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Seismic Performance of Precast Girder-to-Cap Beam Connections Designed for ABC

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Abstract

The behavior of critical connections between prefabricated elements in bridges utilizing accelerated bridge construction (ABC) methods continues to be of utmost interest. Some of these connections will experience excessively high demand in regions that are susceptible to high seismic load. This paper presents a large-scale experimental study that investigated seismic performance of the connection between precast concrete I-shaped girders and a concrete inverted-tee cap beam using two different details. The ability of the girder-to-cap connection to successfully resist positive moment and the corresponding shear under combined gravity and seismic effects was of particular interest. The effect of vertical seismic acceleration on the connection behavior was also considered. This study utilized a half-scale test unit and replicated a portion of a typical inverted-tee cap beam, along with two 35-ft long girders with unique connection details and split bridge decks so each detail could be tested individually. Both connection details were improvements to an existing detail for precast dapped-end girders and inverted-tee cap beams that has been used by the California Department of Transportation (Caltrans). Both connections relied on deck reinforcement as the primary tension-transfer mechanism for negative moment. For positive moment tension transfer, one connection utilized unstressed grouted strands to provide continuity between the girder bottom flange and the cap beam. The other connection implemented a group of large-diameter transverse dowel bars located in the lower portion of the girder that were placed inside looped strands cast in the cap beam and subsequently encased in a cast-in-place diaphragm. Both connections exhibited excellent seismic performance, remaining elastic up to load levels well in excess of what would be required to develop a column plastic hinge, including due consideration to vertical acceleration effects. Both connections were subjected to large girder displacements in order to fully quantify their performance. Experimental results from both connection details and comparisons with the as-built detail will be presented in this paper.

Keywords

accelerated bridge construction, bridges, seismic performance, precast concrete, I-shaped girders

Disciplines

Civil Engineering | Engineering

Comments

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SEISMIC PERFORMANCE OF PRECAST GIRDER-TO-CAP BEAM CONNECTIONS DESIGNED FOR ABC

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ABSTRACT

The behavior of critical connections between prefabricated elements in bridges utilizing accelerated bridge construction (ABC) methods continues to be of utmost interest. Some of these connections will experience excessively high demand in regions that are susceptible to high seismic load. This paper presents a large-scale experimental study that investigated seismic performance of the connection between precast concrete I-shaped girders and a concrete inverted-tee cap beam using two different details. The ability of the girder-to-cap connection to successfully resist positive moment and shear under combined gravity and seismic effects was of particular interest. The effect of vertical seismic acceleration compromising the connection behavior was also investigated.

This study utilized a half-scale test unit and replicated a portion of a typical inverted-tee cap beam, along with two 35-ft long girders with unique connection details and split bridge decks so each detail could be tested independently. Both connection details were improvements to an existing detail for precast dapped-end girders and inverted-tee cap beams that has been used by the California Department of Transportation (Caltrans). Both connections relied on deck reinforcement as the primary tension-transfer mechanism for negative moment. For positive moment tension transfer, one connection utilized unstressed grouted strands to provide continuity between the girder bottom flange and the cap beam. The other connection implemented a group of large-diameter transverse dowel bars located in the lower portion of the girder that were placed inside looped strands cast in the cap beam and subsequently encased in a cast-in-place diaphragm. Both connections exhibited excellent seismic performance, remaining elastic up to load levels well in excess of what would be required to develop a column plastic hinge, including due consideration to vertical acceleration effects. Both connections were subjected to large girder displacements in order to fully quantify their performance. A summary of test results from both connections are presented in this paper.

INTRODUCTION

Accelerated bridge construction (ABC) is increasingly being promoted and pursued all across the country. The desire for rapid construction of bridges is being driven by increased transportation demands due to continued economic and population growth and the need for improvements to the aging transportation infrastructure. With appropriate considerations to seismic demands, Caltrans recognizes the usefulness of ABC techniques and desires to take advantage of the associated benefits (1, 2).

ABC has primary benefits of reducing field construction time and mitigating long traffic delays. Reduced field time is often accomplished by utilizing prefabricated components wherever possible. Prefabricated elements provide additional benefits such as eliminating the need for falsework and improving quality by moving production from the field to the controlled shop environment.

Even though ABC has several advantages including those noted above, there has been an understandable reluctance in incorporating such techniques in moderate-to-high seismic regions, given the poor performance of precast structures in previous earthquakes, primarily because of connection failures between precast components. Such failures were evident in notable earthquake events such as Loma Prieta in 1989 (3) and Northridge in 1994 (4).

