CURVED PRECAST CONCRETE SPLICED BATHTUB GIRDERS MEET SR-22/I-5 SEPARATION WIDENING TECHNICAL CHALLENGES

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ABSTRACT

As part of the $550 million HOV Widening of State-Route 22 in Orange County, California, the separation structure widening over Interstate 5 presented significant challenges, including limited vertical clearance, spans exceeding 170 feet, skews up to 45 degrees and a variable super-elevated alignment with a curvature radius of 1,340 feet. A combination of cast-in-place and curved prestressed concrete spliced bathtub girders allowed for construction of an innovative structure that was economic, fit the aesthetic requirements of the site and met the aggressive design-build schedule with minimum traffic interruptions. Facilitated through the design-build process, this solution required collaboration between the contractor, the designer, the owner, and the Department of Transportation.

Design challenges included the torsion analysis of the open section, differential live-load deflections, the analysis of the bridge subject to multi-stage prestress, while meeting Caltrans rigorous seismic design and detailing guidelines.

Construction challenges included the development of an economic method of lifting, transporting, and erecting curved bathtub girders measuring over 100 feet in length and weighing approximately 240,000 lbs; rebar interference with lifting and prestress hardware; and constructing the girder profiles to meet the variable super-elevated, curved and cambered deck grades.

Keywords: Curved, Spliced, Bathtub Girders, Design-Build, Seismic Design, Innovative Solutions

INTRODUCTION

In November 2006, a major segment of the State Route 22 (SR-22) HOV Widening Project opened adding an HOV lane in each direction and other improvements including auxiliary lanes and flyover structures for over 12 miles extending from Valley View Boulevard to its eastern terminus at SR-55. Achieved through an aggressive 800-day design-build schedule, this $550 million project included widening and/or replacement of 34 bridges. All of this work was completed without significant traffic interruptions on a freeway with an average daily usage of 200,000 vehicles. In recognition of this accomplishment, Post, Buckley, Schuh and Jernigan (PBS&J) received the 2007 Honor Award from the California Engineers and Land Surveyors (Celsoc).[1]

One of the most significant challenges faced by the Granite-Myers-Rados (GMR) Design-Build team was widening the SR-22 Separation over Interstate 5 (I-5). At this location, SR-22 crosses 17-lanes of I-5 traffic, on a curved, skewed alignment with little or no room for falsework. The use of precast/prestressed concrete bathtub girders continuously spliced with cast-in-place girders, shown in Fig. 1, provided for a safe, economic solution that met the structural and aesthetic requirements for this project.

CONSTRAINTS

The decision to use curved precast bathtub girders was developed through a detailed evaluation of the site constraints to include, geometric, traffic, structural, aesthetic, schedule, cost and the design-build team's available resources.

GEOMETRIC

As shown in Fig. 2, SR-22 crosses I-5 at approximately 41° with a straight alignment in Spans 1 through 3. In Span 4, the widening curves to the south with a radius of 1340 ft and continues beyond the end of the bridge. To match this curvature, the cross-slope or superelevation varies from 2 to 5% in Spans 4 and 5. As a result, the vertical clearance is reduced at the edge of the widened structure. Using a structure depth to match the existing bridge, the vertical clearance of the widening in Span 5 is 17.1 ft, measured at the right edge of the I-5 northbound shoulder. The bridge widening has a constant width of 20 ft in Spans 1 through 4 and varies from 20 to 28 ft in Span 5.

TRAFFIC

The interchange connecting I-5 with SR-22 and SR-57 is widely known as the "Orange Crush," due to the reputation this transportation hub has for severe traffic congestion. Therefore, maintenance of traffic during construction was a significant concern during construction especially on I-5, where only evening closures of short duration were permitted.

Of particular concern is the traffic opening in Span 5, where the bridge curves to the south crossing five of the northbound lanes at an effective skew exceeding 45°.

STRUCTURAL

In addition to the geometric constraints discussed previously, the structural response characteristics of the widened structure and the existing structure must match to ensure adequate performance and durability. In particular, the deck spanning between the widen and existing structure could be subject to stresses exceeding design limits if subject to significant differential live load deflection. Therefore, the centerlines of all bents and abutments of the widened structure coincide with those of the existing bridge.

The existing separation structure is a 5-span cast-in-place post-tensioned concrete box girder bridge that is 165 ft wide and 747 ft long. Designed to respond crack free under service loads, this structure is fully continuous for live load with exception to the hinge in Span 3. At this location, the hinge forms a seat for the Northwest connector that ties into the Separation Structure near Bent 3. Under seismic response, columns are monolithic with the superstructure. The widening structure is designed to match these gravity and seismic response characteristics of the existing bridge.

