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Optimization of Design Parameters for Bolted Steel Plate Reinforcing Fatigue Cracks

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Abstract. Bolted steel plate is one of the effective methods to strengthen fatigue cracks. In order to further standardize the selection of reinforcement design parameters, a unidirectional tensile simulation test of cracked plate was carried out in this paper, and the influence of the thickness of reinforced steel plate, bolt specifications, bolt distribution and number on the reinforcement effect of plate fatigue cracks was analyzed. The results show that, Increasing bolt diameter and preloading force can effectively improve the reinforcement effect. The bolt spacing near both sides of the crack is the main factor affecting the reinforcement effect. So,reducing the spacing between the inner bolt and the crack can significantly increase the proportion of the reinforced steel plate in the collaborative stress. The research results can provide reference for the design of fatigue crack reinforcement of bolted steel plate.

Keywords. flat plate fatigue crack; fatigue reinforcement; bolted steel plate; high-strength bolt; design optimization

1. Introduction

Orthogonal steel deck has become one of the preferred structural forms of large-span bridge[1-2] because of its light weight, high strength and good construction characteristics. With the increasing application of orthogonal heterosexual steel bridge panels and the gradual increase of traffic volume, the fatigue problem of orthogonal heterosexual steel bridge panels gradually highlights, which has become the main factor restricting its development[3-5]. Because the orthogonal heterosexual steel bridge panel structure is connected by welding the top-slab, longitudinal stiffening rib and transverse partition into different longitudinal and transverse stiffness structures, so the welding residual stress, welding defects and manufacturing errors are inevitable, so that there are a large number of stress concentration parts in the structure. These stress concentrated parts are prone to serious fatigue problems under the repeated action of the wheel load, which affects the service life of the bridge deck[6-7]. Therefore, it is especially important to find fatigue cracks as early as possible and repair and reinforce them in time.

Scholars at home and abroad have carried out a series of studies on fatigue crack reinforcement. Ji BoHai et al.[8] simulated the effect of the stop-hole through the finite element model, and the results showed that the position and angle of the stop-hole had a great influence on the reinforcement effect, and the increase of the pore size of the hole did not significantly improve the effect. Jiang Xu et al.[9] carried out a test study on the bolt hole method, and the structure showed that the bolt pretension can effectively improve the stress distribution of the stop-hole and reduce the risk of cracking at the stop-hole. Wang Xianqiang et al.[10] conducted fatigue tests on the unilateral cracked steel plate and full-scale diaphragm plate model, which verified the effectiveness of high strength bolt reinforcement, and quantitatively compared the effect of high strength bolt specifications on the fatigue life of the repaired steel plate. On the basis of analyzing the deficiency of traditional thermal maintenance technology, Wang Chunsheng et al.[11] introduced steel or carbon fiber board in some areas of fatigue cracking, proposed the cold maintenance method for

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micro-damage or zero damage of existing structures, and verified its effectiveness and feasibility through model test and solid bridge test. Deng Yang[12] aimed at the cracking problem of U rib-roof weld, proposed a small size reinforced plate on the surface above the top plate, and analyzed the reinforcement effect of 4 mm thick CFRP plate and steel plate. The results show that the cracking effect of steel plate with the same thickness is better than that of CFRP plate, and the fatigue life of the weld details is increased by 87% and 196% respectively.

However, in practical engineering to reinforce the fatigue cracks in the arc gap of the orthogonal steel deck, the combination of stop-hole and bolted steel plate reinforcement is most frequently used. However, there is still a lack of reasonable design parameters for bolt-on steel plate reinforcement. Based on the above background, this paper simulates the design parameters of steel plate and bolt, studies the reinforcement mechanism of bolt steel plate, analyzes the influence of different parameters on the stop hole stress of crack steel plate, and provides reference for the design of fatigue crack and reinforcement of orthogonal steel deck.

2. Finite Element Model Establishment

As shown in Figure 1, the design Q345qD cracked steel plate is 500mm×150mm×8mm, the middle steel plate penetration crack is 70mm long and 2mm wide, and the stop-hole is 17.5mm in diameter. The size of the bolt reinforcing plate adopted in the reference model GK 1-5 is 300mm×140mm×4mm, and is reinforced by cracking of 4 M16 high strength bolts in two rows, as shown in Figure 2.

