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Performance of Rib-to-deck weld joint of an orthotropic steel deck through structural stress method

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Abstract

The rib-to-deck welded connections in orthotropic steel decks (OSDs) used for railway and highway bridges are highly susceptible to experiencing fatigue cracks. The fatigue life, crack initiation position, and steel requirement in these bridges are influenced by the rib shape, size, and wheel load. A parametric study of an OSD was presented in this paper, considering different geometries of U- and V-ribs, deck plate thickness, weld penetration, and patch load. The structural stress (SS) method was employed to determine stresses and fatigue life related to the weld joints, with the analysis conducted using finite element(FE) software. The results indicate that variations in the depths of U- and V-ribs significantly impact the SS in rib-to-deck weld joints. However, the variation in the bottom width of the U-rib has a negligible effect on the SS along the weld line. Increasing the deck plate thickness leads to a reduction in stress within the weld joint. The location of the maximum stress remains substantially away from the ends of the deck and remains unaffected by the depth, bottom width of the rib, and deck plate thickness. However, a rib with a smaller depth exhibits a shorter fatigue life for the deck system. The stresses responsible for failure modes in the toe-deck and deck-root welds show negligible changes as the weld penetration increases. A comparison was made between U- and V-ribs of equal perimeter and equal depth. The conclusions emphasize that for optimal performance of an OSD, the depths of U- and V-ribs should fall within the range of 250-300 mm, and the bottom width of the U-rib should be in the range of 100-125 mm. Excessive depth and bottom width can lead to an uneconomical design. Additionally, it is shown that V-ribs are preferable over U-ribs in the construction of an OSD.

Keywords

Structural stress method, Orthotropic steel deck, U-rib & V-rib, Finite element (FE) analysis.

1.Introduction

Orthotropic steel decks (OSDs) have been used in long-span cable-stayed and suspension bridges for highways worldwide. An OSD may prove to be an excellent replacement to the mostly adopted steel plate girder bridges for railways from the perspective of fatigue strength, multiple carriage, incredibly fast and powerful goods trains. An OSD bridge deck is made out of a structural steel plate that is longitudinally reinforced with an arrangement of ribs joined by welding. Transverse stiffeners may be optional. Different types of stiffeners can be used which may be open ribs (stringers) or closed ribs (U-ribs, or V-ribs) [1].

Over other types of steel bridges, OSDs offer a number of advantages, including as reduced dead weight, significant weight carrying ability, and being able to be produced in sections off-site [2]. However, the stiffening rib's weld connections to the deck plate are sensitive to fatigue and fracture, that significantly influences the reliability and lifespan of the OSDs [3]. Fatigue has been a key problem hindering the performance, design and sustainable development of bridges. Fatigue crack propagation in the deck-rib weld joints has often been reported in OSD bridges worldwide [4–6].

The OSD's reduced dead weight characteristics lead to a substantial reduction of steel consumptions up to 50% when compared to conventional steel plate-girder bridges. Fatigue cracks, especially in the deck-rib joints, can be identified based on the locations. These cracks can be toe-deck crack (Type 1), root-

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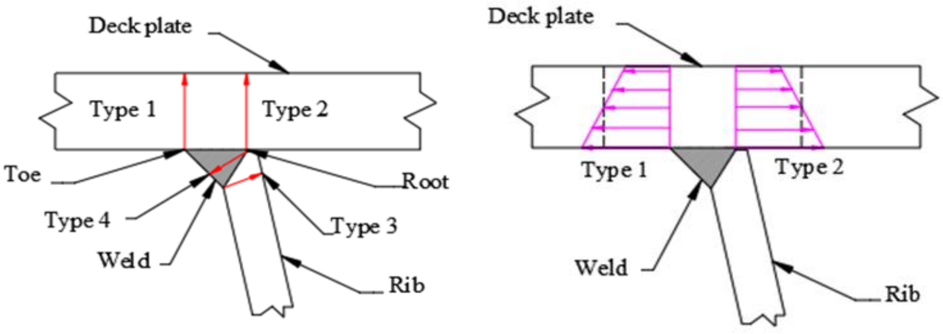
deck crack (Type 2), toe-rib crack (Type 3) and root-weld crack (Type 4) as shown in *Figure 1*. As per the study conducted by Wang et al. [7] it was confirmed that the toe-deck cracking dominated among all the four types of cracks.



(a) (b)

Figure 1 Deck-rib weld joints (a) toe-deck and root crack position (b) corresponding SS distribution

Several analytical and experimental studies have been conducted by researchers on the rib-to-deck weld joints of the OSD bridges stiffened with the U-ribs only. However, the authors have not come across the literature which deals with the economical depth and bottom width of the U-rib. Moreover, the fatigue behavior of the OSD stiffened with another type of rib called V-rib has not been adequately addressed under the distributed patch loads which the deck receives after dispersion from the rail wheel. The fatigue life of a ribbed OSD is mostly dependent on the welds connecting the stiffening ribs to the deck plate. The objective of this paper is to present the fatigue behavior of rib-to-deck weld joints considering various parameters like depth and bottom width of U-ribs, deck plate thickness, weld penetration, load patch area, and V-rib depth. Noticeable variation of stresses in the weld joints and consumption of steel in the bridge deck construction have been found. Moreover, a comparison of OSDs with U-rib and V-rib of equal perimeter and equal depth is also presented. In this numerical investigation SS method is used. The advantage of the SS method is that it is mesh insensitive as compared to the other traditional methods like nominal stress method, hot-spot stress (HSS) method or notch stress (NS) method. The mesh insensitiveness of the SS method is also verified in this work. The SS in the weld joint is determined using the finite element (FE) analysis software's Abaqus and Fe-safe.

This paper is organized as follows. Literature review is presented in Section 2. Methodology of numerical simulation of the FE models and loadings are explained in Section 3. Results in Section 4 and discussion of the results with limitations are explained thoroughly in Section 5. Finally, conclusions and future scope of this research work are presented in Section 6.