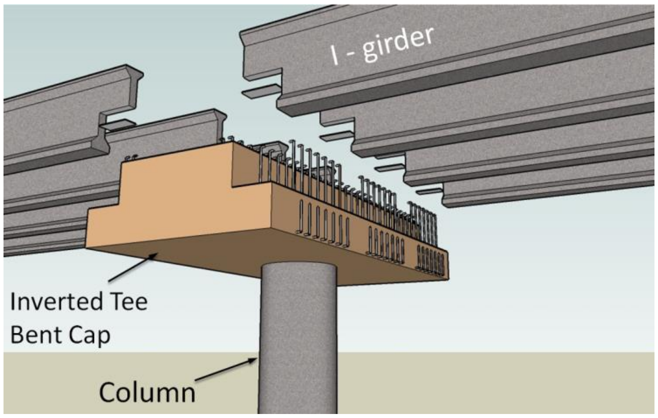


Figure 1. Inverted-tee bent cap concept

Precast connections sufficient for large seismic demands will provide increased opportunity to incorporate ABC methods. A particular detail that provides the opportunity to utilize precast bridge girders is the inverted-tee bent cap. Dapped end I-shaped girders can quickly and easily be placed on the cap beam corbel as shown in Figure 1. Previous Caltrans practice for this detail incorporates dowel bars through the girder ends and a cast-in-place diaphragm in the connection region to establish fixity. This detail provides significant negative moment capacity for vertical loads due to the continuity of the deck reinforcement through the connection. However, previous design practice often disregarded the positive moment capacity of the connection, since there were seldom any quantitative elements that provide tension continuity in the bottom half of the girder. The lack of positive moment capacity in the connection eliminates the possibility of designing for a column plastic hinge just below the superstructure. Having a plastic hinge region only at the bottom of the column increases the column moment and results in larger foundation requirements, making this connection less desirable in seismic regions than the cast-in-place alternatives. Developing a robust girder-to-cap connection will increase the usefulness of the inverted-tee concept in seismic regions and facilitate the ABC techniques.

An additional limitation of the connection is related to vertical acceleration effects. The current Caltrans *Seismic Design Criteria* (*SDC*) stipulates that a static vertical load equal to 25% of the dead load, applied upward and downward, needs to be incorporated for Ordinary Standard bridges where the site peak ground acceleration is 0.6g or greater (5). Where this acceleration must be considered, longitudinal side mild reinforcement in the girders must be capable by means of shear friction of resisting 125% of the dead load shear at the cap beam interface. This requirement, which exists to protect against potential shear failures when the bottom of the connection opens up, has been disadvantageous in utilizing the inverted-tee system, because the detail is not well-suited for incorporation of the additional mild reinforcement. Verifying the necessity of this requirement would be helpful in understanding the usefulness of the inverted-tee detail in seismic regions.

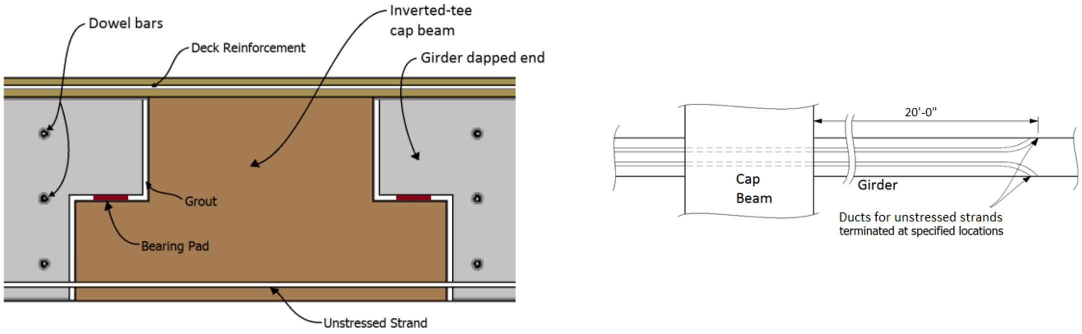
To examine the suitability of the inverted-tee system for seismic regions, a 2010 joint study (6) investigated the connection detail Caltrans has used for inverted-tee dapped-girder systems along with an improved detail that provided additional positive moment tension continuity. The study utilized finite element (7) and grillage (8) analytical investigations along with a large-scale experimental investigation. The study, referred to as the system test, revealed that the as-built detail was expected to act as a fixed connection under service load, but was expected to degrade to a pin connection during extreme seismic events. It also showed that the improved connection considerably increased the performance and capability of the connection at higher ductility demands.

CONNECTION DETAILS

The system test verified the potential of the inverted-tee concept for ABC designs in seismic regions. Girder-to-cap connection details that can be incorporated with the inverted-tee cap design and reliably provide elastic behavior beyond the column overstrength moment will result in a robust ABC system for seismic regions. Two such details have been investigated in this study; they are referred to as the Grouted Unstressed Strand Connection (GUSC) and the Looped Unstressed Strand Connection (LUSC).

GUSC Detail

The GUSC detail, shown in Figure 2a, was a duplication of the improved connection from the system test. The detail incorporated ducts near the bottom of the inverted tee cap beam that mated with ducts in the bottom flange of the I-girder. After girder placement, steel strands such as those often used for post-tensioning were run through the ducts and grouted into place to provide positive moment tension continuity across the connection interface. Pullout tests completed as a part of this research showed sufficient anchorage strength can be attained using high strength grout, so the strands were terminated in



(a) GUSC detail for connecting I-shaped girder and inverted-tee cap beam

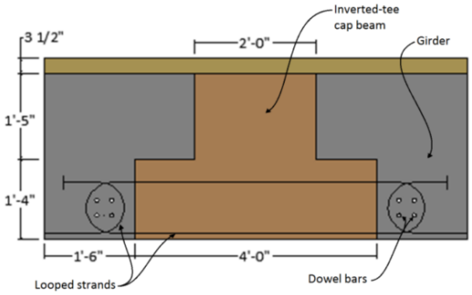
(b) Ducts in girder and cap for unstressed strands in GUSC detail