COST AND SCHEDULE

Since most of the freeway development in California has occurred in semi-arid desert without seasonal construction limitations and, local bridge contractors maintain large inventories of materials used for on-site formwork and falsework, cast-in-place bridges are economically competitive. Hence, the vast majority of newly constructed freeway bridges in California are cast-in-place concrete structures built on falsework.[2] Therefore, cast-in-place alternatives were given careful consideration even with the severe falsework clearance limitations. However, it should be noted that precast concrete girders and deck panels were used widely throughout the SR-22 widening project to meet the aggressive 800-day design-build schedule.

TYPE SELECTION

Type selection included evaluating cast-in-place and precast concrete bridge alternatives. Vertical and horizontal clearance requirements in Span 5 were a deciding factor in the selection for this bridge.

CAST-IN-PLACE ALTERNATIVES

As mentioned previously, to match the existing bridge with a cast-in-place concrete box girder structure, falsework is required to span 5-traffic lanes along with temporary traffic barriers. This falsework span is over 90 ft on a skew that effectively exceeds 45°. At this length, falsework depths greater than 4 ft are required, and the minimum temporary vertical clearance requirement of 15 ft (per Reference 3) cannot be met.

Cast-high-and-lowered post-tensioned box girder was evaluated, where the superstructure is cast on elevated falsework and lowered into position using metal shims and hydraulic jacks. Once the superstructure is in position, contact surfaces between the substructure and superstructure are grouted to provide uniform bearing. Further grouted connections are required to develop full or partial continuity between the column and superstructure. There is a significant level of risk associated with this alternative due to the potential for lateral movement during the lowering operation. This is especially true for this bridge because the entire Frame 2 would have been lowered into position.

Suspended falsework was also considered, where main falsework girders are adjacent to the bridge girders and support transverse falsework beams at or near the bottom flange. However, this method can be cost-prohibitive for soffit widths exceeding 8 ft because the connection details between the longitudinal girders and transverse beams are expensive.

PRECAST CONCRETE ALTERNATIVE

Curved and spliced precast bathtub girders were considered using the standard shapes developed by Caltrans.[4] In this alternative, dual bathtub girders span traffic openings, and splices consisting of 24 in. long cast-in-place regions are located at falsework supports. When complete, the widened structure has gravity load and seismic response characteristics that are similar to the existing bridge. Also, the sloping exterior girder face makes the appearance similar to the existing bridge.

However, sophisticated steel forms are required, due to the curved alignment, and external vibration and steam curing precludes multiple-use timber formwork. Since the cost of these forms is spread over relatively few girders, this alternative is uneconomic.

CAST-IN-PLACE/PRECAST CONCRETE HYBRID

A hybrid of cast-in-place and precast construction was ultimately selected for the following reasons. Sufficient vertical clearance permitted the use of conventional falsework in all locations with exception to the 5-lane traffic opening in Span 5. Precast concrete bathtub girders were used to span the traffic opening in Span 5 because they are similar to the adjacent cast-in-place girders. By limiting the use of precast girders to one location, timber forming could be used economically.

The webs of cast-in-place box girder bridges are vertical (with the exception to the exterior web that is sloped for aesthetics) and, the soffit has the same cross-slope as the deck. In the hybrid alternative, the bottom slab and webs are constructed the same way as if constructed in falsework. Using this technique simplified construction of the adjacent cast-in-place sections.

DESIGN

The use of curved precast/cast-in-place bathtub girder system was designed to minimize cost, meet the site constraints, utilize the contractor's resources and meet the aggressive schedule requirements.

DETAILS

The first frame extending from Abutment 1 to the hinge in Span 3 is a conventional cast-in-place box girder structure, as shown in Fig. 3 where the bottom slab is continuous across the widening. In the second frame, two independent cast-in-place box sections splice with the precast bathtub units.

Design of the precast units centered on minimizing weight, because the weight of the precast units dictated the hauling and erection methods that had a direct effect on the cost, and simplifying the construction details. To minimize weight, the precast bathtub webs have a minimum width of 9 in., whereas, in the cast-in-place regions, the webs are 12 in., as recommended in Reference 3. Shear demands resulted in flared girders at the obtuse corners in each span, where the web width increases from 9 to 24 in. wide. Soffit flares at each girder end allow for placement of the post-tensioning tendon anchorages.

As shown in Fig. 5, the precast girder segments are staggered to only span the northbound lanes of traffic. This figure also shows schematically where the falsework supports were located during construction. At the expense of having longer precast units, the ends of the precast girder segments are orthogonal to simplify detailing. If skewed ends are provided, relatively large diaphragms are required to prevent longitudinal cracks from developing in the soffit.