2.Literature reviews

It is understood that the weld size and its penetration, deck plate thickness, SS are the factors that influence the crack location and its initiation which in turn dictate the fatigue life of the OSD. Some researchers attempted to assess the performance of an OSD through analytical and experimental investigation. Fan et al. [8] tested 9 specimens- 3 single-sided, 3 partially penetrated double-sided and 3 fully penetrated double-sided rib to deck weld joints of an OSD to investigate about the fatigue failure mechanism. To calculate the stresses in the welded joints the nominal stress and the HSS methods were utilized. The OSD specimen has 6000 mm length along the traffic direction, 2700 mm width along the transverse direction and 738 mm height. The deck consisted 4 numbers U-ribs of height 300 mm and deck plate thickness 18 mm. They concluded that the fatigue strength of double-sided rib-deck welded joints is significantly higher than that of single-sided welded joints. Moreover, compared with the nominal stress method, the divergence of the SS method is lower and is more convenient to use to evaluate the fatigue performance of welded joints. Amritraj and Mishra [9] have done analytical investigation of the double sided and single-sided rib-deck weld joint of a full-span OSD bridges due to movement of a locomotive by the SS method. The total span length of bridge was 12.2 m consisting of 3 U-ribs of height 280 mm and 4 diaphragms and the axle load of locomotive was 25 ton. The results show that the rib adjacent to the main girder possesses the highest SS in the deck-toe when the vehicle was on the mid-span of bridge. Additionally, when compared to single-sided weld joints at the root of the weld, double-sided rib-deck weld joints experienced 43.7% less SS. The study was limited to train loads on the bridges and analytical investigation. Experimental study still needs to verify the results. Cheng et al. [10] experimentally investigated the fatigue behavior of six full scale specimen of the rib-to-deck weld joint which is understood to be most prone to fatigue cracking in OSDs using HSS method. Each specimen of OSD consists of deck plate 1000 mm wide, 400 mm long and 16 mm thick. The depth of U-rib was 300 mm and the thickness was 8 mm. A load of 20 kN was applied on the deck surface. The results indicated that the cracking begins at the deck-toe on deck-rib weld joints and spreads longitudinally until the crack tip reaches the deck edge. The cracking then extended across the deck plate's thickness, resulting in a visible fatigue crack on the deck plate's top surface. Yang et al. [11] established a numerical model for fatigue failure mode prediction of the OSD under three point bending conditions by the SS method. The model consists of 16 mm thick deck plate and U-rib of depth 280 mm. The results showed that the fatigue failure mode criteria remained unchanged by the fatigue load patch width along the U-rib width, deck thickness over U-rib, U-rib shape and penetration of weld. Xiao et al. [12] carried out FE analysis for fatigue evaluation of the rib-to-deck weld joints with 75% weld penetration in their OSD models. The OSD model composed of a deck plate thickness of 12 mm and a U-rib whose depth was 250 mm. Their results showed that the fatigue resistance of the rib-to-deck weld connections was greatly increased by thickening the deck plate whereas, any change in the U-rib thickness had no remarkable effect on the fatigue performance. It was also seen that increasing the load patch area and deck plate thickness reduce the stress range. Oh et al. [13] performed the analytical study taking the parameters as height, thickness and sheared area of cross-beam and the results were verified by experiments. The OSD model consisted of a U-rib whose depth of 242 mm, bottom width of 216.5 mm and thickness of 8 mm. The conclusions showed that the maximum principal stress reduced with the increase in the height, thickness and sheared area of the cross-beam. The thickness of the deck plate is not closely associated with the reduction in the maximum principal stress. Sim and Uang [14] performed experimental study on six full-scale OSD specimens to evaluate the fatigue performance of the rib-to-deck weld joints. The outcomes showed that the fatigue cracks at the rib-to-deck weld joint appeared to be more crucial at the deck plate as compared to the rib wall. They observed that with the increase in the deck plate thickness (from 14 to 16 mm), the stress reduced significantly (by about 30%) in the deck plate as well as in the rib wall. Moreover, a parametric study with 40, 60 and 80% weld penetration showed that a deeper weld penetration produces greater NS on both the weld toe and the root. Kainuma et al. [15] experimentally investigated the fatigue behavior of OSD specimens which was 2000 mm long and 1400 mm wide and had a U-rib with weld penetration of 75% and 100%. The results showed that the rib-to-deck weld joints had improved fatigue resistance when the weld penetration was below 75%. Ya et al. [16] have performed fatigue tests on a sample of 300 mm width cut-out from the full-length specimen of an OSD. They found that fatigue cracking predominantly started from the root rather than from the toe of the weld. However, root cracking was less common than the toe cracking in the full-scale model testing in which a 16 mm thick deck plate was used. Wang et al. [17] performed experimental and numerical studies based on local stress method on the fatigue assessment of double-sided full penetration weld with different deck plate thickness. The OSD model of length 300 mm and width 600 mm consisted of a U-rib of depth 280 mm. The conclusion showed that the stress decreased by about 30% when the deck plate thickness was increased by 14mm to 18 mm. They also found that the double-sided weld with thicker deck plate has better fatigue life. Fu et al. [18] performed the experimental study on 40 OSD specimens to evaluate the fatigue performance of rib-to-deck weld joints considering the effect of amplitude weld penetration, loading position and steel strength. The OSD specimen consists of deck plate 300 mm long, 600 mm wide and 14 mm thick. The thickness of the U-rib was 8 mm. The nominal stress amplitude and HSS amplitude of the welds were compared. The experimental results show that the crack propagation rate decreases as the weld penetration increases. A higher strength of steel improves the strength of fatigue crack initiation. A nominal stress of 70 MPa and a HSS of 75 MPa were recommended for fatigue strength of deck-rib weld joints of OSDs. Zhou et al. [19] proposed the fatigue reliability assessment model based on the SS method to improve the fatigue performance for welded structural joints. The outcomes showed that the weld toe was more prone to fatigue as compared to the weld root. An increase in deck plate thickness, however improved the reliability of both the toe-deck and the deck-root joints. Shi et al. [20] conducted the FE analysis of an OSD with U- and V-ribs for a cable styed railway bridge using HSS method. The height of U- and V-ribs were 280 mm and 306.7 mm, respectively. They concluded that the V-rib performs better than the U-rib for the most unfavorable fatigue details of the OSD railway bridges.

Reviewing the above literature, it is found that some researchers have examined the fatigue behavior of the deck-rib weld joints using the U-ribs of different sizes but they have not brought out the suitable size of the U-rib for the OSDs. Available literature related to the OSD bridges have neither clearly mentioned about the standard shape of the U- or V-ribs nor about the SS in the weld joints. Since the shape and size of the ribs greatly influence the steel consumption in manufacturing of an OSD bridge, therefore, it is necessary to perform a parametric study of an OSD bridge with different shapes and sizes of the ribs.

3.Methods

3.1Structural stress(SS) method

For a very long period, traditional evaluation techniques based on the nominal stress approach were used to estimate the fatigue life of the weldments. Since the stress intensity effect of the weldments was not taken into account, the prediction outcomes were typically conservative. Focusing on the extrapolation approach of the stress, another approach the HSS approach is found to be mesh-size susceptible [21–23]. In addition, the size of the notch is also employed to determine the NS in the toe-deck of the weld connection in the NS method [24, 25].

Dong [26, 27] introduced the SS method to get over the drawbacks of the conventional analytical techniques of the weld joint. This methodology is based on fracture mechanics and Paris Law. The method's accuracy for predicting fatigue performance was reportedly shown to be mesh-size insensitive. The SS method provided an accurate explanation of the crack emergence and spreading direction. Some researchers have provided documentation for the SS method [28–30]. The descriptions provide significant clue to analyze the fatigue behavior of welded joints. The stress at the weld toe along via thickness direction is categorized into the normal stress σ_x and shear stress τ_{xy}. With the forces and moments in equilibrium, the normal stress σ_x can be merely broken into membrane stress σ_m and bending stress σ_b. By condensing the in-plane stress of shear, the vertical shear stress τ_m emerged. Although knowing that it doesn't have an enormous effect on the emergence of cracks caused by fatigue, the shear effect is usually neglected. The membrane stress σ_m and the bending stress σ_b used to define the SS is given in Equations 1-3 [2,7]. The notations are explained in the *Figure 2(c)*

$$\sigma_m = \frac{1}{t}\sum_{i=1}^{n} F_i \qquad (1)$$

$$\sigma_b = \frac{6}{t^2}\sum_{i=1}^{n} F_i \times (y_i - t/2) \qquad (2)$$

$$\sigma_s = \sigma_m + \sigma_b \qquad (3)$$

The three-dimensional (3D) FE analysis was adopted. The solid model using Abaqus 2019 software is demonstrated in *Figure 2*. An eight-node linear brick solid element (C3D8R) available in the mesh module in Abaqus was employed in the model [31]. In order to calculate the line forces and line moments corresponding to the central plane of the deck plate, the nodal forces (NFORC) available in Abaqus history output from each element lying on both sides of the central line transverse to the failure plane are fed into the equation in matrix format [5,7]. Using Equations 1-3, the NFORC are utilized to calculate membrane stress σ_m, bending stress σ_b, and SS σ_s. The SS for each node across the weld path at the bottom of the deck, shown in dash line in *Figure 2 (b)*, are then calculated.

3.2Master S-N curve

A two-phase crack growth model is suggested on the basis of an equivalent SS factor determined using the mechanics of fracture theories. The model integrates multiple steel structure weld joint fatigue analysis data onto a small region, master S-N curve [32]. The master S-N curve estimates the fatigue properties of a variety of weld joints using a single curve. The master S-N curve addresses the influence of stress amplitude on the region of issue, the base metal depth, and numerous load types. For the easier application of diverse fatigue test data, the master S-N curves were displayed with varying possibilities. The S-N curves standard deviation σ is 0.246.

Keeping into consideration the impact of deck plate thickness t, the stress ratio r in Equation 4, the loading mode parameter $I(r)^{\frac{1}{m}}$ in Equation 5 and the SS range $\Delta\sigma_s$, can be used to derive the equivalent SS range ΔS_s from Equation 6 [2,7]. The parameter m for fatigue crack growth to be used in Equation 5 and 6 is considered as 3.6. The fatigue failure life of deck-to-rib weld joints of OSD can be calculated with Equation 7 [7] by concerning the master S-N curve parameters h and C_d given in *Table 1*.