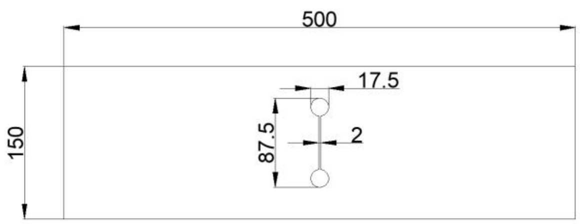


Fig. 1 Dimension of cracked plate (mm)

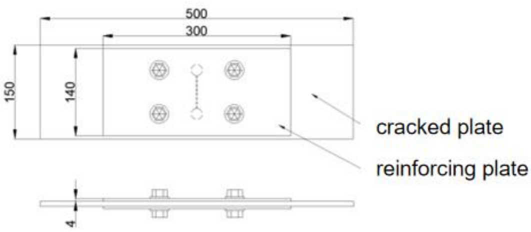
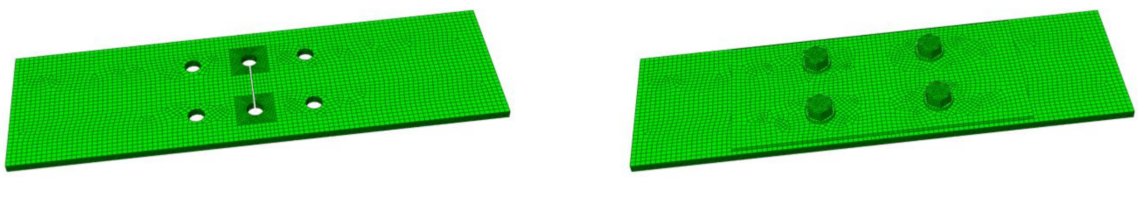


Fig. 2 Design reference model size of bolt reinforcing plate (mm)

Build a finite element analysis model, as shown in Figure 3. Both steel plate and high strength bolts adopt solid unit C3D8R simulation, in which Q345qD steel plate yield strength is 418MPa, the elastic modulus is 2. 06×10^5MPa, and the Poisson ratio is 0.3; the elastic modulus of high strength bolts is 2.1×10^5MPa and Poisson ratio is 0.3. Size of cracked and reinforcing steel plate mesh is 5mm; mesh around crack hole is partially refined at 1mm; size of high strength bolt and gasket mesh is set at 2mm.



(a) Cracked plate + high-strength bolt hole (b) After reinforcing the plate

Fig. 3 Finite element model of bolt reinforcing plate

3. Analysis of the Calculation Results

For the finite element model of Figure 3 ,30MPa tensile stress is used for axial loading and calculation, and 3 paths and the stop-hole stress should be selected for comparative analysis. The

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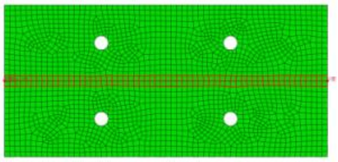
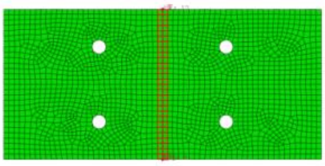
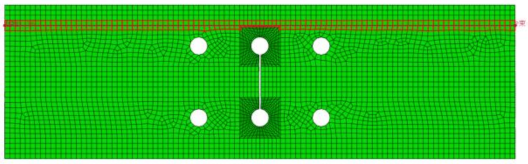
stress of the reinforcing plate is path 1 and 2 S11 respectively; the stress of cracked steel plate at 20mm from the stop-hole is path 3, and the center of the stop-hole edge is the stress σSH, as shown in Figure 4.



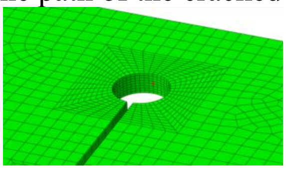
(a) Transverse path of the reinforcing plate



(b) Longitudinal path of reinforcing plate



(c) The path of the cracked plate



(d) Stop-hole stress

Fig. 4 Stress extraction path

3.1 Diameter and Pretension of High Strength Bolts

In order to explore the influence of high strength bolt diameter and pre-tightening force on the reinforcement effect, the setting condition is shown in GK 2-1 ~ GK 2-9 in Table 1. All the working conditions in the table adopt the reinforcing steel plate of 300mm×140mm×4mm, and the number of bolts is two rows and two columns, and the bolt spacing is 60mm.

