Reinforcement Anchorage in Grouted Duct Connections for a Precast Bent Cap System in Seismic Regions

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ABSTRACT

This paper introduces the background, goals and initial test results for development of a seismic moment connection between precast concrete bent caps and cast-in-place columns. Based on previous grouted connection research conducted at the University of Texas at Austin for non-seismic regions, this research investigates cyclic response of grouted duct connections. Grouted duct connections use individual ducts for each column bar that is grouted after the cap beam is lowered into position. This research program is currently in the first of three phases. Phase 1 consists of a series of six pullout tests to determine bond characteristics, failure modes, and development length of epoxy-coated reinforcing bars subjected to increasing levels of tension cyclic loading. Initial tests of straight epoxy-coated reinforcing bars indicates that development can be achieved at an embedment depth of 10 bar diameters. Test results will be used to formulate preliminary recommendations for development length of reinforcing bars in grouted duct connections and to detail specimens for the second phase of the research. Future test phases will include reversed cyclic tests of large-scale beam-column connection assemblages for the precast bent cap system and will provide recommendations for design and construction of the system in seismic regions.

Keywords: Precast Concrete Connections, Grouted Reinforcing Bars, Anchorage, Pullout Tests, Cyclic Tests

INTRODUCTION

Increasingly congested transportation infrastructure in densely populated urban areas has highlighted the need for bridge systems with more efficient construction schedules. Extended lane closures on highways and roads during bridge construction can cause significant traffic delays and hazardous traffic and work zones. These safety and traffic flow issues can contribute to unseen economic and environmental costs not typically considered during budgetary development. Structural systems utilizing precast (PC) or prefabricated components can help accelerate construction, thus limiting impacts on traffic flow. In addition, use of PC concrete components allow for controlled fabrication, resulting in better quality and more durable structural elements.

Although segmental bridge superstructure components, such as PC concrete I-type girders, steel girders and PC box girder sections have been used extensively throughout the world, PC concrete substructure components have been used on a limited basis. Because of the lack of research investigating the seismic performance of connections for segmental bridge substructures, engineers in earthquake-prone areas have inadequate data on which to base designs. As a first step in developing a complete precast bridge system for seismic regions, the current research investigates the performance of a precast bent cap with cast-in-place (CIP) columns using a grouted duct connection.

BACKGROUND

During the last 30 years, most of the seismic research of structural concrete has focused on CIP construction. As a result, building codes have favored designs using CIP concrete and have not adequately addressed precast concrete systems. Because of a lack of experimental data on performance of precast structural systems, the Precast Seismic Structural Systems (PRESSS) Research Program was established in 1991 to develop effective seismic structural systems for precast buildings and to prepare seismic design recommendations for incorporation into building codes.[1] Recent test results from PRESSS have demonstrated promise for PC systems in seismic regions and design methodologies for precast building systems are now being published. However, additional research specific to precast concrete bridge systems is still needed.

Much of the recent testing of precast bridge substructure components and systems has centered on details applicable to non-seismic regions. An example of one test program is the research project conducted at the University of Texas at Austin (UT) and sponsored by the Texas Department of Transportation (TxDOT) entitled, “Development of a Precast Bent Cap System”.[2-4] This project investigated and developed connection details between PC bent caps and CIP columns or precast piles. The UT program included monotonic pullout tests and beam-column connection tests for grouted ducts, grout pockets, and bolted connections that addressed variables such as anchorage of epoxy-coated reinforcing bars (straight and headed), bar size, embedment depth, and grout brand. Culminating in full-scale construction and testing of a precast bent cap system, the project developed several connection types, produced a design methodology including provisions for anchorage of bars within the connection region, and established specific construction guidelines for different grouting procedures, grout selection and mitigation of potential durability problems related to exposed grout surfaces.

Recommendations from the UT research program have been successfully implemented in two recent bridge projects in Texas.[5,6] The Lake Ray Hubbard Bridge, completed in 2002, and the Lake Belton Bridge, currently under construction, use precast bent caps for bents built over water. The Lake Ray Hubbard Bridge used 43 precast bent caps set on drilled shafts, saving an estimated 43 weeks of construction time compared to schedules for CIP caps.

Although the UT research has been successfully applied to bridge projects in Texas, considerable uncertainty exists with regard to the dynamic response of such a system. The force transfer and anchorage characteristics of these connections, in addition to their ultimate strength and ability to deform in a ductile manner through displacement cycles are specific properties of the system that need to be investigated. While a "pin" connection could simplify these issues, a moment connection such as that shown in Figures 1 and 2 is considered to be more desirable from the standpoint of dynamic performance and redundancy.

To efficiently test such a connection, however, uncertainties related to bar anchorage and force transfer should first be investigated through simple pullout tests. Research has indicated that the required development length of headed bars anchored in CIP concrete is significantly less than that for straight bars.[7,8] The UT research program indicated that straight epoxy-coated bars grouted in steel corrugated ducts and tested monotonically in tension can be developed within 13 bar diameters ($13d_b$).[4] To develop a grouted duct connection for seismic regions, research is needed to determine differences in anchorage