CONSTRUCTION STAGING

The following construction sequence was proposed by the design/build contractor, to provide the best economy and within the project schedule. In this sequence, a single-stage of continuity post-tensioning is applied after the deck is cast.

After construction of the bridge substructure including footings, columns and abutments for the widened structure, the falsework is erected. Construction of the precast girders is concurrent with these operations. A concrete slab and timber formwork formed the casting bed for the precast girders. The superstructure was designed assuming the following stages illustrated in Fig. 4:

1. After casting, the girders are prestressed to resist self-weight, the fluid weight of the concrete deck and construction loads spanning between the shoring tower supports. After prestressing, the bathtub girders are transported from the casting bed and placed on shoring towers.
2. The stem and soffit are cast along with the cap beams and all of the diaphragms including the abutment and at intermediate locations within the span. At this time, prestress ducts are made continuous with the precast bathtub units. These ducts extend the full length of each frame extending from hinge to abutment diaphragm.
3. After the deck concrete is placed and reaches a minimum compressive strength, post-tensioning is applied to both frames and falsework is subsequently removed with exception to the shoring tower supporting the hinge diaphragm in Frame 2.
4. After hinge construction is complete, the remaining shoring tower is removed. The bridge is opened to traffic after construction of the traffic barriers and the deck closure.

The construction schedule assumed for design is listed in Table 1 with the age in days of the precast bathtub units. It is recommended that cast-in-place structures have a minimum age of at least 10 days before applying post-tensioning.[5] This restriction is to ensure that the concrete behind the anchorage has developed sufficient strength prior to stressing.

ANALYSIS

Several analysis methods were used to evaluate the service-load stresses and seismic response at critical events throughout the anticipated service life of the structure using the material properties listed in Table 2. The analysis methods used in the design included the following:

- Stage construction analysis, which captured the effects of multiple stages of prestress, continuity and composite behavior.
- Time-dependent analysis to capture the effects of creep, shrinkage and stress redistribution.
- Shell finite-element analysis to evaluate the effect of differential live load deflection on the deck.
- Torsion analysis of the non-composite precast girder section subject to hauling and erection loads, deck loading and related construction equipment loading.
- Seismic dynamic analysis of the widened bridge to evaluate the displacement demands

- Static non-linear pushover analysis and related moment-curvature analysis to assess the displacement capacity.

The analysis required to model the effects of construction staging and multiple-stage prestress used in this design utilized the methodology described in References 5 and 6. To capture the effects of girder torsion, a combination of elastic beam elements and shell elements were required.

In the completed configuration the bathtub girders and composite deck resist torsion as box sections and, as a result, have very little torsional flexibility. Consequently, the girders could experience differential deflections under live loading beyond what the deck spanning between the girders can sustain within allowable stresses, because the girders are closely spaced and are rotationally stiff. Intermediate diaphragms reduce this relative deflection and associated moments and shear forces in the deck spanning between the girders. Shell finite element analysis was used to evaluate the relative deflections of the box girders, the stresses on the deck and the adequacy of the diaphragm spacing.

Prior to the deck hardening, the bathtub girders resist torsion forces as a non-composite section. In this configuration, the torsion stiffness of the girder is a small fraction of the composite section. Prestress on a curved section introduces horizontal tendon forces that are applied above the shear center introducing a torque that counters the torque due to dead load. Further, the weight of the deck finishing equipment induces torsional stresses. By including the intermediate diaphragms, torsion stresses and deflections were within the specified limits under these load cases.

For self-weight, the girder is simply-supported between falsework supports after a single stage of girder prestress is applied. After casting the adjacent webs and soffit, continuity between the cast-in-place and precast bathtubs is developed via mild reinforcement when subject to the fluid weight of the deck. Although continuity is established between the cast-in-place and precast regions, full fixity cannot be assumed because the adjacent stem and soffit will uplift from the falsework. Additionally, cracking is anticipated at the end of the precast girder, which further increases the flexibility at the end. It was conservatively assumed that the bathtub girder was simply supported for non-composite loads for evaluation of service load stress on the precast girder. Conversely, a fixed condition was assumed to evaluate the temporary stress condition at the ends of the girder in order to design the crack-control reinforcement.

SEISMIC DESIGN

The widening is designed to have similar seismic response characteristics as the existing bridge that was constructed in 1995. The seismic design procedure used in this design is in conformance with the methodology developed in References 8, 9 and 10. Connecting the two structures is the deck closure, which has the effect of creating a continuous rigid diaphragm when subject to lateral seismic loads. Therefore, it is assumed that on a horizontal plane, the superstructure responds as a single beam element.

