Seismic Research and Testing of Precast Segmental Bridges

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ABSTRACT

Precast Segmental Bridges are widely being used around the world due to several advantages over conventional type of bridge construction. The use of precast segmental construction has been hampered due to seismic performance concerns. This paper discusses the issues pertaining to Segmental construction in seismic areas, California Department of Transportation's (Caltrans) efforts in investigating the above concerns and investigating the viability of segmental bridges in seismic areas. This paper presents the key findings from a Caltrans funded series of research efforts at University of California, San Diego. The findings have alleviated the seismic performance concerns of precast segmental bridges. In addition, the findings also have given the industry valid research data to update the current code and practice. Due to the vast scope of the research efforts, only pertinent information and key findings are presented in this paper. Specific information regarding the tests could be obtained in the references listed.

Keywords: **Precast, Segmental Bridge, Seismic, Joint Opening, Post-tensioned, Prestressed, Bonded Tendon, Unbonded Tendon, Shear key, Internal Tendon, External Tendon, Balanced Cantilever Construction.**

INTRODUCTION

Segmental construction is increasingly becoming a popular method of construction for the bridge industry particularly in environmentally sensitive areas, spanning waterways and deep canyons, and congested urban construction. The concept of eliminating false work for bridge construction by assembling a bridge using segments built onsite or offsite is beginning to be more appealing for the above situations. Cast in Place segmental construction involves construction of segments at the site using form travelers. Precast construction involves the use of precast segments cast elsewhere and assembled onsite. Although Europe is the leader for modern day segmental construction, this method of construction is widely practiced in the United States and the rest of the world. Rapid pace of construction, least disruption to the environment and traveling public are among the key factors that favor segmental construction over other conventional methods of bridge construction.

This first modern day precast segmental bridge in the United States is the JFK Memorial Bridge built in Corpus Christie, Texas in 1971. The first Cast in Place segmental bridge in the United States is the Pine Valley Bridge built in San Diego, Ca in 1975. Opening and closing of joints, ability to transfer moments and shears across the joints, performance under fatigue loading, corrosion of tendons and seismic behavior were concerns that impeded the progress of segmental bridges during early stages of segmental construction in the United States. The above concerns with the exception of seismic performance concern were quelled by experimental and analytical research conducted at University of Texas, Austin, Florida Atlantic University, Boca Raton and other institutions[1, 2, 3 and 4]. Segmental construction, especially the precast segmental construction thrived in non-seismic regions of the United States such as Florida and Texas in the last few decades.

CALIFORNIA AND SEGMENTAL CONSTRUCTION

Seismic performance concerns and lack of research on segmental bridges subject to seismic loads plagued the acceptance and use of segmental bridges in California. Primary concerns in seismic regions are that large seismic deformations would occur, possibly leading to excessive joint openings, and that in the regions of high shear these large joint openings can be compounded by relative sliding between segments.

Severe damages to bridges during the San Fernando earthquake (1971), Loma Prieta earthquake (1989) and the Northridge earthquake (1994) added significant concerns to the viability of segmental bridges in California. Due to lack of experimental seismic research, conservative design guidelines governed the joint region. The current American Association of State Highway and Transportation Officials (AASHTO) guidelines require epoxied joints for precast segmental construction in high seismic areas. In addition, the external or unbonded tendons are limited to 50 % of the total prestressing in the superstructure.

Although the first cast in place segmental bridge in the United States was built in California in 1975, it took over a decade and a half to build the next cast in place segmental bridge in

California. Precast segmental bridges were not considered viable until recently in California despite the many advantages of precast segmental construction. As the first major precast segmental bridge, the Skyway portion of the new Bay Bridge in Oakland (SFOBB) was designed with a cast in place (CIP) deck closure joints with reinforcing bars across the joint and vertical stirrups in the closure pour to address seismic concerns. The use of lightly stressed auxiliary tendons was contemplated as an alternate design detail. Such design features due to lack of research validation negate many of the benefits of segmental construction by adding time, cost and complexities to construction.

In an effort to alleviate the seismic performance concerns of the precast segmental bridges, California Department of Transportation, (Caltrans) embarked on an extensive research program on precast segmental bridges at University of California, San Diego (UCSD). The SFOBB currently under construction has incorporated valuable research information. Design details have been changed based on the research findings. Additional information from this research program is being used for policy decisions and updating the current seismic code for segmental bridges.

SEGMENTAL RESEARCH PROGRA M

A large-scale experimental research program funded by Caltrans on precast segmental bridge superstructures has been completed at UCSD. This testing consisted of three phases.

Phase I: Investigated the performance of superstructure segment-to-segment joints under fully reversed cyclic loading. Joints with high bending moments and low shears were considered in this phase (joints close to the midspan).

Phase II: Investigated the performance of superstructure segment-to-segment joints under fully reversed cyclic loading. Joints with high bending moments combined with high shears were considered in this phase (joints close to the columns).

Proof test: Investigated the behavior of the above specimens with a lightly stressed auxiliary deck tendon configuration and compared results with the behavior of the cast-in-place deck closure joint configuration examined in the Phase I and Phase II research.

Phase III: Investigated the seismic performance of superstructure-column system under longitudinal seismic loading.

PHASE I – EXPERIMENTAL PROGRAM

The prototype structure (Fig. 1) used for the design of the test units in Phase I is a single cell box girder bridge that consists of five spans with three interior spans of 100ft and exterior spans of 75 feet for a total length of 450 ft. Each span of the prototype structure is post-tensioned with harped tendons and built using the span-by-span construction technique. The critical location of the prototype structure for positive bending under dead load and seismic forces was identified to be approximately at midspan. The test units model the middle of the prototype span in which the tendon is horizontal. For laboratory tests, they were designed at