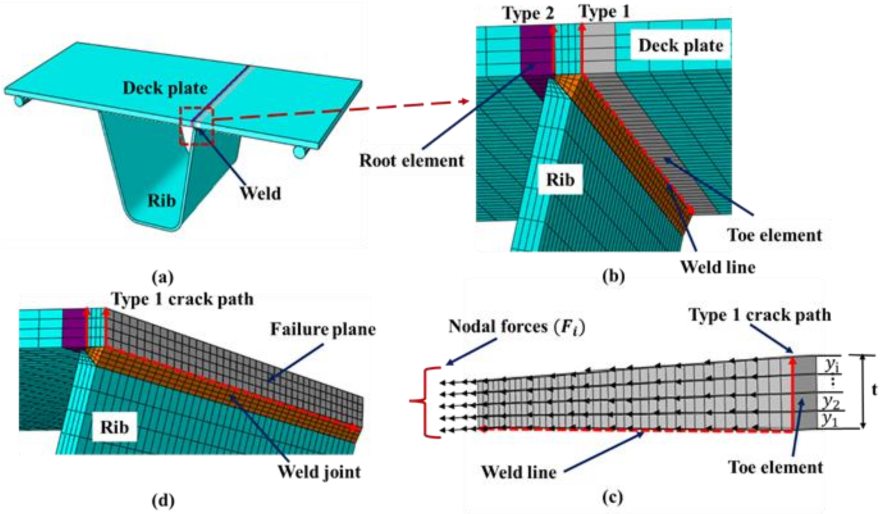


Figure 2 Depiction of 3D solid element model in SS calculation

Table 1 Master S-N curve parameter C_d and h

Statistical basis	**Mean**	$+2\sigma$ **(Upper 95%)**	-2σ **(Lower 95%)**	$+3\sigma$ **(Upper 99%)**	-3σ **(Lower 99%)**
C_d	19930.2	28626.5	13875.8	31796.1	12492.6
h	-0.32				

$$r = \frac{|\sigma_b|}{|\sigma_{m|}+|\sigma_b|} \tag{4}$$

$$I(r)^{\frac{1}{m}} = 0.0011r^6 + 0.0767r^5 - 0.0988r^4 + 0.0946r^3 + 0.0221r^2 + 0.014r + 1.2223 \tag{5}$$

$$\Delta S_s = \frac{\Delta\sigma_s}{t^{(2-m)/2m}.I(r)^{1/m}} \tag{6}$$

$$N = \left(\frac{\Delta S_s}{C_d}\right)^{1/h} \tag{7}$$

3.3 Validation of the method adopted

To assess fatigue behavior of an OSD under the influence of the various parameters an analysis is done which is based on the SS method. The SS is determined for fatigue behavior assessment of the deck and is compared with the results available in the literature [7]. For the validation purposes the loadings, geometry and boundary conditions of the OSDs are taken the same as available in the paper by Wang et al. [7]. Two load cases have been considered in the literature. Load case I is concentric and load case II is eccentric with respect to the center of the ribs. However, it has been found that the load case II is critical for the fatigue behavior study of OSDs. Therefore, Load case II is considered for the validation purpose. The OSD model is 400 mm long and 1000 mm wide. The steel deck plate is 16 mm thick. The rib height is 300 mm with thickness 8 mm. As illustrated in *Figure 3*, the model is loaded with a 20-kN load imposed eccentrically over the deck-rib joint on the deck surface in a patch area of 250 mm×250 mm. The mechanical properties of the steel plates used are given in *Table 2* [33].

The FE model is discretized using 8-noded C3D8R solid element of Abaqus. The SS calculation procedure has already been explained in Sections 3.1 and 3.2. The results of the SS acquired using the Abaqus and Fe-safe are plotted in *Figure 4*. For the purpose of the validation, the results obtained by Wang et al. [7] are also shown in the plot. The SS was acquired for the toe-deck as well as for the root. It is found that the SS obtained along the weld path of the OSD FE model is nearest to the results of Wang et al. [7] with a mere 3% difference which may be treated as admissible.

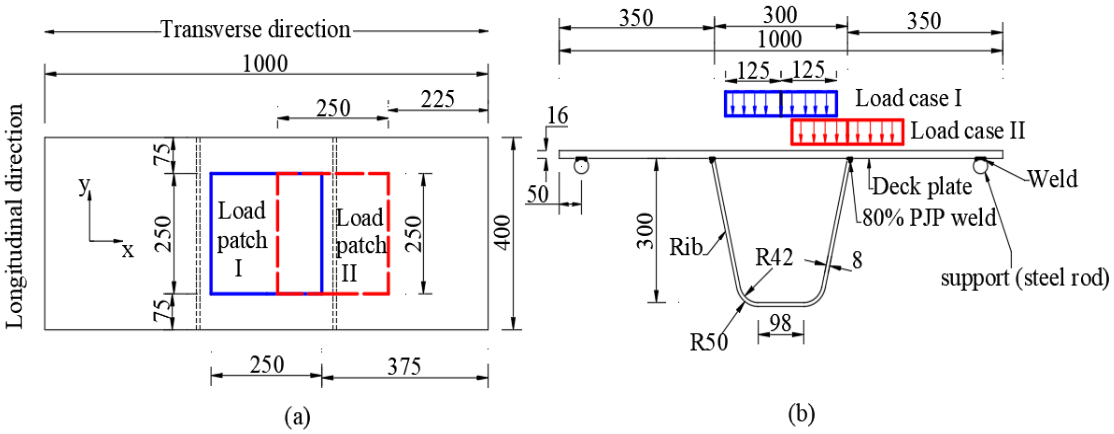


Figure 3 Dimensional details and loading condition of wang's models

Table 2 Mechanical properties of steel plate

Plate thickness (mm)	Yield stress S_y (MPa)	Ultimate tensile strength S_u (MPa)	Young's modulus E (GPa)
16	353	508	200
8	400	495	197

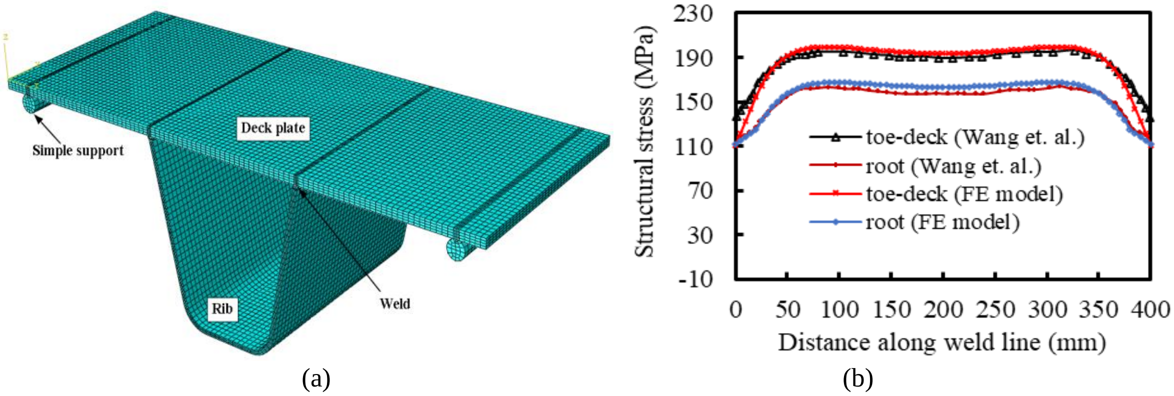
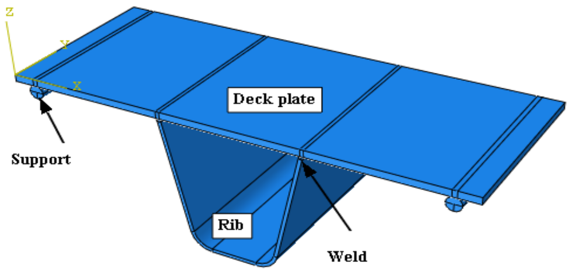


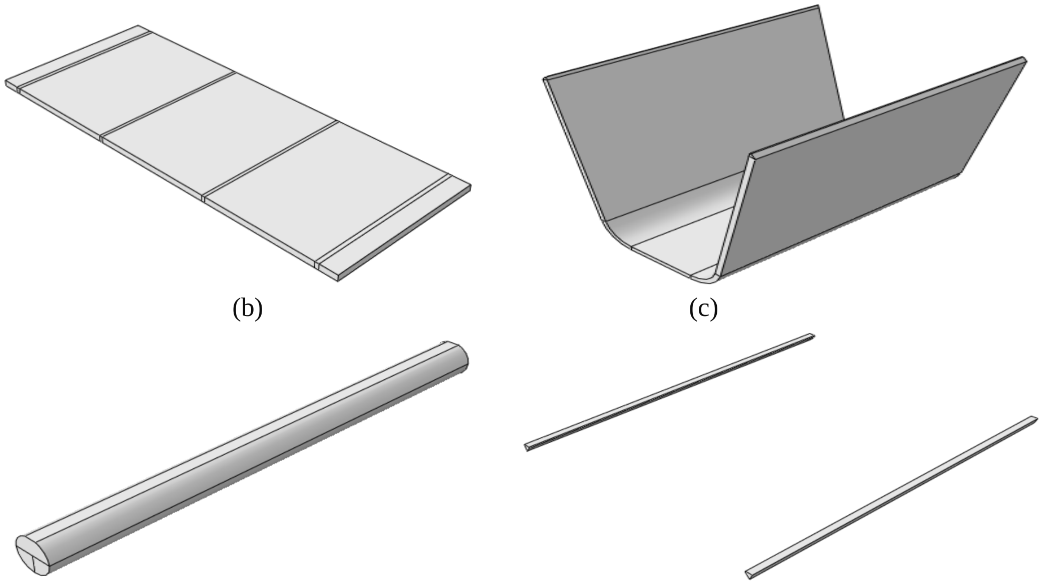
Figure 4 (a) Wang's model (b) SS along the weld line at the rib-deck joint

