RESEARCH ARTICLE

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Case Study : Distortion Control in Orthotropic Steel Deck Welding

P. Raja Rethinam[1], S. Sampath Kumar[2] and Thomas Alphones[3]
Larsen & Toubro Limited (L&T Construction), MTHL PKG -1, STP Yard
Gate No. 1, Near Sewri Railway Station, Sewri (East), Mumbai- 400015
Email: [1]rethinam@lntecc.com, [2]ssampath-kumar@lntecc.com, [3]thomas.alphones@lntecc.com

ORCID : Thomas Alphones: https://orcid.org/0000-0003-0795-5224

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Abstract

Orthotropic Steel Deck (OSD) Bridge is typically a long span bridge around the world. The OSD bridge construction has numerous advantages. OSD has a complete steel superstructure, offering high stiffness to weight ratio, reduces the dead load on foundation of bridge and enables to provide longer span of bridge. This case study particularly deals with achieving bridge camber value during assembly and erection of Orthotropic Steel Deck by adopting suitable methodologies & techniques. The main challenges encountered during implementation of OSD bridge were (a) selecting suitable welding process/techniques, (b) shrinkage control during assembly and erection, (c) thermal expansion during weld joint fit up in marine environment. This case study may be useful for the construction industries adopting Orthotropic Steel Deck technology to construct long span bridges. One of typical span is sampled here to explain the above challenges and methods adopted to overcome them.

Keywords: Orthotropic Steel Deck; Thermal expansion; Welding shrinkage; Design camber.

1.0 Job Details

Construction Code : Japan Road Association (JRA) – Specification for Highway Bridges Part-II Steel Bridges – 2012.

Item Description : Orthotropic Steel Deck (OSD)

The OSD bridge assembly consists of 8 blocks to form a segment (**Fig. 1 & Fig. 2**), 10 segments to form a span (**Fig. 5**) and 3 to 6 spans to form a bridge at the desired location. Typical segment will be 12 m long, 14.8 m width and 6.6 m height. The assembled segments are further joined in longitudinal directions to form OSD span of required length (85 meter to 180 meter). The erection involves massive span weights ranging from 800 MT to 2600 MT for each span.

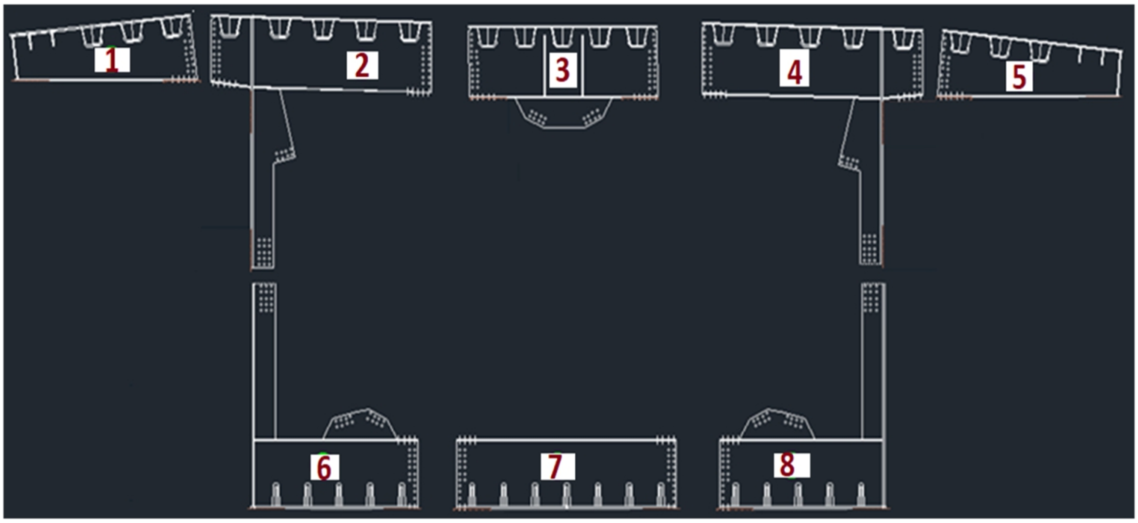


Fig. 1 : View of Orthotropic Steel Deck (OSD) blocks - Before assembly

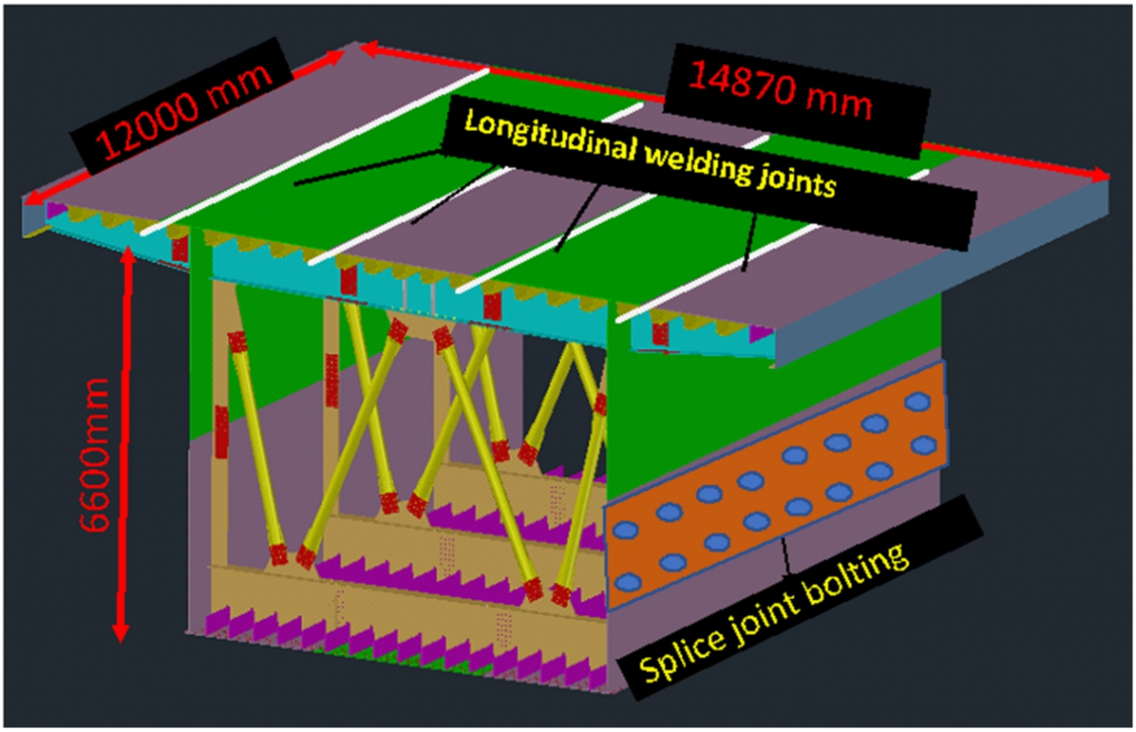


Fig. 2 : View of orthotropic steel deck (OSD) segment – After assembly

The following are the two types of connections involved in forming spans:

1.1 Bolted connections

These authors are using High strength friction grip bolts and tor shear type Tension control bolts in Bottom flange, side web splice and top side. The installation sequence of these fasteners was developed carefully and adopted in-order to control the stress variation in the components and to assist for welding distortion control. The torque & axial load values are typically 600Nm and 208 KN respectively. The detailed bolting sequences are explained in Clause - 5.