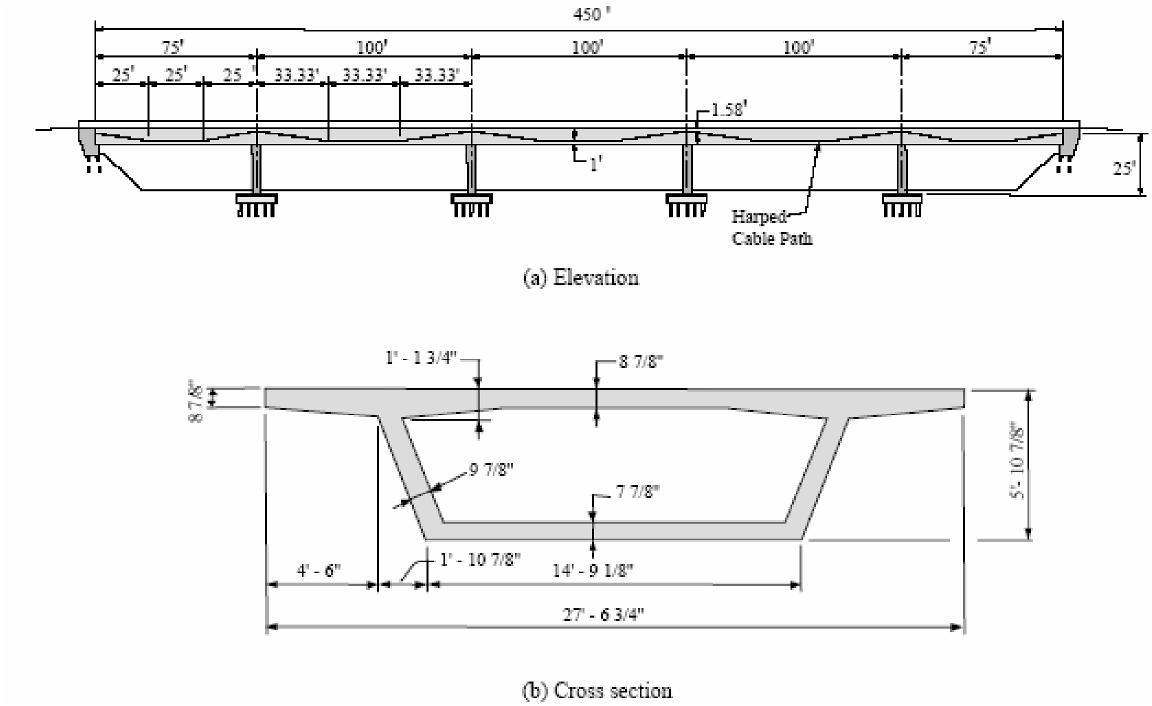


Fig. 1 Prototype Structure for Phase I and Phase II

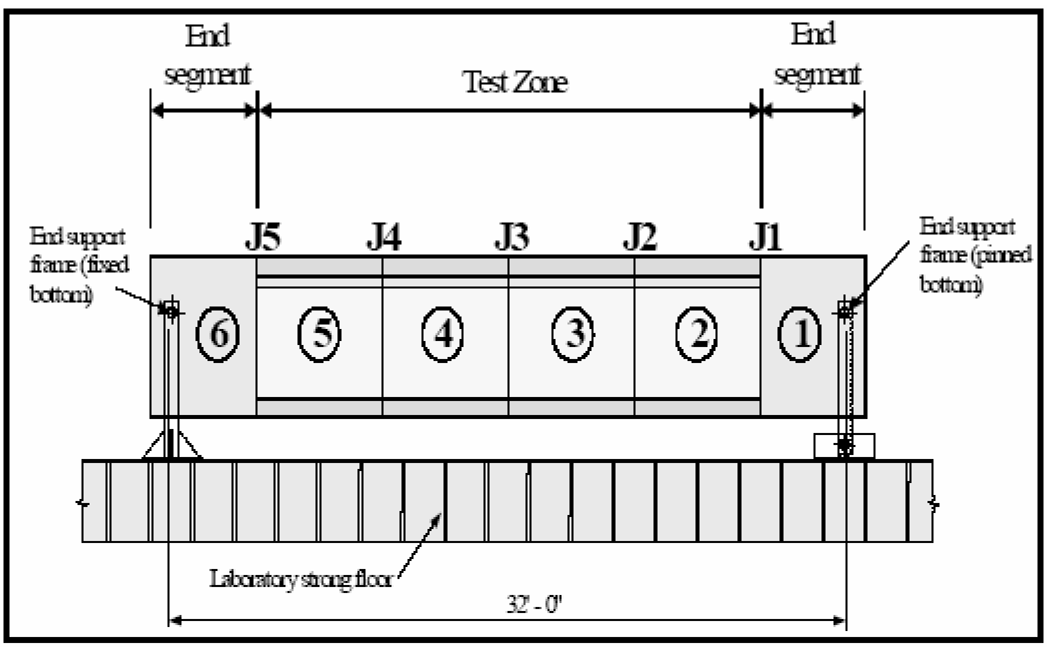


Fig. 2 Test Setup

two-thirds scale of the prototype structure. The test zone had a total length of 24 ft (7.32 m), which represented the center one-third portion of the prototype span. This test zone consisted of four 6 ft (1.83 m) long by 4 ft (1.22m) deep precast segments. Each test unit was supported at its ends through precast end segments. Half of the prototype box girder section was modeled and idealized in the shape of an equivalent I section to simplify the test setup (Fig. 2).

The variable investigated in this experimental program was the type of post-tensioning and the presence of mild steel reinforcement across the segment-to-segment joints as listed in Table 1.

Table 1: Test Matrix for Phase I and Phase II Studies

Unit No.	Description	Nomenclature
1	100% Internal post-tensioning	100INT
2	100% Internal post-tensioning with cast-in-place deck closure joints	100INTCIP
3	100% External post-tensioning	100EXT
4	50% Internal and 50% External post-tensioning	50INT/50EXT

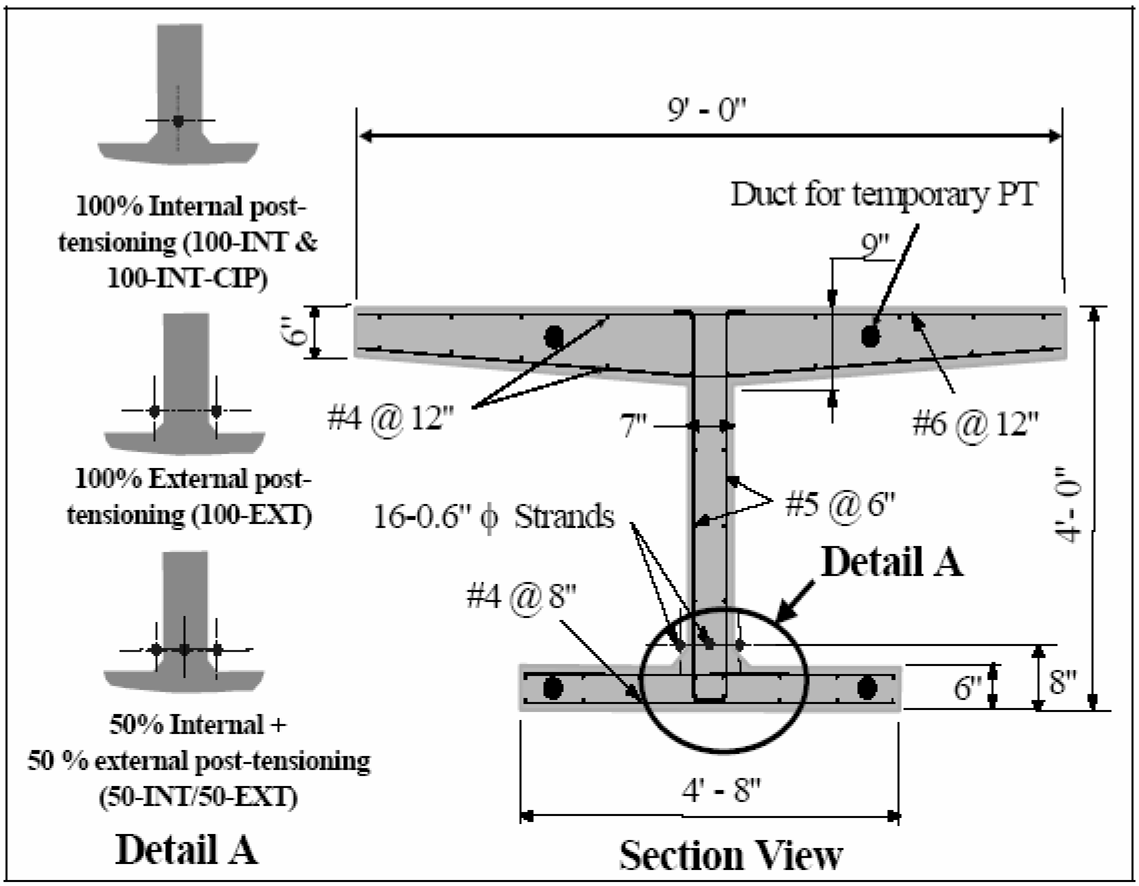


Fig. 3 Test Unit Cross Section

The test unit cross sections are shown in Fig. 3. Test Unit 100INT used 100 percent internal post-tensioning (bonded tendon) with no cast-in-place deck closure joints. No mild steel reinforcement was placed across the segment joints. The segments of unit 100INT were connected by a Segmental Bridge Adhesive (SBA) slow-set epoxy, applied to the entire cross section of the segment-to-segment joints.

Test unit 100INTCIP used 100 percent internal post tensioning (bonded tendon) and reinforced cast-in-place deck closures. Details of the reinforced cast-in-place deck closure joints of test unit 100INTCIP were similar to those used in the original design of the new SFOBB. Two different reinforcement details were incorporated in unit 100INTCIP (Fig. 4) at the cast-in-place deck joints. Bent hairpin bars were used on one half of the cross section and bars with mechanical anchors at their ends were used in the other half. Both reinforcement details provided adequate anchor to the reinforcing bars in the cast-in-place deck joints to mobilize their full yield strength. The objective was to study the effect of each of these details on the performance of the joints. The remaining portions of the joints in unit 100INTCIP, along the web and bottom slab, were connected by SBA epoxy.