Conversely, it is assumed that the deck closure does not restrain the relative vertical displacement of the existing and widened bridges. Hence, for horizontal seismic displacements acting transverse to the bridge centerline, the column resists seismic forces as a cantilever, with fixity at the base of the column. In the longitudinal direction column plastic-hinge moments are transferred to both the footing and the superstructure. Seismic moments are distributed based on relative stiffness of the spans and within each span based on an effective width specified in Reference 5. Continuity for seismic loads is provided by the prestress tendons and deck reinforcement on the negative bending side, and through soffit reinforcement made continuous with mechanical couplers.

The longitudinal reinforcement in the columns and the overstrength moment due to plastic hinging directly impacts the congestion in the critical regions. This reinforcement and associated congestion was minimized by using realistic column and foundation flexibility in the assessment of thermal and prestress shortening forces.

CONSTRUCTION

GIRDER FABRICATION

The contractor cast the curved bathtub girders on site using a concrete slab and timber formwork, as shown in Fig. 6. This concrete slab matched the soffit contours to include vertical curvature, cross slope and camber. As mentioned previously, the webs are cast vertically with exception to the exterior, which has a constant 4 (vertical) to 1 (horizontal) slope. The minimum girder curvature radius is 1,640 ft, which is greater than widening curvature of 1,340 ft.

The initial prestress consisted of six 4-strand (0.6 in. diameter) tendons with circular ducts measuring 2.0 in. in diameter placed in the soffit. The tendon profile was a constant 3.5 in. from bottom of the soffit, with exception to the end regions where the profile was elevated to fit the anchor plate. Securing the ends of tendon was challenge because anchor plates contact the outside face of the girder. As a result, insufficient clearance was provided at the ends of the girders and continuity reinforcement bars were cut to clear anchor plates at select locations. The reduced capacity from the elimination of these bars was replaced by allowing 14.0 ft long strand to extend into the cast-in-place regions.

TRANSPORTATION AND ERECTION

The contractor selected a single crawler crane to lift the units out of the casting bed, transport and set on falsework supports, as shown in Fig. 7. This crane had a 295 kip capacity at a reach of 32 ft. The units were required to be picked from the ends due to the initial prestress configuration. As a result the contractor selected a 150 ft boom to accommodate the necessary rigging without a spreader beam.

For each girder, a total of 16 10.5-ton commercially available lifting anchors, with 3 ft spacing in the webs, were used for the pick with rolling blocks to distribute the loads evenly at each corner. These anchors are typically used in building applications, with an embedded length of 24 in. Minor adjustments to the reinforcement and the anchor layout were required to resolve interference with the continuity post-tensioning ducts. Although anchors on the outside radius curvature experience more load than the inside, it was shown that the allowable loads were not exceeded.

DECK PLACEMENT

After placement, deck and diaphragm formwork was suspended from the girders to support the fluid weight of the concrete and the deck finishing equipment, as shown in Fig. 8. Torsion forces are applied to the non-composite girder from self-weight, deck concrete fluid weight and the weight of the deck finishing equipment on the overhang bracket, as mentioned previously.

Stay-in-place metal deck forms were used between the bathtub girders and timber forms within the girder cells. These forms allowed the contractor to eliminate the stripping operation after the falsework had been removed.

CONTINUITY PRESTRESS

Prestressing was applied to both frames after the deck reached the initial compressive strength requirement of 3,500 psi. At this time, the falsework supports could be completely removed with exception to the support at the hinge. It should be noted that no deflections were noted after prestress and removal of the falsework supports in Span 5. All long term deflections are a result the application of superimposed dead load, which includes bridge railing and future overlay.

The continuity, or second stage, prestress consists of three 12-strand (0.6 in. diameter) tendons in circular ducts measuring 3.25 in. in diameter in each web. These tendons were secured to the outer leg of the girder stirrups, but on the inside radius of curvature to simplify construction. Analysis showed that placement of the prestress ducts on the inside radius of curvature would not cause lateral bursting, and special detailing was not required.

SUMMARY

Curved precast concrete bathtub girders were essential to the successful completion of this challenging freeway widening project. The concept of using a hybrid of precast and cast-in-place methods evolved through a detailed analysis of site constraints and interaction between the contractor and designer that can only be achieved in a design-build environment. As a result, an innovative solution was developed for a challenging heavily-congested freeway bridge widening project. A summary of relevant project facts is listed in Table 3.

PROJECT PARTICIPANTS

Owner:	OCTA
Contractor:	Granite-Myers-Rados, J.V.
Bridge Engineers:	PBS&J
Civil Engineers:	URS
Program Management:	Parsons Transportation Group
Post-tensioning:	AVAR

ACKNOWLEDGEMENTS

The authors would like to thank the Orange County Transportation Authority and the Granite- Myers-Rados joint venture for the opportunity to work on this project.