1.2 Welding

There are two directions of welding involved in bridge assembly and erection as below (**Fig. 3**) :

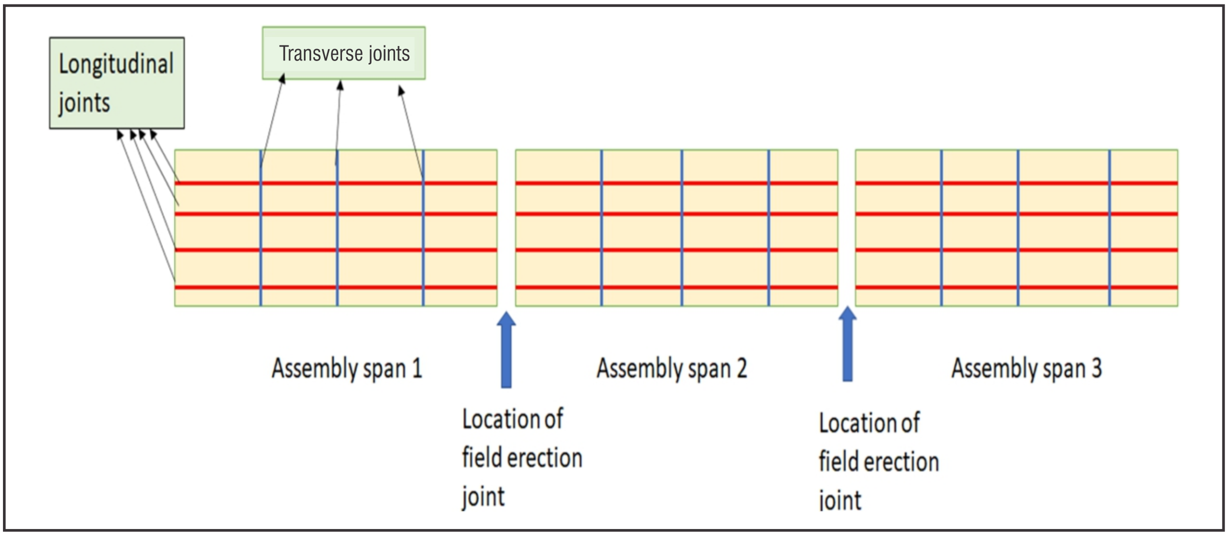


Fig. 3 : Key plan for weld directions

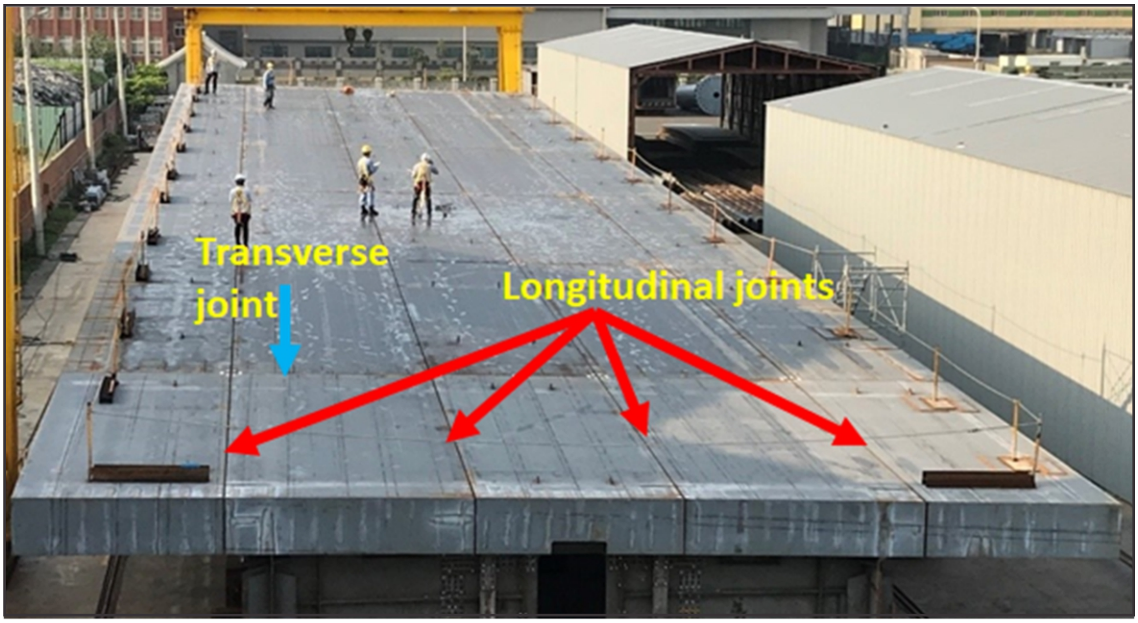


Fig. 4 : Span Assembly Showing Longitudinal and Transverse Joints

- Longitudinal direction welding joint (along with bridge traffic direction)
- Transverse direction welding joint (across the bridge traffic direction)

One of the key challenges in OSD assembly and erection is to achieve the design camber value. Due to the design requirement of camber in OSD, welding processes / techniques plays a vital role wherein heat input / welding shrinkage / welding distortion need to be controlled.

In every assembly, the longitudinal joints are to be welded first and then the authors follow the transverse joint welding sequence which are explained in clause 6.

2.0 Base Material Details

The base material is "Rolled High Strength Carbon-Manganese Steel" having Mn 1.6 % with yield stress 460 MPa and notch toughness requirement of minimum 47J at -5 Deg C. The steel used in blocks are meeting the requirements of Japanese Industrial Standard (JIS) G 3106 and base material thickness ranging from 16 to 38 mm.

3.0 Welding Standard & Processes

The welding standard adopted is AASHTO AWS D1.5 (Bridge welding code) and welding processes employed are Flux Cored Arc Welding (FCAW) + Submerged Arc Welding (SAW) with removable ceramic strip used as backing.

The adoption of AWS D1.5 was based on the provision permitted in JRA Part-II construction code.

FCAW process is adopted for root welding which is suitable for field welding (to reduce the impact of wind during welding) with ceramic backing strip **(Fig. 5**), and subsequent layers are filled by SAW which is providing better finishing and productivity.