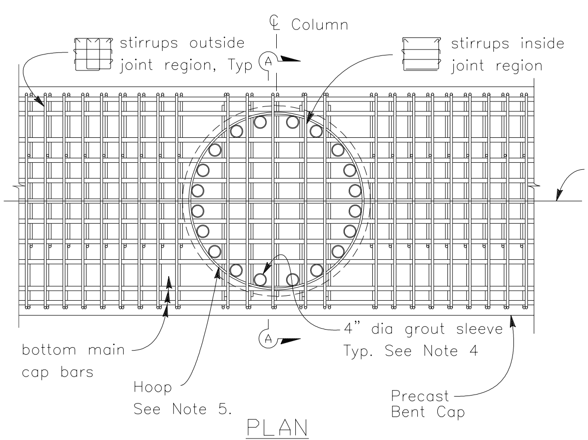


Figure 1. Reinforcement Plan for Moment Connection

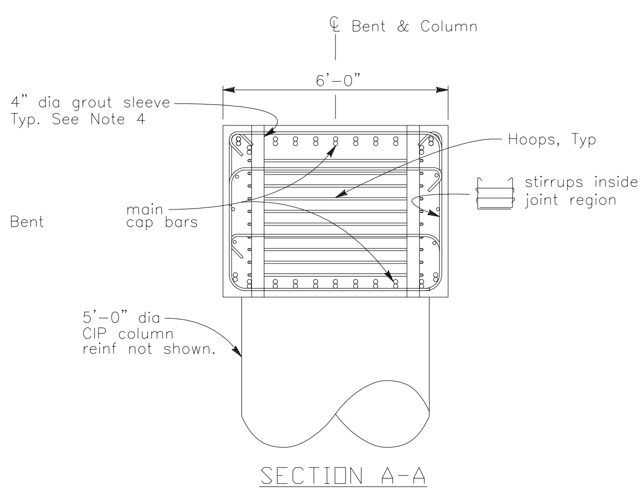


Figure 2. Section through Bent Cap at the Connection

behavior and development length requirements for grouted bars when subjected to cyclic loading. The current research specifically addresses these issues as a basis for future test phases that will investigate a moment connection.

In addition to technical concerns in implementing a PC bent cap system in seismic zones, other issues such as regional differences in preferred bridge types and constructability exist. For example, prestressed girder superstructures for short to medium span bridges are widely employed throughout the mid-western and eastern states. However, such a system is less common in California, where CIP post-tensioned box girders dominate. Nevertheless, based on recent discussions with various bridge firms, it is anticipated that, even in regions such as California, a PC bent cap system could be a competitive alternative for bridges that use PC concrete or steel girder superstructures, as well as for flat slab bridges. As indicated by implementation of the system in Texas, speed of construction also makes the system a desirable alternative on projects built over water and for bridges with numerous bents. In addition, a PC bent cap system may be an important option for cases in which restrictions on falsework clearances exist or in which extended periods of traffic control would be required for CIP construction.

Challenges also exist with respect to transporting and erecting PC bent caps. In seismic zones, where bent caps can be significantly more massive than those used in Texas, special truck permits or precasting on-site may be required. In addition, larger capacity cranes may be needed to set the caps. Another challenge that must be carefully addressed is congestion in the joint region of the cap. Main reinforcing bars as well as joint shear stirrups must be threaded between the ducts used for the main column reinforcing bars (see Figures 1 and 2). The details shown in the figures assume approximately 1% column reinforcement with respect to the column gross area. The four-inch ducts that are shown in the figures provide an annular clearance of approximately 1.30 inches around a #11 rebar. This clearance is considerably larger than that provided on a similar system used in constructing the Getty Museum People-Mover System in Southern California[9]. The People-Mover structure used a PC bent cap and CIP columns with single- and two-column bents. The main column reinforcement, comprised of 16 bars as large as #11, was grouted in 1.5-inch diameter ducts embedded within the bent cap. Although a clearance of less than 1/16 inch was provided around some column bars, the cap was successfully placed by using special reinforcing bar templates that helped ensure a close match between column bars and ducts.

RESEARCH OBJECTIVES

Building upon the research conducted on grouted connections at the University of Texas for non-seismic regions, research is underway to develop a seismic moment connection between a PC concrete bent cap and CIP columns using grouted duct connections. The program is comprised of the following three phases:

1) Tension cyclic pullout tests of epoxy-coated reinforcing bars grouted in ducts
2) Reversed cyclic tests of large-scale PC bent cap-to-CIP column connections
3) Full-scale construction of a PC cap-to-CIP column bent.

The two objectives of Phase 1 are to determine bond characteristics and failure modes of straight epoxy-coated reinforcing bars in grouted ducts as the bars are cycled in tension to increasing load levels, and to formulate recommendations for development length. This will be accomplished through a series of six pullout tests, in which the primary variables are embedment depth and grout brand. Although reinforcement in a typical bent cap-to-column joint must be designed to handle a complex state of stresses related to axial, shear, and bending forces, these pullout tests are designed to investigate only cyclic tension as a starting point to understanding connection behavior. This paper is limited to a discussion of Phase 1 (first three tests).

Phase 1 results will become the basis for design of Phase 2 specimens. Phase 2 will develop and test large scale PC bent cap-to-CIP column connection assemblages subjected to reverse cyclic displacements. These tests will be used to validate assumptions and predictions made in modeling force transfer through the joint. Phase 3 will verify constructability of the precast bent cap system. Results from all three phases will be used to develop recommendations for design and construction of a PC bent cap system in seismic regions.

RESEARCH SIGNIFICANCE

As urban areas have become more congested, traditional cast-in-place methods of bridge construction have become increasingly expensive. Precast concrete bridge systems using grouted connections can expedite construction, provide more durable components, and help control costs. Because there is limited data for design of a precast bent cap system in seismic regions, experimental research is needed to understand connection behavior and to provide a basis for design. Successful development of a precast bent cap system for seismic regions would provide designers the important advantages of a precast bent cap system, and could also serve as the first step toward an entirely precast bridge system.

EXPERIMENTAL PROCEDURES

TEST MATRIX

Based on prior pullout tests of grouted bars subjected to monotonic tension[2], a small test program consisting of six pullout tests was developed to investigate cyclic response of epoxy-coated reinforcing bars grouted in steel corrugated ducts that are embedded within a precast concrete beam. Table 1 shows the test matrix. Each beam specimen allows for three individual tests. To date, the first three tests (Beam 1) have been completed. Thus, not all parameters have been fully defined in the table. Five of the six tests (GD1-GD5) use #9 epoxy-coated bars grouted within 4-in. steel corrugated ducts. As shown in the table, straight epoxy-coated #9 bars will be used for all tests. However, different embedment depths and grout brands will be selected. The grout selected for GD1 and GD2 was Masterflow 928, a proprietary, prepackaged nonshrink grout. One test, CIP1, is a cast-in-place control test with a #9 bar embedded 18 inches.

