Design Details of Post-Tensioned Concrete Bridge Girder, Sustainability and Resilience Score

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Abstract: The bridge superstructure flyover built on National Highway route 16 (NH-16) near Benz circle in Vijayawada to act as grade separated highway for vehicles to cross over National Highway route 65 (NH-65) is made of precast and post-tensioned concrete girders. The first part of this two-part publication discussed the analysis of the concrete bridge girders subjected to vehicular loads considered as per Indian Roads Congress Specifications. The design bending moments and shear forces for the girders and slab are computed using grillage analysis model. The current article, which is the second part of this study details the superstructure girder design of post-tensioned members precast at the concrete plant. The girders are two-stage post-tensioned at precast yard and transported to the site for erection on piers. The post-tensioning design and details are presented in this paper along with sectional geometry and reinforcement detailing sketches for the girders and the diaphragms. The reinforcement schedule is presented. Finally the bridge superstructure is rated for sustainability and resiliency score based on the design and construction practices followed during the engineering of this bridge.

Keywords: Design, Post-tensioning, Sustainability, Resilience, Bridge, Concrete

1. Introduction

The bridge on NH-16 near Benz Circle in the city of Vijayawada is built as two separate carriageways each of 3-lane post-tensioned concrete girder bridges to cross over the at-grade vehicular traffic on NH-65. The bridge has a total carriageway of 11.5m curb to curb. The total deck width including crash barriers at both ends is 12.5m. The deck is supported by four post-tensioned concrete girders spaced at 3.1 m on center and supporting an overhanging slab of 1.6m cantilevered on the edge girders. The four bridge girders are connected by three cross diaphragms one at each support location and one at the midspan. The concrete girders along with cross diaphragms are supported on elastomer bearing pads installed on top of reinforced concrete pedestals cast monolithic with pier caps. The girders are rectangular at support locations and taper to become I-shaped along the rest of their length. The first part of this two-phase article focused on the analysis methods and details of the bridge superstructure [1]. The bridge girders and slab system were analyzed as a grillage system in Staad Pro software. The maximum bending moments and shear forces were determined after considering Indian Roads Congress [2, 3, 4, 5, 6] vehicular load effects. The summary of design forces on the girder and slab system was provided at the end of the first phase article. Both the analyses and design of these bridge elements have been performed in accordance with IRC code specifications and recommendations [7, 8]. The seismic design has been performed in accordance with IS 1893 [9, 10].

The current article, which is the second phase of this study details the girder designs for this bridge superstructure. The girders are designed as post-tensioned concrete members. The girders are precast at the plant and then post-tensioned by four cables in multi-stage post-tensioning operations. The girders are post-tensioned when the girder concrete reaches the specific characteristic strength or specified age whichever is later. The girders are shipped to the site after the two-stage post-tensioning is completed. This article provides the details of the post-tensioning such as jacking forces, number of cables, the strand type, size and number of strands, the horizontal and vertical profile of the cables along with any other details pertaining to post-tensioning of the cables. The article also provides the drawings showing the prestressing forces, cable profiles and anchor zone details. The article also provides the main reinforcement and shear reinforcement detailing followed in the girders to ensure composite beam action when tied with the cast-in-place deck slab reinforcement. Finally, the author discusses the engineering and construction practices followed in the design and construction of this bridge superstructure and assign a sustainability score to the bridge which is an indicator of the impact of the bridge construction on environmental sustainability and its resilience to major weather related disasters and accidental forces that exceed design basis loads.

Design Details of the Bridge Girders

The girders are designed for vehicular forces including gravity, centrifugal and braking forces in addition to the self weight loads, imposed dead loads and the wearing coat on the bridge deck [11]. The analysis of the bridge girders is performed using linear member analysis using STAAD structural analysis software. In this analysis the beam members are discretized as longitudinal 1D or line members [12] whereas the slab is discretized as transverse line members to form a grillage of finite element mesh members. The results of the analyses were published in the first phase of this study. This second phase presents the post-tensioning details of the prestressing of the girders.

The precast beams are designed as I-girders with an overall depth of 1.9 m. This depth appears to be slightly over conservative because the typical span-to-depth ratios for prestressed girders is in the range of 20-25, this means a girder depth of 1.5m would be sufficient for this span. However an extra 400 mm depth is not overly conservative. The girders are rectangular in geometry at the support section and transition to an I-girder towards the midspan. The webs of the girders are 300 mm thick, and the bottom flange is made 800 mm wide with a top flange of about a meter wide. The depth of the top flange varies from about 250 mm at the face of the web to about 150 mm at the end of the flange. Figure 1 shows the geometry of the precast girder at the support section where the webs are wider (800mm) and rectangular while at other sections away from the support where the girder is I-shaped. The girders and the decks slab are made of concrete grade M45. For reinforcement steel grade of 500 MPa is used.