4.0 Design Requirement for Camber

As the bridge construction involves with various loads and stresses in different stages, which in turn affects the bridge profile, the deflection values at those stages were estimated by design and plotted as bridge camber. The following are the major stages of cambers involved:

4.1 Different stages of cambers :

- Production camber - (A)
- Welding camber - (B)
- Assembly camber - (C)
- Design camber - (D)

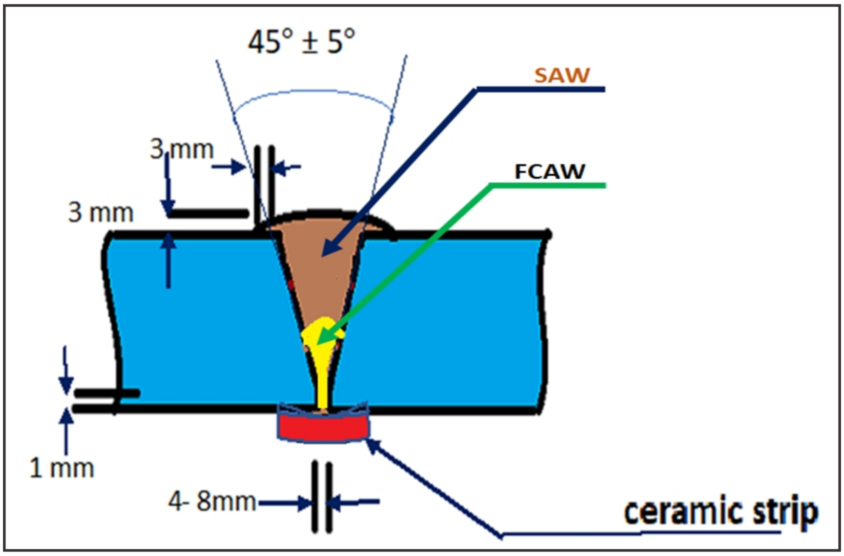


Fig. 5 : Schematic diagram of weld joint configurations

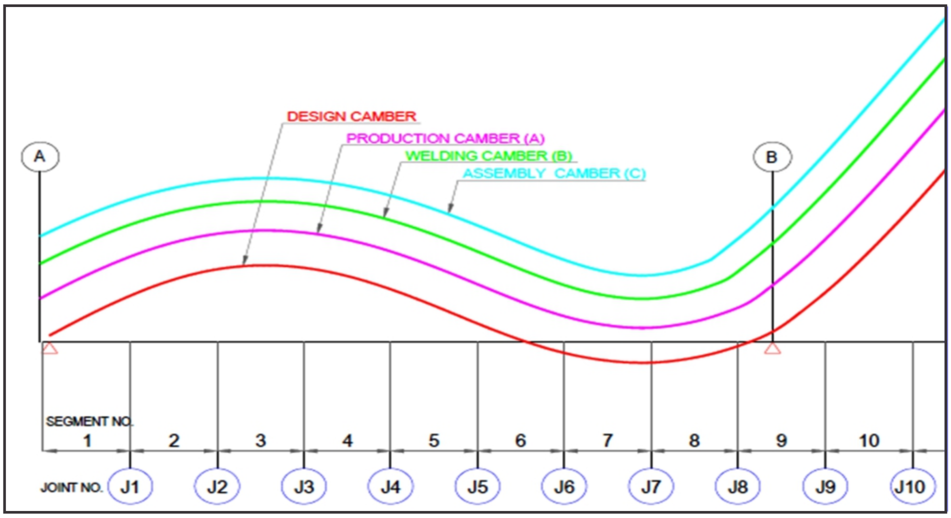


Fig. 6 : Diagram showing different cambers – (Between pier A & B)

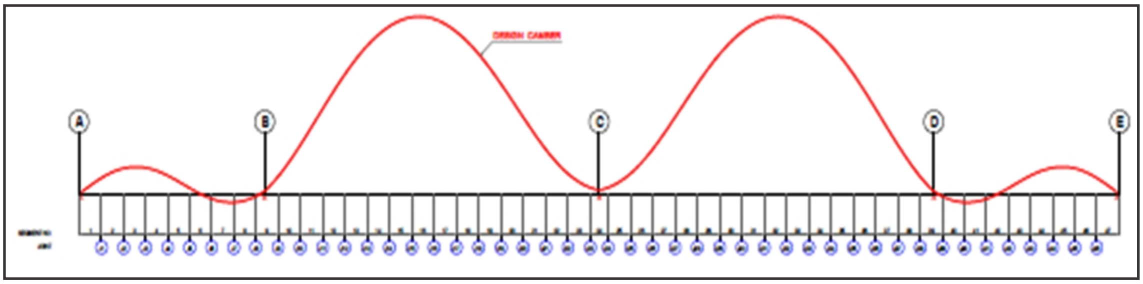


Fig. 7 : Design Camber across the spans – (Indicative)

4.2 Brief description about different cambers

In-order to achieve design camber D (**Fig. 7**), different stages of camber during construction are estimated with certain design assumptions.

The following are affecting the design camber value:

Production Camber (A) :

- Self weight of Steel
- Tuned mass damper (TMD)
- Utility / Walkway
- Vehicle barrier
- Pavement
- Noise/View/safety barrier

Welding Camber (B) :

- Estimated welding shrinkage

Assembly camber - C is arrived by adding estimated deflection due to production camber -A (consisting of self-weight) and expected welding camber - B, (C = A+B) (**Table 1**).

Initially the assembly was raised to certain level (C) using support stools at different locations during joint fit up and then welding commenced (**Fig. 6 & Fig. 7)**.

Welding camber (resulting from welding shrinkage and distortion) was only an estimate, and these values need to be confirmed after welding and removal of support stools. Hence stringent monitoring and control was necessary during welding which is explained in clause 6.

To maintain the assembly camber dimension, stools are placed under the span to maintain the required height. (Ref. **: Fig. 8 & Fig. 9**)

5.0 Bolting Sequence

Tightening of high strength bolts (except bottom side) was performed after welding, to reduce the restraint of welds and to prevent the decrease of slip strength due to the welding distortion. This sequence was particularly helpful in managing misalignment of bolt holes between the splice plate and the base material, the camber change of the girder, etc.

Note: JRA Part II, (steel bridges guideline) requires an appropriate treatment for the faying surface in-order to ensure slip co-efficient value of 0.4 or more. In this case, the faying surfaces were applied with inorganic zinc rich primer.

Table 1 : Estimate of Assembly camber between piers (Sample)

Description	Camber Value in mm									
Segment No.	1	2	3	4	5	6	7	8	9	10
Production camber (A)	5	36	53	53	35	9	-12	-17	-2	43
Welding camber (B)	0	59	112	162	207	250	288	325	359	392
Assembly Camber (C) = (A+B)	5	95	165	215	242	259	276	308	357	435

5.1 Bolt installation & tightening before longitudinal direction welding (In assembly)

- For the marked area, (**Fig. 10**) all bolts were tightened to full torque value before longitudinal welding.
- Other than marked area on top deck side (**Fig. 11**) temporary (20 % of qty) bolts were provided before welding to match the splice joint hole.

5.2 Bolt installation & tightening after longitudinal direction welding

- After completion of longitudinal welding, the temporary bolts were removed, and permanent bolts were placed and tightened. (**Fig. 12**).