Beam	Test	Bar Type	Bar Size	Coating	Embedment (inches)	Embed./d_b	Grout Brand
1	CIP1	Straight	#9	Epoxy	18	16.0	N/A
	GD1	Straight	#9	Epoxy	18	16.0	MF928
	GD2	Straight	#9	Epoxy	11.5	10.2	MF928
2	GD3	Straight	#9	Epoxy	TBD	TBD	TBD
	GD4	Straight	#9	Epoxy	TBD	TBD	TBD
	GD5	Straight	#9	Epoxy	TBD	TBD	TBD

Table 1. Test Matrix

Although #11 reinforcing bars are the most common size for column reinforcement in seismic regions such as California, #9 bars were selected for testing due to the limited capacity of the actuator. Previous UT research[2] was used as a basis for selection of straight epoxy-coated bars and for initial embedment depths. It was recognized that results from tests using epoxy-coated bars can conservatively be applied to black bars. An embedment depth of 18 inches (16d_b) was chosen as an embedment that would possibly develop the #9 bar when subjected to tension cycles, resulting in a ductile failure. The embedment depth of 11.5 inches (approximately 10d_b) was expected to result in a brittle pullout failure. Demonstrations of both types of failure are desirable.

TEST SPECIMENS

As shown in Figures 3 and 4, test specimens were 30 in.×24 in.×13 ft. (H×W×L) reinforced concrete beams, with three four-inch diameter, semi-rigid, spirally-crimped (corrugated) steel ducts spaced at three locations along the beam length. Ducts extended through the entire beam depth. Spacing of ducts was based on crack patterns observed in Reference 2. Reinforcement was based primarily on Caltrans Bridge Design Specifications.[10]

Specimens were constructed using standard Caltrans Class D mix, with a minimum 28-day compressive strength of 3600 psi and a water-cement ratio of 0.44.[11] The maximum coarse aggregate size of ¾ inch and 4 inch slump helped ensure proper placement and consolidation. The average 28-day compressive strength was 3900 psi. Specimen reinforcing bars were ASTM A706 Grade 60 steel. Corrugated ducts used cold-rolled steel per ASTM A619, with a thickness of 26 gage (0.23 inch) and a corrugation height of 0.13 inch.

Test bars were also ASTM A706 Grade 60 steel, with a yield strength of approximately 65 ksi and a tensile strength of approximately 95 ksi. The embedded end of test bars was straight; however, the opposite end of these bars used an HRC Type 220 T-Head[12] that allowed connection to a specially designed gripping system. Bars were epoxy-coated by Fletcher Coating Company (Orange, California) using 3M *Scotchkote 426* per ASTM A934/934M.

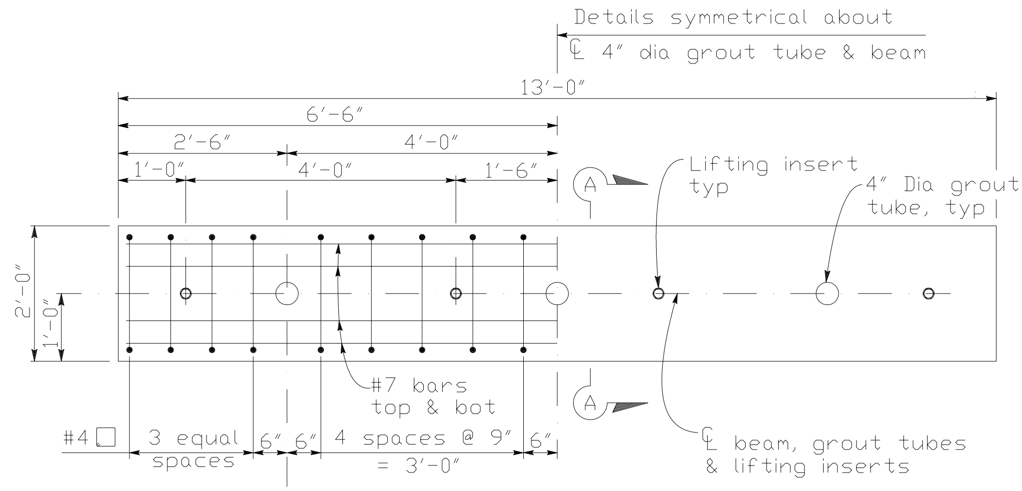


Figure 3. Test Specimen Plan

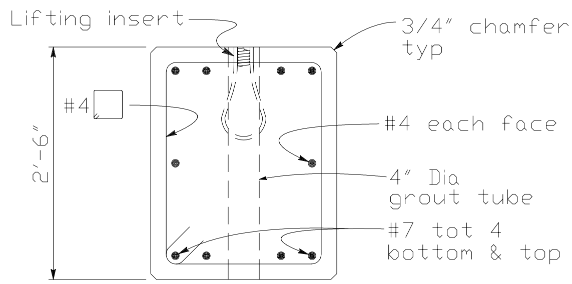


Figure 4. Test Specimen Section A-A

GROUT AND GROUTING PROCEDURES

Master Builders Technologies Masterflow 928 (MF928) non-shrink grout was selected for grouting operations, based on previous research that demonstrated MF928 to have exceptional strength and fluidity, extended working time and versatility under a wide range of temperatures.[2] For each batch of grout, 2-inch cubes were prepared, cured, stored, and tested in accordance with ASTM C109.

A gravity-flow tremie tube system was used for grouting ducts (Figure 5). The tremie tube system consisted of a 2-liter funnel, $^3/_4$" ball valve, and $^3/_4$" and $^5/_8$" inner diameter tubing. The fluidity of grout was determined using a flow cone, in accordance with the ASTM C 939. During grouting, the tremie was placed at the bottom of the duct and slowly raised as the duct filled up. Figure 6 shows the control valve used to ensure a continuous flow of grout into the duct. This important feature helped prevented air entrapment during grouting operations. After grouting a duct, the grout was gently tamped with a #3 rebar. A trowel was used to smooth the grout surface and a water-based curing compound was applied to the surface to complete the grouting process.

