Analysis on Stop-hole Parameters for Fatigue Cracks at Arc Notch in Steel Bridge Deck

Liangping Feng\textsuperscript{1, a}, Lipeng Ling\textsuperscript{1, b}, Cheng Meng\textsuperscript{2, c} and Bohai Ji\textsuperscript{2, d}

\textsuperscript{1} China Communications Construction Company Highway Bridges National Engineering Research Center Co., Ltd., Huangsi Street A23#, Beijing, China
\textsuperscript{2} College of Civil and Transportation Engineering, Hohai University, No.1 Xikang Road, Nanjing, China
Email: \textsuperscript{a}fengliangping@bnerc.com, \textsuperscript{b}linglipeng@163.com, \textsuperscript{c}ycmc1995@163.com, \textsuperscript{d}bhji@hhu.edu.cn

Abstract. Two types of fatigue cracks at arc notch in steel bridge deck were repaired by drilling stop-holes. The effect of stop-holes with different diameters and positions was considered. Based on finite element models, the variation laws of stress distribution and the effects of stress concentration were compared for different stop-hole diameters and positions. Analysis results indicated that stop-hole can effectively improve the stress concentration at crack tip and the fatigue life of components can be considerably increased. The crack-stopping performance enhances with the increase of stop-hole diameter, but large stop-hole cannot effectively retard crack growth. The stop-hole performs well with the location at -0.5\textit{D}~0.5\textit{D}. The maximum stress point still appears at crack tip when the stop-hole is outside or inside the crack. The stop-hole diameter has no effect on the stop-hole location.

1. Introduction
Orthotropic steel deck has been widely used in the construction of long-span bridges because of its advantages, such as light weight, good stability and strong spanning capacity [1]. Barring the weight loading of cars, with welding residual tensile stress and welding defects, it is easy to cause fatigue cracks in orthotropic steel deck. The arc notch between diaphragm and longitudinal rib is one of the typical fatigue crack details because of its special structure [2].

With the continuous emergence of fatigue problems, the research on the cause mechanism, damage detection and maintenance of fatigue cracks has been carried out. There are many effective maintenance methods to repair fatigue cracks. Drilling stop-holes is one of the most common maintenance methods to delay or hinder the crack propagation now. The principle of drilling stop-hole is to drill a smooth hole, and relieve the stress concentration [3, 4].

Current researches on drilling stop-holes mainly focus on the parameters and technology of stop-holes. Wu et al. [5] predicted the fatigue crack initiation lives by employing classical concepts properly modified by short crack theory to model the stop-hole effect. Liu et al. [6] measured residual stress after drilling cold expansion hole and carried out a series of uniaxial fatigue tests. Fu et al. [7] proposed drilling advice and conducted fatigue testing of the cracks in steel bridge deck with stop-hole. Castro et al. [8] analysed fatigue cracks after drilling stop-holes and proposed a calculation method of crack fatigue life after drilling stop-holes.
In this study, fatigue crack details at arc notch of the diaphragm were studied. Based on the data analysis of a real bridge and the results of finite element models, the reasonable position and diameter of stop-hole were proposed to optimise the drilling technology in real bridges.

2. Finite Element Models

2.1. Model Size

Annual check records of a long-span suspension bridge with steel box girder shows that there are many fatigue cracks grow in the arc notch, which are mainly divided into two types of fatigue details:(1) cracks grow obliquely upward from the bottom of weld between diaphragm and U-rib, named as crack C1; (2) cracks grow horizontally from the arc notch, named as crack C2.

According to the size of the real bridge, Q345qD steel was used as the bridge material with the Young’s modulus of 2.06×10^5 MPa and Poisson’s ratio of 0.3. The thickness of roof and diaphragm were 12mm and 10mm respectively, and the section size of U-rib was 324mm×262mm×6mm, the specific model was shown in figure 1.

