)</th>
<th>LB13-CL (TAE)</th>
<th>LB10-S1 (TDI)</th>
<th>LB10-CL (Node D)</th>
<th>LB10-N1 (TBD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>260*</td>
<td>496</td>
<td>747</td>
<td>1386</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.12*</td>
<td>0.22</td>
<td>0.34</td>
<td>0.62</td>
</tr>
<tr>
<td>Theoretical</td>
<td>446</td>
<td>548</td>
<td>942</td>
<td>1429</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.20</td>
<td>0.25</td>
<td>0.42</td>
<td>0.64</td>
</tr>
<tr>
<td>Actual/Theor.</td>
<td>0.58</td>
<td>0.91</td>
<td>0.79</td>
<td>0.97</td>
</tr>
</tbody>
</table>

*Indicates assumed strain, see section 3.4

#### Table 4-3. Theoretical vs. Actual Longitudinal Bar Strain Comparison Push — GD

<table>
<thead>
<tr>
<th>Bar (Tie)</th>
<th>LB13-CL (TAE)</th>
<th>LB10-N1 (TBD)</th>
<th>LB10-CL (Node D)</th>
<th>LB10-S1 (TDI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>683</td>
<td>1229</td>
<td>1138</td>
<td>523*</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.31</td>
<td>0.55</td>
<td>0.51</td>
<td>0.24</td>
</tr>
<tr>
<td>Theoretical</td>
<td>576</td>
<td>1324</td>
<td>1247</td>
<td>731</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.26</td>
<td>0.60</td>
<td>0.56</td>
<td>0.33</td>
</tr>
<tr>
<td>Actual/Theor.</td>
<td>1.19</td>
<td>0.93</td>
<td>0.91</td>
<td>0.72</td>
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</table>

#### Table 4-4. Theoretical vs. Actual Longitudinal Bar Strain Comparison Pull — GD

<table>
<thead>
<tr>
<th>Bar (Tie)</th>
<th>LB13-CL (TAE)</th>
<th>LB10-S1 (TDI)</th>
<th>LB10-CL (Node D)</th>
<th>LB10-N1 (TBD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Strain</td>
<td>587</td>
<td>550*</td>
<td>826</td>
<td>1533*</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.26</td>
<td>0.25*</td>
<td>0.37</td>
<td>0.69*</td>
</tr>
<tr>
<td>Theoretical</td>
<td>446</td>
<td>548</td>
<td>942</td>
<td>1429</td>
</tr>
<tr>
<td>$\varepsilon/\varepsilon_y$</td>
<td>0.20</td>
<td>0.25</td>
<td>0.42</td>
<td>0.64</td>
</tr>
<tr>
<td>Actual/Theor.</td>
<td>1.32</td>
<td>1.00</td>
<td>0.88</td>
<td>1.07</td>
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</tbody>
</table>

*Indicates assumed strain, see section 3.4
Table 4-5. Theoretical and Actual Strain Compared to Yield — GD & CIP Push

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-CL</th>
<th>LB10-S1</th>
<th>LB10-CL</th>
<th>LB10-N1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical $\varepsilon/\varepsilon_y$</td>
<td>0.26</td>
<td>0.60</td>
<td>0.56</td>
<td>0.33</td>
</tr>
<tr>
<td>CIP $\varepsilon/\varepsilon_y$</td>
<td>0.31*</td>
<td>0.60</td>
<td>0.57</td>
<td>0.37</td>
</tr>
<tr>
<td>GD $\varepsilon/\varepsilon_y$</td>
<td>0.31</td>
<td>0.55</td>
<td>0.51</td>
<td>0.24</td>
</tr>
</tbody>
</table>

*Indicates assumed data, see section 3.4

Table 4-6. Theoretical and Actual Strain Compared to Yield — GD & CIP Pull

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-CL</th>
<th>LB10-S1</th>
<th>LB10-CL</th>
<th>LB10-N1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical $\varepsilon/\varepsilon_y$</td>
<td>0.20</td>
<td>0.25</td>
<td>0.42</td>
<td>0.64</td>
</tr>
<tr>
<td>CIP $\varepsilon/\varepsilon_y$</td>
<td>0.12*</td>
<td>0.22</td>
<td>0.34</td>
<td>0.62</td>
</tr>
<tr>
<td>GD $\varepsilon/\varepsilon_y$</td>
<td>0.26</td>
<td>0.25*</td>
<td>0.37</td>
<td>0.69*</td>
</tr>
</tbody>
</table>