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Table 1 Design construction sequence.

#	Days	Event	Loads
1	10	Prestress bathtub units (Stage 1)	Girder self weight
2	30	Set precast bathtub units	Girder self weight
3	50	Pour CIP Stem and Soffit	N/A
4	80	Pour CIP Deck	Fluid weight of deck concrete
5	90	Stage 2 P/T and P/T Frame 1	N/A
6	120	Release hinge falsework	Weight of hinge + hinge transfer force
7	130	Place barriers	Traffic barriers
8	140	Open to full traffic	HS 20-44
9	3,650	Service	Future wearing surface
10	27,375	Service	HS 20-44 (after all losses)

Table 2 Material properties.

Bathtub Girder concrete		
28 day strength	f'_c	5,500 psi
Transfer	f'_{ci}	5,000 psi
Elastic Modulus	E	4,200 ksi
Unit weight	γ	150 pcf
Cast-in-place concrete		
28 day strength	f'c	4,000 psi
Transfer	f'ci	3,500 psi
Elastic Modulus	E	3,600 psi
Unit weight	γ	150 pcf
Prestressed steel		
Tensile strength	f_{su}	270 ksi
Elastic modulus	E_s	28,500 ksi

Table 3 Project facts.

Bridge Geometry	• Bridge Length: 747 ft • No. of spans: 5 • Height of Bridge: 24 to 31 ft
Widening	• Widened structure width: 20 to 28 ft • Total width of widened bridge: 165 ft • Radius of curvature: 1,340 ft • Longest span: 170 ft
Bathtub Girder	• Maximum Girder Length: 103 ft • Maximum Girder Weight: 240 kip • Girder depth: 6.2 ft • Girder width (soffit): 6.0 ft • Minimum radius of curvature: 1,640 ft
Prestress	• Girder prestress: 4-0.6 in. tendons (6 per girder) • Post-tensioning Frame 1: 27-0.6 in. tendons (2 per web) • Post-tensioning Frame 2: 12-0.6 in. tendons (3 per web) • One-end stressing (both frames)

Fig.1 Curved precast concrete bathtub girders span the northbound lanes of I-5.