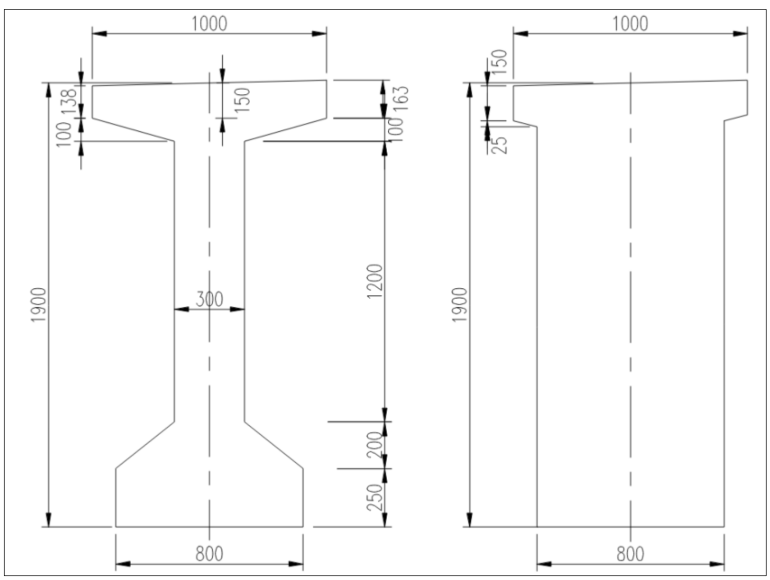
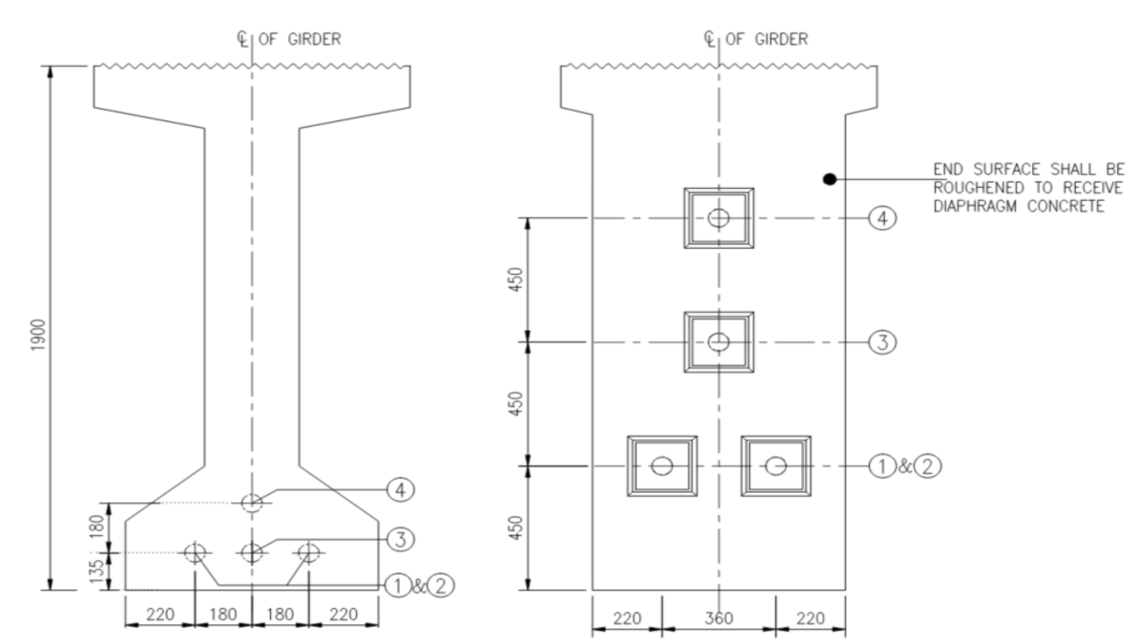


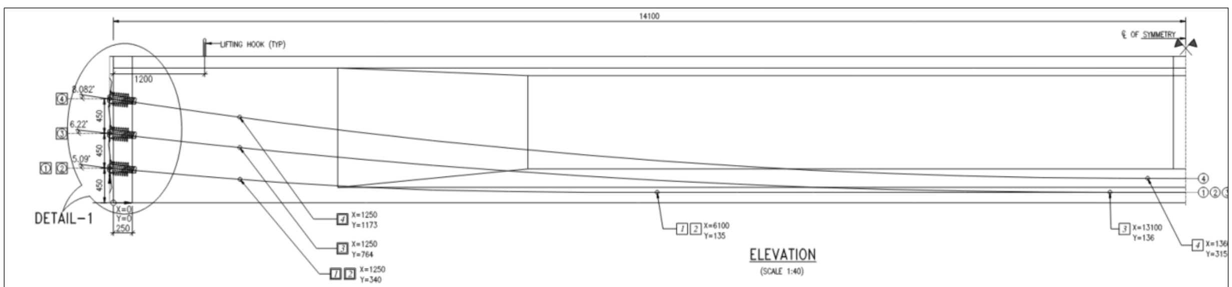
Figure 1: Precast Girder Geometry; At midspan (L), At Support (R)