Table 1. Table of analysis of working conditions

number	High strength bolt diameter	Pre-tightening force / (kN)	number	High strength bolt diameter	Pre-tightening force / (kN)
GK1-1	M12	50kN	GK1-6	M16	155kN
GK1-2	M12	100kN	GK1-7	M20	50kN
GK1-3	M12	155kN	GK1-8	M20	100kN
GK1-4	M16	50kN	GK1-9	M20	155kN
GK1-5	M16	100kN			

In this paper, the stress concentration reduction coefficient β is selected to describe the reinforcing effect of the bolted plate. The stress concentration reduction coefficient β is defined as the ratio of the stop-hole stress concentration coefficient αSH，s reinforced by the bolted plate and the stop-hole stress concentration coefficient αSH，n of the unreinforced plate, namely:

$$\beta = \frac{\alpha_{SH,s}}{\alpha_{SH,n}} \tag{1}$$

The change of the stop-hole stress concentration coefficient αSH, s and stress concentration reduction coefficient β with bolt specification is shown in Figure 6. For high strength bolts of different specifications, the stress concentration reduction coefficient β decreases with the increase of the pre-tightening force of the bolts, and the reinforcement effect is significantly improved: for different specifications of bolts, the stress concentration reduction coefficient when the pre-tightening force is 155 kN is reduced by 20% compared with when the pre-tightening force is 55 kN. For the influence of the bolt specification, the stress concentration reduction coefficient β

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decreases with the increase of the bolt specification, and the decrease is not affected by the shaft force of the bolt.

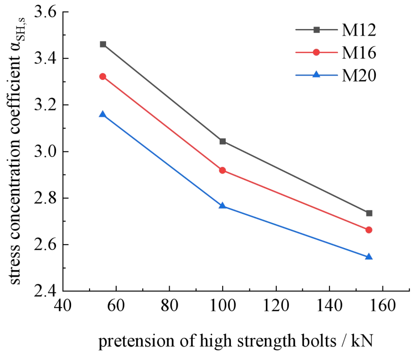


Fig. 5 The stop-hole stress concentration coefficient (different bolt pre-tension)

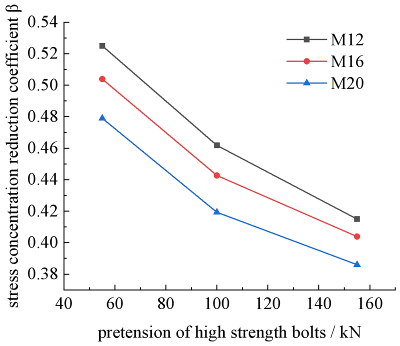


Fig. 6 Stress concentration reduction coefficient (different bolt pre-tension)

The change of the transverse stress S11 with the bolt specification is shown in Figure 7. According to the figure, with the increase of the bolt specification, the stress of the cracked plate does not change much, but the stress level of the cracked plate after the bolt hole decreases, and the peripheral stress of the stop-hole decreases accordingly. From Figure 8, with the increase of the bolt specification, the stress area of the reinforcing steel plate is almost constant, but the stress level is significantly increased. The main reason is that with the same bolt pre-tightening force, improving the specification of high strength bolt can significantly improve the synergistic force level of reinforcing steel plate, so as to reduce the force of cracked plate.

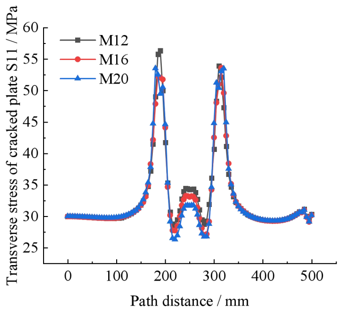
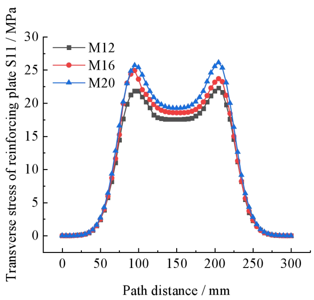
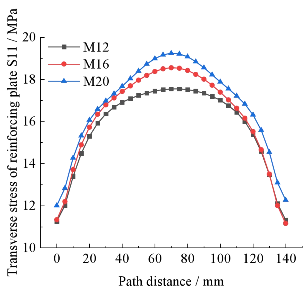


Fig. 7 Path stress of cracked plate (path 3)



(A) Transverse path stress of reinforcing plate (path 1)



(B) Longitudinal path stress of reinforcing plate (path 2)