*Indicates assumed data, see section 3.4

Table 4-7. Ratio of Actual to Theoretical Strain— CIP Push LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-S2</th>
<th>LB10-S1</th>
<th>LB10-CL</th>
<th>LB10-N1</th>
<th>LB10-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Theory</td>
<td>1.51</td>
<td>1.33</td>
<td>N/A</td>
<td>12.67</td>
<td>3.00</td>
</tr>
<tr>
<td>2D STM</td>
<td>N/A</td>
<td>0.91</td>
<td>N/A</td>
<td>1.15</td>
<td>N/A</td>
</tr>
<tr>
<td>3D STM</td>
<td>N/A</td>
<td>1.00</td>
<td>1.02</td>
<td>1.15</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4-8. Ratio of Actual to Theoretical Strain – CIP Pull LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-S2</th>
<th>LB10-S1</th>
<th>LB10-CL</th>
<th>LB10-N1</th>
<th>LB10-N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Theory</td>
<td>4.0</td>
<td>11.58</td>
<td>0.52</td>
<td>1.82</td>
<td>1.87</td>
</tr>
<tr>
<td>2D STM</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.94</td>
<td>N/A</td>
</tr>
<tr>
<td>3D STM</td>
<td>N/A</td>
<td>N/A</td>
<td>0.81</td>
<td>0.97</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4-9. Ratio of Actual to Theoretical Strain – GD Push LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-N2</th>
<th>LB10-N1</th>
<th>LB10-CL</th>
<th>LB10-S1</th>
<th>LB10-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Theory</td>
<td>0.97</td>
<td>1.20</td>
<td>N/A</td>
<td>N/A</td>
<td>0.13</td>
</tr>
<tr>
<td>2D STM</td>
<td>N/A</td>
<td>0.92</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3D STM</td>
<td>N/A</td>
<td>0.92</td>
<td>0.91</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4-10. Ratio of Actual to Theoretical Strain – GD Pull LB10

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB10-N2</th>
<th>LB10-N1</th>
<th>LB10-CL</th>
<th>LB10-S1</th>
<th>LB10-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Theory</td>
<td>27.00</td>
<td>-0.50</td>
<td>N/A</td>
<td>N/A</td>
<td>3.67</td>
</tr>
<tr>
<td>2D STM</td>
<td>N/A</td>
<td>-0.33</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3D STM</td>
<td>N/A</td>
<td>-0.09</td>
<td>0.88</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

(Negative values indicates a switch from compression to tension.)
Table 4-11. Ratio of Actual to Theoretical Strain – GD Push LB13

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-N2</th>
<th>LB13-N1</th>
<th>LB13-CL</th>
<th>LB13-S1</th>
<th>LB13-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex Theory</td>
<td>0.67</td>
<td>-1.5</td>
<td>N/A</td>
<td>1.63</td>
<td>0.20</td>
</tr>
<tr>
<td>2D STM</td>
<td>N/A</td>
<td>N/A</td>
<td>1.19</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3D STM</td>
<td>N/A</td>
<td>N/A</td>
<td>1.19</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

(Negative values indicates a switch from compression to tension.)

Table 4-12. Ratio of Actual to Theoretical Strain – GD Pull LB13

<table>
<thead>
<tr>
<th>Bar</th>
<th>LB13-N2</th>
<th>LB13-N1</th>
<th>LB13-CL</th>
<th>LB13-S1</th>
<th>LB13-S2</th>
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</thead>
<tbody>
<tr>
<td>Flex Theory</td>
<td>0.83</td>
<td>2.13</td>
<td>N/A</td>
<td>-0.91</td>
<td>-0.48</td>
</tr>
<tr>
<td>2D STM</td>
<td>N/A</td>
<td>N/A</td>
<td>2.00</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3D STM</td>
<td>N/A</td>
<td>N/A</td>
<td>1.30</td>
<td>N/A</td>
<td>N/A</td>
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</tbody>
</table>

(Negative values indicates a switch from compression to tension.)
4.6 Figures

Figure 4-1. Elevation View of 3D STM Model

Figure 4-2. Elevation View with Rebar Labeled
Figure 4-3. Single Strut Splice Model (SSSM)

Figure 4-4. Symmetric Out-of-Plane Splice Model (SOSM)
Figure 4-5. Additional Struts along Bottom Cap Bar

Figure 4-6. North Hoop Gages Profile during DC — CIP
Figure 4-7. East Hoop Gages Profile during DC — CIP

Figure 4-8. North Hoop Gages Profile during FC and 55 kip Cycle — GD
Figure 4-9. East Hoop Gages Profile during 55 kip Cycle — GD

Figure 4-10. Hoop Locations in 3D Model
Chapter 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This report, Development of Preliminary Strut-Tie Models for Precast Bent Cap Connections (Cast-in-Place and Grouted Duct), analyzes a beam-cap connection of the NCHRP 12-74 Cast-in-Place and Grouted Duct specimen. The test specimens were a 42% scaled version of a prototype bridge, consistent with a typical overpass in an urban environment. The specimens represent the center T connection of a three column bent. The specimens were inverted and loaded vertically, to simulate gravity load, and were loaded quasi-statically in the horizontal direction, to simulate seismic load in the transverse direction. The connection of the GD specimen consists of steel ducts cast in the bent cap to allow for insertion of column bars prior to placing high strength grout in the ducts to provide an emulative connection. The overall goal of this research is to compare the performance the GD to the CIP specimen as a viable alternative to Cast-in-Place construction of bent cap column connections.

The test specimens were compared using three different theoretical models: beam theory, 2D strut-tie models, and 3D strut-tie models.