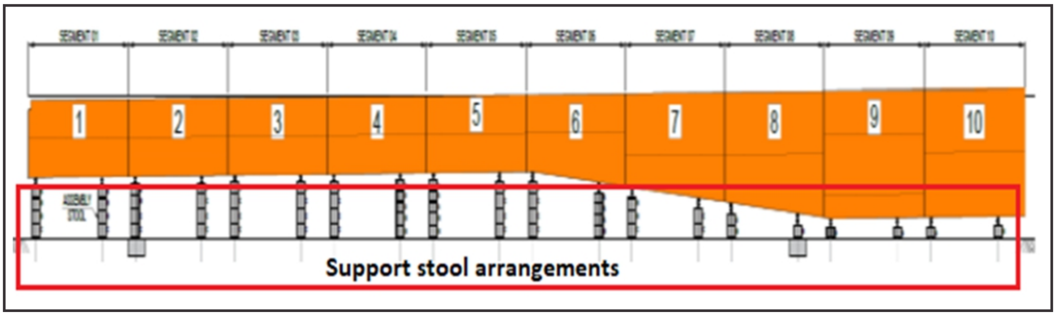


Fig. 8 : Provision of support stools

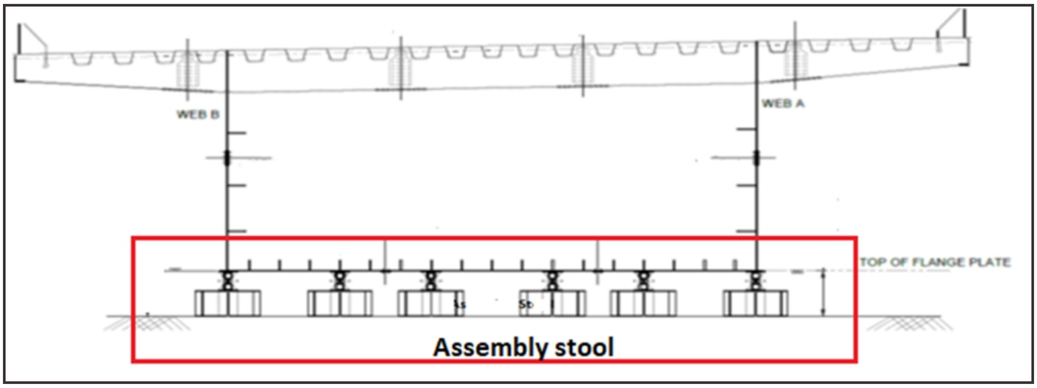


Fig. 9 : Provision of support stools for assembly– Section view

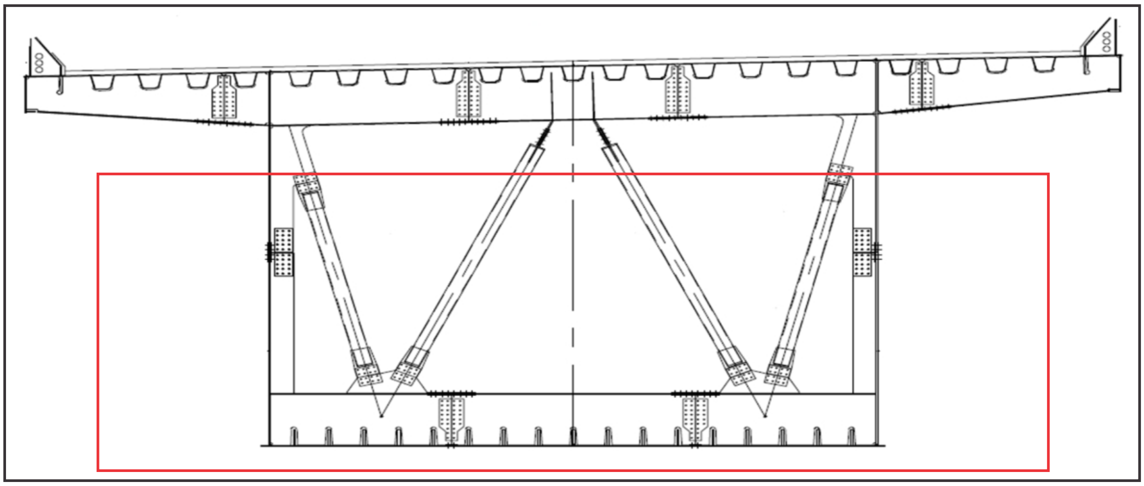


Fig. 10 : Bolt sequence before longitudinal direction welding

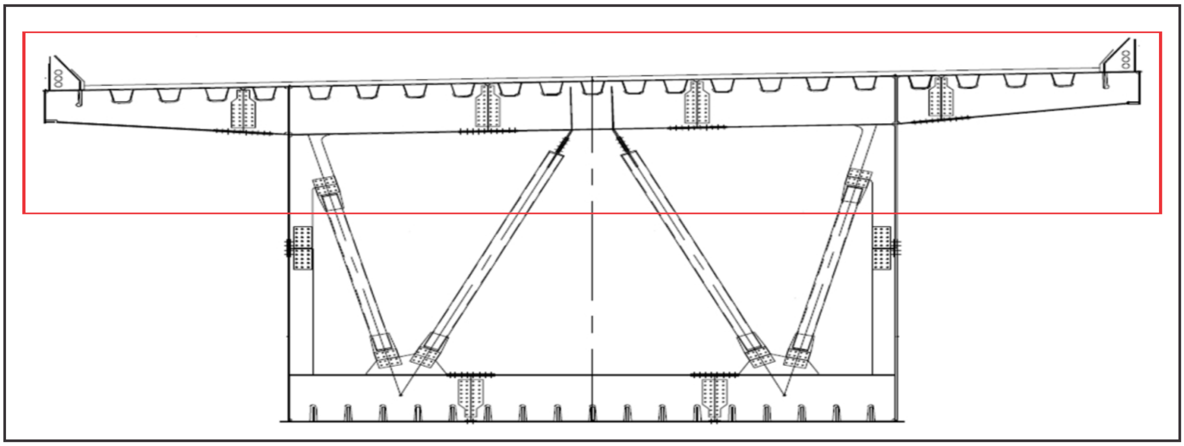


Fig. 11 : After Welding

5.3 Bolt placement & tightening after transverse direction welding

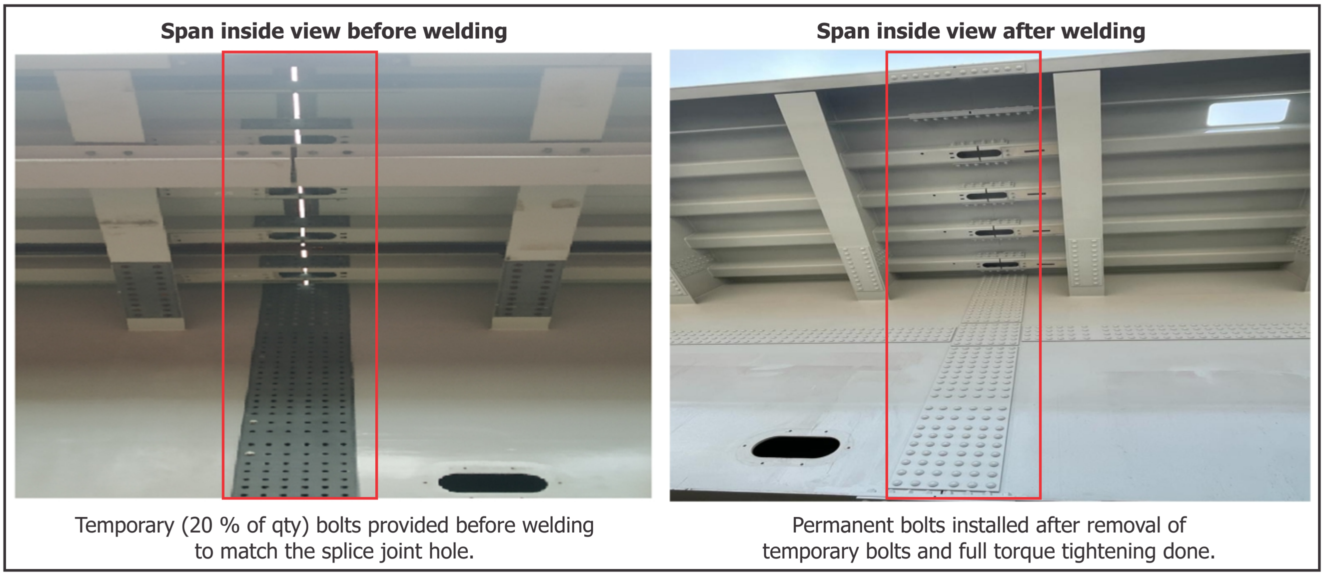


Fig. 12 : Bolt tightening before and after welding

6.0 Welding Sequence

To achieve the welding camber (B) within specified value, the authors have adopted following methodology:

Welding Sequence:

The following sequence for transverse direction welding was adopted for achieving the estimated camber (B) by minimizing the welding shrinkage/ distortion (**Fig. 13**).

Note: Though the thermal expansion effect was felt during segments assembly welding, the same was minimal due to:

- The segments joined during assembly were shorter in length and span ends were free to expand.