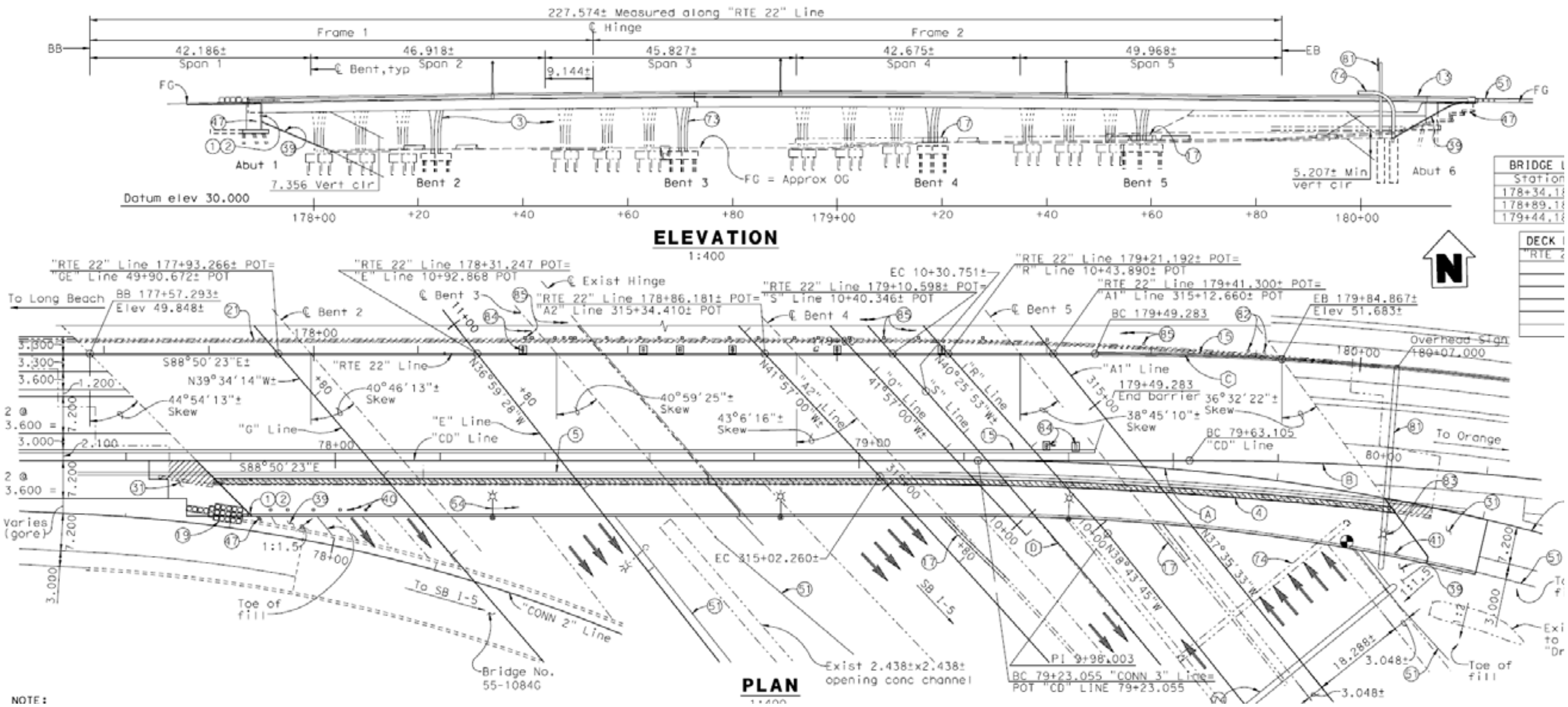
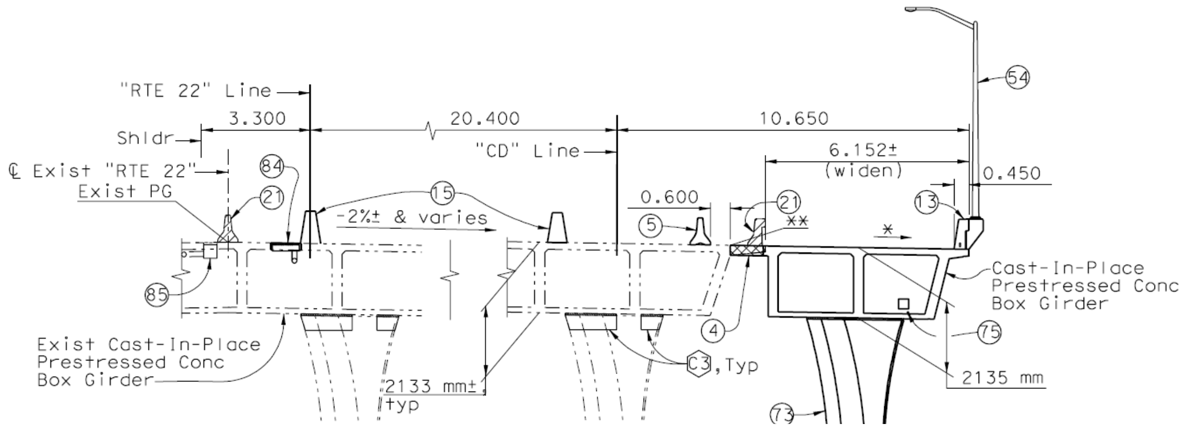
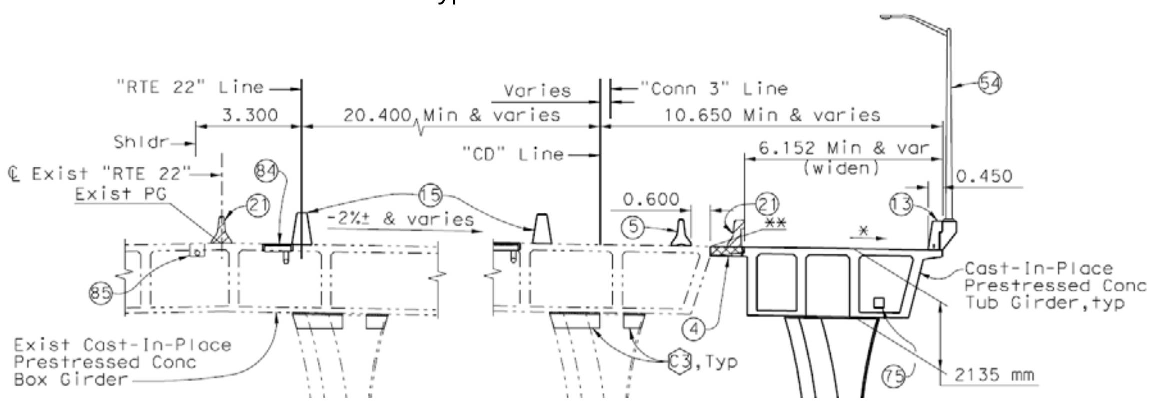