3.4 Numerical simulation of models

In this study to evaluate the fatigue performance of the deck-to-rib weld components using the SS method, the FE analysis software Abaqus and Fe-safe are used. For the fatigue life of this OSD, the deck-rib weld connection was the focus of the analysis [31, 34]. For the study total 30 models were considered. These models were: (i) five models of the OSD with U-ribs (RD-1 to RD-5) of different depths of 200 to 400 mm with a constant bottom width of 100 mm, (ii) four models of the OSD with U-ribs (RW-1 to RW-4) of different bottom widths of 100 to 260 mm with a constant depth of 300 mm, (iii) five models of the OSD with different deck plate thicknesses of 12 to 20 mm whose other parameters remained unchanged, (iv) six models of the OSD with U-ribs of different weld penetrations in the joint, (v) three models of the OSD with U-ribs of different load patch area on the deck surface, (vi) five models of OSD with V-ribs (VRD-1 to VRD-5) of different depths of 200 to 400 mm (vii) two models of OSD, first with a U-rib and another with a V-rib of the equal perimeter. All these models were analyzed for the following parameters- U-rib depth variation, bottom width variation, deck plate thickness variation, weld penetration, load patch area and V-rib depth variation. Comparison of U and V-ribs for the equal perimeter and equal depth were also done. All simulated models had four parts which were used in Abaqus. They were deck plate, rib, weld, and supports as shown in *Figure 5*.



(a) OSD model



(b) (c)

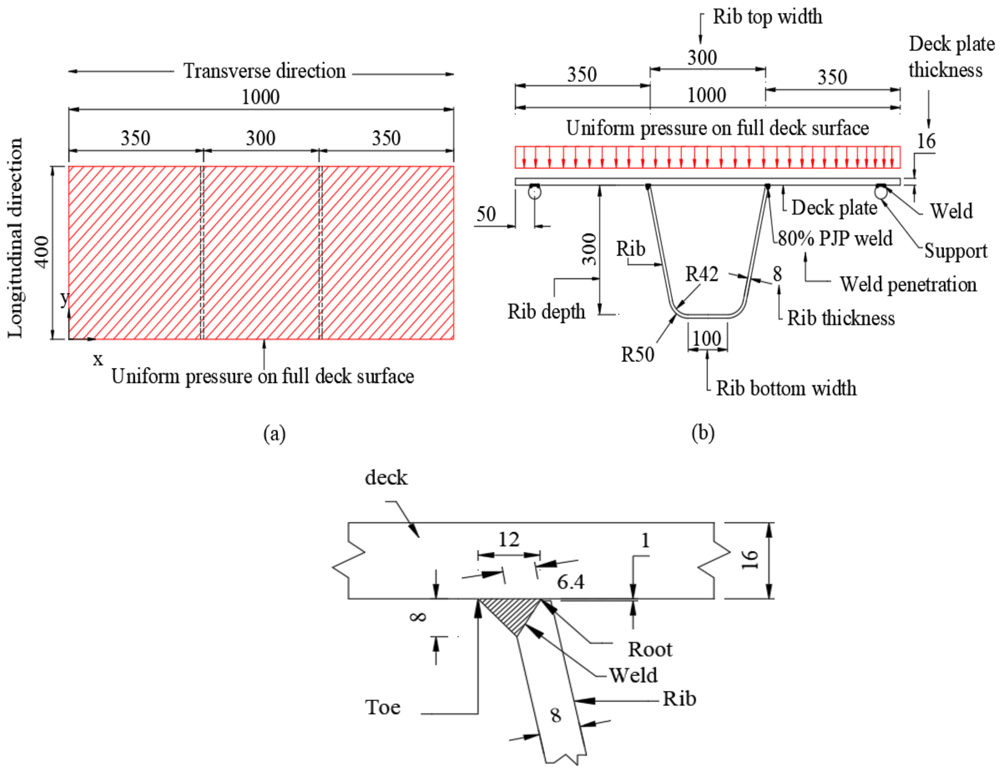
(d) (e)

Figure 5 (a) The entire OSD model and its four parts are: (b) deck plate (c) Rib (d) Support (e) Weld

All the four parts in each model were meshed by an eight-node linear brick element (C3D8R) available in Abaqus. The contact surfaces between the weld-to-deck, weld-to-rib, and deck-to-support were connected by tie constraints. Material properties of steel plate of grade E350 (yield stress 350 MPa) conforming to IS:2062 have been considered [35]. The elastic modulus and Poisson's ratio of the steel plate have been taken as 200 GPa and 0.3 respectively. The material properties of fillet weld conforming to E501T-1 (yield stress 495MPa) have been considered [36]. The weld is having a triangular shape with its throat thickness of 8 mm and is an 80% partial joint penetration (PJP) weld. The weld geometry and shape are chosen from the literature [37–39]. The constraints of the models have been taken against the movements in the horizontal (X) and vertical (Z) directions. The dimensional details and loading conditions for this analysis are shown in *Figure 6.*

3.5 Loadings

In this investigation, the axle loads due to the Indian freight locomotive (train type-5) of 22.5 tons are considered [40]. Axle load is applied to the rails as point loads which are then transferred to the sleepers and finally over to a certain area of the deck plate after dispersing through the ballast longitudinally and transversely. The angle of longitudinal and transverse dispersion of axle load below the sleeper is 1H:4V, as per the European Code EN 1991-2 [41, 42]. According to the Indian railways, the sleeper length is 2750 mm, the cross-section is 250 mm × 250 mm and the ballast layer depth is 400 mm. A uniform pressure of 0.17 N/mm^2 on the deck surface is considered in this analysis for all models which is obtained by dividing the axle load by the patch area as shown in *Figure 7.*



(a) (b)

(c) Details of welded joints

Figure 6 Dimensional details, loading condition of U-shaped rib and weld dimension