- The better control on bolting at yard (i.e. adopting sequence in less time) was sufficient to overcome the thermal expansion effects.

Note: To facilitate easier fit-up of erection joint, the longitudinal joints adjacent to transfer joints were kept unwelded for 300 mm (**Fig. 14**).

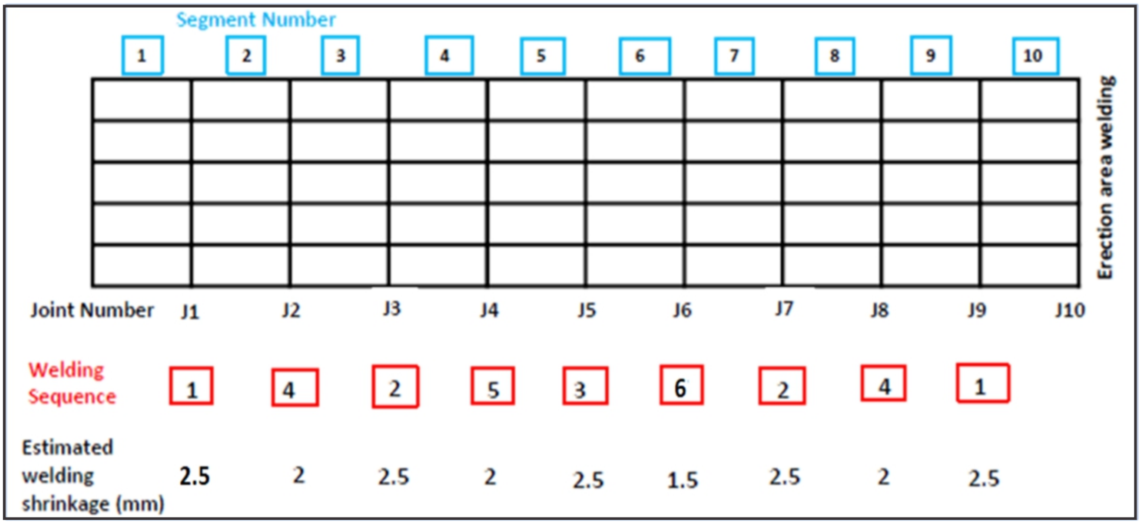


Fig. 13 : Sketch showing estimated welding shrinkage & welding sequence adopted

Fig. 14 : Un-welded portion(300mm) of longitudinal joints

7.0 Challenges Faced in Assembly

In adopting bolting and welding sequence, the authors encountered two challenges as below:

- Upward distortion of wing portion during longitudinal welding (Challenge -1)
- Excess distortion in transverse joint welding (Challenge -2)

7.1 Issue description – Challenge -1

The required alignment value was maintained at top of the deck (i.e. span) as per design during longitudinal direction joint fit-up (**Fig. 15**). After camber verification,welding was started and noted that wing side block (cantilever) got excessively distorted than the original estimate (20 mm upwards).