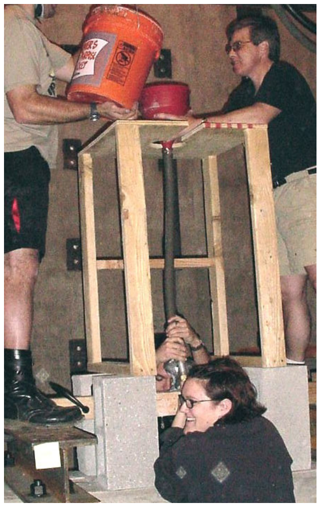


Figure 5. Grouting Procedure

Figure 6. Control Valve

INSTRUMENTATION

Figure 7 shows a schematic of the instrumentation for the first grouted duct test, GD1. Strain gages were placed along the axis of the bar in increments (B1-B5), as well as along the duct, circumferentially (D3-D5). D4S refers to a strain gage placed along the duct spiral. The exit end of the bar is referred to as the "lead" end, and the bottom of the embedded bar is called the "head", despite the absence of an actual head on the bar. Displacement transducers (LVDT's) measured slip at the ends of the bar (L1-L3), as well as relative grout-concrete deflection at the top of the specimen (L4), and beam deflection (L5). Strain and displacement data was sampled at a frequency in the range of 1-2 Hz. A similar instrumentation scheme was used for other tests.

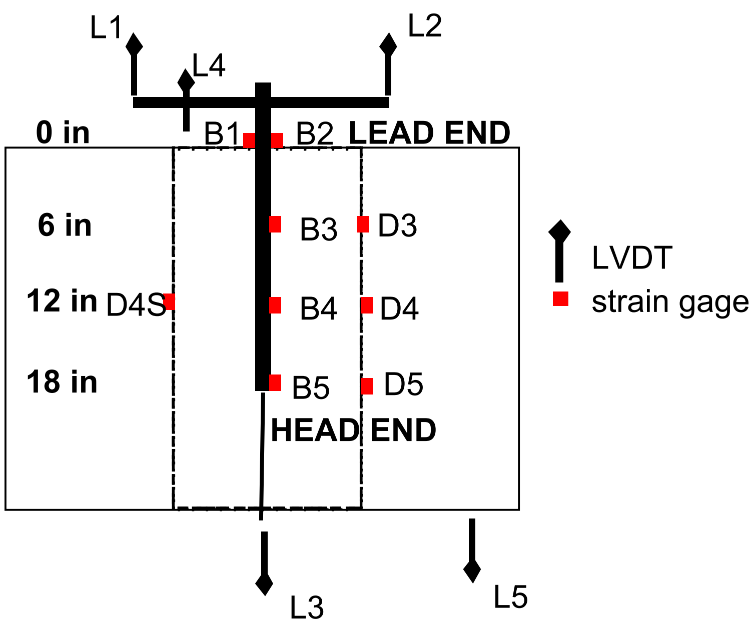


Figure 7. Instrumentation Schematic

LOADING SEQUENCE

To investigate degradation and loss of bond due to cyclic effects, reinforcing bars were loaded through several cycles with increasing levels of tension applied. Although this is a simplification of what actually occurs at a beam-column connection[13], the basic bond mechanism can still be investigated. References 14 and 15 were used as a basis for establishing a reasonable strain path. Testing of sample reinforcing bars to fracture prior to conducting GD1 enabled load control to be reasonably used for initial tests.

Figure 8 plots an idealization of the reinforcing bar force versus bar strain outside the grouted duct for five levels of strain up to the yield strain, ε_y, as well as three levels within the strain hardening region. At each stage, one cycle consists of tensioning the bar up to the maximum designated strain from an initial strain corresponding to 10 percent of the yield force, and then unloading the bar back to the initial strain. The bar is tensioned through three cycles for each stage. After cycling through eight stages, bars that are still anchored are then loaded monotonically in tension to failure. Bars were loaded at a rate of approximately one kip per second.