The beam theory analysis used statics, moment-curvature analysis, and actual material properties of the specimens to determine the theoretical bent cap bar strains. The results included limited comparisons of actual-to-theoretical flexural strains for two locations adjacent to the joint, top vs. bottom bars, and CIP vs. GD specimens. The difference in the actual tension bar strain when compared to the theoretical in the CIP at
the joint face and 12 inches from the joint face was 467 and 303 respectively. Over the entire range of loading stages, differences in actual-to-theoretical strains were generally larger for locations closer to the joint, indicating a more pronounced local disturbance compared to locations further away from the joint. The average percent differences of the actual to the theoretical strains for the CIP was 49 and 146 for the compression bar strain, 12 inches away from the cap face and at the cap face respectively. Bars that were in compression for most of the loading sequences exhibited a much closer match to theoretical strains than bars that were primarily subjected to tension. Local cracking and other effects are believed to have influenced gage readings. CIP and GD strains for the same locations generally displayed similar trends and values, especially for bars in compression. Due to loss of gages on the north side, this comparison could not be made but, it is assumed that the gages at N2 follow the trend closer than the gages would have at N1.

The modified external strut force transfer model (EFTM) was used as a basis for the 2D strut-tie model. [10] Also, the computer aided strut-and-tie (CAST) program was used to run several models to further the development of a 2D strut-tie model. [15] A comparison between the actual data to the CAST output served as a reference to how close the correlation was between the theoretical model and actual strains. Based on the reinforcement and the boundary conditions, the geometry most of the model was put into place with only one of the nodes (Node F) having not yet been determined. In an iterative process, Node F was given several sets of X and Y coordinates and ran in the CAST program. The output forces, corresponding to the cap bars, were then calculated
into strain, and then compared to the actual data. When the closest possible correlation between the ties in the model and the corresponding actual bent cap bar strain data were found, then the location of Node F was assumed to be correct.

In creating a model for the pull direction, the modified EFTM was revised, and a tension tie was added along the bottom face of the bent cap where tension was shown to be present based on CIP strain data. The results of the CIP specimen showed that the actual strain data fell within 28 percent of the theoretical data and with some of the actual data being less than 2 percent different than the theoretical data. For the GD specimen, the differences were as large as 44 percent except for one location, which reached a 98 percent difference.

For the 3D strut-tie modeling a 3D model, built in SAP 2000, was created using frame elements as the compression struts and tension ties. The geometry was extrapolated from the final node coordinates of the 2D strut-tie model. In addition the splice transfer mechanisms, the single strut splice model (SSSM) and the symmetric out-of-plane splice model (SOSM), were incorporated in order the capture the out-of-plane nature of the splice transfer. [1] For a basis of comparison, actual-to-theoretical ratios of the bent cap bars were calculated for both the CIP and GD. The results showed that the difference between actual and theoretical strains for the CIP specimen were limited to 28 percent and averaged approximately 16 percent for both push and pull directions. For the GD specimen, the differences were as large as 44 percent except for one location, which reached a 98 percent difference. On average, the differences averaged 27 percent in the push direction and the 45 percent in the pull direction. It is assumed that the 3D
representation of the splice transfer mechanism is why there is close coloration between the actual and theoretical data and reflects the flow of forces within a joint and their effects.

5.2 Conclusions

Based on the results of the 3 different theoretical analysis the following conclusions were reached:

- Beam theory does not accurately represent strains that develop in longitudinal reinforcement at the face of CIP and precast bent cap joints.
- The limit of the disturbed (D) region appears to extend a distance of approximately half of the bent cap depth ($h_b/2$) from the face of the joint.
- The developed 2D STM, including the additional tension tie, provides a reasonably simple and accurate model for the flow of forces through a bent cap joint using CIP or GD connections.
- The modified EFTM requires an additional tension tie in the pull direction to accurately represent tension that develops in the exterior face of bent caps.
- The developed 3D STM is the most complicated yet accurate model for analyzing joint forces and associated reinforcement strain in a CIP or precast bent cap joint.
- The presence of ducts in the GD specimen did not noticeably affect specimen strain values compared to the CIP specimen nor affect the development or results of the 2D or 3D STM’s.
• Analytical results from this study do not indicate the need for any changes to existing NCHRP 12-74 recommendations for non-integral precast bent caps using CIP or GD connections.

5.3 Recommendations

Based on the research done in this report the following recommendations for further study include the following:

• Perform finite element analysis (FEA) of the CIP and GD specimens in the pull direction to confirm the need for the additional tension tie.

• Further develop the 2D STM, with special focus on determination of strains in the joint hoops and joint stirrups (interior and exterior) and comparison to test data.

• Perform FEA for CIP and GD precast bent caps to validate the three splice transfer mechanisms and their impact on joint behavior.

• Incorporate data from the CSUS Preliminary Grouted Duct specimen to supplement these analytical results
REFERENCES


[27] E. E. Matsumoto, M. C. Waggoner, M. E. Kreger, J. Vogel and L. Wolf,