Test Unit 100EXT used 100 percent external post-tensioning (unbonded tendon). No mild steel reinforcement was placed across the segment joints. The segments of unit 100EXT were connected by a Segmental Bridge Adhesive (SBA) slow-set epoxy, applied to the entire cross section of the segment-to-segment joints.

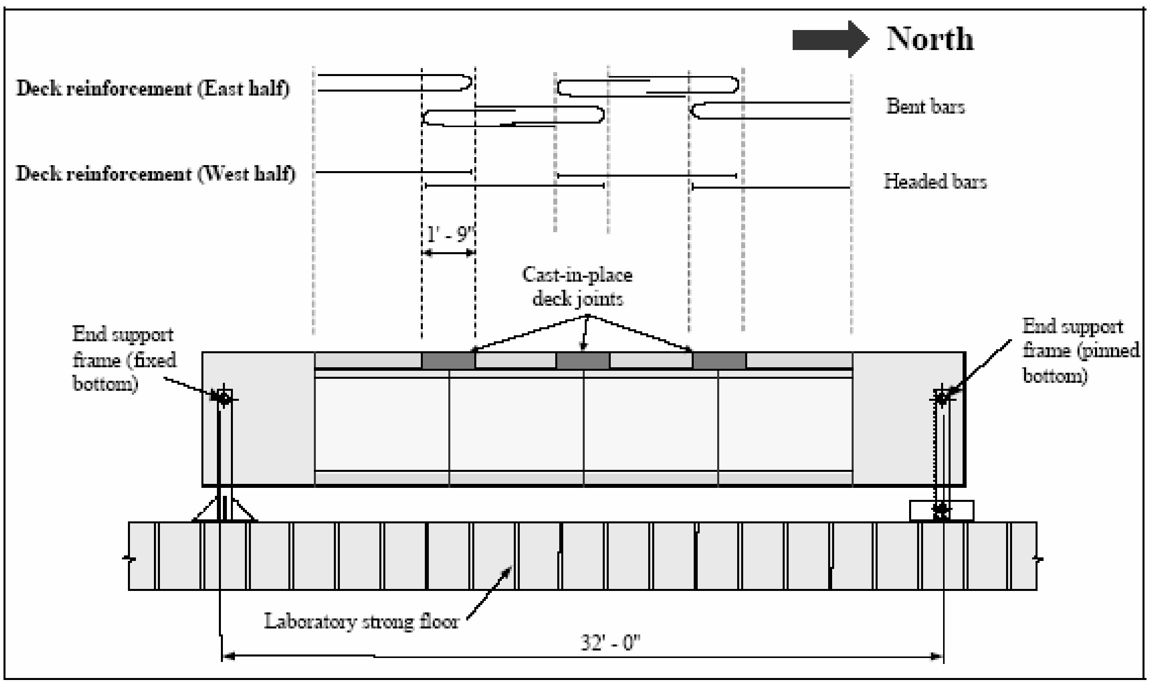


Fig. 4 Cast-in-place Deck Joint for Test Unit 100INTCIP

Each test unit was post-tensioned with 16 strands each of 0.6 in. (15.2 mm) diameters. The magnitude of the prestressing force was equal for all test units and calculated to ensure that the concrete stresses resulting from post tensioning are the same as for the prototype structure. Except for the cast in place deck reinforcement in test unit 100INTCIP, the layout of the reinforcing bars (grade 60) was the same for the test units. The segments of unit 100INTCIP had a gap in the deck at the location of joints, which was closed later by a cast-in-place concrete slab strip. After joining of the precast segments and closure of the cast-in-place deck joints (Unit 100INTCIP), each test unit was post-tensioned.

Loading

This load level will be referred to as the reference load level throughout this paper. The test setup for the Phase I tests in shown in Fig. 5. Testing of each unit was divided into two stages. Stage 1 test was the service load conditioning where each segment underwent load conditioning for 100,000 cycles between maximum and minimum service load conditions. Stage 2 test was the seismic test that involved fully reversed loading cycles with increasing displacement amplitudes. Three cycles were performed at each displacement level through 4 inches. Beyond 4 inches, only one cycle was performed at each displacement level. Each unit was loaded until failure.

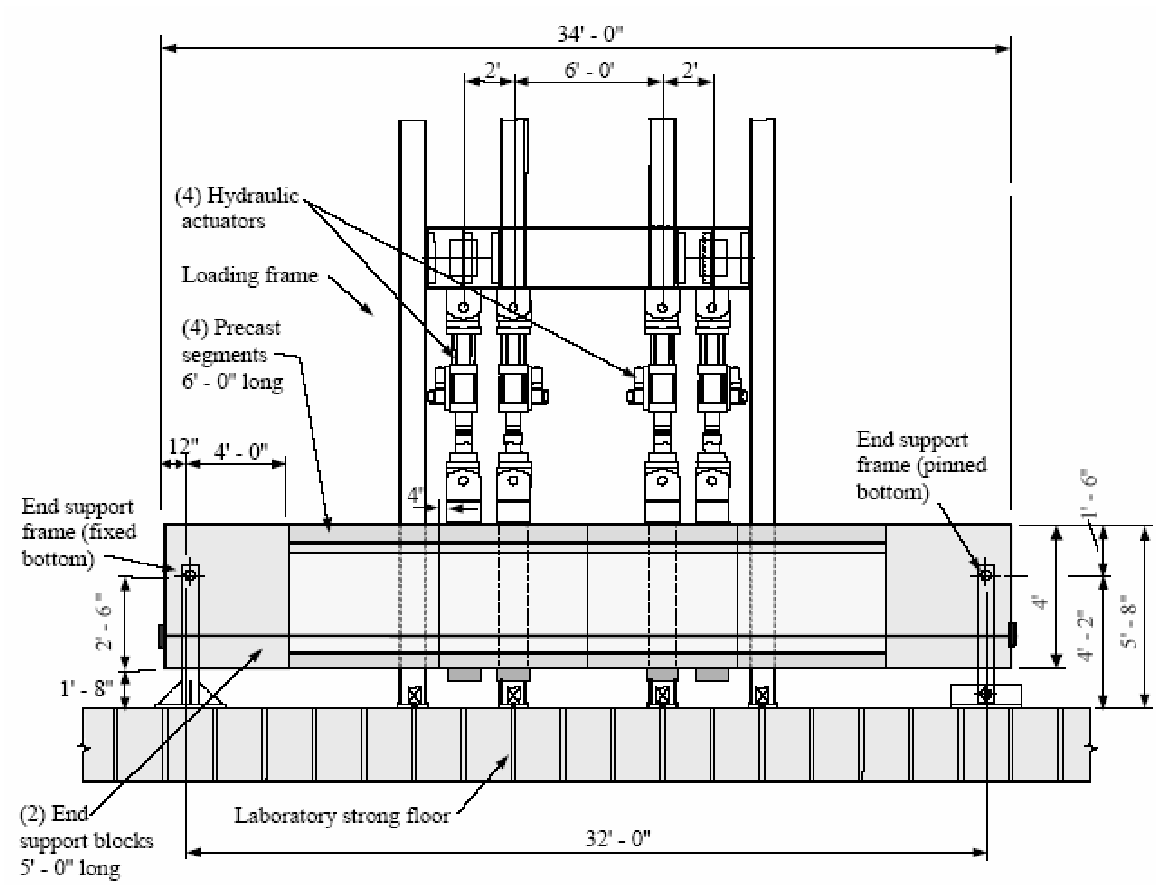


Fig. 5 Test Setup Elevation

Findings

- Combination of bonded and unbonded (internal and external0 tendons need to be avoided in high seismic areas as the two system does not participate in the force resistance in parallel. The internal bonded tendon carries most of the loading up to their failure.