The girders in this bridge are designed as prestressed concrete members. The members are post tensioned in the precast yard. Each girder has 4 prestressing cables in total. Out of the 4 cables, 3 cables have about 19 strands bundled together whereas the 4th cable is made of 12 strands. However, in all cables, one of the strands is not stressed because it is added an extra just in case any of the strands snap or need to be removed if they do not meet required ductility. Also, the inner girders have lesser number of strands as compared to outer girders because the load demands on the outer girders is higher than inner girders. The strands are 12.7mm in diameter and have an area of 98.7 sq mm. The strands have a minimum ultimate strength of 1860 MPa. The strands are tensioned to a jacking force of about 70% of the ultimate strength of the strand. The friction coefficient is taken as 0.17 whereas the wobble coefficient is taken as 0.002 per meter of girder length.



CABLE NO.	LENGTH (mm)	EMERGENCE ANGLE ø (DEGREE)	JACK END FORCE (MT)		STRANDS IN GIRDER					
					OUTER			INNER		
			OUTER GIRDER	INNER GIRDER	NO.OF STRANDS	STRESSED	DUMMY	NO.OF STRANDS	STRESSED	DUMMY
1	30225	5.09	252.770	252.770	19	18	01	19	18	01
2	30225	5.09	252.770	252.770	19	18	01	19	18	01
3	30260	6.22	252.770	252.770	19	18	01	19	18	01
4	30305	8.082	266.810	98.300	12	11	01	12	07	05

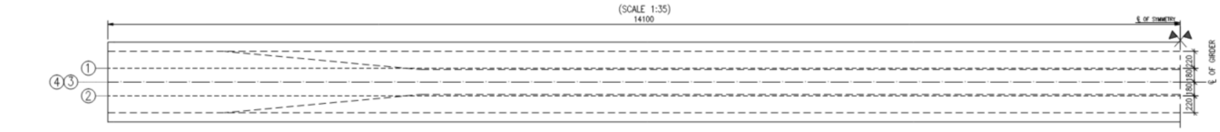
(R)



CABLE NO.	X	000	250	1250	2250	3250	4250	5250	6250	7250	8250	9250	10250	11250	12250	13250	14100
4	Y	1350	1315	1173	1040	918	807	711	622	544	480	422	382	349	327	319	315
3	Y	900	873	764	663	570	486	414	347	290	243	202	174	153	140	136	135
1 & 2	Y	450	428	340	264	206	165	147	135	135	135	135	135	135	135	135	135

ELEVATION – VERTICAL PROFILE OF CABLES

(SCALE 1:35)



PLAN – HORIZONTAL PROFILE OF CABLES

Figure 3: Profile Details of Post-Tensioning Cables

Figures 2 and 3 show the layout of the post-tensioned cables and the details of the strands. The figures also present the vertical and horizontal profile of the cables along the length of the girders. The cables follow a parabolic profile which is the most preferred profile to match the bending moment profile of beams. The coordinates of the cable along the length of the girder are tabulated for each of the cables. Looking at Figure 3, it can be found that vertical profile of cable 3 blends with cables 1 and 2 at about 13.1m from the support. The post tensioning force is applied in two stages. In the first stage, cables 3 and 4 are stressed on the 7th day after the girders are cast and have reached a minimum strength of 30 MPa. This strength is required so the girders can be taken off the precast bed and they are self-sufficient to carry their self weight, lifting and handling of the girders within the yard [13]. The cables 3 and 4 are stressed after the concrete reaches an age of 28 days and has a minimum strength of 45 MPa. The details of anchorage zone reinforcement in the form of steel spiral ties are presented in Figure 4. The spirals are 16mm dia bars with a pitch of 60mm for about 360mm length along the anchorage region. The details of the 19 ton anchorage cone are also shown in the same figure. The slip of the strand at anchor cone is limited to 6mm for design purposes.