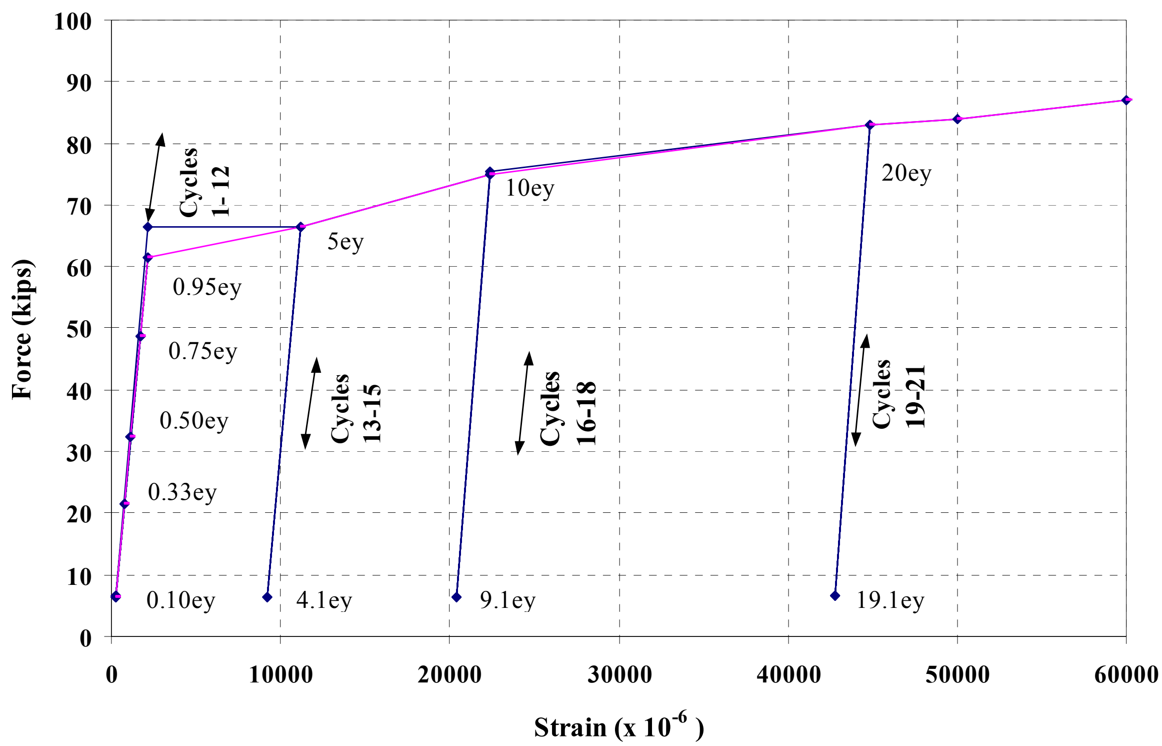


Figure 8. Bar Force vs. Bar Strain for Tension Cycles

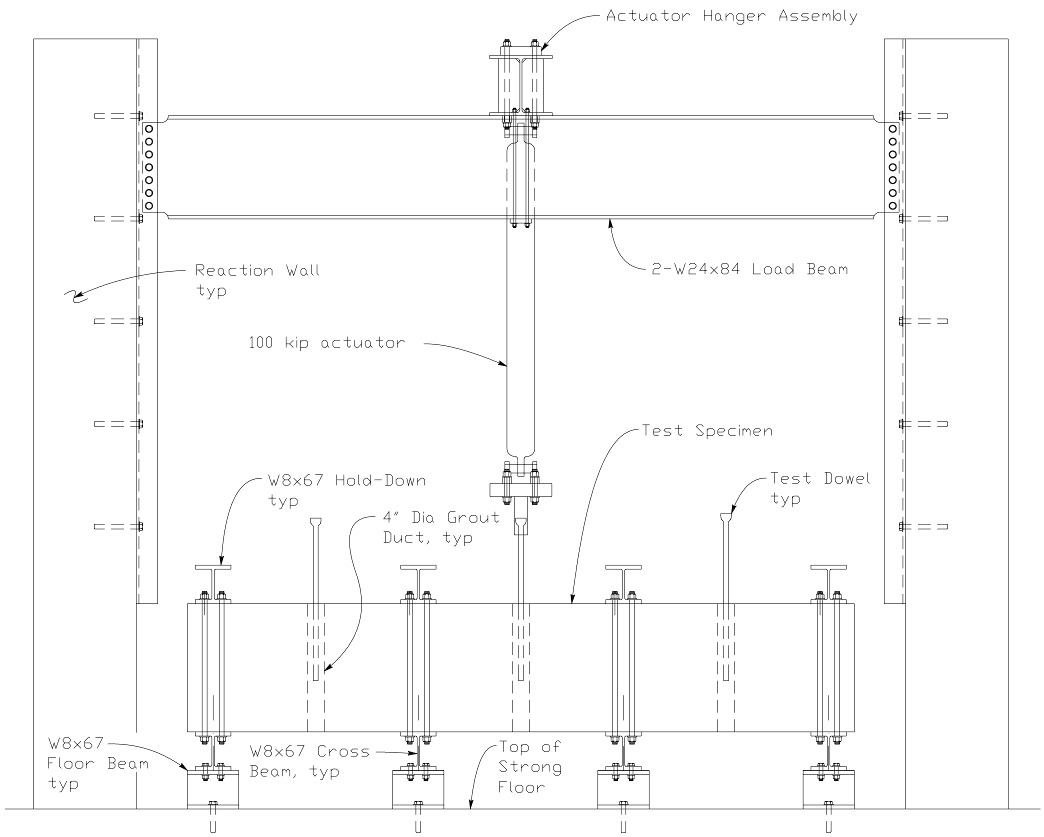


Figure 9. Test Setup Elevation

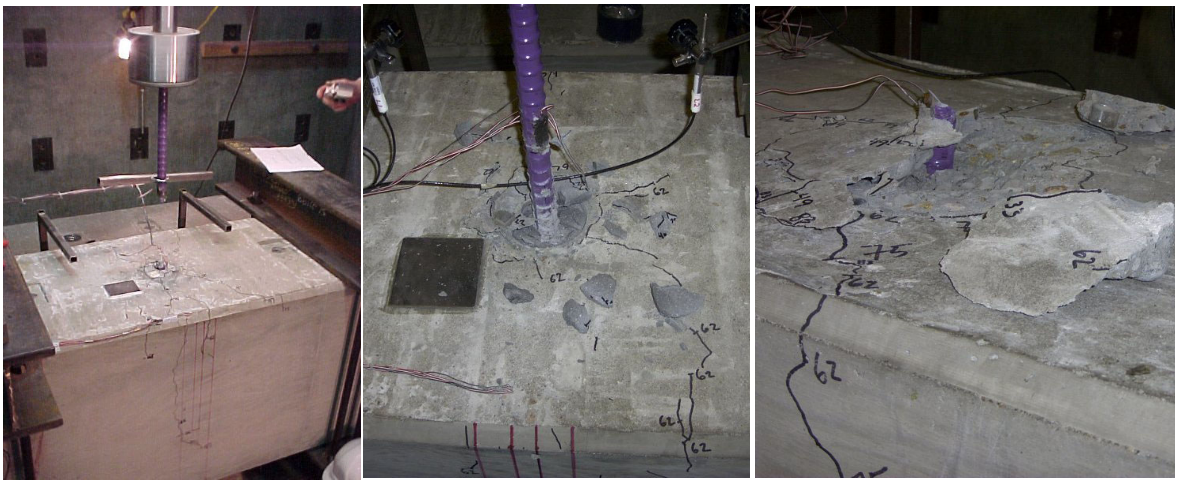
TEST SETUP

Figure 9 shows a schematic of the test setup for tension cyclic loading. As the 100-kip actuator pulls on the test bar, the specimen remains anchored to the strong floor through a series of cross beams on top of the specimen that are tied to floor beams by rods. A set of overhead reaction beams provide support for the actuator.