- Crack patterns for all test units were similar under downward loading. Only the midspan joint opened during testing of the unit with 100 % external post-tensioning.
- The segment-to-segment joints can experience significant repeated openings and closures under reversed cyclic loading without failure even if there is no mild steel reinforcement crossing the joints. Precast segmental superstructures can undergo significant seismic displacements without failure.
- Permanent deformation and joint openings are reduced if there is mild steel reinforcing bars crossing the segment-to-segment. The cast in place deck joints originally proposed for the new SFOBB enhances the seismic performance of precast segmental bridges in terms of energy dissipation and reduction of permanent displacements and permanent joint openings.
- The 100INT unit and 50INT/50EXT units failed explosively by rupture of the prestressing tendon, whereas compression failure occurred in the deck of the 100INTCIP test unit following buckling of the mild steel reinforcement of cast in place deck joint. Load carrying capacity dropped gradually in the 100EXT Unit and hence did not have the explosive failure.
- The seismic response of precast segmental bridge superstructures with cast in place closure joints will not differ if headed or bent hairpin bars are used as longitudinal reinforcement in the closure joints. However, headed bars are recommended over bent hairpin bars for constructible reasons. Buckling of the deck longitudinal reinforcement should be prevented by means of closed stirrups that confine the top and bottom reinforcing bars.
- Finite element analyses indicated that under severe earthquake loading the prestressing force in the tendons could diminish under repeated cycling in the inelastic strain range.
- Opening of an epoxy-bonded joint occurs due to cracking of the concrete cover adjacent to the joint rather opening of the epoxy joint itself. The concrete cover adjacent to the joint has relatively low cracking strength compared to the concrete of the precast segments. The dominant flexural vertical crack adjacent to the joint occurs through the alignment and shear keys.

PHASE II – EXPERIMENTAL PROGRAM

The prototype structure used for the design of Phase II test units is the same prototype used in the design of Phase I units. In addition to the harped shape tendon, horizontal tendon was included in the design of the Phase II test units based on the recommendation of the Seismic Research Committee of American Segmental Bridge Institute (ASBI). Since the test units in Phase I had linear elastic behavior, the service load conditioning stages for Phase II program was eliminated.

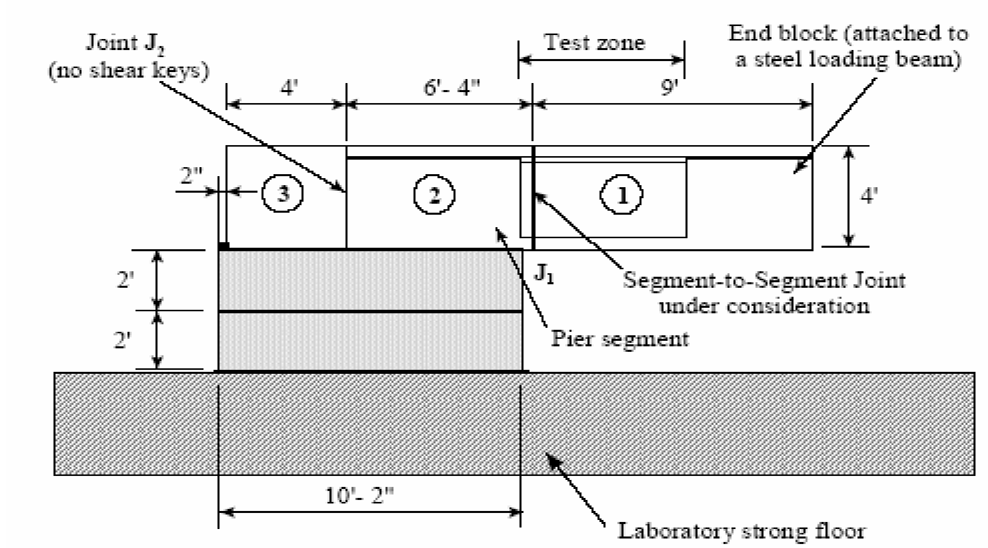
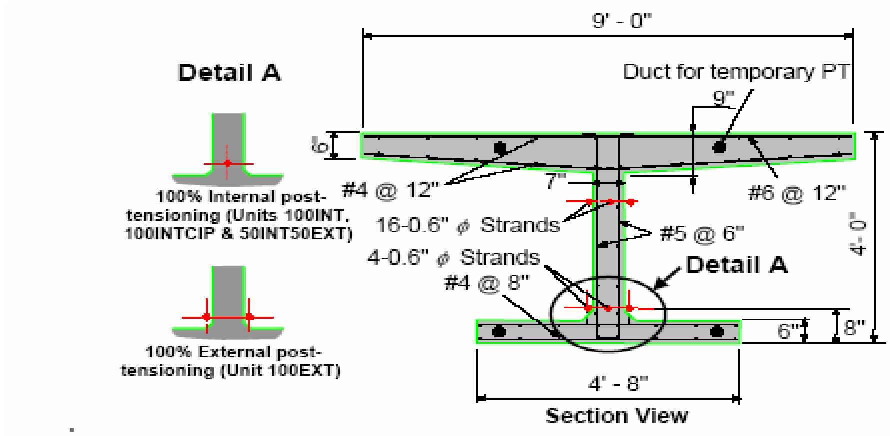
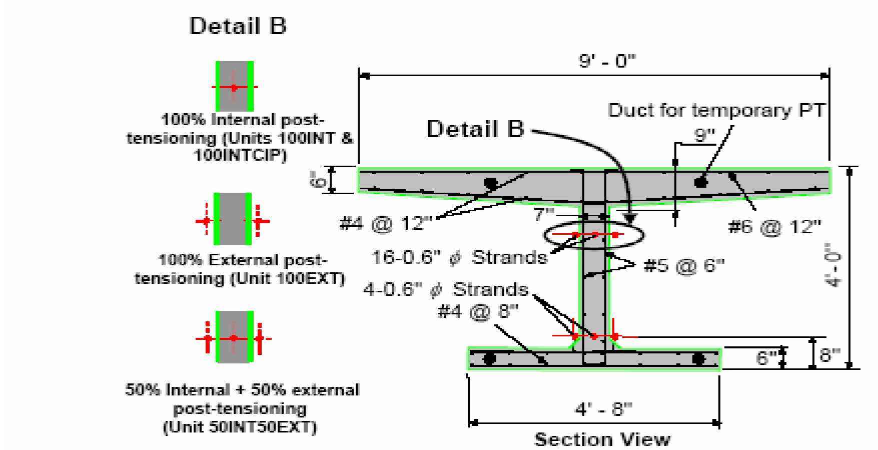


Fig. 6 Typical Test Unit Elevation



a) Cross Section of the Test Zone and the Horizontal Tendon



b) Cross Section of the Test Zone and the Harped-Shape Tendon

Fig. 7 Test Unit Cross Section

Four test units were constructed as outlined in Table 1and tested. Each test unit (Fig. 6) consisted of three precast segments Two segments were connected to a footing block to mimic the pier table. The segment attached outside the footing block to the segments above the footing block represents the first precast segment of the superstructure. The harped tendons consisted of sixteen 0.6 in. diameter seven wire strands. The harped shaped tendon had a straight-line profile with 10% slope within the first precast segment and continued up to the center of the pier. Four 0.6 in. tendons were internally bonded to model the bottom tendon in the 100INT, 100INTCIP and 50INT/50EXT test units. In Unit 100EXT, the bottom tendons were external and unbonded. Fig. 7 indicates the tendon locations and sizes for the different test units.

Loading

After reaching the reference load, each unit was subject to fully reversed cyclic vertical displacements until failure. Three cycles were completed at each displacement level up to 4 in. displacement; one cycle was performed at each displacement level beyond 4 in. Each unit was loaded until failure in the downward direction and the loading reversed in the upward direction until failure.

Findings

- Segment to segment joints can experience significant repeated openings and closure from reversed cyclic loading without failure, even if there is no mild steel reinforcement crossing the joints. Precast segmental bridge superstructures can undergo significant displacements without failure.
- Relative vertical sliding between precast segments would not occur before flexural failure of the superstructure. Based on experimental observation, vertical sliding between precast segments is not a concern.
- Test units 100INT, 100INTCIP and 50INT/50EXT experienced explosive compression failure in the bottom slab. With 100 percent external post tensioning the explosive failure mode was avoided and the load carrying capacity dropped gradually in unit 100EXT, with increased displacement in the post peak range; failure was initiated by concrete crushing in the bottom slab.
- Ductility and displacement capacity can be substantially enhanced by use of 100 percent external post tensioning. Use of only external tendons will also minimize post earthquake permanent displacement of the superstructure and permanent openings of the segment-to-segment joints.
- The combination of internally bonded and external tendons in precast segmental bridge superstructures should be avoided in high seismic zones.
- The use of cast in place deck closure joints improves the energy dissipation capability of the superstructure but complicates the precast segmental construction concept. It also slows down construction and increases construction costs.