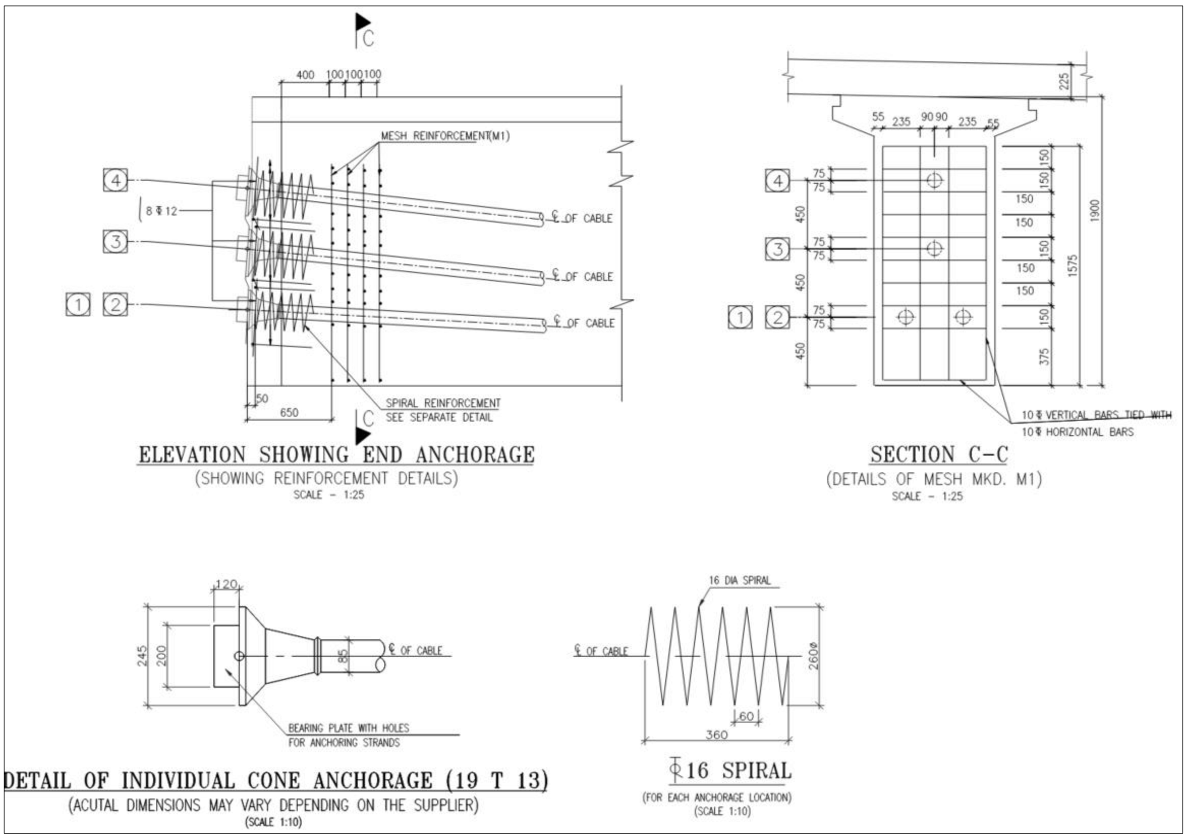


Figure 4: Post-tensioning Anchorage Zone Details

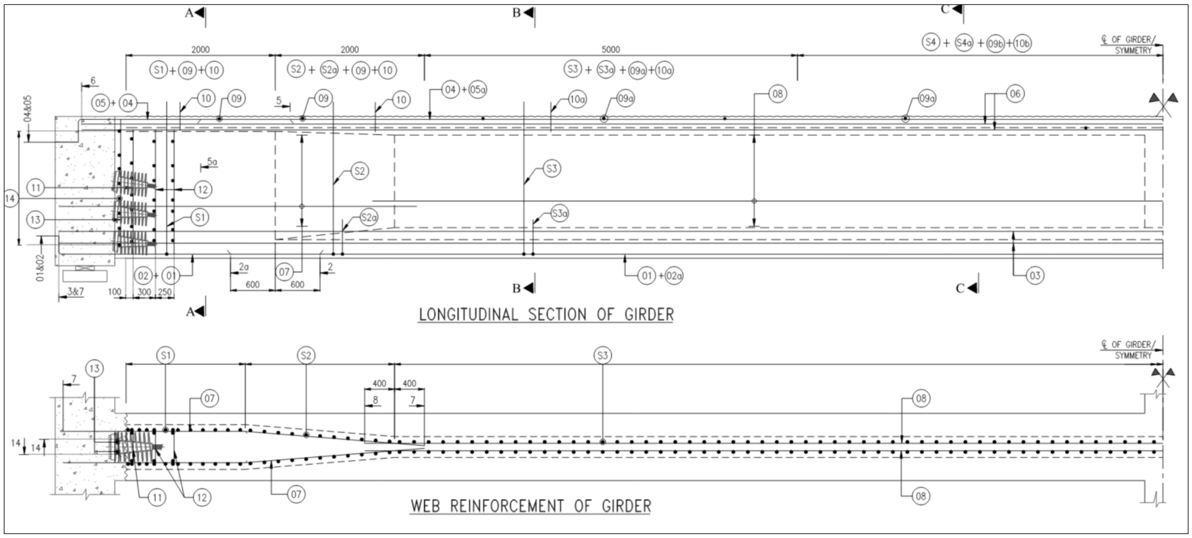


Figure 5: Girder Reinforcement Details (Elevation)