Figure 2. Grouted Unstressed Strand Connection (GUSC)

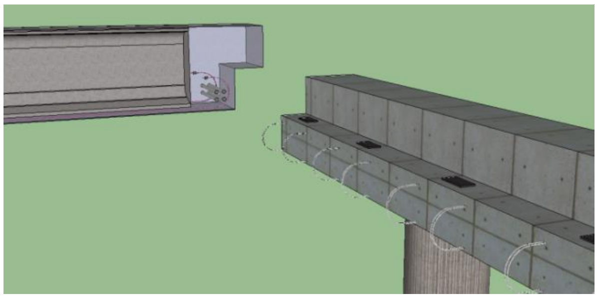
the girder flange 20 ft at prototype scale as shown in Figure 2b. In the test unit, a pair of 0.375-in. diameter strands were incorporated in each of the two ducts running through the connection interface. At the prototype scale, the number of ducts, strand size, and number of strands could be adjusted according to connection demand requirements and configuration convenience.

Unstressed strand offers several advantages over traditional reinforcement. Strand is easier to install than reinforcement. Typical strand also has significantly higher strength than typical reinforcement, resulting in smaller required diameters. It is worth noting that the strand does have significantly reduced plastic strain capability as compared to mild steel; however, since the girder-to-cap connection is designed to remain elastic, the lower plastic strain capability is not a major concern in this application. For this detail, the unstressed strand was sized by considering the overstrength moment of the column plastic hinge and distributing it appropriately to the girders to determine the maximum shear and moment expected in a single girder-to-cap connection. Additional information on the distribution of column overstrength moment due to horizontal seismic load can be found in Vander Werff and Sritharan (9). Once the moment demand in each girder was established, a typical reinforced concrete design approach was utilized to determine the necessary tension steel area to provide sufficient positive moment capacity, and the strand was sized accordingly.

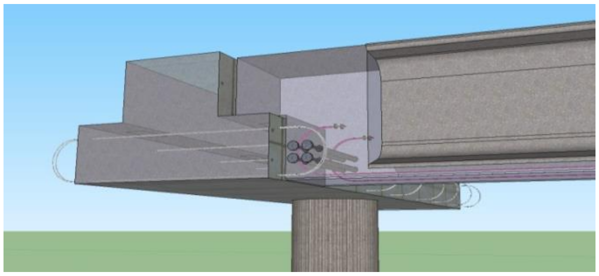
Although the combination of deck reinforcement for negative moment and strand for positive moment was expected to provide a robust integral connection, the dowel design from Caltrans' as-built detail was duplicated in the GUSC detail. The dowels were anchored by using a cast-in-place concrete diaphragm in the region above and beside the cap beam corbel.



(a) Cross-section through girder-to-cap connection region



(b) Cutaway view of girder loops and dowel pipes



(c) Cutaway view of assembly before diaphragm concrete placement

Figure 3. Looped unstressed strand connection (LUSC)

LUSC Detail

A cross-section of the second proposed girder-to-cap connection detail, the LUSC, is shown in Figure 3a. Positive moment tension continuity in this connection was achieved by enlarging and relocating the dowel bars to the lower portion of the girder and extending them through continuous looped unstressed strands that extended out from the cap beam ledge. The desired tension load path at the bottom of the girder was completed by additional unstressed strand loops cast in the girder. The dowel bars were grouted in place in the girder; then the entire connection region was again encased by a cast-in-place concrete diaphragm, similar to the GUSC detail. The positive moment continuity in the LUSC detail was different from the GUSC detail in that the LUSC detail utilized an offset path of continuous longitudinal steel between the girder bottom flange and the cap beam. However, the LUSC did not require precise alignment of strand ducts during field assembly like the GUSC detail. The looped strands that protruded from the cap beam ledge on either side of the girder provided ample clearance as they wrapped around the T-headed dowel bars that ran through the girder and formed a link with the looped strand in the girder, as shown in Figures 3b and 3c. The interaction between the dowel bars and the looped strands was expected to be the primary mechanism for tension load transfer related to positive moment demand. As for negative moment continuity, there was little difference in the LUSC and GUSC concepts; both details incorporated continuous deck reinforcement that extended over the girders and cap beam, providing tension reinforcement to resist negative moment demand.

EXPERIMENTAL VERIFICATION OF DETAILS

Test Configuration and Plan

To fully quantify and verify the GUSC and LUSC details, a 50% scale component test unit was designed and constructed in the Iowa State University Structures Laboratory. The unit consisted of a single column, footing, and cap beam, along with two I-girders, as shown in the three-dimensional representation in Figure 4. The connection between the column and the cap beam in the test unit was completed by leaving reinforcement exposed at the top of the column and grouting the reinforcement into ducts in the cap beam after positioning it above the column. While the column itself in this configuration was simply a test stand and not part of the experimental study, incorporating this detail verified the possibility of using a precast inverted tee cap beam in a similar way along with precast girders. A photograph of the cap beam is shown in Figure 5a, after being positioned and grouted atop the column. Note that the cap width varies to match with the two different connection detail requirements. The girders used in the test unit were 50% scale models of the largest standard California I-girder, matching the girders used previously in the system test. Modifications were made to the girders according to each connection detail; ducts were added to the bottom flange of the GUSC girder, and anchored looped strands and dowel bar ducts were added to the LUSC girder. Figure 5b shows the girders being positioned on the cap beam. The test unit incorporated deck and diaphragm details that modeled current Caltrans recommendations.