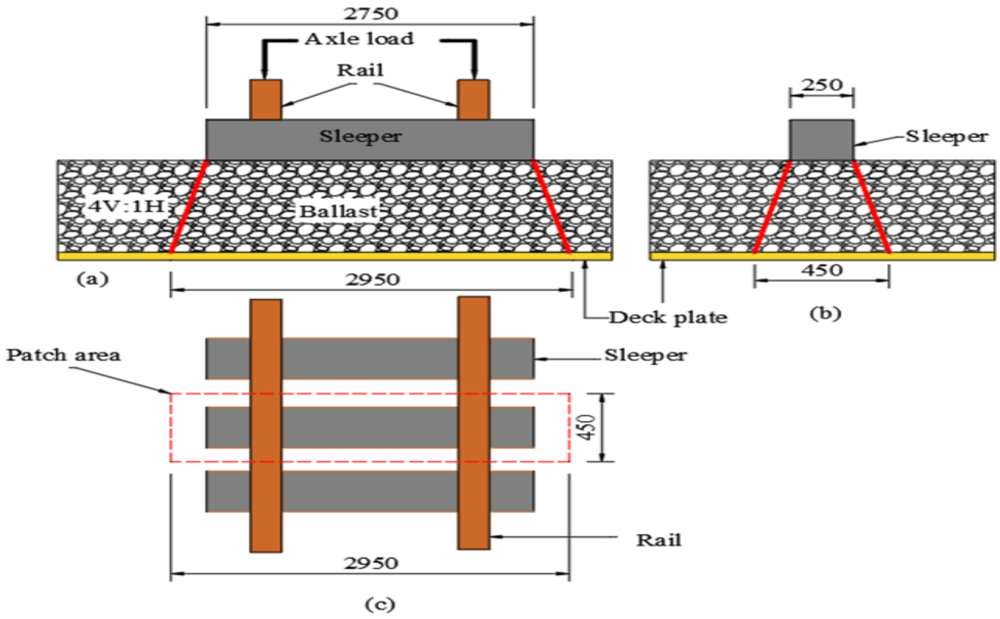
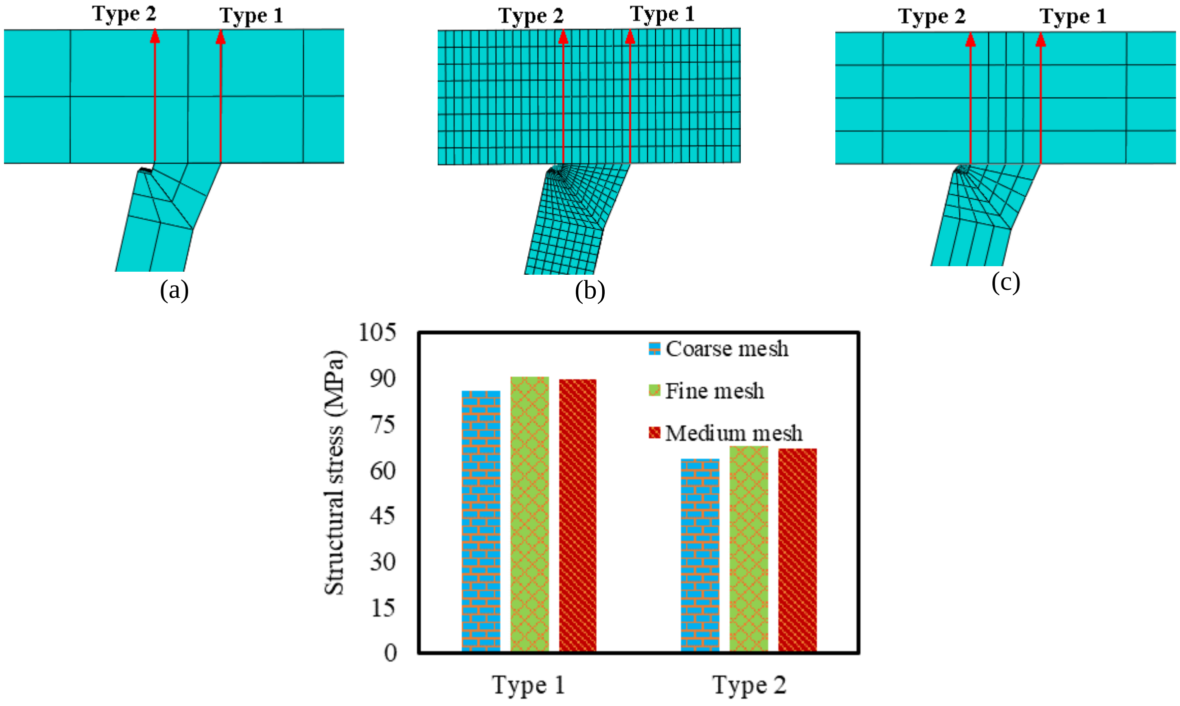


Figure 7 Load distribution through ballast (a) transverse section and (b) longitudinal section (c) top view

3.6 Mesh insensitivity

To demonstrate the mess insensitivity of the SS method, the geometrical details of the model is as shown in *Figure 6*. The FE analysis outcomes using the SS approach (described in section 3.1 and section 3.2) corresponding to a uniform pressure of 0.17 N/mm^2 on the full deck surface are outlined in *Figure 7*. For both Type 1 and Type 2 crack paths, three distinct mesh layouts- coarse, medium and fine were taken which are shown in *Figure 8*, for observing the mesh-insensitivity of the method used. In the coarse meshing layout, 4 mm mesh size was used in the vicinity of the weld whereas, 8 mm mesh size was used elsewhere in the model considered. In the medium meshing layout, 2 mm size was used in the vicinity of the weld whereas, 4 mm mesh size was used elsewhere in the model. In the fine meshing layout, 1 mm mesh size was used in the vicinity of the weld whereas, 2 mm mesh size was used elsewhere in the model considered. Medium mesh layout has been adopted in this analysis because the medium and fine mesh layout gave almost same stresses as shown in *Figure 8*. In other words, the SS shows negligible change by changing the mesh size from medium to fine. Therefore, the SS method is called 'mess-insensitive'. The SS method is mesh-size insensitive; this aspect is also mentioned in [2, 7, 26, 28, 30]. This is a significant advantage of SS method to get good results with very less computational effort even with the mesh size which is neither coarse nor very fine. Therefore, for the SS method, a medium-mesh size is suitable to be on the safer side in the FE analysis.



(a) (b) (c)

(d)

Figure 8 Demonstration of mesh-insensitiveness to SS corresponding to three distinct FE mesh layouts (a) Coarse mesh (b) fine mesh and (c) Medium mesh

4. Results

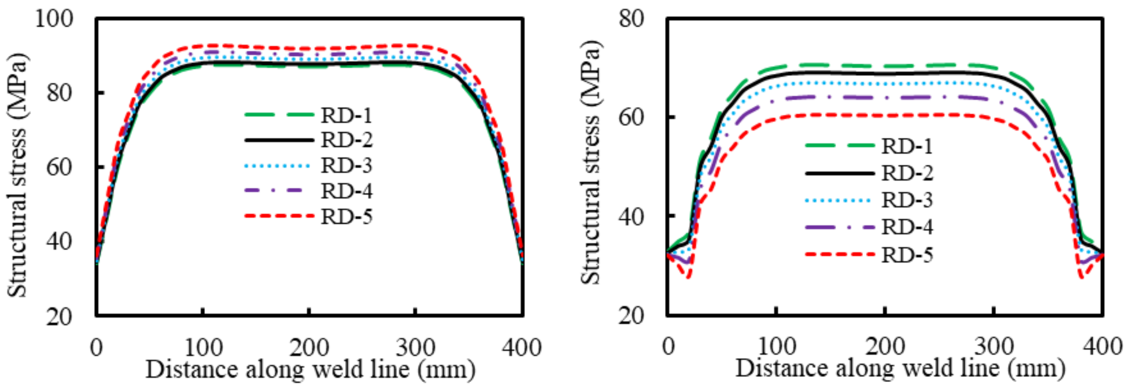
4.1 Effect of U-rib depth variation

To investigate the fatigue behavior of the weld joint of the deck to U-rib connection due to the varying depth of the U-rib, five models of OSDs with U-rib of different depths (RD-1 to RD-5) have been considered as shown in *Table 3*. The top and bottom widths of the U-ribs were fixed 300 mm and 100 mm respectively, the models were simulated for analysis. The weld geometry, material properties, and boundary conditions were kept same as described in section 3.4. A uniform pressure of 0.17 N/mm^2 was applied on the deck surface as described in Section 3.5. The methodology utilized for calculation of SS (σ_s), equivalent SS (ΔS_s) and fatigue life (N) have already been explained in Section 3.1 and 3.2 using Equation 1-7. The values are shown in *Table 3*.

Table 3 Structural stress, equivalent SS, and fatigue life of the OSD with U-ribs of different rib depths

U-rib model	**Depth (mm)**	**Structural stress σ_s (MPa)**		**Equivalent SS ΔS_s(MPa)**	**Fatigue life N (No. of cycles)**
		toe-deck	**root**		
RD-1	400	87.48	70.66	107.553	12222290
RD-2	350	88.37	68.97	108.918	11749947
RD-3	300	89.48	66.87	110.598	11201276
RD-4	250	90.88	64.16	112.731	10551990
RD-5	200	92.70	60.58	115.485	9785524

Figure 9 depicts the variation in SS along the weld length in the toe-deck and root weld joint. These stresses develop along the weld line between the weld toe and the bottom face of the deck plate i.e., toe-deck weld joint, and also between the weld root and bottom face of the deck plate i.e., root weld joint. It is seen that there are two peak locations of the SS for all five models, consistently at 120 mm inside from the deck edges in the toe-deck joint and 130 mm inside from the deck edges in the root joint respectively. These locations may be the common fatigue crack initiation position in the toe-deck joint and root joint respectively. From the *Table 3* as well as from *Figure 9*, it has been seen that the SS in the toe-deck joint increases with the decrease in the depth of the rib, whereas in the root joint SS increases with the increase in the depth of the rib. However, the toe-deck joint has the higher SS as compared to the root joint. Therefore, the toe-deck joint is the most critical position for fatigue, and based on SS in toe-deck joint, a parametric study has been done in this research work.