The post-tensioned girders still need to be reinforced with steel bars for multiple reasons such as side face reinforcement requirements, local shear force effects in the girder stems, for ductile failure and for the shear reinforcement across the interface with slab. Figure 5 shows the side face reinforcement and shear reinforcement distribution in the girder along its length. While bars of size 10mm are used as side face reinforcement along the depth of the girder (though 16mm bars used at end sections), 12mm size shear stirrups are used in general at about 150mm spacing for shear strengthening of the girder. In total 4 legged shear ties are used as interface shear reinforcement at support whereas 2-legged stirrups are used at sections away from supports. The girders have 4 bars of 16mm size at their bottom layer. These shear details for the girders are shown in Figure 6.

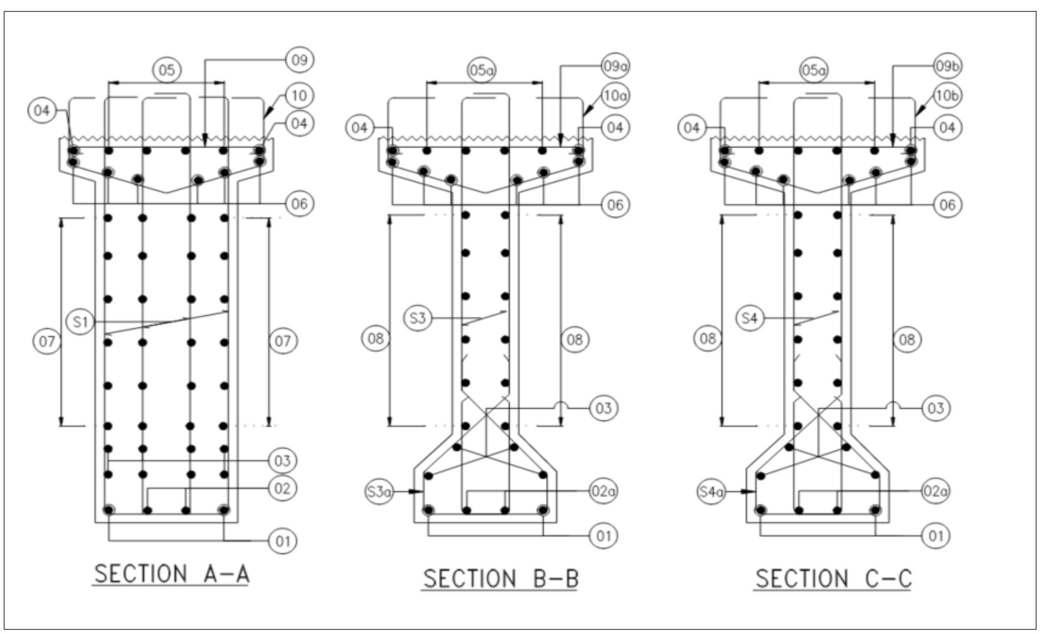


Figure 6: Sectional Details of Girder Reinforcement

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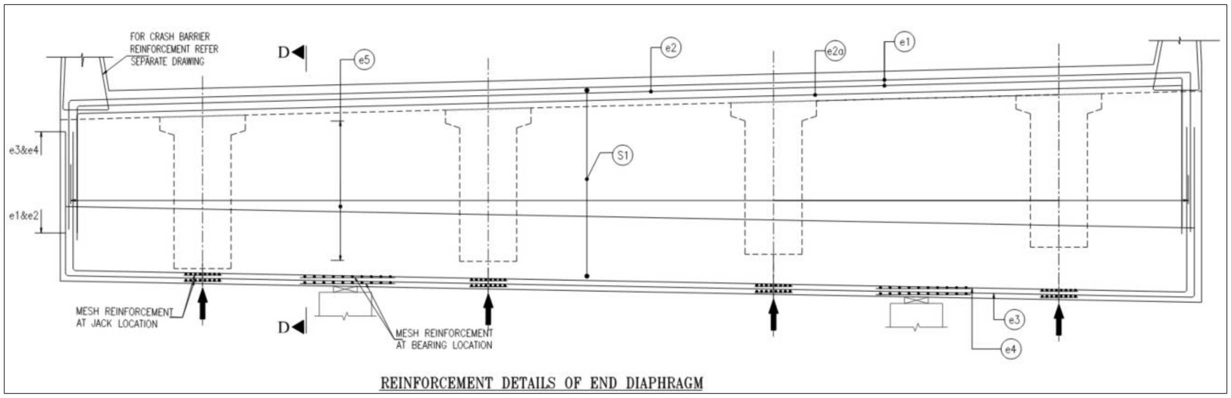
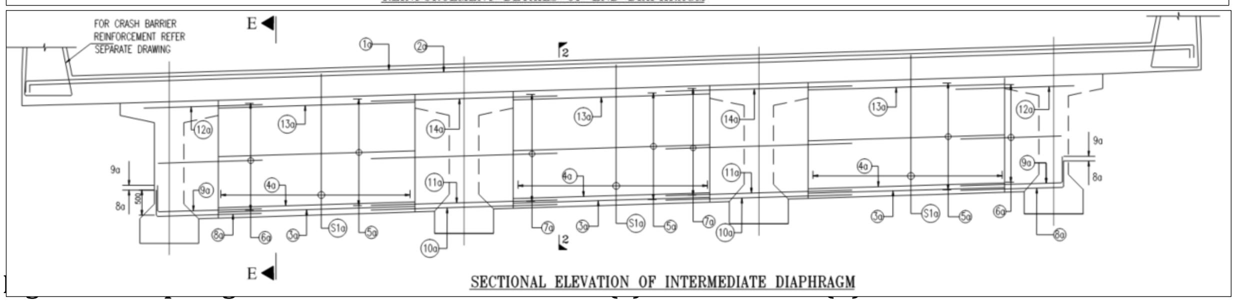