PROOF TEST – EXPERIMENTAL PROGRAM

The first two phases included test units with cast-in-place deck closure joints, to investigate the behavior of precast segmental box girder sections with cast-in-place deck closure joints – a design feature originally contemplated for the new SFOBB. Proposed revisions to the design plan involved addition of auxiliary deck tendons to replace the cast in place deck closure joints. The auxiliary tendons are stressed to low levels to remain in the elastic range during an earthquake even if the main tendons reached inelastic strains. Since the auxiliary deck tendons are designed to remain elastic during a seismic event, they will provide a clamping force that serves to limit permanent joint openings in the deck region. In an extension of the Phase I testing, Caltrans funded one additional test (proof test) that sought to investigate the effects of auxiliary deck tendons in precast segmental superstructures.

Main goals of the proof test were to study the effects of fully reversed cyclic loading on segment-to-segment joints in regions of high moments and low shears (midspan location) for precast segmental superstructures with fully bonded internal deck tendons; investigate permanent residual deformations and damping characteristics. The results of the proof test could be directly compared to the results of the two Phase I units that had fully bonded internal tendons, so that behavioral characteristics, advantages and disadvantages of each construction technique could be pointed out. The objective of this test was to obtain the general response of precast segmental bridge superstructures under seismic loads using auxiliary deck tendons; thus a generic bridge superstructure was tested. Test results are not specific to the new SFOBB but can be used as guidelines for basic seismic performance of precast segmental bridges with lightly stressed auxiliary tendons in the deck slab.

Although complex three-dimensional finite element models were developed for analysis of test units in Phase I, such representations were not within the scope of the Proof Test program. A basic moment-curvature analysis was performed and verified by hand calculations in order to predict the response of the test unit, including maximum loads, displacements and joint opening characteristics.

Loading

This load level will be referred to as the reference load level throughout this paper. Testing of each unit was divided into two stages. Stage 1 test was the service load conditioning where each segment underwent load conditioning for 100,000 cycles between maximum and minimum service load conditions. Stage 2 test was the seismic test that involved fully reversed loading cycles with increasing displacement amplitudes. Three cycles were performed at each displacement level through 4 inches. Beyond 4 inches, only one cycle was performed at each displacement level. Each unit was loaded until failure.

Findings

- The load carrying capacity in positive bending is not affected by the use of either cast-in-place deck closure joints or auxiliary deck tendons.

- The load carrying capacity under upward loading is significantly affected by the addition of cast in place deck closure joints or deck tendons. Cast-in-place closure joints curtail maximum joint opening more under upward loading than auxiliary deck tendons, but the use of deck tendons can substantially reduce permanent residual joint opening in the deck.
- Sudden failure by either tendon rupture or concrete crushing is likely to occur for the precast segmental superstructures with internally bonded tendons. However, failure occurred at high displacements that significantly exceeded demands from the expected earthquake levels.
- Considerable joint opening capacity is expected for precast segmental superstructures with fully bonded internal tendons, with or without the use of cast-in-place deck closure joints or auxiliary deck tendons. Cast-in-place deck joints inhibit joint openings on the deck without adversely affecting load carrying or vertical displacement capacities.
- Relative vertical sliding is not a major concern for precast segmental superstructures, and is not affected by the use of either cast-in-place deck joints or deck tendons.
- The use of cast-in-place deck closure joints can greatly reduce the amount of permanent residual displacements if located away from the piers (close to midspan).
- Using either cast-in-place deck closure joints or auxiliary deck tendons allows for stable hysteresis in both loading directions and leads to high-energy dissipation capability.
- Precast segmental bridge superstructures can undergo large vertical displacements, and the use of cast-in-place deck closure joints or auxiliary deck tendons allows for large upward displacements to occur without sacrificing load carrying capacity.
- Using auxiliary deck tendons can significantly improve construction time and cost. Additionally, complexities arising from the construction of cast-in-place deck closure joints can be avoided by the use of deck tendons, especially if vertical stirrups are added in the cast-in-place deck closure joints to combat longitudinal bar buckling.

PHASE III – EXPERIMENTAL PROGRAM

Phase III program studied the seismic behavior of a precast, post-tensioned, segmental bridge superstructure with a cast-in-place, hollow, rectangular column. The half-scale specimen modeled a prototype bridge (Fig. 7) from midspan to midspan and down to midheight of the column. The bridge was built using the balanced cantilever method and the tendon layout of the specimen was designed to most closely match that of the prototype segment (Fig. 8) joints nearest to the column. This was done to examine issues relating to the interaction of the column and superstructure as well as corroborating the findings of the earlier phases of the test program. The prototype bridge modeled had span lengths of 100' (30.5m) and assumed to be constructed using the balanced cantilever method. The model bridge was built at half scale of this prototype and erected according to the balanced cantilever method to approximately match the time-dependant stresses across the joints. A series of hydraulic actuators and hollow-core jacks provided boundary conditions matching those on an interior span of the prototype structure. The column used for the test was a hollow CIP column with highly confined boundary elements. A similar column was also used in a previous test and subjected to an aggressive bi-directional seismic loading pattern.

The test was split into two stages. The first stage was designed to validate the existing design philosophy of maintaining the superstructure of the bridge undamaged. To achieve this the level of post-tensioning in the superstructure was selected to not allow any opening of the segment-to-segment joints under plastic hinging of the column. The second stage sought to allow some opening of the joints. For this purpose a portion of the superstructure tendons were left unbonded in the initial stage and later removed. Additional vertical loads simulating vertical acceleration were added to the structure resulting in a more severe loading demand as well as a reduced capacity of the superstructure joints.