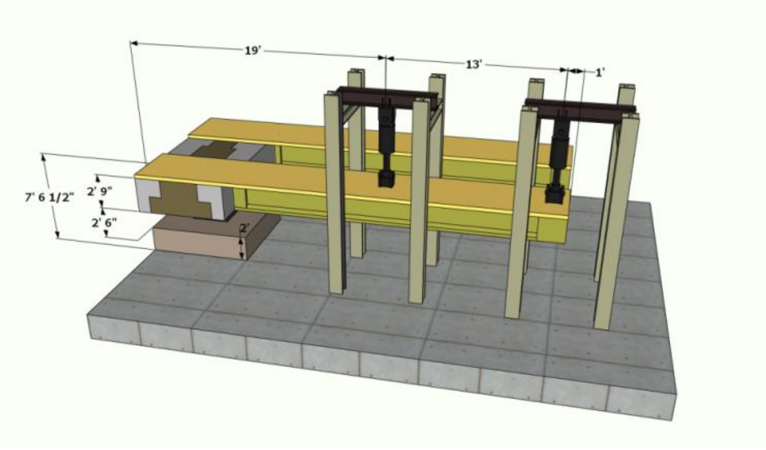
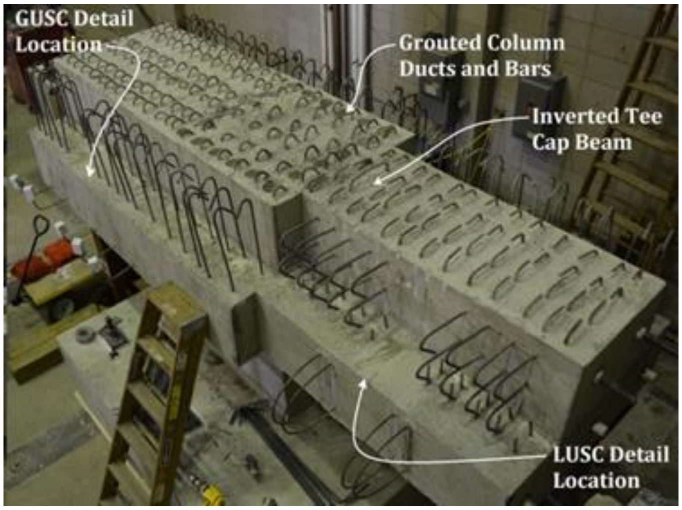
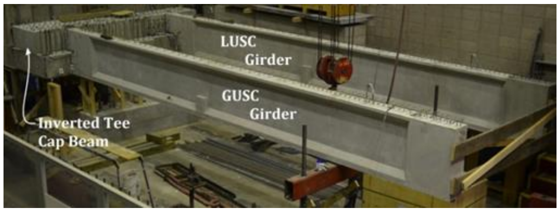


Figure 4. Connection test configuration

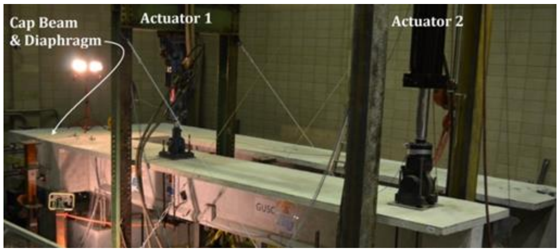
Connection of both the GUSC and LUSC details proceeded smoothly. The strands in the GUSC detail were able to be positioned through the cap beam and girder ducts without difficulty. Grouting the strands with the use of high strength grout ($f'_c = 8500$ psi) in place was accomplished by using a grout pump, and after the grout was placed and cured two small view ports were drilled (one in the girder and one in the cap beam) to verify adequate grout placement. Construction of the LUSC detail was even simpler. Since no duct alignment and no strand grout was required, the dowel bars could simply be inserted through the girder ports and grouted in place, followed by the placement of the diaphragm concrete.

Although construction progressed relatively smoothly for both details, construction of each detail revealed minor challenges. For the GUSC detail, pumping grout through a relatively small duct over a relatively long length may not always be simple. Also, effective pumping of the grout requires the interface between the girder duct and the cap beam duct to be tightly sealed in order to prevent loss of grout after placement. For the LUSC detail, the precast cap beam will have looped strands protruding from its sides, producing some inconvenience and requiring care during shipping and handling. As will be shown, the improved performance of both details far outweighs these challenges.