Figure 7 shows the schedule of reinforcement to be referred to to understand the reinforcement details provided in the girder and slab. The diameter, spacing and the length of the steel bars shown in the schedule are in mm. This figure 7 should be referred to while reading the reinforcement details shown in Figures 5 and 6.

SCHEDULE OF REINFORCEMENT				
BAR MKD.	DIA OF BAR	SPACINGS	DESCRIPTION	REMARKS
01	16	2 NOS.	300 300	BOTTOM BAR
02	16	2 NOS.	300 3000	BOTTOM BAR
02a	12	2 NOS.		BOTTOM BAR
03	12	4 NOS.		BOTTOM BAR
04	10	2 NOS.	300 300	TOP BAR (FLANGE)
05	12	4 NOS.	300 3000	TOP BAR (FLANGE)
05a	12	4 NOS.		TOP BAR (FLANGE)
06	10	6 Nos		BOTTOM BAR (FLANGE)
07	16	9 NOS (2ROWS) (ON EACH FACE)		SIDE FACE BAR (END SEC.)
08	10	9 NOS (ON EACH FACE)		SIDE FACE BAR (MID SEC.)
09	10	150 C/C		LINK
09a	10	125 C/C		LINK
09b	10	150 C/C		LINK
10	12	150 C/C		STIRRUPS
10a	10	150 C/C		STIRRUPS
10b	10	150 C/C		STIRRUPS
11	16	2 SETS		BEHIND ANCHORAGE
12	16	2 SETS		BEHIND ANCHORAGE
13	10	2 NOS	75 75	ANCHORAGE FACE BAR
14	10	200 C/C	300 1600	SIDE FACE BAR (END SEC.)
S1	4L-12	150 C/C		STIRRUPS
S2	4L-12	150 C/C		STIRRUPS
S2a	10	150 C/C		STIRRUPS
S3	2L-12	125 C/C		STIRRUPS
S3a	10	125 C/C		STIRRUPS
S4	2L-12	150 C/C		STIRRUPS
S4a	10	150 C/C		STIRRUPS