![Figure 1. Model size and fatigue detail (dimensions in mm).](image)

2.2. Finite Element Model

Local finite element models of diaphragm-to-rib weld were established by ABAQUS, as shown in figure 2. The roof was fixed constraints with full degrees of freedom, the loading area was set on the surface of the diaphragm, directly below the arc notch. The reference point was set at 10mm from the weld toe both in the horizontal and vertical directions with the nominal stress (σ_{nom}) of 100 MPa.

According to the actual statistics of fatigue cracks in real bridge, the average length of crack C1 and C2 were 35mm and 120mm respectively. The angle of 45° and 0° between the cracks and weld toe were adopted as the crack parameters in the finite element models. The cracks were set with lengths of 35mm and 120mm respectively, and width of 0.1mm both.

The models were meshed with hexagonal solid element type C3D8R and tetrahedral solid element type C3D10 and the meshes of crack regions were refined.
2.3. Determination of Cracks
Based on Extended Finite Element Method (XFEM) analysis, stress intensity factors (SIFs) of two cracks were calculated and the results were shown in figure 3.

![Finite element model](image)

(b) Crack C2

**Figure 2.** Finite element model.

**Figure 3.** Stress intensity factors of two cracks.

According to the calculations of SIFs, $K_{II}$ of crack C1 was smaller than $K_I$ and $K_{III}$, which showed crack C1 was a I-III mixed mode fatigue crack dominated by type I. In addition, crack C2 was a I-II-III mixed mode fatigue crack.

3. Influence of Stop-Hole Parameters
The stresses of two fatigue details under different stop-hole diameter and location were calculated. The stress concentration factor ($K_t$) and the fatigue notch factor ($K_f$) were compared to evaluate the fatigue performance. The solutions for $K_t$ and $K_f$ are given in equation (1) and equation (2).

$$K_t = \frac{\sigma_{\text{max}}}{\sigma_{\text{nom}}}$$  \hspace{1cm} (1)

$$K_f = 1 + \frac{K_t - 1}{1 + c \frac{\rho}{\rho}}$$  \hspace{1cm} (2)

Where $\sigma_{\text{max}}$ is obtained from the finite element model. And $\sigma_{\text{nom}}$ is the nominal stress, here the value is 100MPa. $c$ is a constant related with material, here the value is equal to 0.45. Then $\rho$ is the radius of stop-hole.
3.1. Effects of Stop-Hole Diameter
Circular stop-holes with different diameters were drilled at the tip of crack C1 and C2, of which the center located at the extend line of crack tip. The stress concentration factor ($K_t$) and the fatigue notch factor ($K_f$) under different diameters were shown in table 1.

| $D$ (mm) | $\sigma_{nom}$ (MPa) | Crack C1 | Crack C2 |
|----------|-----------------------|----------|----------|
|          | $\sigma_{max}$ (MPa) | $K_t$    | $K_f$    | $\sigma_{max}$ (MPa) | $K_t$    | $K_f$    |
| 0        | 1583.5                | /        | 758.4    | /        | 7.584    | /        |
| 8        | 555.8                 | 5.558    | 4.963    | 402.4    | 4.024    | 3.630    |
| 10       | 489.6                 | 4.896    | 4.502    | 363.5    | 3.635    | 3.369    |
| 12       | 420.2                 | 4.202    | 3.938    | 336.7    | 3.367    | 3.172    |
| 14       | 403.5                 | 4.035    | 3.823    | 316.7    | 3.167    | 3.016    |
| 16       | 343.4                 | 3.434    | 3.287    | 300.9    | 3.009    | 2.888    |
| 18       | 313.7                 | 3.137    | 3.023    | 287.7    | 2.877    | 2.777    |
| 20       | 298.4                 | 2.984    | 2.890    | 277.6    | 2.776    | 2.692    |
| 22       | 292.3                 | 2.923    | 2.840    | 269.3    | 2.693    | 2.620    |
| 24       | 278.1                 | 2.781    | 2.711    | 262.8    | 2.628    | 2.564    |

As shown in table 1, the maximum stress of crack C1 and C2 before drilling stop-holes were 1583.5 MPa and 758.4 MPa respectively, which means if left untreated, the cracks would continue to grow and cause structure destruction. After drilling stop-holes at the crack tips, the maximum stress, $K_t$ and $K_f$ decreased significantly. The stop-hole performance enhanced with the increase of stop-hole diameter.

