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Numerical simulation of rib distortion in orthotropic steel decks

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Abstract. When adopting the trapezoidal section of ribs in orthotropic steel decks, the torsional rigidity of ribs losses radically because of rib distortion especially when the load is eccentric from the axis of the rib. Hence, the rib distortion causes high stress concentrations at the rib-to-crossbeam joint which makes this joint easily prone to fatigue. In this paper, the influence of 4 conventional design parameters on distortional behaviour is investigated by numerical simulation adopting the hot spot stress approach and the sub-model analysis technique. A refined finite element model of an orthotropic steel deck specimen with the dimension of 8.2 m × 4.1 m is built. Research results indicate that the distortional stress rises with the increment of the spacing of crossbeam or the weld length of rib-to-crossbeam joint. The thickness of rib is negatively correlated with the distortional stress. The influence of the spacing of rib on distortional stress depends on the relative size between the width of load area and the spacing of rib. The most unfavourable load position is determined by rib geometries, i.e. the thickness of ribs, whereas rest three parameters do not have obvious influence.

1. Introduction

The orthotropic steel deck is widely adopted in long-span bridges around the world since it has many merits e.g. high load carrying capacity, light weight, rapid construction, etc. However, stress concentrations caused by complex structure and the existence of numerous welds have impeded the further usage of orthotropic steel deck. According to previous research, there are four positions in total where fatigue cracks typically appear: rib-to-deck joint, splice joint of the longitudinal rib, deck plate at the position of crossbeam and rib-to-crossbeam joint [1]. Even though relevant research of these fatigue-prone details had been reported, the stress concentration at the rib-to-crossbeam joint caused by rib distortion was more or less ignored in previous research.

In orthotropic steel decks, one of the broadly adopted rib geometries is the trapezoidal section. Nevertheless, the torsional rigidity of rib is essentially reduced by distortion because of the existence of cut-outs in crossbeams, especially when the load is eccentric from the axis of the rib [2]. High stress concentrations are caused by the rib distortion at the rib-to-crossbeam joint. Moreover, the eccentric load that causes tension stress on one stem of the rib always causes compression stress on the other stem of the rib in the meantime. Thus, the rib-to-crossbeam joint carries positive and negative stress alternately when vehicles passing by, which makes the joint more vulnerable to fatigue damage. Unfortunately, no explicit recommendations on relevant parameters with respect to the influence of rib distortion are given in current major design codes.



This paper presents the influence of a number of classical design parameters on the distortional behavior. Firstly, the finite element model of an orthotropic steel deck specimen ($8.2 \text{ m} \times 4.1 \text{ m}$) was developed. The sub-model including the investigated rib-to-crossbeam joint was also built to achieve a more accurate assessment. Then, the influence of the considered parameters was calculated and analyzed by getting influence lines of different parameters, which will provide the foundation for relevant experiments of the orthotropic steel deck specimen in the nearest future.

2. Numerical simulation of rib distortion

2.1. Finite element model

In order to investigate the influence of classical design parameters on the distortional behavior, parametric analyses were performed by ANSYS. The standard orthotropic steel deck is composed of 6 ribs, 3 crossbeams and 2 main girders. The dimensions of the longitudinal ribs are 300 mm high, 300 mm wide at the top and 125 mm wide at the lower soffit. Relevant geometries are shown in Figure 1.