(b) Girders positioned on cap beam



(a) Cap beam after placement on column

(c) Completed test unit just prior to testing

Figure 5. Connection test configuration

To adequately test the designed connections, a loading protocol was developed that would replicate the connection moment and shear values for the gravity-only condition (Phase I, Part 1), gravity-plus-horizontal-seismic condition (Phase I, Part 2), and the gravity-plus-horizontal-and-vertical-seismic condition (Phase II). In addition, a large-displacement sequence (Phase III) was incorporated to fully exercise the connections beyond any expected simulated connection actions. The incorporation of two vertical actuators on a single girder, as seen in the photograph in Figure 5c, allowed different combinations of load and direction in each actuator to be used to produce any combination of shear and moment in the connection region. For each phase, a reversing cyclic sequence was incorporated. Figure 6 shows the load sequence for Phase II as representative of the type of sequence used for all three phases. Note that the zero-positive-moment cycle near the midpoint of the test was simply due to a temporary pause in the testing.

Phase II in particular was developed to simulate vertical acceleration effects on the girder-to-cap connection. The Caltrans SDC mild side reinforcement requirement for vertical acceleration shear is a major impediment to implementation of the inverted-tee cap and dapped-end girder system, because there is often little room in the bottom flange of the girder to include this additional steel. In addition, recent earthquakes (especially the 2011 Christchurch, New Zealand, event) raised awareness of the susceptibility of structures to vertical acceleration effects (10). System test observations had suggested that the GUSC detail had sufficient shear capacity to meet the vertical acceleration demands without including additional reinforcement, and the LUSC detail was expected to behave similarly. Thus, one of the goals of the connection test

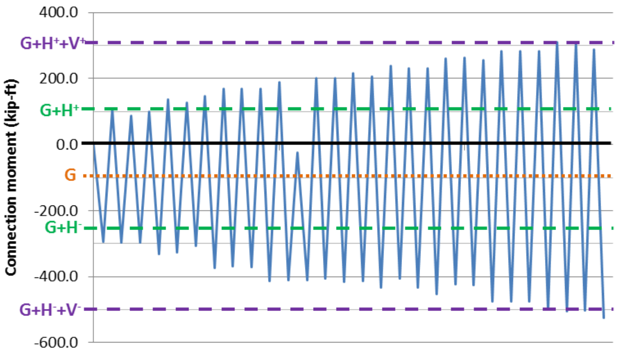


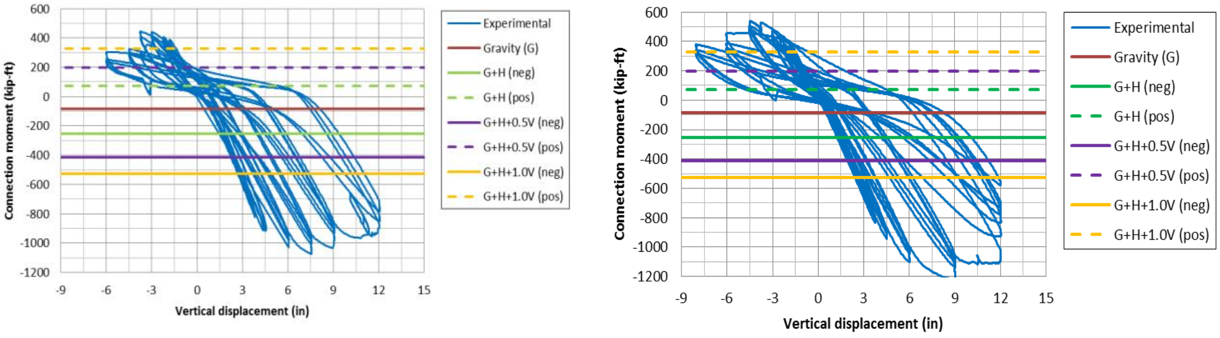
Figure 6. Phase II Load Protocol

was to subject the connection details to simulated vertical acceleration action and verify that the connections could be implemented without including the additional reinforcement required by the current Caltrans SDC (5).

Experimental Results

Overall Behavior of the Two Details

Both the GUSC and LUSC details performed very well during the experimental testing. Both exhibited elastic behavior for positive moment magnitudes considerably higher than the expected demand at the full horizontal seismic condition. In fact, for both details the elastic behavior continued to magnitudes approximately 1.25 times higher than the demand expected at full horizontal seismic load plus 1.0-g vertical acceleration. Figure 7 shows the connection moment history for both tests plotted as functions of vertical displacement at the Actuator 2 location. In these plots, “H” signifies the maximum expected horizontal seismic demand based on the column overstrength moment and “V” signifies the demand expected from 1.0-g magnitude vertical acceleration. These plots are helpful in identifying the magnitude of moment demand generated during the tests. Both connections demonstrated elastic behavior up to positive connection moment magnitudes near 400 kip-ft, almost 2.4 times higher than the expected full horizontal seismic positive moment of 170 kip-ft, and almost double the full horizontal plus 1.0-g vertical condition of 215 kip-ft. The plots demonstrate elastic moment behavior in both connections up to magnitudes considerably higher than expected seismic demands, including both horizontal and vertical effects. In addition, the plots show that both connections exhibited considerable ductility for both positive and negative moment response.