![Figure 4](image)

**Figure 4.** Parameter variation under different diameters.

Figure 4 shows that with the increase of stop-hole diameter $D$, the change of $K_t$ and $K_f$ got slower. Besides, stop-hole could weaken the stiffness and strength of structure. Therefore, the reasonable diameter for crack C1 and crack C2 should be controlled at 12-16 mm.

3.2. Effects of Distance Between Stop-Hole and Crack Tip
The influence of stop-hole position on crack arrest effect was studied under the condition that the stop-hole was not eccentric, namely the center of stop-hole and the crack were on a straight line. The sketch of hole location was shown in figure 5, $X$ is the horizontal distance between the center of stop-hole and crack tip.
The hole diameters of stop-hole were 12mm, 14mm and 16mm in model calculation. Calculation results of the maximum stress around stop-hole or at crack tip were shown in figure 5.

![Figure 5. Sketch of hole location.](image)

4. Conclusions
(1) These two typical types of fatigue cracks at arc notch are both mixed mode fatigue cracks. Drilling stop-holes can effectively relieve the stress concentration at the tips of crack C1 and crack C2, and stop crack propagation.

(2) For these two types of fatigue cracks, the crack-stopping performance improves with the increase of stop-hole diameter. And the reasonable stop-hole diameter should be in range of 12-16mm considering the weakening effect of the stop-hole on structure.

(3) The most efficient crack stopping performance occurs when the distance between the center of stop-hole and crack tip is in range of -0.5D~0.5D. The stress concentration cannot be improved when

![Figure 6. Variation law of the maximum stress.](image)
the stop-hole is drilled completely inside or outside the crack. And the stop-hole diameter has little effect on the stop-hole location.

Acknowledgments
The research reported herein has been conducted as part of the research projects granted by Guangdong Key Areas Research and Development Project (2019B111106002), Academician Project Foundation of CCCC (YSZX-03-2020-01-B) and National Key Research and Development Project (2017YFE0128700). The assistance are gratefully acknowledged.

References
[1] Ya S, Yamada K, Ishikawa T. 2011 Fatigue Evaluation of Rib-to-Deck Welded Joints of Orthotropic Steel Bridge Deck [J] Bridge. Eng 18 492-499.
[2] Kolstein M H. 2007 Fatigue classification of welded joints in orthotropic steel bridge decks Publication of Transport & Road Research Laboratory.
[3] Song P S, Shieh Y L. 2004 Stop drilling procedure for fatigue life improvement Int. J. Fatigue. 26 1333-1339
[4] Yao Y, Ji B, Fu Z, Zhou J, Wang Y. 2019 Optimization of stop-hole parameters for cracks at diaphragm-to-rib weld in steel bridges [J] Constr. Steel. Res 162 105747
[5] Hao W, Imad A, Benseddiq N, Maeda K. 2010 On the prediction of the residual fatigue life of cracked structures repaired by the stop-hole method Int. J. Fatigue 32 670-677
[6] Liu J, Shao X, Liu Y, Yue Z. 2008 Effect of cold expansion on fatigue performance of open holes [J] Mat. Sci. Eng. A-Struct. 477 271-276
[7] Fu Z, Ji B, Xie S 2017 Crack stop holes in steel bridge decks: Drilling method and effects [J] Cent. South. Univ 24 2372–2381.
[8] Castro J, Meggiolaro M, Miranda A, Hao W, Imad A, Benseddiq N. 2012 Prediction of fatigue crack initiation lives at elongated notch roots using short crack concepts Int. J. Fatigue 42 172-182.