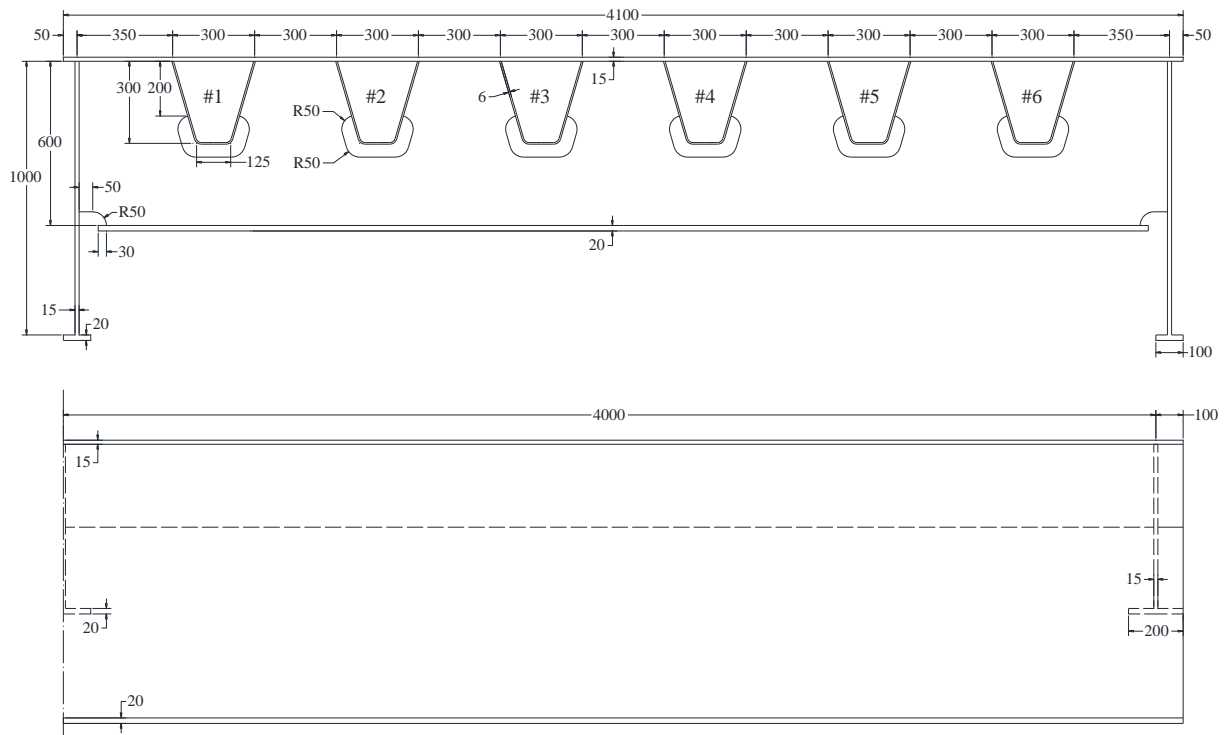


Figure 1. Geometries of the standard orthotropic steel deck (unit: mm)

Based on the geometries of the standard orthotropic steel deck, a global model was first built using shell element with relatively coarse mesh. Then, a sub-model was developed using solid element with the reference of the global model, which took the influence of welds into account. The sub-model was composed of segmental deck, crossbeam, rib and relevant welds as shown in Figure 2(b). The position of the sub-model was at the intersection of the third rib (see Figure 1) and the middle crossbeam, as shown in Figure 2(a). The cross section of weld in the sub-model was modelled as a triangular. The weld throat thickness of 4 mm was adopted.

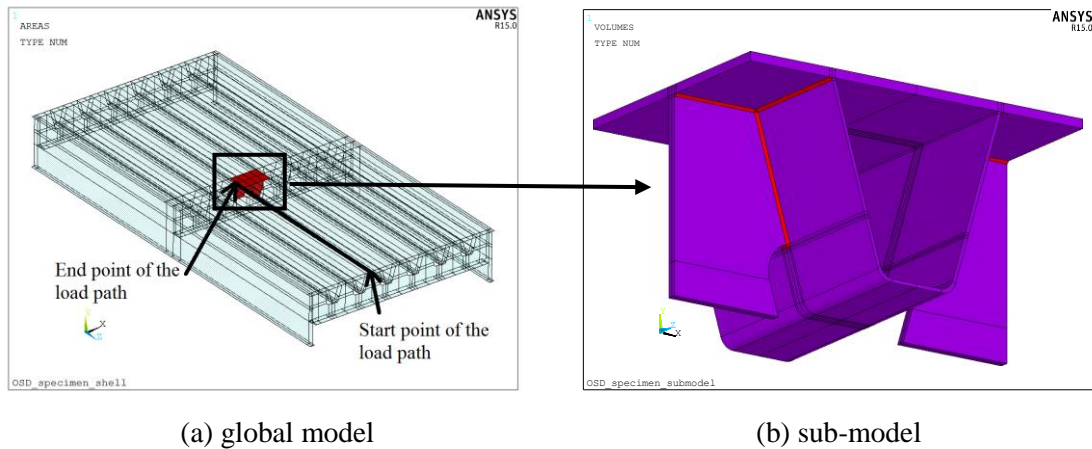


Figure 2. Finite element models: (a) global model; (b) sub-model

The numerical simulation is based on linear elastic properties of the material. The modulus of elasticity is 210 GPa for steel and the Poisson's ratio in the elastic stage is 0.3. The structural hot spot stress approach is more appropriate for this joint according to previous research [3]. Meanwhile, the liner extrapolation method is also adopted. Based on the IIW recommendations [4], two reference points are at a distance of 0.4 times and 1.0 times the thickness of the rib separately. The mesh size of the elements at the investigated area is 0.1 times the thickness of the rib in order to fit the IIW recommendations. Figure 3 displays locations of two reference points and relevant mesh nearby.