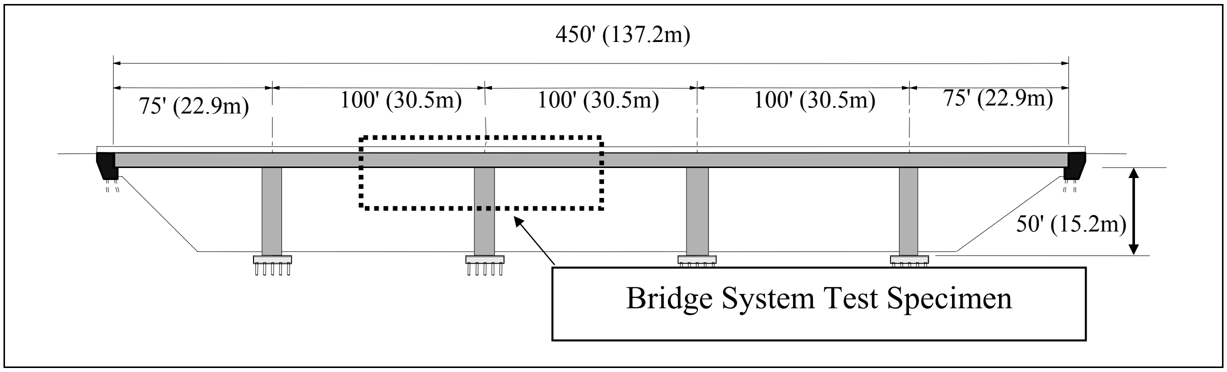


Fig. 7 Prototype Bridge Structure

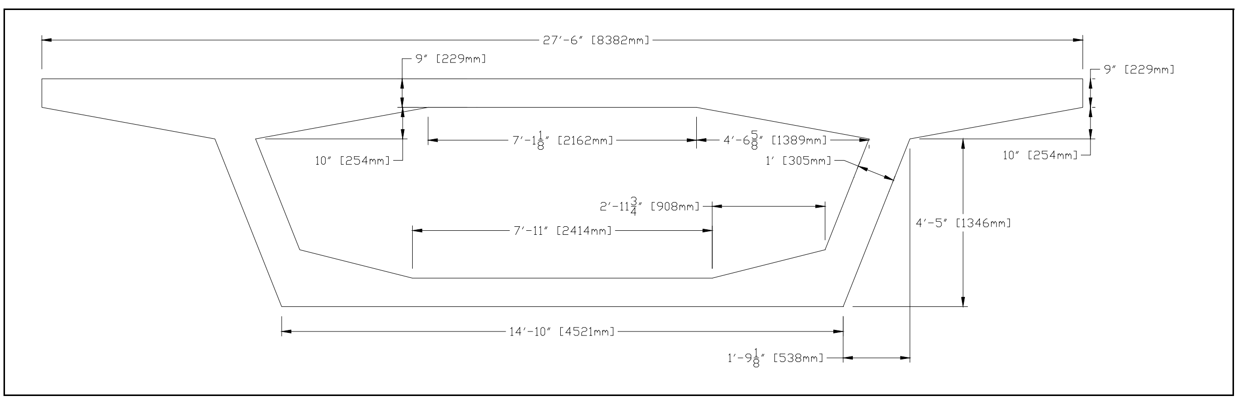


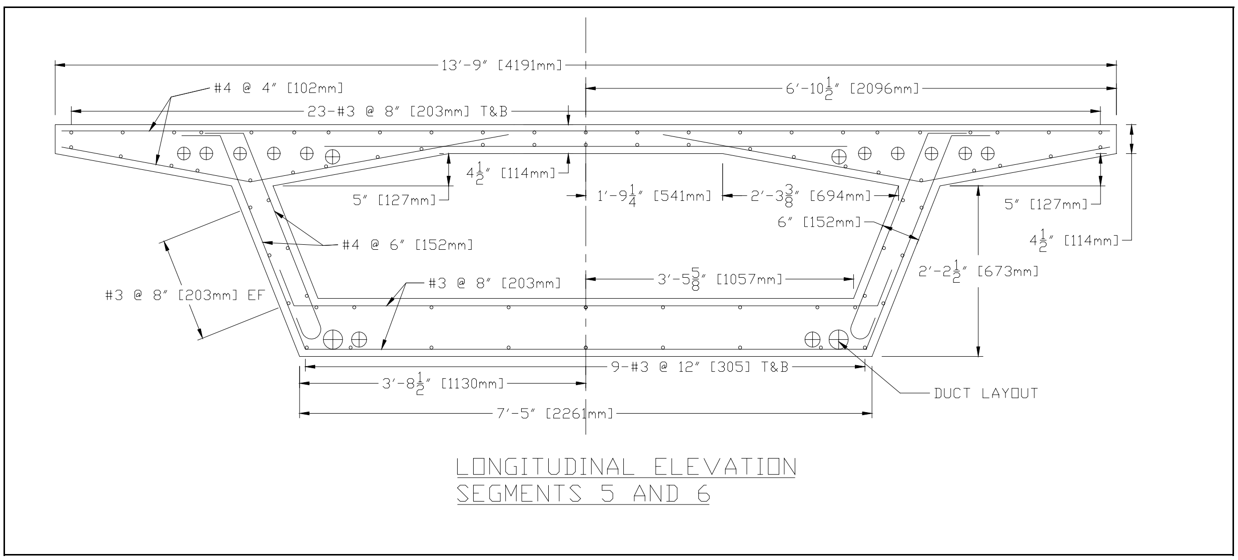
Fig. 8 Prototype box girder cross section

The principal issues addressed by the segmental bridge test include: the superstructure joint opening under seismic loading; validate design parameters based on superstructure behavior under seismic loading; column - superstructure interaction; the formation and performance of the plastic hinge in hollow rectangular column; failure of the bridge system.

Test Limitations

The prototype used throughout all phases of the segmental bridge test program was meant to be a general bridge reflecting the types of situations in which a segmental bridge construction scheme would be advantageous while still resulting in a test specimen that the lab could accommodate. The prototype does not seek to model a specific existing bridge; rather it was designed using characteristics generally associated with this type of bridge.

The prototype structure modeled in the bridge system test is a five-span segmental bridge designed according to Caltrans seismic design criteria [3] with three interior 100' (30.5m) spans and exterior spans of 75' (22.9m). The column height is 50' (15.2m). The test specimen models from mid-height of the column and to the midspan on each side of the column



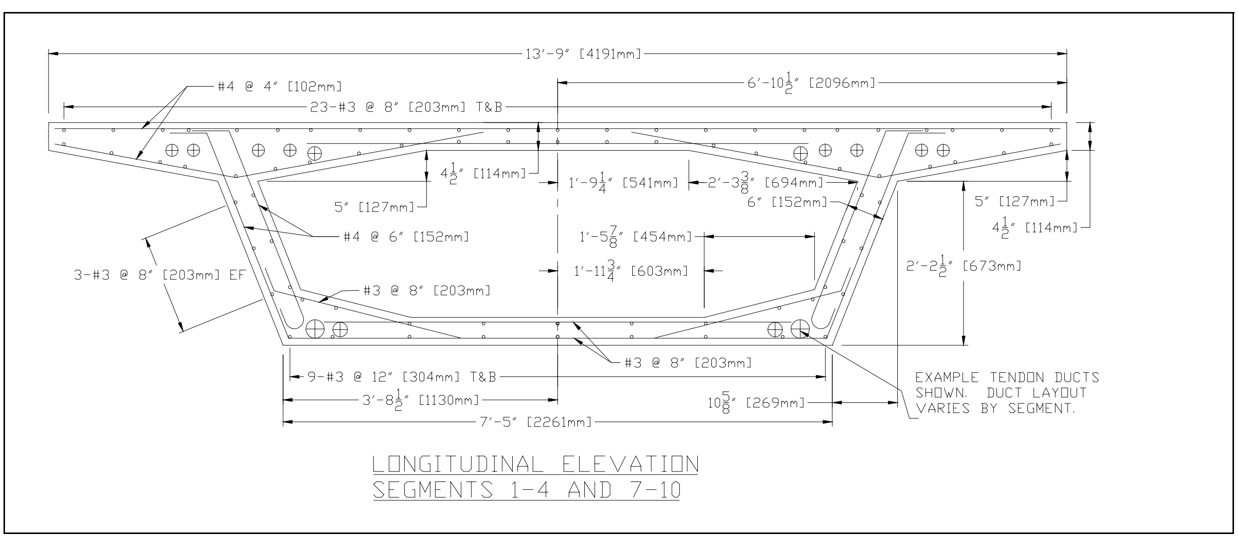


Fig. 9 System Test Cross Section

The bridge was designed with a segmental superstructure constructed using the balanced cantilever method. This is different from the previous phases of the research project in which a span-by-span construction scheme was used. However, for the systems test it was decided that a balanced cantilever system would provide data more relevant to current research needs. Although a 100' span would be considered a very short span length for a balanced cantilever bridge, lab space limitations and consistency with previous test phases led to a decision not to lengthen the prototype bridge's span length.

The superstructure box girder shape was based on the ASBI standard section for short balanced cantilever span lengths. The superstructure cross-section (Fig. 9) had a depth of 71 in. (1800 mm) and a total width of 331 in. (8400 mm). For the segments nearest to the column a thicker bottom flange was designed to handle the high negative moments. The prototype substructure was hollow rectangular column with octagonal boundary elements on each of the corners. These types of columns have been used recently in several bridges in the San Francisco Bay Area.

Loading

The test unit (Fig. 10 and 11) was loaded in the longitudinal direction according to a displacement-based, incrementally increased, fully reversed cyclic loading pattern. The lateral load was applied using four 225 kip, 48 in. (1000kN, 1.2m) stroke MTS actuators. The two northern horizontal load actuators were anchored to the lab strong wall and the southern horizontal actuators were held in place by steel A-frames atop concrete blocks. Two 300 kip (1320kN) hollow core jacks provided the gravity load. Because the bridge system represents a single span of a continuous span bridge the moments at the ends of the spans are not zero. A pair of vertical actuators on each end applied a constant moment at the bridge ends. These actuators were 225 kip, 18 in. (1000kN, 0.46m) stroke MTS actuators. One applied a force directly under the end block and the other an equal and opposite force with a moment arm of 8ft using the steel nosepiece attached to the bridge ends.