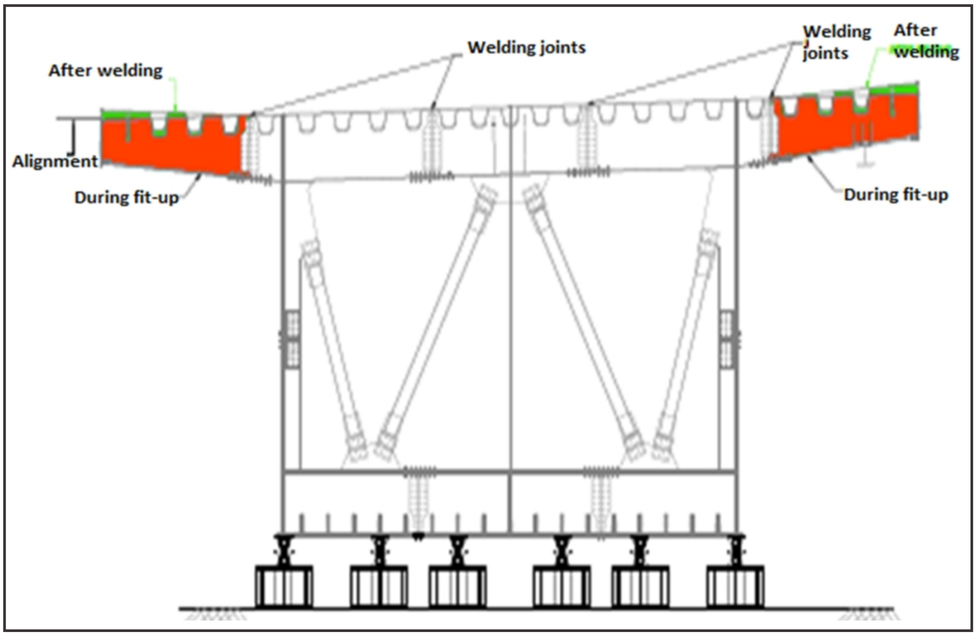


Fig. 15 : Upward distortion

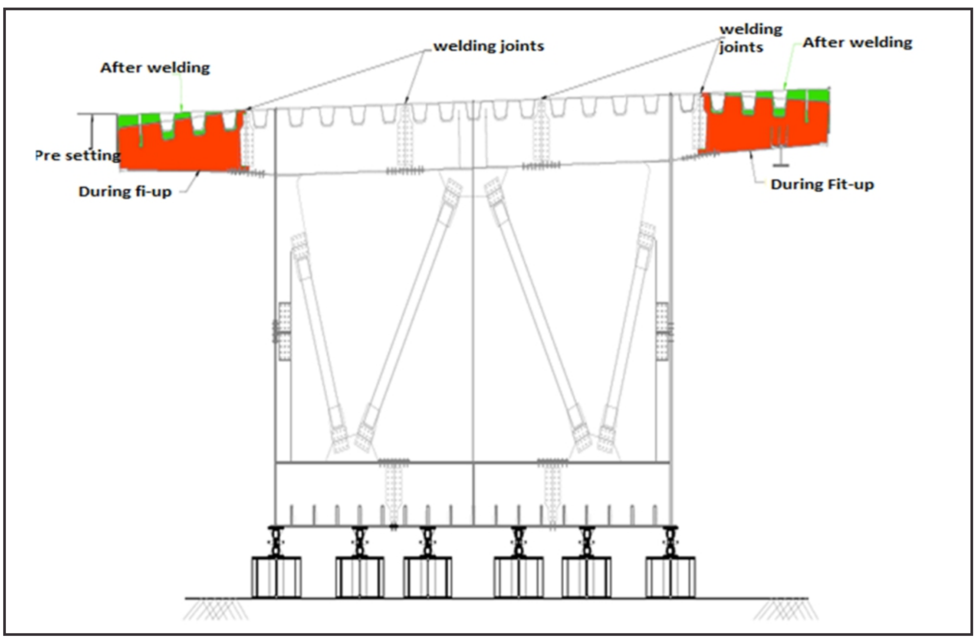


Fig. 16 : Presetting of Wings to avoid distortion

Solution: Further studies were carried out and it was re-confirmed that weld heat input was maintained and controlled in the range of 2.5 to 4.0 kJ/mm and inter-pass temperature of 250 Deg. C Max in-line with WPS parameters. Then the authors decided and executed the following:

- While doing fit-up of wing block, the authors have kept the wing alignment value in downside (5 mm) w r t required value. (**Fig. 16**).
- Also provided extra restraint to avoid more distortion

7.1 Issue Description – Challenge -2

Transverse direction joint welding was performed as per planned sequence, and it was observed that welding shrinkage exceeded the estimated value.

Solution: Welding shrinkage values were monitored, and it was noted that 70% of shrinkage was occurred during the root welding. So, it was decided to execute the following:

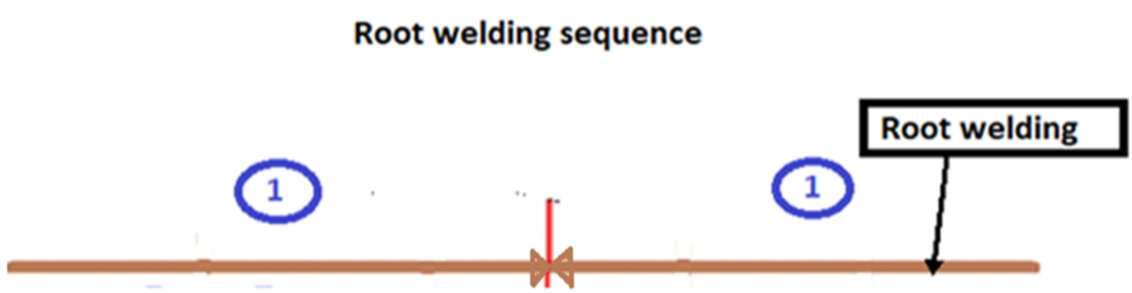
- Root welding sequence of individual joint changed (**Fig. 17**)

Table 2 : Welding Shrinkage value in transverse joint welding

Joint No.	Estimated shrinkage (mm)	Observed shrinkage (mm)	Difference in mm
J1	3.0	4.12	1.12
J2	2.0	3.04	1.04
J3	2.5	2.82	0.32
J4	2.0	2.67	0.67
J5	2.5	3.06	0.56
J6	1.5	2.17	0.67
J7	2.5	3.02	0.52
J8	2.0	2.66	0.66
J9	2.5	2.82	0.32

Initial Sequence:

- Root gap adjusted marginally 4-6 mm instead of 6-8 mm.



Modified Sequence :

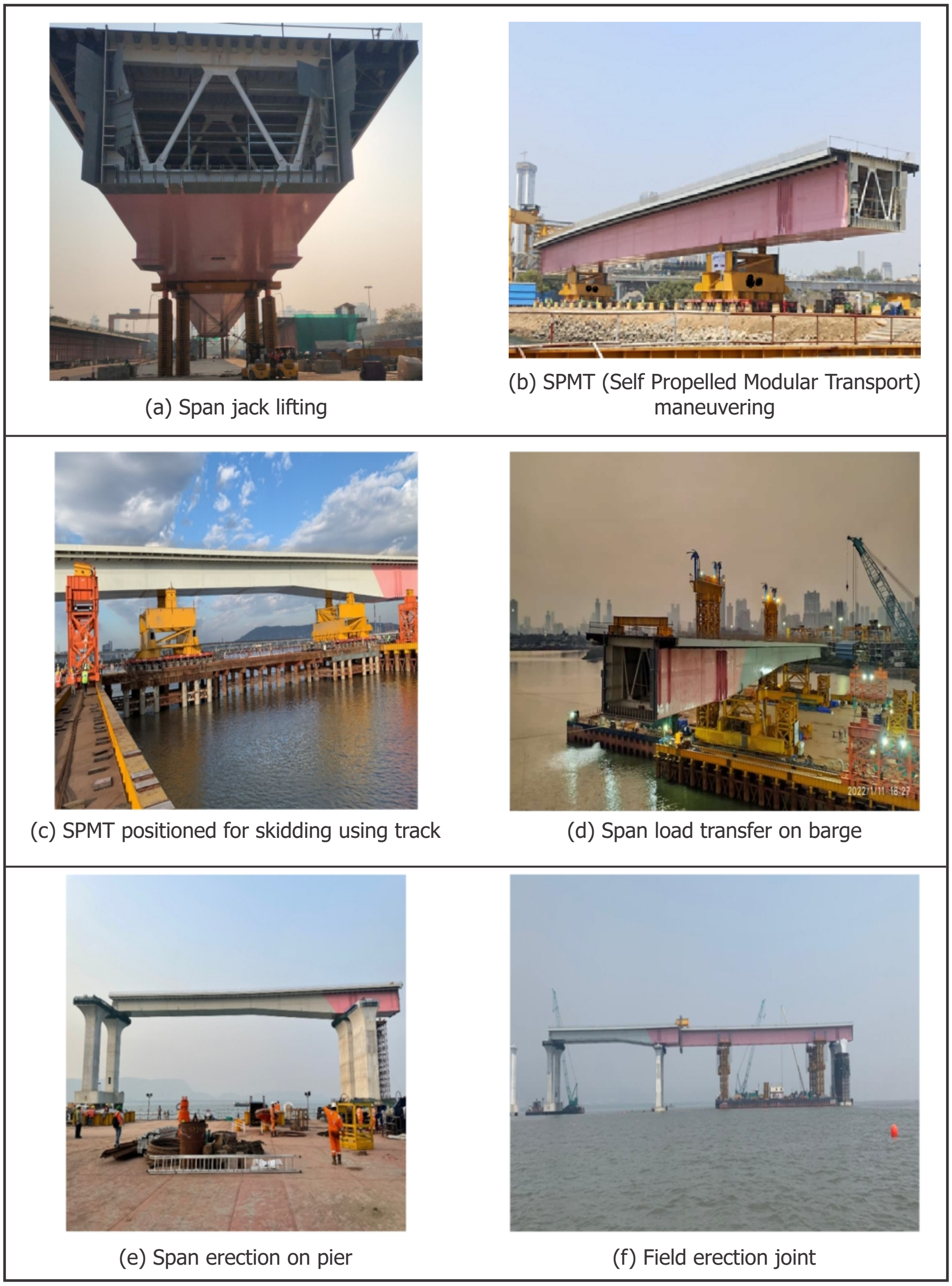
Fig. 17 : Initial & modified welding sequence