Figure 7 : Schedule of Reinforcement for Girders





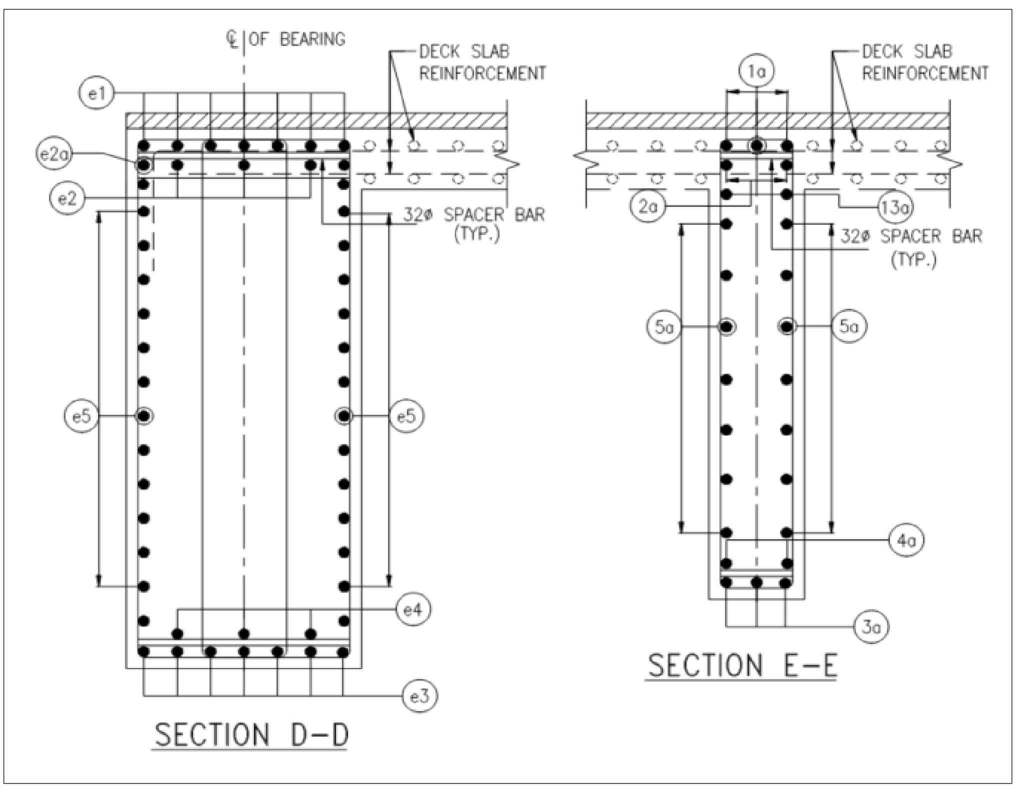


Figure 9 : Diaphragm Reinforcement Sections; End (L), Intermediate (R)

The bridge has three diaphragms connecting the 4 girders across and improving the stiffness and structural robustness of the system for better distribution of forces to each of the girders as well as to slab both directions. Two of the diaphragms are located at support locations, one at each support. The third diaphragm is thinner with 300mm thick rib at the midspan of the superstructure connecting the 4 girders at midspan. Figure 8 shows the reinforcement details of the diaphragms at support location and at midspan location. The main reinforcement in the diaphragms consists of 32mm and 25mm bars and runs parallel to the diaphragm length. The side face reinforcement in these diaphragms is arranged using 10 bars of 20mm size as these diaphragm beams are deeper than the threshold for side face reinforcement. The shear reinforcement is made of 16mm bars with 4 legged fully enclosed stirrups. Figure 9 shows sectional details of reinforcement in these diaphragms. The shear stirrups enclose the deck slab for monolithic action of the diaphragms with deck slab. While the end diaphragms have 4 legged shear stirrups, the intermediate diaphragm is only 300mm thick, so 2 legged stirrups are used for this member. The shear ties in interior diaphragm are spaced at 150mm on center whereas they are at 125mm on center in the end diaphragms. To fully understand the reinforcement scheme inside these diaphragm members, the readers may refer to the schedule of reinforcement outlined in Figure 10.

SCHEDULE OF REINFORCEMENT

INTERMEDIATE DIAPHRAGM REINFORCEMENT				
1a	32	3 NOS	1200 1200	TOP BAR
2a	25	2 NOS	1200 1200	TOP BAR
3a	32	3 Nos	1000 1000	BOTTOM BAR
4a	32	2 Nos		BOTTOM BAR
5a	16	7 NOS (ON EACH FACE)		SIDE FACE BAR
6a	16	7 NOS (ON EACH FACE)		SIDE FACE BAR
7a	16	7 NOS (ON EACH FACE)		SIDE FACE BAR
8a	32	3 Nos	1000	BOTTOM BAR
9a	32	2 Nos	1000	BOTTOM BAR
10a	32	3 Nos		BOTTOM BAR
11a	32	2 Nos		BOTTOM BAR
12a	20	2 NOS		TOP BAR
13a	20	2 NOS		TOP BAR
14a	20	2 NOS		TOP BAR
S1a	2L-12	150 C/C		STIRRUPS

SCHEDULE OF REINFORCEMENT

END DIAPHRAGM REINFORCEMENT				
e1	32	5 NOS	1200 1200	TOP BAR
e2	32	3 NOS	1200 1200	TOP BAR
e2a	25	2 NOS	1200 1200	TOP BAR
e3	25	5 Nos	1000 1000	BOTTOM BAR
e4	25	3 Nos	1000 1000	BOTTOM BAR
e5	20	10 NOS (ON EACH FACE)		SIDE FACE BAR
S1	4L-16	125 C/C		STIRRUPS