EXPERIMENTAL RESULTS

SUMMARY OF RESULTS

Results are presented for the first three pullout tests: GD1, GD2 and CIP1. Reinforcing bars (connectors) in all three tests were anchored adequately to reach yield, but exhibited different failure modes, as shown in Figure 10. In GD1, the connector was embedded $16d_b$ and exhibited excellent anchorage through bar yield up to fracture at a maximum load of 88 kips. At an embedment of approximately $10d_b$, the GD2 bar reached yield and entered the strain hardening regime, but exhibited a pullout failure at a load of 85 kips. Like GD1, the control specimen, CIP1, was also embedded $16d_b$ and anchored adequately to reach fracture at a load of 88 kips.



A. GD1 B. GD2 C. CIP1

Figure 10. Failure Modes for Test Bars

Test results are summarized in Table 2 by materials, load-deflection and onset of cracking. To prevent premature pullout failure, the compressive strength of the grout exceeded that of the concrete by at least 1000 psi per Reference 2. All connectors exhibited excellent anchorage characteristics as indicated by the limited bar slip at the head (i.e., embedded end) of the connector. At the yield load, slip values were fairly consistent for all tests and relatively small in magnitude. Excellent bond was maintained between the beam and duct for GD1 and GD2. In GD1 and GD2 tests, hairline splitting cracks developed in the grout during the first load cycle while, in CIP1, cracks emanated from the connector in the third cycle of the first loading stage. In all tests, cracks emanated from the connector and extended down the side face of the beam at higher loads.

Test	**Embed. (in)**	**Materials**		**Load-Deflection**			**Cracking**	
		f'c (ksi)		**P_{yield}**	**P_{max}**	**Slip[B]**	**P_{split}**	**Width**
		Grout[A]	**Concrete**	**kips**	**kips**	**10^{-3} in**	**kips**	**10^{-3} in**
GD1-1	18	5.6	3.5	57	67	18[C]	16.5	2
GD1-2				N/A	67	10	16.5	2
GD1-3				N/A	88	--[D]	16.5	2
GD2	11.5	5.4	3.7	61.5	85	22	21	5
CIP1	18	N/A	3.7	66	88	--[D]	22	2

Footnotes

A. Grout cube strength modified by 0.8 factor
B. Slip corresponds to head slip at yield unless noted otherwise
C. Slip contains specimen deflection due to unreliable beam displacement records
D. Data not available

Table 2. Summary of Test Results

TEST GD1

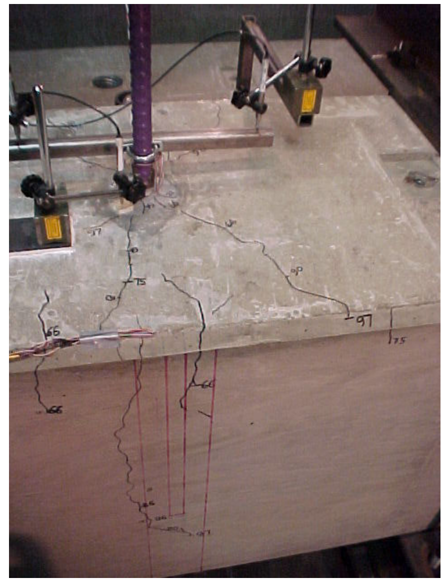


Figure 11. GD1 Crack Pattern

Due to various limitations, GD1 was tested in three sessions (GD1-1 to GD1-3). In GD1-1, the specimen was loaded through the first four stages of the load sequence previously described. The connector was reloaded through the final three stages in GD1-2, and loaded monotonically in tension to fracture in GD1-3. Data was corrected to account for a discrepancy in the calibration of the load cell.

Splitting cracks with a maximum width of 0.002 inches emanated radially from the bar in the grout at a force of approximately 17 kips. As shown in Figure 11, cracks propagated into the concrete and down the side face of the beam at larger loads. Extensions of grout and concrete cracks corresponded to increasing strain levels in the test bar and duct. Strains were largest at the lead end and decreased with embedment along the bar, as bond developed. Along the grouted duct, however, the largest strains were measured at gages D4 and D4S, located at 12 inches from the top of the specimen (see Figure 7). These relatively small duct strains (no larger than approximately 650 microstrain) exhibit the mobilization of the duct in confining the bar-grout mass.

A plot of applied load versus bar strain at the lead end shows bar yield occurred at a force of about 57 kips (Figure 12). Significantly larger forces were applied as the bar was tested into the strain hardening region. Load-slip response for the lead end is shown in Figure 13. Stiff response of the bar is exhibited prior to bar yield. Fracture occurred at a load slightly lower