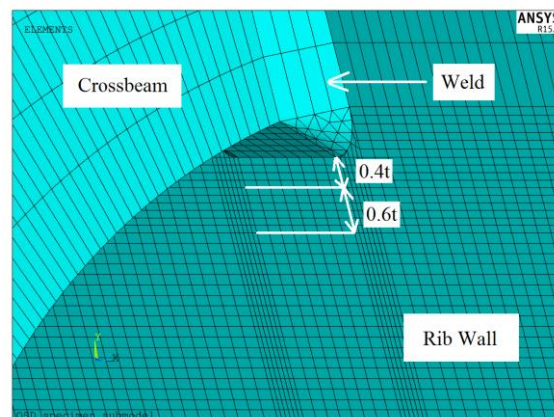


Figure 3. Reference points and mesh

2.2. Boundary conditions and load case

The boundary conditions of the global model are based on the real support conditions of the orthotropic steel deck specimen. Six bearings are situated at both ends and at the middle of two main girders separately. The contact area of a bearing is 80 mm × 80 mm. The boundary condition of the sub-model comes from the calculation result of the corresponding global model. Displacements and rotations of nodes along the cutting boundary between two models are placed on the sub-model as external loads.

In order to achieve the most unfavourable load position of distortional stress and to analyse the influence of different parameters, a movable unit load is considered to get the influence lines of distortional stress. The unit pressure of 1 MPa is adopted with the load area of 100 mm wide and 100 mm long and a load of 10kN. The load path is at the central line between rib 2 and rib 3 as shown in Figure 2(a). The interval distance between two loading points is 200 mm.

2.3. Results and discussion

In total 4 classical design parameters are considered, namely the thickness of rib, the transversal spacing of rib, the weld length of rib-to-crossbeam joint and the longitudinal spacing of crossbeam. Specially, the thickness of rib is determined by the stiffness of rib, which is normally selected in accordance with the traffic category, etc. The second moment of area of ribs acts as the constant reference when adjusting the thickness of rib. Relevant models with various parameters are shown in Table 1. The hot spot stress of following figures is the average of hot spot stress calculated from the two reference lines which are shown in Figure 3.

Table 1. Parameters of geometries

Model number	Height of rib (mm)	Upper width of rib (mm)	Bottom width of rib (mm)	Thickness of rib (mm)	Spacing of rib (mm)	Spacing of crossbeam (mm)	Weld length of rib-to-crossbeam joint (mm)
0(standard)	300	300	125	6	300	4000	200
1	275	-	-	8	-	-	-
2	255	-	-	10	-	-	-
3	-	-	-	-	200	-	-
4	-	-	-	-	375	-	-
5	-	-	-	-	-	2500	-
6	-	-	-	-	-	5000	-
7	-	-	-	-	-	-	150
8	-	-	-	-	-	-	240

2.3.1. Rib thickness

Figure 4 shows the influence lines of different rib thicknesses. Generally, the distortional stress decreases as the rib thickness increases. On the tension side, the maximum distortional stress decreases from 10.27 MPa to 5.27 MPa when the rib thickness increases from 6 mm to 10 mm. On the compression side, the maximum distortional stress decreases from 7.94 MPa to 4.19 MPa as the rib thickness increases. Figure 4 also presents that the most unfavorable load position moves toward the middle crossbeam for about 400 mm when the rib thickness changes from 6 mm to 10 mm.