(a) GUSC Detail

(b) LUSC Detail

Figure 7. Recorded connection moment as a function of displacement at the far actuator

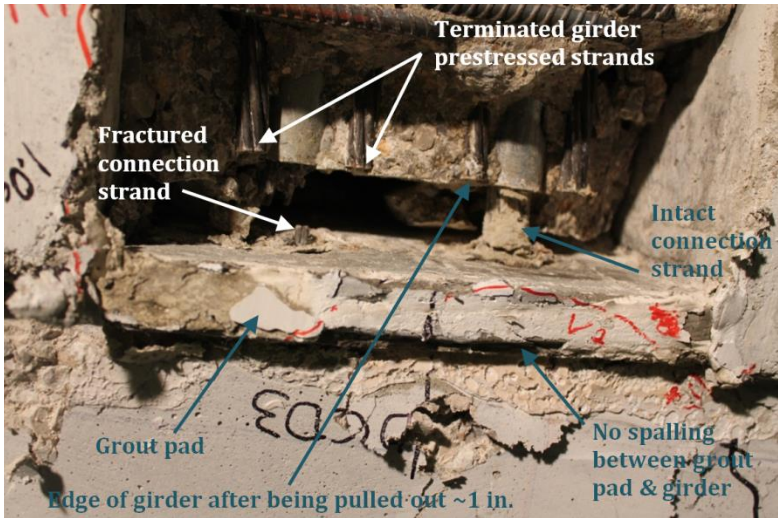
The failure mechanisms in the two details were unique. In the GUSC detail, the concrete in the connection region remained largely intact for the duration of the testing. The primary failure mechanism was the fracture of one of the pairs of unstressed strands at the girder-to-cap interface. The photograph in Figure 8a provides a view vertically upward into the interface at the maximum positive displacement. The strands on the right remained intact, while the strands on the left fractured. Strand fracture as the primary failure mechanism provided two important findings: (1) the grout on both sides of the interface provided sufficient anchorage to fully develop the strand strength, and (2) the strand was a primary contributor in the positive moment performance of the connection, as per the design intent. The strand fracture occurred when the girder end was subjected to positive displacement of 4.5 in. The corresponding simulated moment was more than double the expected connection moment at full gravity, horizontal seismic, and 1.0g vertical acceleration.

The positive moment failure mechanism in the LUSC detail was not quite as straightforward as the GUSC detail. Observations at the conclusion of the LUSC test indicated that the failure of the connection under positive moment loading was related to the interaction of the diaphragm concrete, the looped strands, and the dowel bars. At the highest displacement cycles of Phase III loading, a clearly defined crack and separation of the diaphragm around the dowel bars was observed, as shown in Figure 8b. The complexity of the components working together in this detail make it difficult to pinpoint a specific failure mechanism for the test unit; examination and deconstruction of the connection region at the conclusion of the test indicated that softening and crushing of the concrete around the dowel bars and loss of overall confinement strength of the diaphragm concrete around the entire looped strand region were instrumental in the connection failure. Even so, the eventual failure occurred when the simulated moment was many times greater than the full gravity, horizontal seismic, plus 1.0g vertical acceleration load.

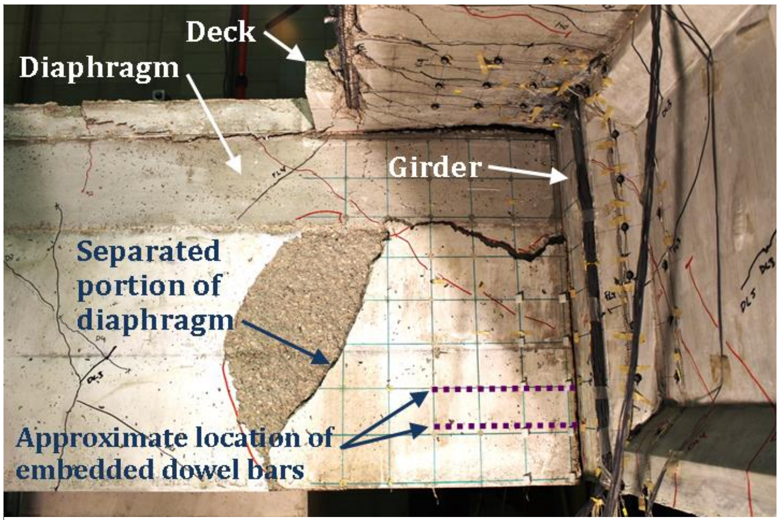
GUSC Performance

Strain gages were used to monitor the strain in the unstressed strands throughout the GUSC test. Figure 9a provides strain values from near the connection interface in one of the strands for the positive moment peak conditions for most of the Phase III portion of the test. The labels by the points on each curve in Figure 9a indicate the corresponding load/displacement peak; the points labeled as “F” were the peaks from the force-control portion of Phase III, whereas the points labeled as “D” were the peaks from the displacement-control portion.

The increase in slope in Figure 9a at high connection moments indicates that the strand mechanism carried a greater portion of the connection load at higher connection moments and displacements. To provide more insight into other moment mechanisms in the connection, the dowel bar strains are plotted in Figure 9b for the same peak displacements that were used in Figure 9a. The dowel bar strains show the same trend as the strand strains. The data indicate that the dowel bars and strand acted in concert to resist the positive moment tension, and this combined mechanism picks up more load under high displacements as the ability of the concrete to provide tension capacity and shear friction resistance independent of the reinforcement lessens.