(a) (b)

Figure 9 SS variation in (a) toe-deck and (b) root joint along weld line for different U-rib depths in OSDs

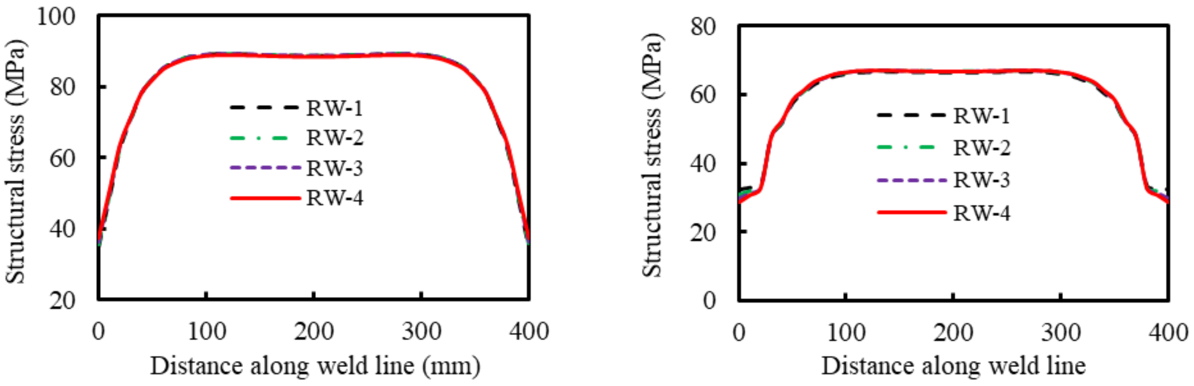
4.2 Effect of U-rib bottom width variation

To evaluate the performance of the U-rib connection due to variation in the bottom width of the rib keeping the rib depth 300 mm constant, four U-ribs (RW-1 to RW-4) were considered. 3D FE solid models of each U-rib with different bottom widths were analyzed keeping the numerical simulation method, the material properties, boundary conditions, and loadings same as mentioned in Sections 3.4 and 3.5. The SS, equivalent SS, and fatigue life analysis procedure for all four OSD models have already been described in section 3.1 and in section 3.2. *Table 4* shows peak SS, equivalent SS, and fatigue life of the toe-deck and root of the weld connection corresponding to different U-rib bottom widths of the OSD models. *Table 4* shows that when the bottom width of the U-rib increases, the SS in the toe-deck weld joint of the OSD decreases. The SS variation along the weld line for the models is plotted in *Figure 10.*

Table 4 SS, equivalent SS, and fatigue life for the OSD with U-ribs of different bottom widths

U-rib model	**Bottom width (mm)**	**Structural stress σ_s (MPa)**		**Equivalent SS, ΔS_s(MPa)**	**Fatigue life N (No. of cycles)**
		toe-deck	**root**		
RW-1	100	89.48	66.87	110.598	11201276
RW-2	125	89.36	66.98	110.409	11261138

U-rib model	**Bottom width (mm)**	**Structural stress σ_s (MPa)**		**Equivalent SS, ΔS_s(MPa)**	**Fatigue life N (No. of cycles)**
		toe-deck	**root**		
RW-3	150	89.24	67.09	110.224	11320240
RW-4	175	89.12	67.21	110.027	11383991

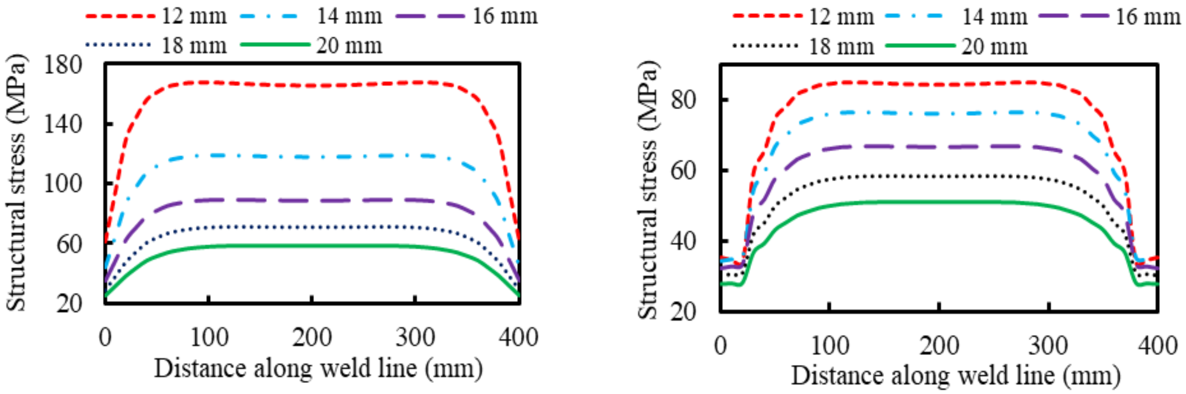


(a) (b)

Figure 10 SS variation in (a) toe-deck and (b) root joint along weld line for different bottom widths of U-rib in OSDs

4.3 Impact of deck plate thickness

The influence of the thickness of the deck plate on the SS of the deck to rib welded joint was investigated using different thickness of the deck plate. The plate thickness chosen were 12 mm, 14 mm, 16 mm, 18 mm, and 20 mm, keeping other parameters constant. The dimensional details of the OSD model considered for analysis are shown in *Figure 6*. The weld geometry, material properties, and boundary condition were kept the same as described in section 3.4. A uniform pressure of 0.17 N/mm^2 was applied on the deck surface as described in Section 3.5. The effects of the thickness of the deck plate on the SS at the toe-deck and root weld joint of the OSD are shown in *Figure 11*.



(a) (b)

Figure 11 SS variation in (a) toe-deck and (b) root of the weld joint along weld line corresponding to deck plate thickness

4.4 Weld penetration impact

The influence of the penetration of the Weld on the fatigue behavior of the deck-to-rib weld connection was evaluated via the SS calculation in the weld joint under the loading condition of uniform pressure of 0.17 N/ mm^2 on the deck surface. The dimensional details of the OSD model considered for analysis are shown in *Figure 6*. The weld penetrations used to determine the SS in the deck to rib weld joint was 0%, 20%, 40%, 60%, 80%, and 100%, keeping the other parameters unchanged. *Figure 12* and *Table 5* shows the maximum SS and fatigue life respectively, along the weld line in the toe-deck and root.

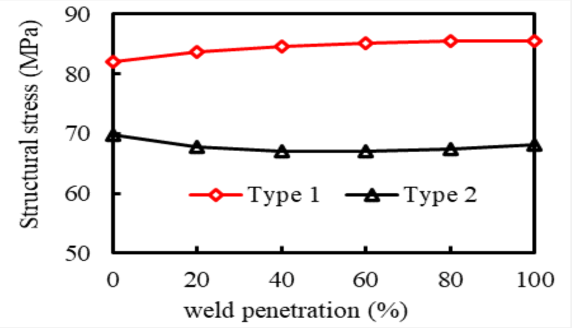


Figure 12 SS corresponding to percent weld penetration

4.5 Load patch size effect

The effect of the load patch on the fatigue performances of the deck-rib weld joint was evaluated via the SS calculation in the joint under uniform pressure of 0.17 N/ mm^2 of each load patch on the deck surface. Model geometry details are the same as shown in *Figure 6* and the SS calculation procedure is already discussed in section 3.1 and section 3.2. Keeping the other parameter same, the three load patches of size 250×250, 250×500, and 400×1000 mm^2 were taken for study of the SS behavior in the weld joint. *Table 6* shows the SS of different load patches and percent difference in the SS in the toe-deck and root of the weld joint.

Table 5 Fatigue life corresponding weld penetration

Weld penetration (%)	0	20	40	60	80	100
Fatigue life (Cycles)	15564847	14416076	13803366	13461725	13252601	13168009

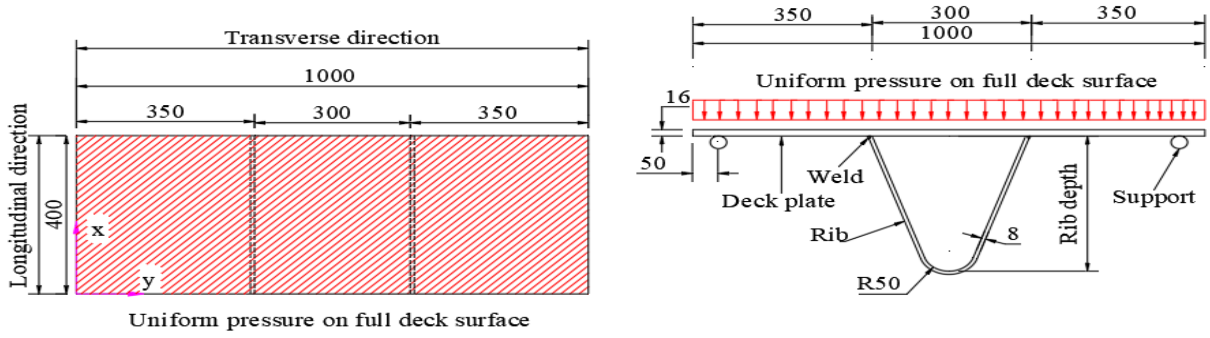
Table 6 Percentage of SS increment corresponding to load patch size