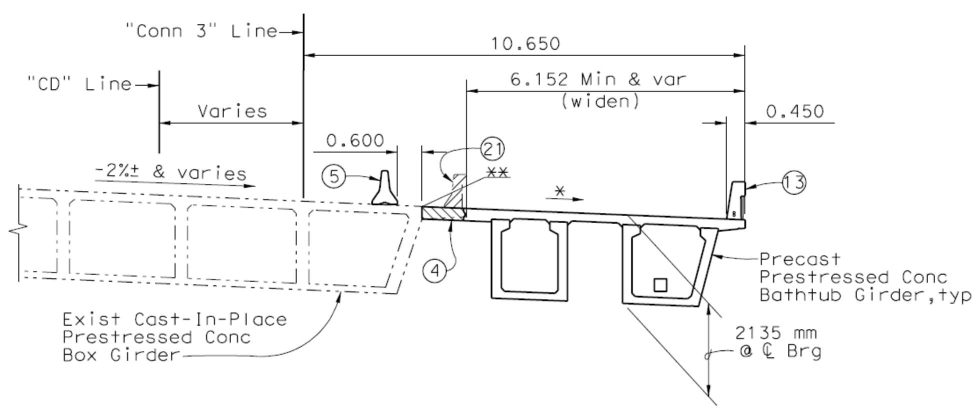
Fig. 2 General plan and elevation of the SR-22/I-5 Separation Widening.



Typical Section - Frame 1



Typical Section - Frame 2



Typical Section - Frame 2/Span 5 Precast Bathtub Girder

Fig. 3 Typical Sections.

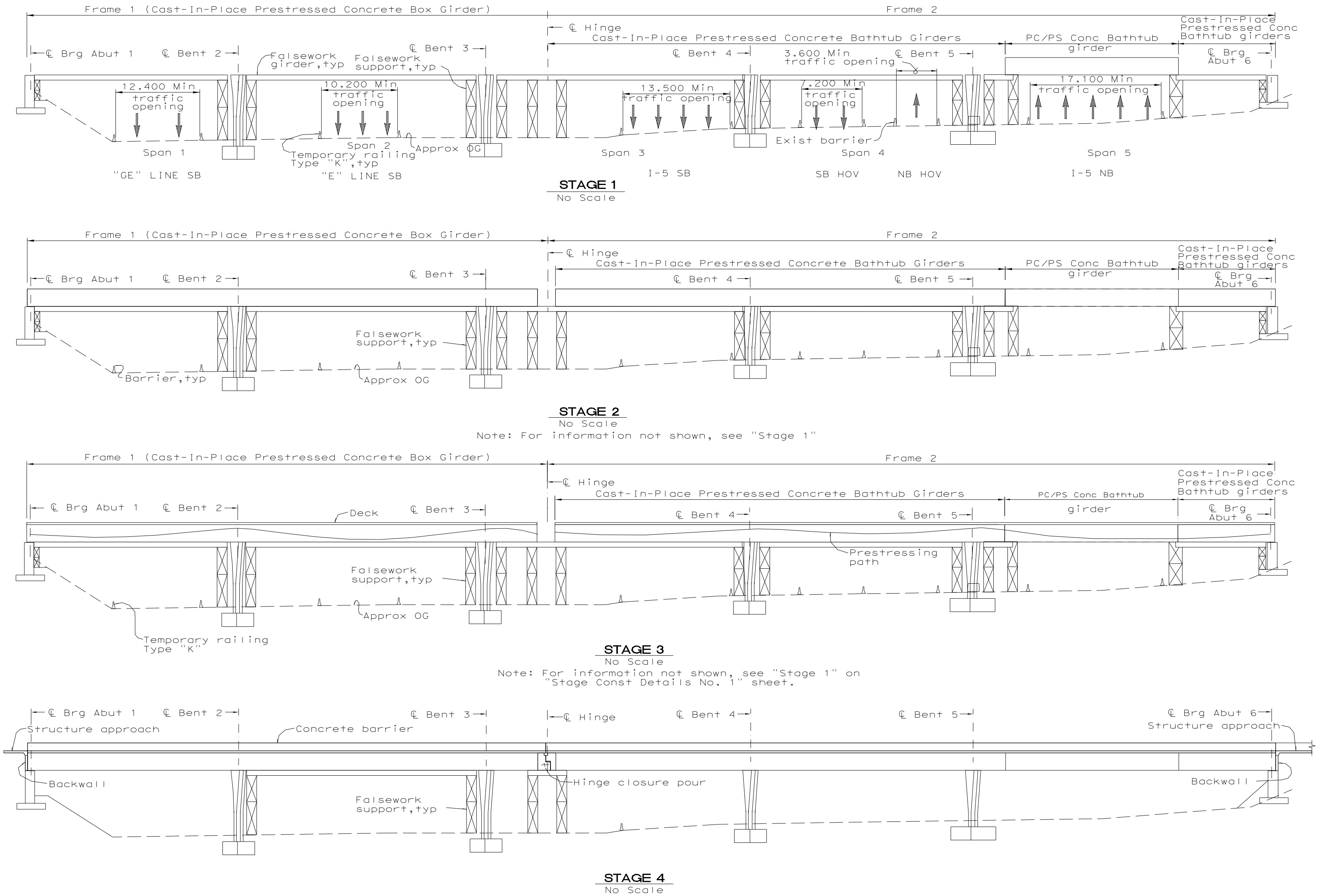


Fig. 4 Construction stages.