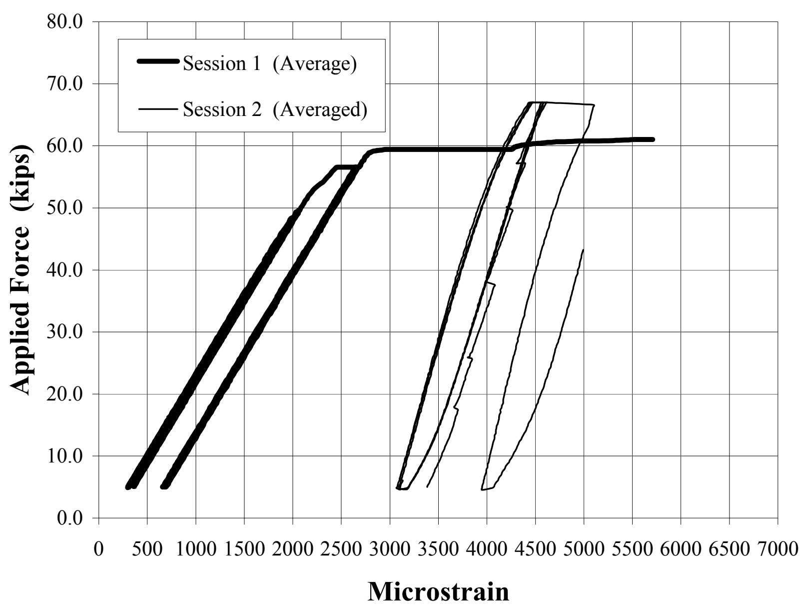


Figure 12. GD1 Applied Force vs. Strain at Bar Lead

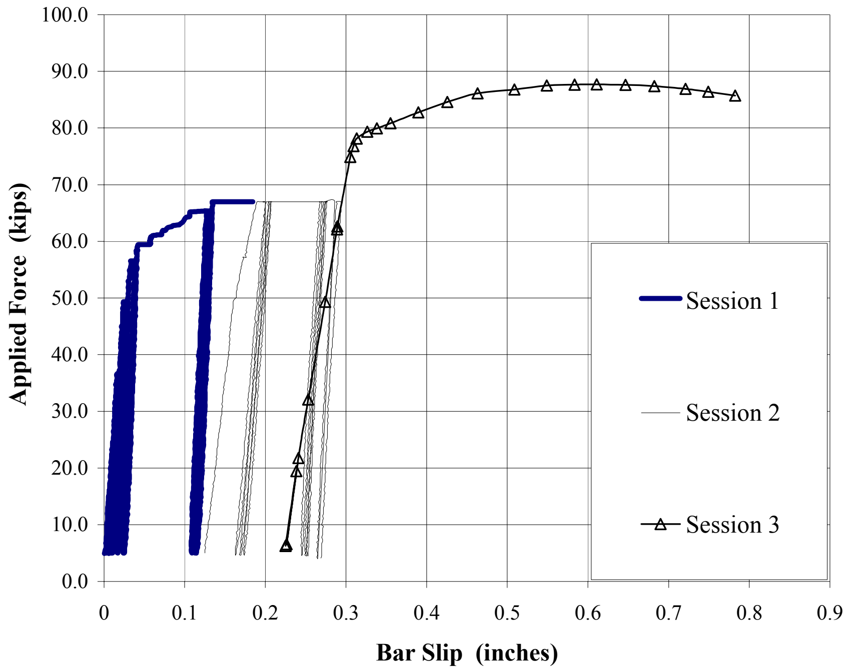


Figure 13. GD1 Applied Force Vs. Bar Slip at Bar Lead

than the maximum load of 88 kips. Adequate bond developed at the interfaces between the bar, grout, duct, and concrete, enabling the bar-grout mass to act as a unit without appreciable slip.

Overall GD1 response was similar to that of the VD03 test reported in Reference 2 for monotonic loading in tension. VD03 used a larger #11 epoxy-coated bar, but was similarly embedded in a 4-inch corrugated duct using MF 928 grout with a similar compressive strength. Load cycles generally caused little to no discernable crack growth at each stage.

TEST GD2

The GD2 bar demonstrated a response similar to that of GD1 through the sixth stage of the loading sequence, including bar yield and strain hardening. However, the connector exhibited a sudden pullout failure during the first cycle of stage 7 (Figure 10B). The brittle failure was marked by a loud bang as the grout around the bar ruptured. Figure 14 shows the increase in lead slip due to bar yield and strain hardening. (The lead slip record is truncated at 82 kips). A sudden increase in head slip is shown as the failure load of 85 kips is approached.

GD2 exhibited the same failure mode as the VD01 test reported in Reference 2 (#11 epoxy-coated bar embedded 12 in.), but differed in failure load and crack pattern. VD01 achieved a failure load of only 76 kips, 12% less than that for GD2, although VD01 was tested monotonically in tension. However, it should be noted that the grout cube strength for VD01 was 4.2 ksi, 1.2 ksi less than the concrete compressive strength. In contrast, GD2 used grout with a compressive strength of 5.4 ksi, 1.7 ksi larger than the concrete strength. This

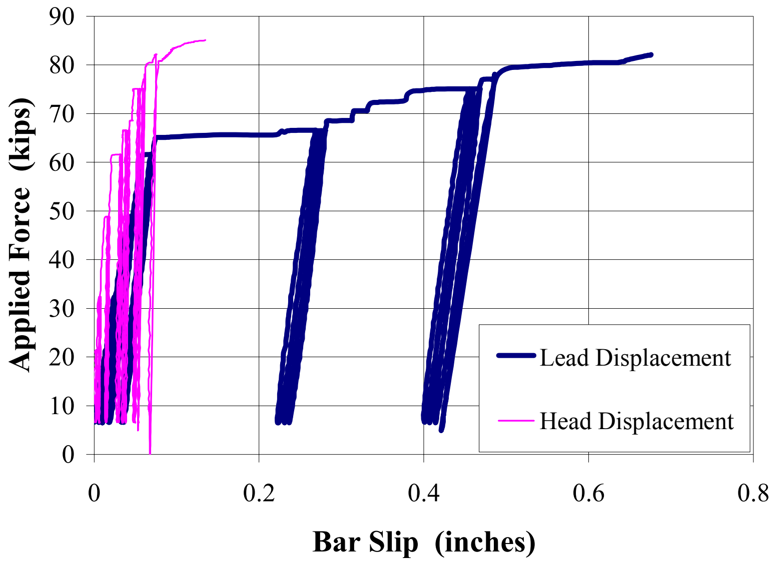
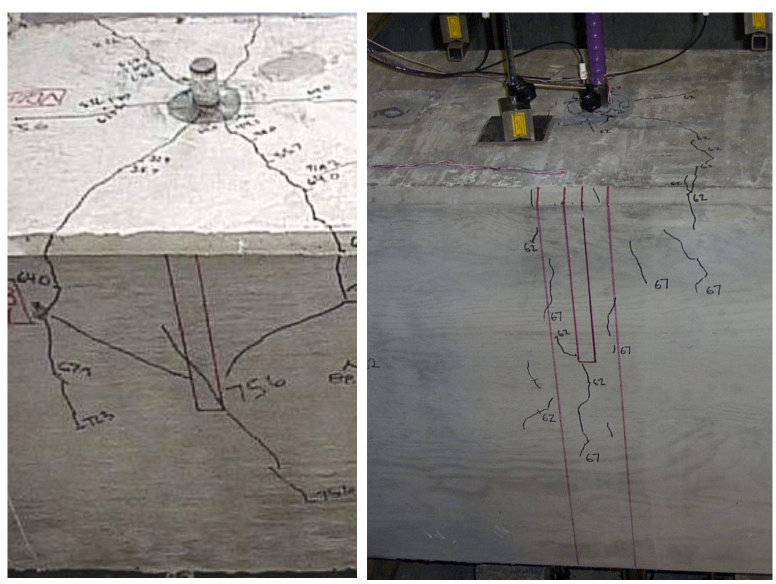


Figure 14. GD2 Applied Force vs. Slip at Bar Lead

difference, and perhaps data scatter and bar diameter, may explain the larger failure load for GD2. Figure 15 shows a more widespread VD01 crack pattern than that of GD2.