Patch size (mm^2)	**Structural stress σ_s (MPa)**		**SS difference (%)**	**Equivalent SS ΔS_s(MPa)**	**Fatigue life N (No. of cycles)**
	toe-deck	**root**			
250×250	47.41	39.93	15.8	63.46	63548918
250×500	64.86	52.29	19.38	85.46	25069199
400×1000	89.13	66.55	25.33	110.06	11371285

4.6 Effect of V-rib depth variation

To investigate the fatigue behavior of the weld joint of the deck to rib connection due to the varying depth of the V-rib, five models of OSDs with V-rib of different depths (VRD-1 to VRD-5) have been considered as shown in *Table 7*. The top width of the V-ribs was fixed to 300 mm. The dimensional details and loading conditions in this analysis are shown in *Figure 13*. The weld geometry, material properties, and boundary condition were kept same as described in section 3.4. A uniform pressure of 0.17 N/mm^2 was applied on the deck surface as described in Section 3.5. The methodology utilized for calculation of the SS (σ_s), equivalent SS (ΔS_s) and fatigue life (N) have already been explained in Sections 3.1 and 3.2. The values are shown in *Table 7*.

Figure 14 depicts the variation in the SS along the weld length in the toe-deck and root weld joint. It is seen that there are two peak locations of the SS for all five models, consistently at 120 mm inside from the deck edge in the toe-deck joint and 150 mm inside from the deck edge in the root joint respectively. These locations may be the common fatigue crack initiation position in the toe-deck and root joints respectively. From *Table 7* as well as from *Figure 14*, it has been seen that the SS in the toe-deck joint increases with the decrease in the depth of the V-rib, whereas in the root joint the SS increases with the increase in the depth of the rib. However, the toe-deck joint has the higher SS as compared to the stress at the root joint. Therefore, the toe-deck joint is the most critical position for fatigue.

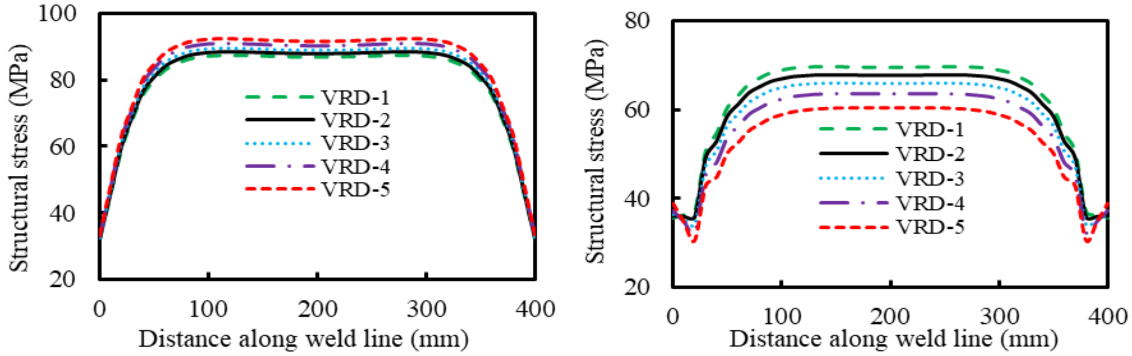


(a) (b)

Figure 13 Dimensional details and loading condition of V-shaped rib (a) plan view and (b) cross-sectional view

Table 7 SS, equivalent SS, and fatigue life of the OSD with V-ribs of different rib depths

V-rib model	**Depth (mm)**	**Structural stress σ_s (MPa)**		**Equivalent SS, ΔS_s (MPa)**	**Fatigue life N (No. of cycles)**
		toe-deck	**root**		
VRD-1	400	87.46	69.56	107.557	12220863
VRD-2	350	88.38	67.91	108.947	11740330
VRD-3	300	89.47	65.93	110.612	11196646
VRD-4	250	90.81	63.44	112.658	10573506
VRD-5	200	92.50	60.29	115.222	9855388



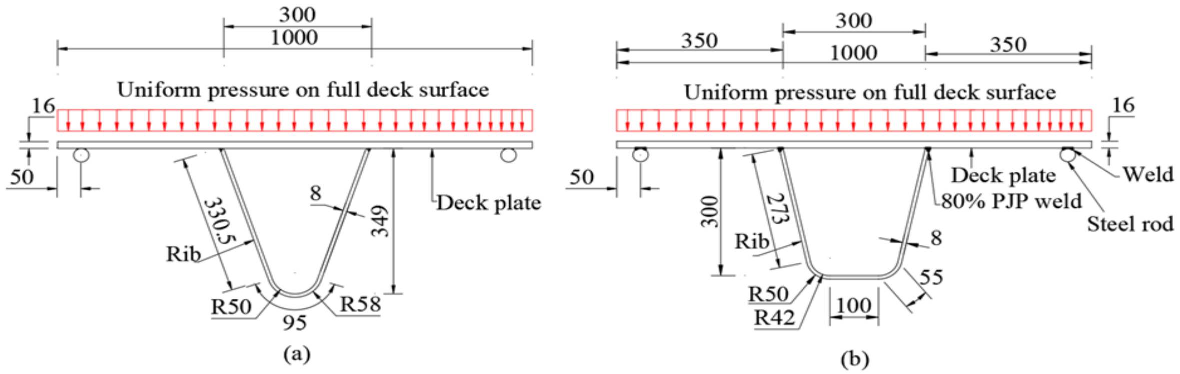
(a) (b)

Figure 14 SS variation in (a) toe-deck and (b) root joint along weld line for different V-rib depths in OSDs

4.7 Performances of V- and U-shaped ribs of equal perimeter

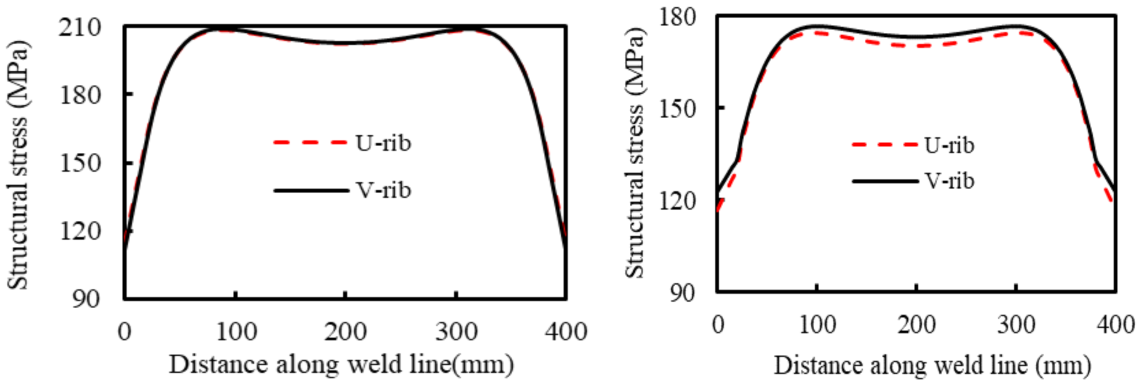
To compare the performance of the U- and V-ribs, two models of the OSD one consisting of the U-rib and another consisting of the V-rib having equal perimeter were considered. The U- and V-ribs are considered to have an equal perimeter of 756 mm as shown in *Figure 15*. The SS analysis procedure for both the OSD models as described in Sections 3.1 and 3.2 was carried out. The weld geometry, material properties, and boundary condition were kept as the same as described in Section 3.4. A uniform pressure of 0.17 N/mm^2 described in Section 3.5 is applied on the deck surface of both the OSD models.

FE analysis results plotted in *Figure 16* show that the OSD models consisting of V-rib and U-rib have approximately equal SS of 208.81 MPa and 208.19 MPa, respectively in the toe-deck joint. Whereas, in the root joint the SS in the V-rib and U-rib are 176.45 and 174.56 MPa respectively. The findings conclude that the OSD with a V-shaped rib performs equally good as compared to a U-shaped rib for the equal perimeter or equal quantity of steel.