The test unit was subjected to a reversed cyclic loading pattern in the longitudinal direction. Two cycles at increasing ductility levels were used in order to allow for further testing of the system without considerable strength deterioration in the column. Testing stage 1 consisted of the cycles up to and including a system displacement ductility of 4 (μ=4) which is a minimum requirement for seismically designed bridges. During stage 1 the vertical load and end moments applied to the superstructure were equivalent to those caused only by gravity loads. At the commencement of stage 2 a cycle was repeated at μ=4 to easily compare any differences in behavior between the two stages. During stage 2 the vertical load and end moments applied to the superstructure were equivalent to a vertical acceleration of 0.75g plus the gravity load.

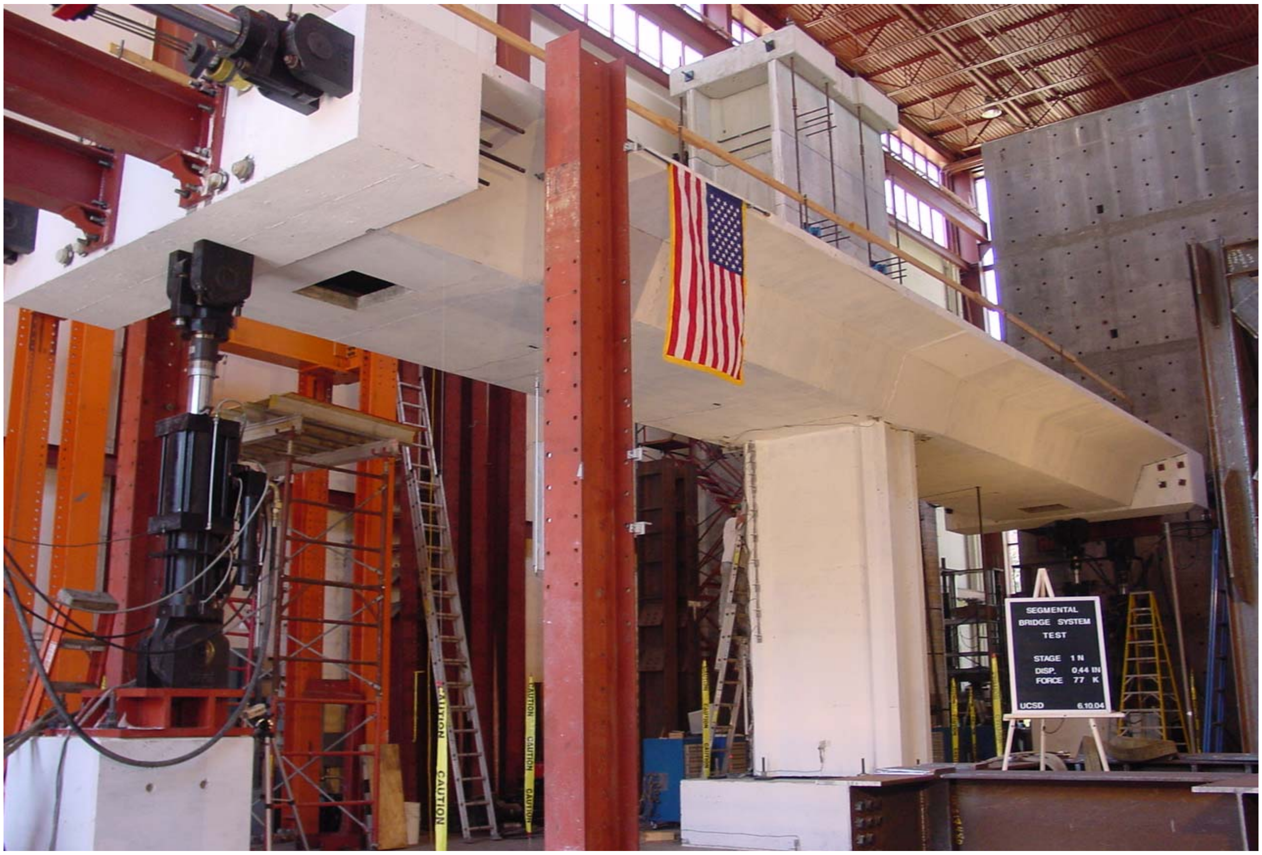


Fig. 10 System Test

Findings

- The joints began to crack at the locations of the cast-in-place closure joint.
- The hairline cracks that formed along the joint were not easy to see, and closed up completely upon unloading.
- This cracking was likely due to a lack of tensile strength across the joint after decompression of the prestress force occurred.
- No other joints were seen to open during any stage of testing.
- In the second stage of testing the joints nearest to the column experienced noticeable opening.
- The cracks opened and closed throughout the cyclic loading of the bridge.
- No residual damage in the joint region occurred and upon unloading the joints closed again.
- The crack width did not expand greatly as the system displacements rose from a ductility of 4 to ductility 8.
- The crack widths ranged from approximately 0.5 to 0.8 mm.
- The combined effect of the reduced number of tendons and the increased load caused the joints to open.
- The response at each ductility level was similar during the first and second cycles.