(a) GUSC girder-cap interface during peak positive-moment displacement (looking up)



(b) Condition of the diaphragm of LUSC detail at peak positive-moment displacement (looking along side of girder toward cap)

Figure 8. Photographs of connection conditions under large positive-moment displacements

LUSC Performance

Data from the dowel bars, diaphragm looped strands, and girder looped strands in the LUSC detail were investigated and compared to quantify the connection performance and investigate the positive moment tension transfer mechanism. Figure 10a shows measured strain in one of the four dowel bars near the girder web plotted as a function of the relative displacement of the girder lower flange and the diaphragm. The relative displacement was determined using data from LED position indicators located on the concrete surfaces of the diaphragm and girder. The positive relative displacements correspond with positive moment loading are of primary interest. These data points reveal a regular, linear trend throughout the Phase III test. The uniformity of this relationship suggests that the dowel bars are indeed a primary contributor in the positive moment performance of the LUSC detail. The strain magnitudes measured in the dowel bars are seen to be noticeably lower than the approximate yield strain of 2300 $\mu\varepsilon$.

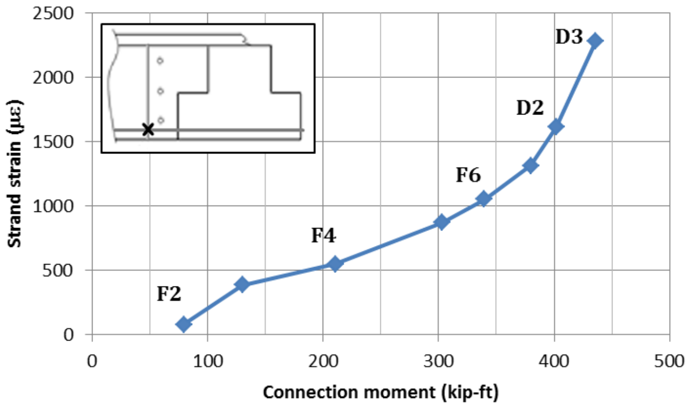
The relatively low strain demand indicates that the dowel bars were sufficiently sized for the connection demand.

Confinement for the dowel bars was expected to be provided by the looped strands in the diaphragm and girder. Figure 10b provides looped strand strain from both the diaphragm and girder at peak displacements as a function of the dowel bar strain. These relationships are relatively linear throughout the test. The regularity of these data suggests that both the diaphragm and girder looped strands were an important component in the successful positive moment behavior of the connection detail.

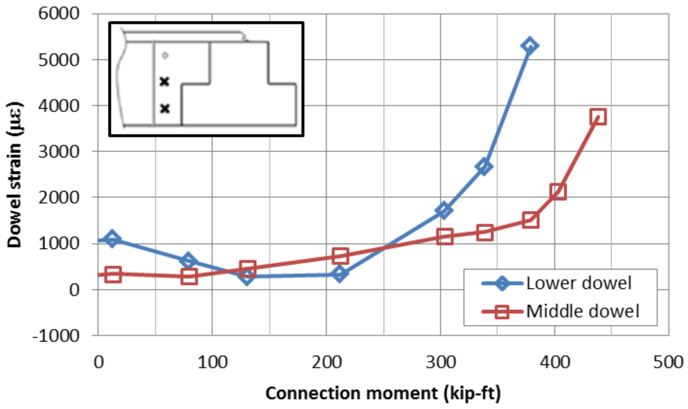
APPLICATIONS AT THE PROTOTYPE LEVEL

Both the GUSC and LUSC details exhibited successful performance under experimental testing simulating significant seismic accelerations in both the horizontal and vertical directions. In particular, the details improved the positive-moment performance of the connection over the detail used previously. Figure 11 compares the GUSC and LUSC negative and positive moment performance with the previous (as-built) detail from the system test joint study mentioned in the introduction. Both details show marked improvement over the as-built detail.

The successful positive moment performance of both connection details, along with the excellent constructability and overall performance of both details, allow for direct application of the seismic design principles to structures at the prototype level. Appropriate scale values correlate the 50% scale test unit to a full-size prototype bridge and allow for implementation of specific connection design details. Application of the connection details results in cost and time savings by the reduction of column cross-section and footing proportions at intermediate bridge bents by creating a fixed superstructure connection with adequate capacity to resist required vertical acceleration forces. Utilization of the precast inverted-tee bent cap eliminates falsework resulting in material and labor savings and also requires less concrete to be poured onsite. The connection tests also demonstrated that dowel bars are able to provide significant positive moment resistance at the prototype level despite not providing direct tension continuity across the girder to cap connection. Overall, the connection tests show that the benefits of ABC methods can be effectively utilized in the state of California and regions subject to high seismic forces.