(a) (b)

Figure 15 Dimensional details of the equal perimeter of (a) V-rib and (b) U-rib



(a) (b)

Figure 16 SS variation in (a) toe-deck and (b) root joint along weld line for U-and V-shaped rib

5. Discussion

From *Figure 9*, the plotted results indicate that the SS decreases by 5.63 % when the depth of the rib doubles. In other words, very little change in the SS occurs when the depth of the rib decreases. This shows a little gain. Therefore, the depth of the rib should be kept as minimum as possible. An increase in the rib depth results in more steel requirement causing more dead weight and handling difficulty and a lesser depth of the rib requires less steel quantity but there may be difficulties in the molding of the ribs. For better performance of the OSDs, the depth of the rib should be such that stress concentration in the joint is less with lower steel consumption. Therefore, the height of the U-rib between 250 mm to 300 mm should be a better option considering the ease in fabrication, molding of ribs and also for sufficient margin against stress fluctuation in the OSD bridge designers. From *Figure 10*, the plotted results shows that when the bottom width of the rib changes from 100 mm to 175 mm (i.e.,75% increment), the peak SS variation is negligible (only 0.4%). The peak SSs of all four OSD models (RW-1 to RW-4) are found along the weld lines consistently at 120 mm inside from the deck edges in the toe-deck joint and 130 mm inside from the deck edge in the root joint. Similarly, variation in the equivalent SS and fatigue life are also negligible. Therefore, the designers should choose the minimum bottom width possible to save steel quantity. FE analysis results indicate that the bottom width of the U-rib in the range of 100 mm to 125 mm may be sufficient for the OSD bridges.

From *Figure 11*, it is noticeable that as the deck plate thickness increases, the SS in the deck to rib weld joint decreases. Similarly, the equivalent SS decreases, and the fatigue life increases. From *Figure 12*, it is shown that the SS responsible for the deck-toe and the root failure mode undergoes a negligibly change as the weld penetration increases. The result is consistent with the results available in the literature [7, 15].

From *Table 6*, as the load patch size increases with co2nstant pressure intensity, the load on the deck surface increases along with the SS and the equivalent SS increases in the weld joint but it is worth noticing that the percentage difference of SS between the toe-deck and root in the weld joint increases.

From *Figure 14*, the plotted results indicate that the SS decreases by 5.44 % when the depth of the V-rib doubles and follows the same behavior as of the U-rib. For better performance of OSDs, the depth of the rib should be such that stress concentration in the joint is less with lower steel consumption. Therefore, the height of the V-rib between 250 mm to 300 mm should be a better option considering the ease in fabrication, molding of ribs and for sufficient margin against stress fluctuation for the OSD bridge. Form *Figure 17*, it is seen that the SS in the U and V-ribs are almost same for a given depth in the toe-deck weld joint. However, the V-rib has slightly less SS as compared to the U-rib in the root joint. On the basis of FE analysis results given in the *Table 3* and *Table 7* for U- and V-rib models, results for depth variation have already been described in Sections 4.1 and 4.6, respectively. From *Table 8* it is noticeable that for the equal depth of the U- and V-ribs, the perimeter of V-rib is 11.4 % lower as compared to the U-rib. It means that the V-rib consumes less steel in comparison to U-rib at the same stress level. However, it could be seen from the analysis results in Section 4.7 that the U-rib performs equally good as compared to V-rib for the same quantity of steel. In summary, the performance of V-rib is much better as compared to the U-rib in respect of equal depth but performance of both the ribs are equally good in respect of equal perimeter.

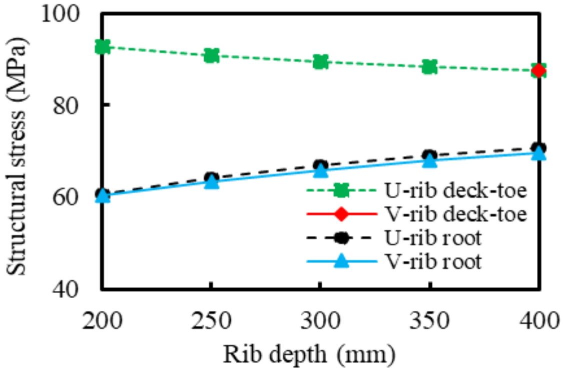


Figure 17 SS variation in toe-deck and root of the weld joint of U- and V-rib

Table 8 Comparison of stresses and perimeter at equal depth of U- and V-rib

Depth (mm) U/V-rib	Perimeter (mm)		Structural stress σ_s (MPa)			
	U-rib	V-rib	U-rib toe-deck joint	V-rib toe-deck joint	U-rib root joint	V-rib root joint
400	947.91	850.86	87.48	87.46	70.66	69.56
350	849.68	758.59	88.37	88.38	68.97	67.91
300	752.49	669.03	89.48	89.47	66.87	65.93
250	655.75	581.64	90.88	90.81	64.16	63.44
200	561.80	497.62	92.70	92.50	60.58	60.29

Limitations: This study was limited to conducting numerical simulations of a part of an OSD bridge under train loads. Although the critical stress location and stress distribution pattern along the weld line in the full-span OSD bridge may be the same, the magnitude of the stress is expected to vary. The parameters considered in this study were limited to the shape of the ribs (U/V-ribs), depth of ribs, bottom width of U-ribs, deck plate thickness, weld penetration, and load patch area. A complete list of abbreviations is shown in *Appendix I.*

6. Conclusion and future work

In this study, a detailed FE analysis was conducted on the deck-to-rib weld joints in an OSD subjected to a uniform pressure load on the full deck surface. The goal was to determine an efficient stiffener in the form of the U or V-rib. The results were validated by comparing them with those reported in the literature. The study evaluated the relative performance of U- and V-ribs, considering the shape and size of the rib in OSD construction, based on SS, equivalent SS, and fatigue life. Additionally, the steel quantity performance of U- and V-ribs was also assessed. The SS method proved to be not only relevant in calculating accurate stress in the weld joint but also mesh-insensitive in FE computation. Potential crack locations in the weld joints were also identified. Based on the study results, the following conclusions were drawn:

- The variation in the depths of the U- and V-ribs significantly affects the SS in the welds of the rib-to-deck joints. Conversely, variations in the bottom width of the U-rib have a negligible effect on the SS along the weld line. To achieve better performance in OSDs, it is recommended to maintain depths of U- and V-ribs within the range of 250 mm to 300 mm and a bottom width of the U-rib between 100 mm to 125 mm. Excessive depth and bottom width can lead to an uneconomical design.

- An OSD with a V-shaped rib performs as well as a U-shaped rib for equal perimeter. However, when comparing the performances of U- and V-ribs based on equal depth, the V-rib demonstrates better performance. Therefore, the V-shaped rib is preferable over the U-shaped rib, as it consumes less steel due to a smaller perimeter in the equal depth scenario.
- Increasing the thickness of the bridge deck plate leads to a decrease in SS in the deck-to-rib weld joint, resulting in lower equivalent SS and increased fatigue life.
- The SS responsible for toe-deck and root failure modes appears to undergo negligible changes as the weld penetration increases.
- Increasing the load patch size while maintaining constant pressure leads to a higher percentage difference of SS between the toe-deck and root in the weld joint. Additionally, it was observed that the maximum stress location shifts towards the center of the weld length when the patch area extends to the entire surface of the deck.

Experimental research could be conducted to study the fatigue behavior of the deck-to-rib joint in an OSD. This may involve conducting laboratory tests on all the simulated models used in these investigations. For future studies, additional parameters such as residual stress and double-sided welds could be considered. The literature survey indicates that, to date, no OSD bridge with V-ribs has been constructed in real practice. Consequently, further numerical and experimental investigations are required to understand the fatigue performance of V-ribs thoroughly. More research is needed to assess the viability and effectiveness of V-ribs in practical applications.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Radha Krishna Amritraj: conceptualization, validation, writing-original draft, analysis and interpretation of results. **Shambhu Sharan Mishra:** Supervision, conceptualization, writing-review and editing.

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Appendix I

S. No.	Abbreviation	Description
1	σ_b	Bending Structural Stress
2	m	Crack Growth Parameter
3	ΔS_s	Equivalent Structural Stress
4	FE	Finite Element
5	HSS	Hot-Spot Stress
6	I(r)	Loading Mode Parameter
7	σ_m	Membrane Structural Stress
8	N	Fatigue Life in Cycles
9	NFORC	Nodal Forces
10	NS	Notch Stress
11	σ_x	Normal Structural Stress
12	OSD	Orthotropic Steel Deck
13	PJP	Partial Joint Penetration
14	C_d, h	S-N Curve Parameter
15	σ	Standard Deviation
16	τ_{xy}	Shear Stress in Plane
17	σ_s	Structural Stress
18	r	Stress Ratio
19	SS	Structural Stress
20	S-N	Stress Versus N
21	3D	Three Dimensional
22	t	Thickness of Deck Plate
23	τ_m	Vertical Shear Stress