8.0 Introduction to OSD Span Erection

After completion of assembly bolting and welding, the entire span of varying length 85 ~ 180 meters was transported to the marine pier location using specialized jacking, SPMT (Self Propelled Modular Transport), skidding arrangements, barge, lifting tower using strand jack method (**Fig. 18**).

As the total bridge length varying in the range of 320m to 660m, it was not safe in marine environment to erect such a long span in a single stretch and accordingly each span length was designed to 100m -180m. approx. Hence welding after erection was inevitable for joining the spans at site locations. Refer clause 10 for the challenges associated with erection joint.

9.0 Span Transportation Activities Sequences Until Erection at Site



(a) Span jack lifting

(b) SPMT (Self Propelled Modular Transport) maneuvering

(c) SPMT positioned for skidding using track

(d) Span load transfer on barge

(e) Span erection on pier

(f) Field erection joint

Fig. 18 : Stages of Span transportation from assembly yard to erection at marine location

10.0 OSD Span Erection at Marine Location

Due to massive nature of OSD spans, erection, alignment, bolting and welding at field posed a lot of challenges and same has been meticulously planned and executed to achieve the design intent. The following were the major challenges encountered and were tackled appropriately.

- Differential angular deformation
- Fastener installation considering load and stress involved in erected spans
- Thermal expansion issue during fit up and welding.

10.1 Differential angular deformation (θ) challenge

During the erection of OSD-4 span 3, span 1 and span 2 are already monolithically connected and resting on the temporary bearings at location (A, B, C & D). Span 3 is to be lifted from the barge and will be resting on temporary bearing of location D and cantilever end of Span 2 by setting beam in intermediate erection stage. Therefore, at this intermediate erection stage, the deflection of Span 1&2 / Span 3 are different from the final erection stage deflection as shown in **Fig. 19**. Accordingly, the angular deformation of both ends of blocks at interface splice location could not match at this intermediate erection stage, having differential angular deformation (θ) and opening gab at top flange.

Solution: In-order to match the both angular deformations block at each end of blocks, the differential angular deformation at interface splice location shall be compensated by raising the other end of Span-3. Then, bolting and welding connection of the site splice joint was completed.

10.2 Bolted connections Challenges

After jack lifting to minimise the angular deformation, bolts were installed from bottom to top flange. During this activity, the authors found that the top side wing portion splice holes were not matching due to misalignment.

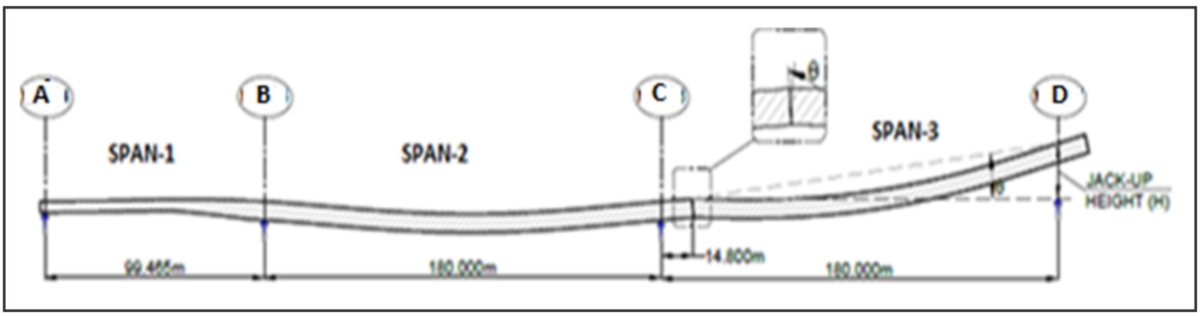


Fig. 19 : Span angular deformation (Indicative)

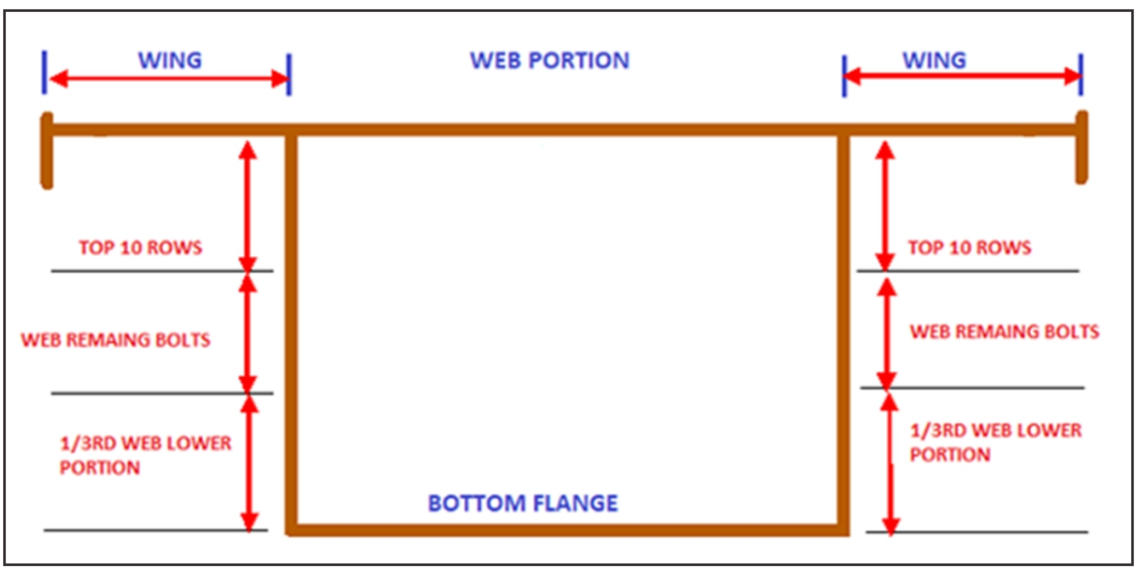


Fig. 20 : Bolting sequence details

Solution: After finding the difficulties in bolting, the authors have slightly modified the bolting sequence (**Fig. 20**), in-order to minimise the mismatch. The bolting sequence adopted after modification are briefed in **Table 3**.

10.3 Thermal expansion issues / welding sequence challenge

Although the sequence of bolting adopted during fit up minimized the effect of thermal expansion, it could not be completely avoided. Required root opening of 4 to 8 mm could not be maintained due to expansion & contraction resulting from temperature variation. The authors studied the thermal expansion at every 3 hrs for whole day (24 Hrs) and the values are tabulated as below (**Table 4**).