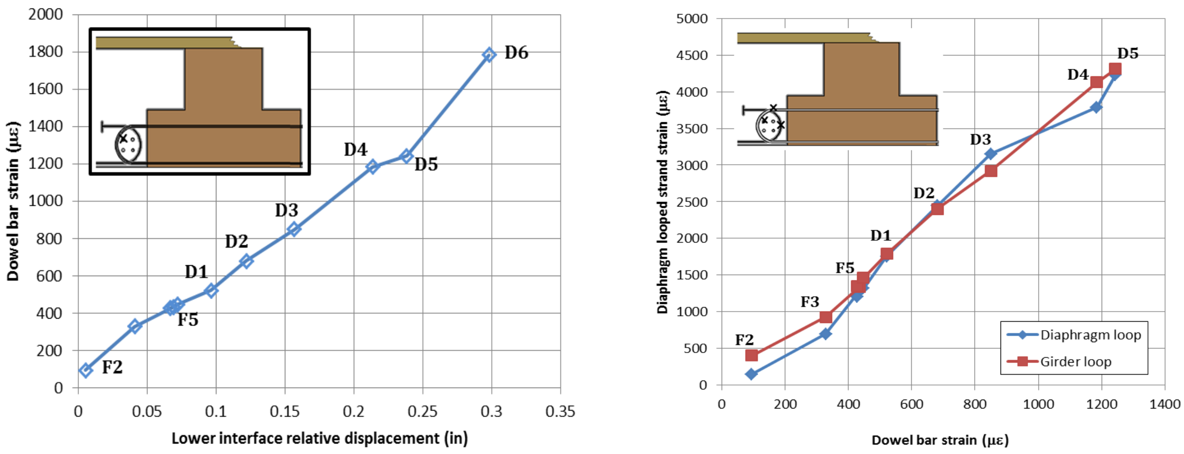


(a) Unstressed strand strain for positive moment peaks



(b) Dowel bar strain for positive moment peaks

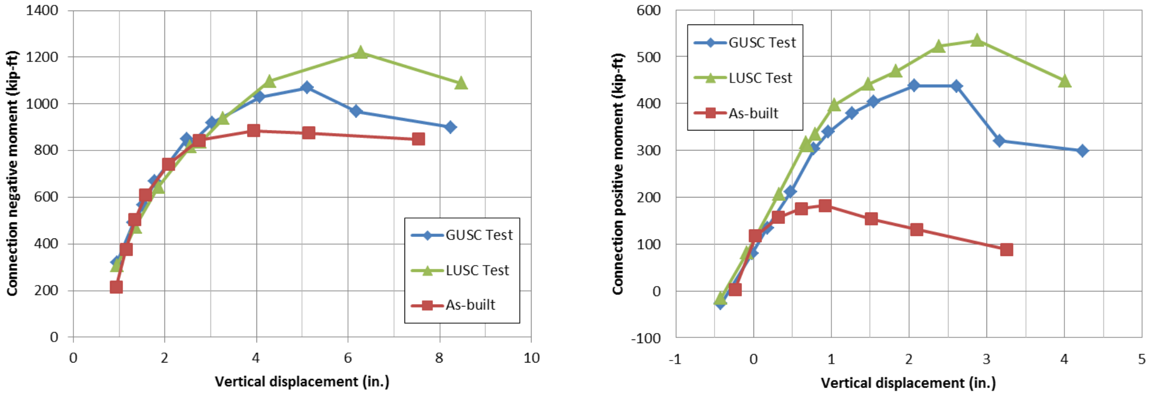
Figure 9. Strain in GUSC unstressed strand and dowel bars at positive moment peaks during Phase III testing



(a) LUSC dowel bar strain as a function of displacement

(b) LUSC looped strand strain as a function of dowel bar strain

Figure 10. LUSC strand and dowel bar strains at positive moment peaks during Phase III testing



(a) Negative moment

(b) Positive moment

Figure 11. Connection moment performance during Phase III testing

CONCLUSIONS

The connection tests of the GUSC and LUSC details have provided further development and quantification of connection details for inverted-tee and dapped-end I-girder bridge systems for seismic regions. Both details use unstressed strands to improve positive moment tension continuity and shear performance across the girder-to-cap connection interface. Some specific conclusions can be stated as a result of this investigation:

1. Both the GUSC and LUSC details provide sufficient moment and shear resistance for integral bridge designs in high seismic regions. Both details remained elastic for negative moment demand and positive moment demand as much as four times higher than the maximum expected gravity and horizontal seismic demand.
2. Both details were sufficient for simulated gravity and seismic loads that included significant vertical acceleration contribution. Both connections were subjected to demands that included simulated vertical acceleration in excess of 1.25g before exhibiting any inelastic tendencies.
3. The successful performance of both details when subjected to vertical acceleration effects confirms that the Caltrans SDC requirement of including additional girder side mild reinforcement may be unnecessarily conservative for these details. While this requirement is intended to guarantee sufficient shear connection performance when the connection is subjected to vertical acceleration demands, both connections demonstrated shear capacities considerably higher than the vertical acceleration demands without the inclusion of the additional mild steel.

4. High strength grout pumped into the strand ducts provided sufficient anchorage to fully develop the strength of the strand.
5. In the GUSC detail, the dowel bars that are similar to the existing Caltrans detail act with the unstressed strand in the girder lower flange; each mechanism resists a portion of the connection moment.
6. In the LUSC detail, the interaction between the dowel bars in flexure and the looped strands in confinement tension provides a viable positive moment tension transfer mechanism.
7. Moment strength comparison of the GUSC and LUSC details with previous connection details shows that both new details showed marked improvement over the previous details, especially in the positive moment direction.

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