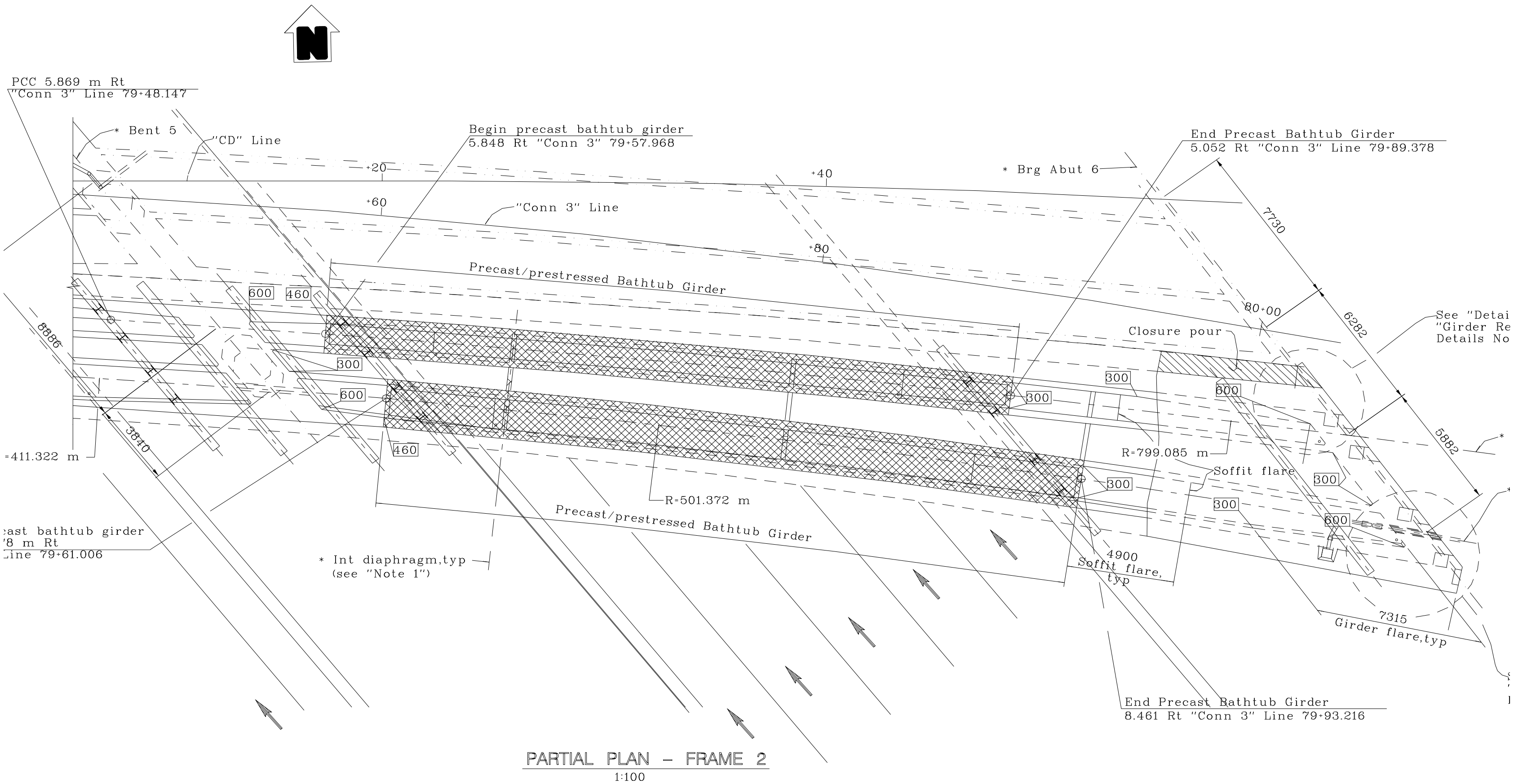


Fig. 5 Precast girder layout for Span 5.

Fig. 6 Precast Bathtub Girder Casting Bed.

Fig. 7 A single crane lifts and transports the 240,000 lb girder from casting site to shoring supports.

Fig. 8 Deck and intermediate diaphragm forms are suspended from the precast girders.