150mm match marking maintained with the root gap of 6±2mm at 25-30 deg (**Fig. 21**).

Table 3 : Bolt sequence for erection joint

Step	Location	Type of fasteners (Temporary/Permanent)	Quantity	Requirement
Step -1	Bottom flange	Permanent	100 %	Snug tightening
Step -2	Lower 1/3rd & web remaining bolt portion	Permanent	100 %	Snug tightening
Step-3	Top 10 rows	Temporary	100%	Machine tightening
Step-4	Top web splice and wing portion	Temporary	4 nos. bolts in each splice	Hand tightening
Note: After transverse welding, permanent bolts to be installed after removing temporary bolts with full torque tightening.				

Fig. 21 : Measuring match marking 150mm before welding

Fig. 22 : Locking of 2-meter span near fit-up area

Table 4

OSD	Time	Temperature (Deg. C)	Reference dimension (in fit up stage) (mm)	Observed dimension (mm)	Difference in (mm)
1st Span	6 AM	23.0	150.0	149.37	-0.63
	9 AM	28.0	150.0	150.42	0.42
	12 PM	35.0	150.0	153.89	3.89
	3 PM	53.0	150.0	158.23	8.23
	6 PM	38.0	150.0	156.15	6.15
	9 PM	29.0	150.0	151.88	1.88
	12 AM	23.0	150.0	149.60	-0.40

Theoretical calculation of thermal expansion of OSD span:

dl = L0 α (t1 - t0)

Where,

dl = change in object length (m)

L0 = initial length of object (m)

α = linear thermal expansion coefficient (m/ deg C,)

t0 = initial temperature (deg.C,)

t1 = final temperature (deg.C)

In this case, L0 – 180m, t0 – 27 dec C, α = for steel is 12.5X10-6 m/ deg C,

Dimension during lowest temperature (23 Deg C)

dl = - (.09 m) or 90 mm (contraction)

Dimension during highest temperature (53 Deg C)

dl = (.585m) or 585 mm (expansion)

Though the calculated values are huge for total span, they are accommodated at free ends of the spans. Practically approximately 2-meter-long span near fit up (**Fig. 22**), locked by bolting only affecting root opening. By substituting this 2 m, in above formula, the authors get 0.24 mm contraction and 6.24 mm expansion.

Considering unaccounted deviations in torquing and other locking forces acting on the joint, the authors got 8.63 mm as maximum expansion.

From the Table, the authors established 9 PM to 9 AM as favourable time for initiating welding where the temperatures are near design value and expansion values are minimum. And started welding in about 6 AM. Root and hot passes were welded continuously with sequence to gain the sufficient weld strength to overcome expected thermal stresses during daytime due to rise in temperature.

Solution: The authors monitored the temperature continuously to meet the required root gap and started the welding in the following sequence (**Fig. 23**).

Welding sequence of erection joint: By adopting the welding sequence as shown in (**Table 5**), the authors have minimised the welding shrinkage.

Table 5 : Actual welding sequence

Step details	Actual welding sequence
Step - 1	Longitudinal joints welding (300mm) by FCAW + SAW (L2 & L3 then L1 & L4)
Step -2	Root & hot pass welding of web portion from (B to CL) & to CL) - Web portion
Step -3	Root & hot pass welding of web portion from (B to A) & (E to F)- Wing portion
Step -4	Further layers of SAW can be start from any direction until capping

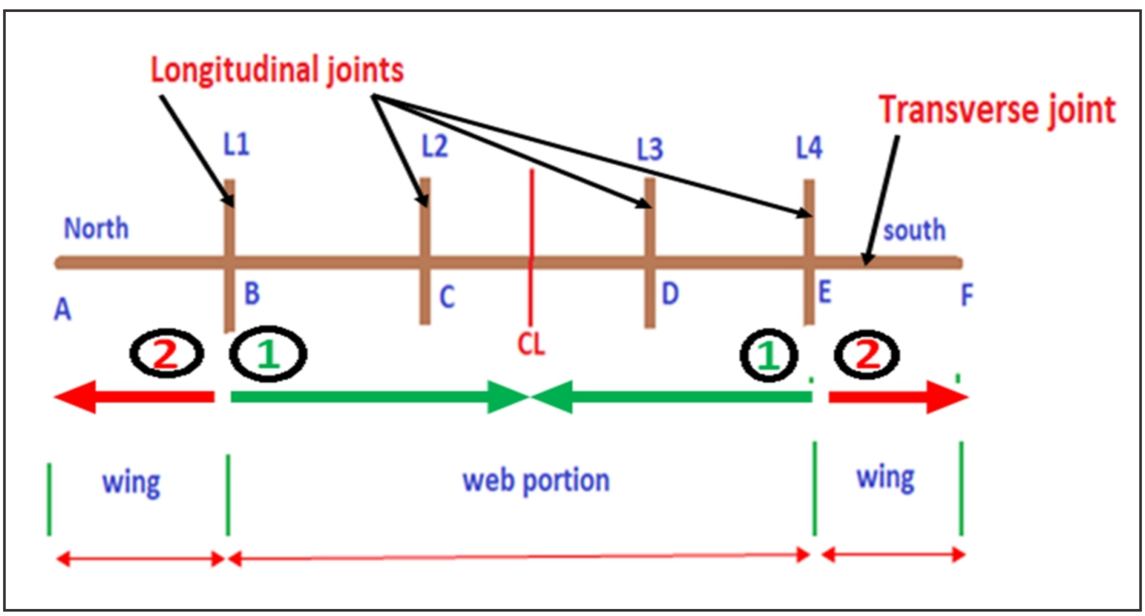


Fig. 23 : Modified welding sequences

Table 6 : Camber Value

Description	Camber Value in mm									
Segment No.	1	2	3	4	5	6	7	8	9	10
Required	5	36	53	53	35	9	-12	-17	-2	43
Achieved	10	40	58	58	39	13	-24	-31	-13	57

By adopting the above sequence and techniques, the authors minimized the welding shrinkage.

11.0 RESULTS

11.1 Weld joint soundness:

The field joint has been welded and NDT tested (Ultrasonic Testing) and accepted as per JRA Part – II & AWS D 1.5M / D1.5. This confirms that the methodology adopted proved to be successful to overcome the mechanical & thermal stresses in the field joint.

11.2 Camber value after erection:

The required camber values (Prior to design camber D) were achieved after the span erection and welding when the span is resting on concrete piers. **Table 6** showing the camber value achieved between sampled piers.

These values vary in the range of + 5 to -14 mm which within the design tolerance limits of +5 mm to – 20 mm.

Note: The Design camber value (D) will be achieved after installation of the following items :

- TMD installation
- Vehicle barrier installation
- Pavement
- Noise/ View/ Safety barrier.

12. CONCLUSION

- Weld shrinkage shall be estimated based on design requirement and practicality.
- Sequencing of welding of longitudinal joint first followed by transverse joint will minimize distortion.
- Proper study on thermal expansion is essential to control the field joint geometry.
- It is essential to verify the bridge camber at every stage to confirm the design estimation.