A. VD01 (monotonic) B. GD2 (cyclic)

Figure 15. Comparison of Crack Patterns

TEST CIP1

Little difference in response was observed between CIP1 and GD1. Like GD1, the CIP1 control bar failed in fracture in the final stage of loading. Figure 16 compares the bar slip at the lead end for CIP1 and GD1-3. Similar stiffness, maximum slip, and failure loads are

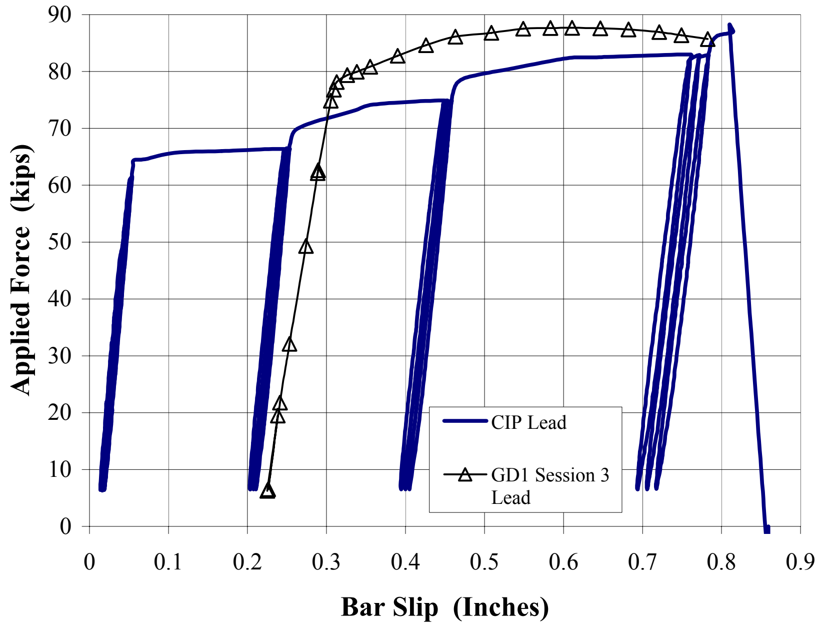


Figure 16 CIP1 and GD1 Applied Force vs. Bar Slip at Bar Lead

evident. Strain histories also show a close comparison (Figure 17). Figures 10A and 10C do show a difference in the top surface of the specimens at failure. However, the spalling of concrete at the top surface of CIP1 was only a secondary failure surface due to the large straining of the bar near the surface as the fracture load was approached.

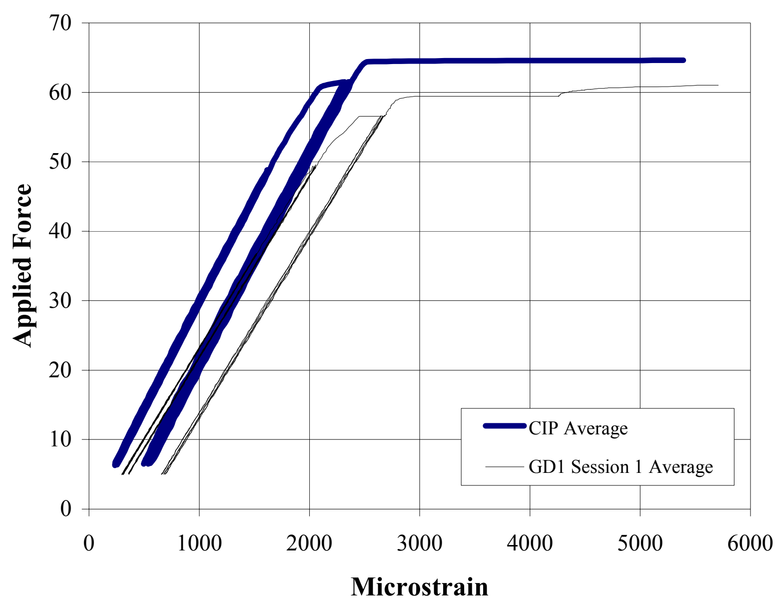


Figure 17 CIP1 and GD1 Applied Force vs. Strain at Bar Lead

SUMMARY AND CONCLUSIONS

Use of a precast bent cap system with grouted duct connections in seismic regions will expedite construction, provide more durable components, help control costs, and serve as the first step toward an entirely precast bridge system. The current test program is producing data to help engineers develop a better understanding of grouted duct connection behavior and to provide a basis for design. The first three pullout tests of the first phase of research have examined bond characteristics and failure modes of straight epoxy-coated reinforcing bars in grouted ducts as the bars are cycled in tension to increasing load levels. Test results suggest that #9 epoxy-coated straight bars can be developed to fracture in grouted ducts within a length of only $16d_b$, and that bar yield can be achieved within a length of approximately $10d_b$. Anchorage characteristics of grouted bars compared favorably with cast-in-place bars and with previous grouted bar research. Only a minor degradation of bond can be attributed to cyclic effects. These results indicate that the grouted duct connection appears to be a viable alternative for use in seismic regions and warrants further investigation in the second phase of the research program.

All Phase 1 pullout tests will be completed by October 2002. One of the final tests will again investigate bar anchorage using MF 928 grout and an embedment depth in the range of $10d_b$ to $16d_b$ to demonstrate repeatability. The final two tests will investigate bar response using a second grout brand. Test results will be used to develop development length recommendations and to detail specimens for the second phase of testing.

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