Fig. 8 reinforcing steel plate path stress

3.2 Combination and Arrangement of Bolts' Size

Existing studies show that the reduction of the bolt spacing significantly improves the reinforcement effect of the high strength bolts. So the closer bolt spacing can be obtained by reducing the specifications of the first column of bolts, so as to improve the reinforcement effect and reduce the cost. In order to explore the influence of the bolt combination on the reinforcement effect, the setting conditions are shown in GK 2-1 ~ GK 2-6 in Table 2. All the working conditions

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in the table adopt the reinforcing steel plate of 480mm×140mm×4mm, and the number of bolts is two rows and 4 columns. Among them, the bolt near the edge of the plate is set as the main bolt, and the bolt near the middle of the plate is set as the subordinate bolt. The schematic diagram of the working condition is shown in Figure 9.

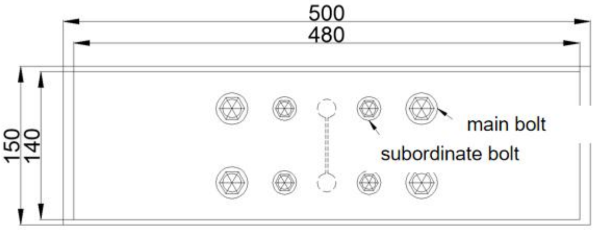

Fig. 9 Schemram of Size Bolts (mm)

Table 2. Table of analytical working conditions

number	Bolt specifications (subordinate + main)	Pre-tightening force (subordinate + main)	pitch of bolts (subordinate + main)
GK2-1	M12+M12	55kN+55kN	40mm+40mm
GK2-2	M12+M16	55kN+100kN	40mm+50mm
GK2-3	M12+M20	55kN+155kN	40mm+70mm
GK2-4	M16+M16	100kN+100kN	50mm+50mm
GK2-5	M16+M20	100kN+155kN	50mm+70mm
GK2-6	M20+M20	155kN+155kN	70mm+70mm

The change of the stop-hole stress concentration coefficient αSH, s and stress concentration reduction coefficient β with the bolt combination condition is shown in Figure 11. As can be seen from the figure, compared with the working conditions GK 4-4 and GK 4-6 using large size bolts alone, the combined working conditions GK 4-2, GK 4-3 and GK 4-5 can significantly reduce the stress level around the stop-hole and have a better reinforcing effect. Compared with the combined working condition of large and small bolts, the stress concentration coefficient of GK 4-1 in the working condition of small bolts alone is large. It is considered that the bolt pre-tightening force of small bolts is low, and the reduction of bolt spacing cannot make up for the overall strength of the structure. The bolts' specification and pre-tightening force of GK 4-6 are stronger than those of GK 4-4, but the difference between the stress concentration coefficient and the reinforcing effect is not large. It is believed that the high strength of the stop-hole is caused by the excessive spacing of the bolts in GK 4-6.

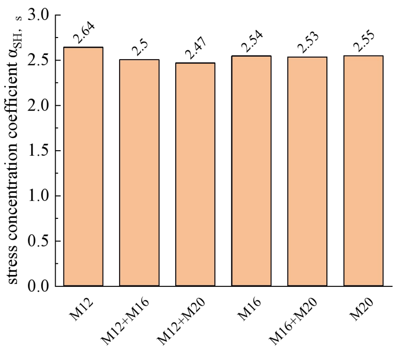

Fig. 10 The stop-hole stress concentration coefficient (different bolt combinations)

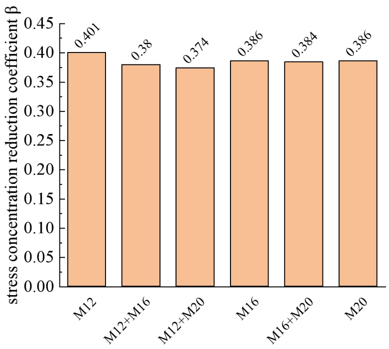

Fig. 11 Stress concentration reduction coefficient (different bolt combinations)

The path stress of cracked plate and reinforcing plate of GK 4-1, GK 4-2 and GK 4-3 is shown in Figure 12 and 13. As can be seen from Figure 12, with the improvement of the specification of the main bolts, the stress at the front end of the main bolts is greatly increased, and the stress at the rear end is significantly reduced, which effectively reduces the stress level in the middle crack area of the cracked steel plate. From Figure 13, with the improvement of the main bolts' specification, the

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stress level in the main bolts' area increases significantly. It is believed that there are more stress transferred to the reinforcing steel plate, and the stress level in the middle of the reinforcing steel plate has also been greatly improved, and the reinforcing steel plate has apportioned more stress, and the reinforcing effect is better.