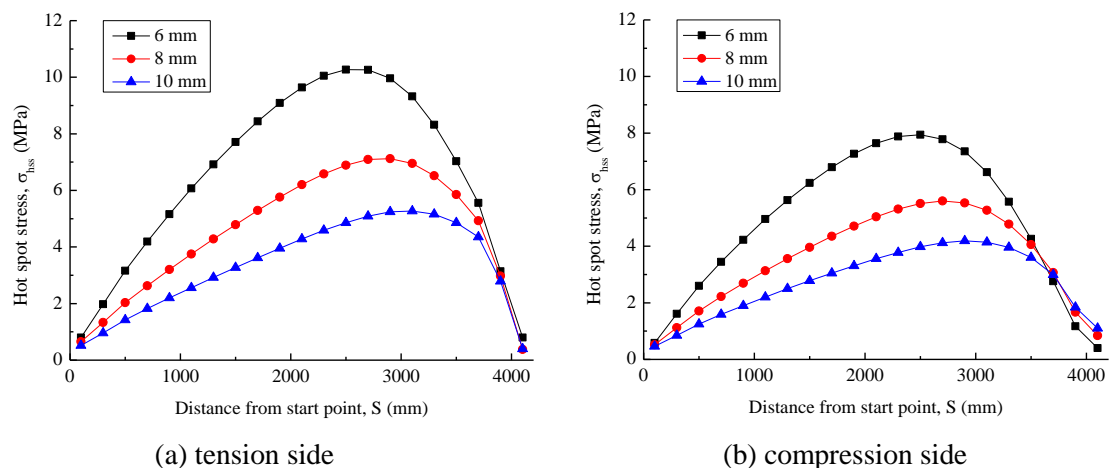


Figure 4 Influence lines of different rib thicknesses: (a) tension side; (b) compression side

2.3.2. Rib spacing

Figure 5 displays the influence lines of different rib spacing. When the rib spacing decreases from 375 mm to 200 mm, the maximum distortional stress increases from 9.30 MPa to 10.18 MPa on the tension side and the maximum distortional stress increases from 7.07 MPa to 8.16 MPa on the compression side. According to previous research, when adopting a larger load area, the distortional stress would increase when the rib spacing increases [5]. Thus, the load dispersal is correlated with the relative size between the rib spacing and the width of load area. The most unfavourable load positions of both sides are not influenced by the changes of the rib spacing, which are about 400 mm away from the middle span in the direction to middle crossbeam.

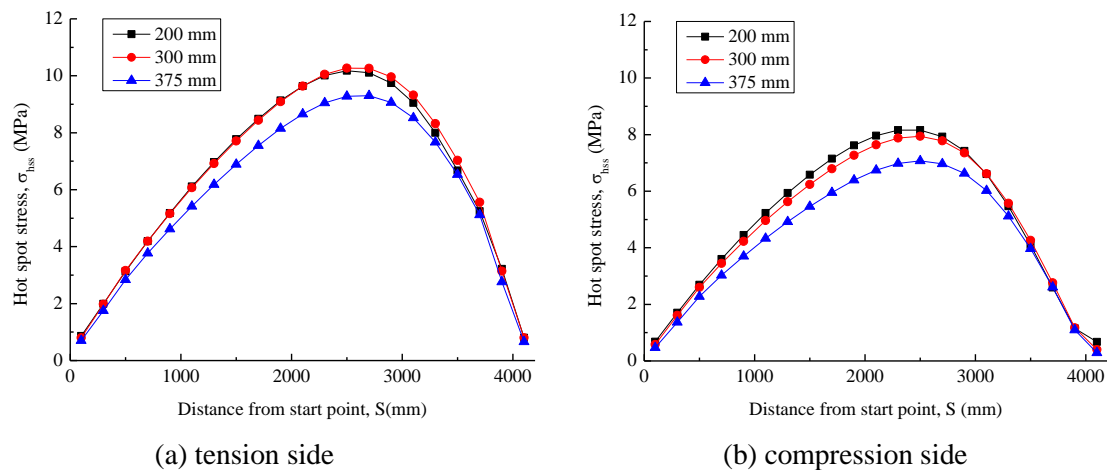


Figure 5 Influence lines of different spacing of rib: (a) tension side; (b) compression side

2.3.3. Crossbeam spacing

Figure 6 presents the influence lines of different spacing. The distortional stress and the crossbeam spacing are also positively correlated crossbeam. On the tension side, the maximum distortional stress decreases from 11.57MPa to 6.90MPa as the crossbeam spacing decreases from 5000 mm to 2500 mm. Meanwhile, on the compression side, the maximum distortional stress decreases from 9.14MPa to 5.28MPa. The most unfavourable load position is around 1600 mm away from the middle crossbeam, which does not change with the crossbeam spacing.