Figure 10: Reinforcement Schedule for Diaphragms; Intermediate (R), End (L)

Sustainability and Resilience Index for the Bridge

From the review of the engineering and construction process of the bridge superstructure members and the deck, it can be noted that some good sustainable practices have been implemented in the engineering and construction of this bridge. Prestressing with post-tensioned girders not only contributes to high design efficiency, but also improves the durability of concrete significantly. Prestressed structural members are reported to have significantly higher resistance to cracking and spelling of concrete [14]. These members have higher corrosion resistance as compared to reinforced concrete members (RCC) by virtue of their improved densities and lower water permeability. Prestressed girders show much higher stiffness and thus lower deflections during service stage as compared to RCC girders. Prestressed girders also have high resilience to impact loads and vibrations [15]. As such they are an excellent fit for bridge structures where dynamic vehicular loads transfer heavy impact forces to the girders. It is also reported that the deterioration and ageing of prestressed girder bridges are slower as compared to RCC girder bridges [16]. Also, the maintenance requirements as well the cost of maintenance treatments for prestressed girders are significantly lower than RCC girders owing to improved engineering properties of these members. Prestressing concrete members improves their resilience to extreme weather conditions triggered by climate change by avoiding complete failure of these members owing to their redundancy and resilience to short-term high intensity forces beyond design basis forces [17].

In addition to post-tensioning, the construction of these bridges adopted a few more good practices. The girders are fabricated and post-tensioned in the precast yard. Precast concrete offers many benefits such as greater quality control, efficiency in fabrication that offers speed and economy in construction of members. Precast concrete offers the solution for field problems such as onsite stacking, expensive formwork and traffic restrictions and inconvenience to road users. The girders for this bridge are fabricated in precast plant, post-tensioned in the yard and brought to site at the time of erection. This process is very efficient and removed the problems associated with traffic restrictions, onsite material stacking and labor supply issues [18]. Precast combined with prestressing made this project construction achieve higher sustainability and resilience score compared with traditional bridges built in India.

Another good practice applied in the construction of this bridge is the use of steel decking on girders to aid the casting of deck slab. The use of deck slab significantly removes the need for expensive formwork at site during concrete pouring and curing of slab [19]. Typically this is very laborious with huge formwork supported from at grade road under the bridge deck. The formwork is not only expensive but also time consuming and labor intensive. It causes great inconvenience to road traffic throughout the duration of its construction and until the completion of the bridge deck and till the bridge reaches 14 day strength. The use of steel decking completely removes the need for formwork support from under the bridge and thus enhances the sustainability score of the bridge.

Though this bridge has a good sustainability score, there is still a good scope for improving its sustainability and resilience score. The author likes to point out a few missed opportunities in further enhancing the sustainability and resilience score of the bridge. One such opportunity would be the use of Ultra-High-Performance concrete (UHPC) for bridge joints. UHPC joints greatly enhance the durability of bridge joints and reduce maintenance costs [20]. UHPC joints are being used in the construction of longitudinal and transverse joints in bridges in advanced countries and show very good performance. By virtue of its high tensile strength, low water permeability, greater impact resistance and minimal spalling and cracking, UHPC offers excellent applications to bridge joints [21] because joints in bridges are most susceptible to impact loads and usually are the high maintenance elements of a bridge due to wear and tear from traffic and weather conditions. The overall structural system would achieve a very good resilience score as well if the joints on the bridge are cast with UHPC. These high strength joints when combined with post-tensioned girders and solid diaphragms at support and end location [22] would make this superstructure system not only sustainable in terms of high life span, low maintenance, low life cycle costs and high resilience to extreme weather events such as seismic, wind [23], flooding and hurricane forces the occurrence of whose has increased over the last few decades due to climate change on the planet.

Conclusions

This is the second part of the two-part study on the bridge superstructure on NH-16 in India near Vijayawada city. While the first part detailed the analyses and design methods used in the engineering of post tensioned superstructure girders for this bridge, this second part presents the post-tensioning details of the superstructure girder along with the reinforcement in these girders and cross diaphragms. The post-tensioning cable layout, quantity and number of strands and the sequence of prestressing are explained in detail. The vertical and horizontal profile of the cables along the girder length are shown. The supplemental reinforcement details of the girder such as side-face reinforcement, the girder shear reinforcement and the interface shear ties across the slab interface are presented. Finally, a detailed discussion is presented about the sustainability practices implemented in the engineering and construction of the bridge superstructure and the authors acknowledge the good practices followed along with recommendations for further improvement of novel practices to enhance the sustainability and resilience of the bridge to natural forces stemming from intense weather events caused by global warming and climate change happening across our earth.

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