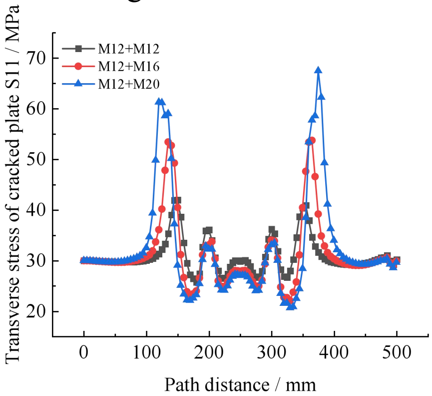

Fig. 12 Path stress of cracked plate (path 3)

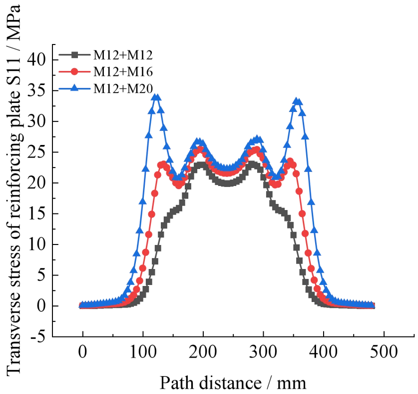

Fig. 13 Transverse path stress of reinforcing plate (path 1)

The path stress of cracked plate and reinforcing plate of GK 4-3, GK 4-5 and GK 4-6 is shown in Figure 14 and 15. As can be seen from Figure 14, with the decrease of the subordinate bolts specification, the bolt spacing decreases, and the distance between the main bolts and the crack also decreases. The stress level before the bolt remains unchanged, but the stress level after the bolt decreases. After using the bolts of small size on the inside, due to the small pre-tension of the bolt, the stress level in the central area tends to flatten out, and the stress does not change significantly. As can be seen from Figure 15, although the specification of the subordinate bolt is reduced, the stress level of the center position of the reinforcing plate is not significantly reduced, the reinforcing effect is not significantly changed, and the force of the reinforcing plate is more uniform, and the stress amplitude is reduced, which can prolong its fatigue life. At the same time, due to the reduced spacing of the subordinate bolts and the reduced stress distribution width of the reinforcing steel plate, a smaller area of the reinforcing steel plate can be used to reduce the cost. Therefore, from the reinforcement effect and economy of two aspects, the inner bolt choice to use small size bolts is a better choice.

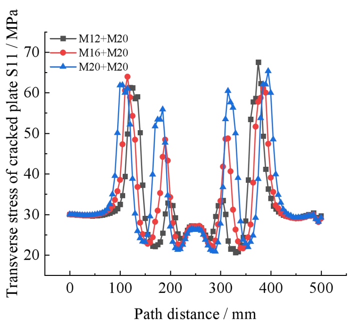

Fig. 14 Path stress of cracked plate (path 3)

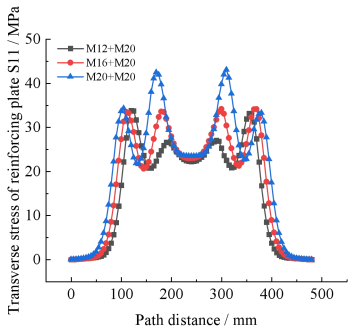

Fig. 15 Transverse stress of reinforcing plate (path 1)

4. Conclusion

In this paper, finite element analysis was used to study the strengthening parameters of bolted steel plates for planar cracked plates, and the following conclusions were drawn:

(1) Without considering the bolt spacing, the reinforcing effect of the bolt reinforcement increases with the bolt specification and the bolt preload force increase. The stress concentration reduction factor at a pre-tightening force of 155kN is reduced by 20% compared to that at a

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pre-tightening force of 55kN. Moreover, the enhancement of the repair effect due to the increase in bolt size is not influenced by the magnitude of the bolt preload.

(2) However, if the factor of bolt spacing is considered, because the reinforcement effect is more sensitive to the bolts closer to the crack, the combination of size and bolt can better increase the reinforcement effect and reduce the cost. According to the simulation results, the bolt combination of M12 + M16 and M12 + M20 improved 1.6% and 3.1% over M16 and M20 bolts alone. At the same time, it can effectively reduce the stress amplitude of cracked steel plate and reinforcing steel plate, and improve the fatigue life of the structure.

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