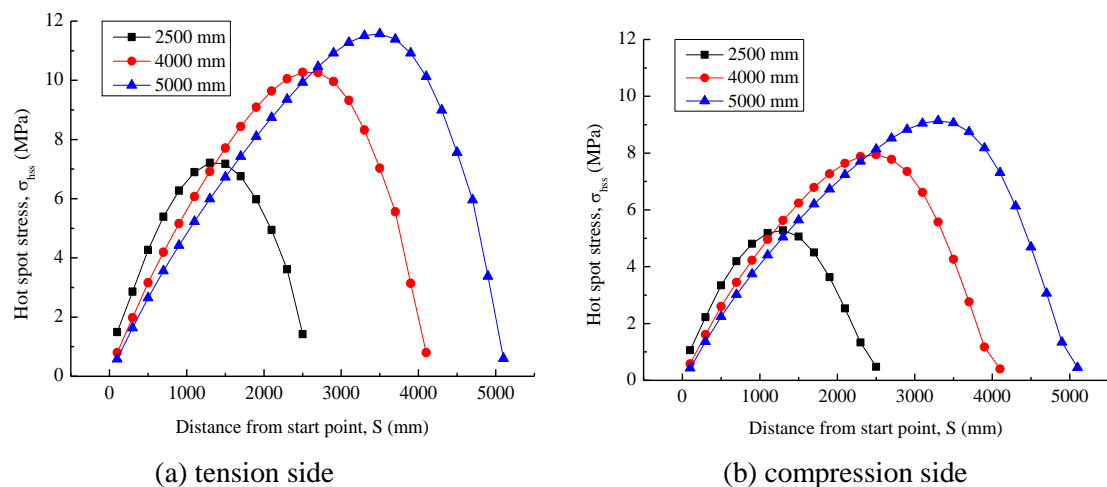


Figure 6 Influence lines of different spans: (a) tension side; (b) compression side

2.3.4. Weld length of rib-to-crossbeam joint

Figure 7 shows the influence line of different weld length of rib-to-crossbeam joint. The distortional stress and the weld length of rib-to-crossbeam joint are positively correlated as well. On the tension side, the maximum distortional stress increases from 9.32 MPa to 11.18 MPa while the weld length of rib-to-crossbeam joint increases from 150 mm to 240 mm. At the same time, on the compression side, the maximum distortional stress increases from 6.20 MPa to 9.44 MPa. The most unfavorable load position is not affected by the weld length of rib-to-crossbeam joint which remains around 1600 mm to the middle crossbeam.

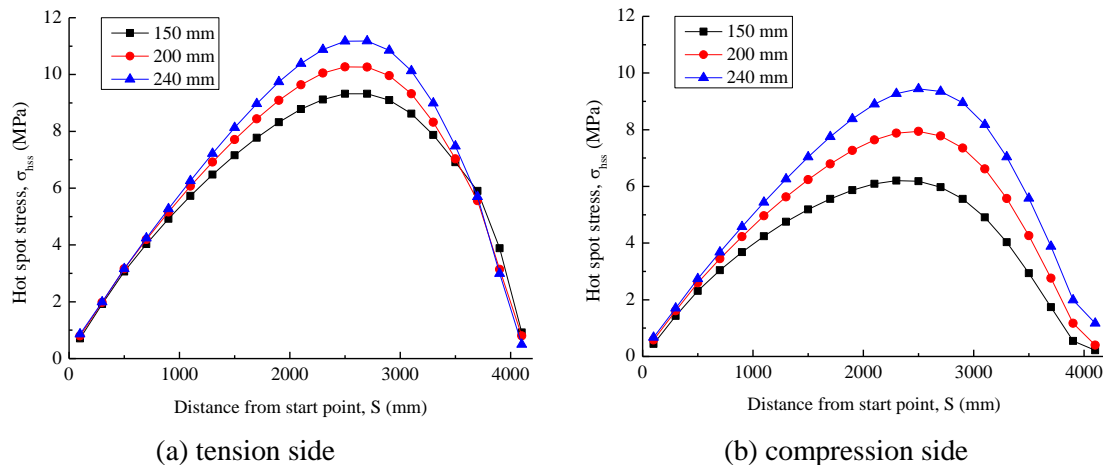


Figure 7 Influence lines of weld length of rib-to-crossbeam joint: (a) tension side; (b) compression side

3. Conclusions

This paper presents the parametric analysis of 4 classical design parameters on the distortional behavior of ribs in orthotropic steel deck. Based on the presented results, the following conclusions can be drawn:

- Among these 4 parameters, the spacing of crossbeam and the weld length of rib-to-crossbeam joint have positive correlations with the distortional stress. The rib thickness has a negative correlation with the distortional stress. The influence of the rib spacing on distortional stress depends on the relative size between the width of load area and the rib spacing, which requires further research.
- The most unfavourable load position of distortional stress is determined by the geometries of ribs, whereas rest three considered parameters of this paper do not show obvious influence. In this case, the most unfavourable load position of distortional stress is at a distance of about 1600 mm away from the investigated crossbeam. When the rib thickness increases, the most unfavourable load position moves toward the investigated crossbeam.
- Analysis results will be verified by experiments in the nearest future. Simplified calculation method of distortional stress and possible alternatives to reduce the distortional behaviour require further research.

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