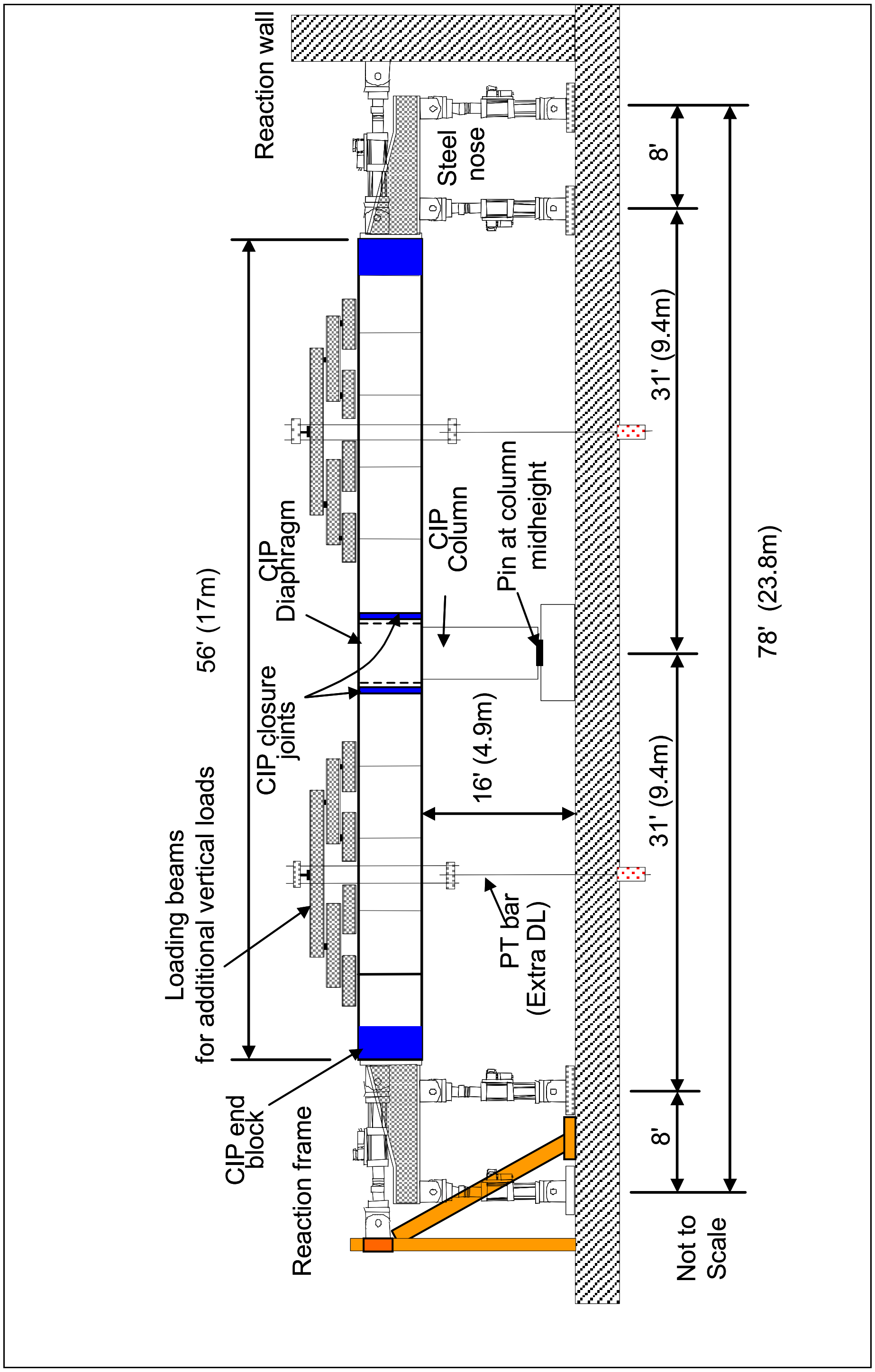


Fig. 11 System Test Elevation

➢ The overall performance of the column was typical of a well-confined, reinforced concrete column showing high-energy dissipation capacity, high displacement ductility, and stable hysteretic response.

- The amount of damage to the column was limited due to the unidirectional loading used in the test. Extensive spalling of the cover concrete occurred after μ=4.
- The system was not brought to failure due to stability issue and possible future uses of the test unit. However failure was certain to occur in the confined corner elements of the column by rupture of the longitudinal or spiral reinforcement or crushing of the corner element concrete.
- At a displacement ductility level of 4 the plastic hinge length was similar to that predicted.
- At the extremely high displacement levels (μ=8), after significant spalling of the unconfined concrete had occurred, the plastic hinge length continued to extend down the column reaching a length approximately 1.5 times longer than the initial prediction.

The pier segment used was similar to those of CIP bridges. No access opening through the pier segment was used in the design as this highly complicated the already congested region of the pier segment. The access holes on the bottoms of the superstructure midspan segments functioned as the entry point into the center of the box girder sections.

DESIGN IMPLICATIONS – PHASE I STUDY

- Opening of the epoxy bonded joints, or cracking at the joint locations, occurs when the concrete reaches a tensile stress of about $3\sqrt{f}$ (psi)[=$0.25\sqrt{f}$(Mpa)]. Cracking of the deck with cast in place closure joints occurs at a relatively low concrete tensile stress of about $4\sqrt{f}$(psi)[=. $33\sqrt{f}$(Mpa)]
- The flexural capacity of precast segmental bridge superstructures can be accurately predicted using the provisions of article 9.17 of the AASHTO standard specifications.
- Finite element analyses showed that the effective prestressing force reduces after earthquake occurrence especially if the superstructure segment-to-segment joints are subject to significant joint openings or notations during the earthquake. External post-tensioning may be a good alternative in which case less reduction in the effective prestressing force is expected in external tendons.
- To prevent the explosive compression failure of precast concrete superstructures with cast in place deck joints, the deck top and bottom layers of longitudinal mild steel reinforcement should be enclosed by means of closed stirrups in the cast in place closure zone. The same should be done if the ductility of the super structures needs to be increased.

DESIGN IMPLICATIONS – PHASE II STUDY

- The combination of internally bonded tendons with external tendons, as currently allowed by the AASHTO guide specifications may result in yielding and loss of the initial prestressing force in the internally bonded tendons at lower displacements than for superstructure with 100 percent internally bonded tendons or 100 percent external tendons. In relation to seismic design, the combination of internally bonded and external tendons is not recommended.

- The use of only external tendons improves seismic performance in terms of ductility, displacement capacity, permanent displacements and permanent openings of joints.
- The flexural capacity of precast segmental bridge superstructures can be well predicted using the provisions of Article 9.17 of the AASHTO standard Specifications and Article 11.2 of the AASHTO guide specifications.
- Vertical sliding between the precast segments does not occur, even with wide joint openings and high shearing forces. Flexural failure occurs first, and it may be by compression of the bottom slab at sections near the columns. The thickness of the bottom slab is commonly increased in the segments near the columns to avoid premature compression failure. Closed stirrups can also be used in the bottom slab of the superstructure near the columns to provide anti buckling confinement if large superstructure ductility is required. The presence of high shears does not have any adverse effects on the seismic performance of segment-to-segment joints.

DESIGN IMPLICATIONS - PROOF TEST STUDY

- The use of auxiliary deck tendons in precast segmental bridge superstructures leads to ample displacement capacity and relatively high load carrying capacity in both loading directions.
- Test data indicates that superstructure segment-to-segment joints can undergo large joint openings at deck by providing a clamping force across the deck region.
- Vertical sliding between adjacent segments is negligible prior to failure of the test specimen. Based on experimental results of the proof Test and those of phase I and Phase III], vertical sliding between precast segments of superstructures should not be a design concern as flexural failure occurs prior to vertical sliding between segments.
- The use of auxiliary deck tendons does little to mitigate permanent vertical residual displacements after a seismic event has occurred. However, the deck tendons allow for stable hysteresis in the upward loading direction, leading to very high levels of energy dissipation.
- The flexural capacity of precast segmental bridge superstructures with auxiliary deck tendons can be estimated using the provisions set forth in the AASHTO Guide Specifications [2] in conjunction with the AASHTO Standard Specifications for Highway Bridges. However, it is recommended that strain compatibility or a similar method be used for more accurate prediction of flexural capacity when using auxiliary deck tendons, especially for negative bending.

DESIGN IMPLICATIONS – PHASE III STUDY

- It is possible to apply the existing bridge design philosophy of limiting all damage to the column with this type of bridge provided the prestressing steel and column strengths are properly designed.

- When the joints are allowed more flexibility and less prestressing is used, the behavior of the system is not compromised by minor opening of the joints.
- These findings are limited by the fact that the test used only loading in the longitudinal and vertical directions and that adding transverse loading may cause additional damage or changes to the system behavior once the joints open. This is a likely area of future research.
- The pier segment design intended to safely transfer shear forces through to the column once the joints open. The vertical headed bars placed at each corner of the pier segment accomplished this. These were seen to take significantly more load during the stage of the test in which the joints open.

FUTURE RESEARCH

Although, the extensive research program has provided insight to the behavior of precast segmental bridges, there still remain lingering questions on several aspects. Such questions need to be addressed through experimental and analytical research. The following are areas of potential research interest:

- All tests to date are static. A dynamic test would provide valuable information on real time joint behavior.
- External tendons behavior during seismic shaking needs attention.
- Isolate variables to gather specific experimental data related to the change in stiffness to compliment analytical work in progress as the continuation of this program.
- Areas of interest for future research include the change in behavior of the joints as the bonded tendons gradually debond.
- The seismic behavior of precast segmental bridges with auxiliary deck tendons in regions of high shears should be studied experimentally.
- Complex three-dimensional modeling of precast segmental superstructures with auxiliary deck tendons should take place in order to provide more adequate design and analysis tools.
- Experimental investigations of the behavioral differences between various auxiliary deck tendon layouts, both internal and external, subjected to seismic loading, in regions close to midspan and adjacent to piers. This research should be similar to that of Phase I and Phase II, with the inclusion of the auxiliary deck tendons.
- The possibility of joint openings at service load levels following the seismic event during which the tendons experience inelastic strains is a concern for precast segmental bridges. Testing should occur such that the test specimen is loaded cyclically to a predetermined seismic displacement level that causes inelastic effect of joint openings following a large seismic event.

CONCLUSIONS

The studies sponsored by Caltrans at University of San Diego provided the needed vital information pertaining to the seismic performance of Precast segmental Bridges. The research has provided the comfort for the use of precast segmental bridges in seismic zones. Additional research as identified in the future research section of this paper will provide information on dynamic behavior of these bridges as we move forward with precast construction.

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