Research Progress on Fatigue Reinforcement of Orthotropic Steel Deck

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Abstract. In view of the currently widely-used orthotropic steel deck (OSD), the problems of fatigue damage of the bridges are summarized based on the analysis of OSD fatigue damage of the related research results. From two aspects: local reinforcement measures and integral reinforcement measures, this paper discusses the principles of some techniques in this field, as well as the existing advantages and deficiencies of each technique. This paper also provides suggestions and directions for future research: To establish and improve the industry standards of OSD fatigue, which is conducive to the innovation and development of related technologies; Multidimensional cooperation associated with other fields is conducted to explore new ideas and technologies for fatigue damage reinforcement of OSDs.

Keywords: Fatigue Reinforcement, Orthotropic Steel Deck, Local Reinforcement Measures, Integral Reinforcement Measures.

1. Introduction

In the 19th and 20th centuries, large steel case beam bridges were widely used in the world. An orthotropic bridge tray was usually used on the top of a beam. After The Second World War, the problem of bridge damage was received the attention. German bridge engineers put forward the novel idea of orthotropic steel bridge (OSD) decks on steel box girder Bridges [1]. Since then, the advantages of the orthotropic steel board bridge compared to the conventional bridges have made it widely used in countries such as Europe, America and China. In the early stage of OSD bridge, the open longitudinal rib was adopted, which was simple in structure, simple in installation process, and not very complicated in manufacturing technology. However, because of welding procedures on the open longitudinal rib, this greatly increased the possibility of fatigue damage of the bridge, and the economic benefit was very low in the follow-up maintenance. Therefore, the longitudinal rib section formed from the open section into the closed section, mainly a V-shape, U-shape, rectangular shape and so on.

The OSDs have complex connection forms and many connection positions, and that the steel bridge deck subjected to cyclic stress is prone to fatigue cracks or complete fracture. Many steel-bridge decks at home and abroad have experienced fatigue cracks of varying degrees [2]. Due to large loads of railway bridges and fast speeds of trains, the impact state of bridges is more complicated. When the train passes by, the length of the influence line at each part of the orthotropic steel bridge deck is short, and the same part may produce multiple stress cycles. As the number of trains in operation increases on the bridge of high-speed railway, the number of repeated stresses of the component increases. Therefore, more attention should be paid to the fatigue problem of orthotropic bridge deck of railway bridges.

The main research content of this paper is to summarize major measures as well as the reinforcement procedure and some significant discoveries for fatigue reinforcement of OSD bridges. The benefits and shortcomings will be discussed for different measures by listing some important parameters of each type. Reinforcement measures for fatigue of orthotropic steel deck

The local reinforcement measures of bridge are to strengthen the damaged part of orthotropic plate to reduce or eliminate the influence of stress on orthotropic plate. The particularity of these measures lies in the fact that the local damage is strengthened only for the part where the damage occurs. Several common reinforcement measures include cold-strength technique, bonded and sandwich plate system (SPS), and iron-based shape memory alloys (Fe-SMA). The integral reinforcement measures of OSD bridge are generally contrary to the local reinforcement measures. They strengthen the overall stress state to improve the stability and fatigue resistance of the bridge. At present, major measures using integral reinforcement measures for OSD fatigue include using ultra-high-performance concrete (UHPC), steel fiber reinforced concrete (SFRC), and some creative materials such as non-woven fabrics (NWF) and ultra- thin asphalt overlayer (UTAO) on the pavement.

1.1 Local reinforcement measures

In the reinforcement of bridges, local reinforcement can be adopted. Local reinforcement is directed at the local area of the damaged part of OSD. Therefore, the aim of reducing or eliminating the impact of stress on the OSD as well as preventing the breeding of cracks on the OSD can be realized.

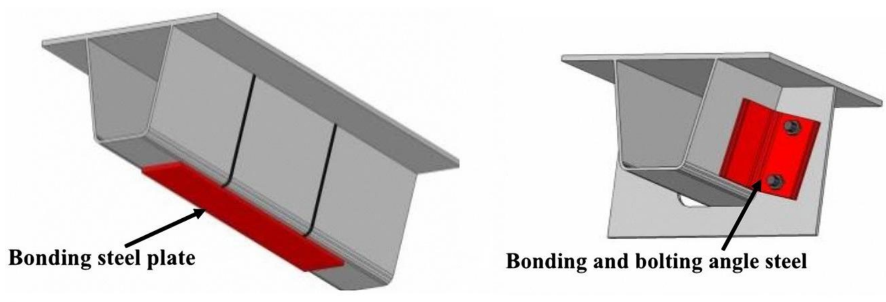
There are several methods for local reinforcement, such as cold reinforcement technique, bonding system and SPS as well as the use of Fe-SMA. They have a certain effect on extending the life of OSD. And they are introduced in the following.

Cold reinforcement technique

Cold reinforcement technique is proposed because it is relative to the hot reinforcement technology. In the use of the hot reinforcement technology, the original structure of the orthotropic steel deck can be easily damaged again at high temperature. It will aggravate the problem of fatigue damage. Cold reinforcement technique strengthens fatigue from the local range of OSDs. It is a method that does not produce or produce small residual stress. Therefore, this method can solve some problems of fatigue cracks in important parts of the bridge or the gap between webs. After reinforcement applying this technique, it can expand the lifetime of bridge. The cold reinforcement technique can be divided into several methods: drilling stop-hole method, cold connecting plate method, ultra-high performance fiber reinforced concrete - OSD composite system (UHPFRC).

The purpose of drilling stop-hole method is to reduce stress and prolong the life of OSD. The method is to reduce the concentrated stress at the crack tip by drilling smooth holes in the crack source. Combined with other methods, the crack propagation can also be prevented. However, satisfactory results can be achieved only when the in-plane bending stress is less than 42MPa and the out-of-plane stress is within a small range.

Cold connecting plate method prolongs the life of OSDs through enhancing local stiffness of the damaged part. As shown in Figure 1, this method has two branches according to different damaged parts: steel plate reinforcement and angle reinforcement. However, the principles of both are generally the same: on the original basis and add a steel plate to reinforce. The technique has a significant effect to reduce the stress range outside the surface. At the same time, it shows a good durability for the environment.



(a) (b)

Figure 1. (a) steel plate reinforcement; (b) angle reinforcement [3].

UHPFRC can both reduce stress and improve local stiffness. Laying a layer of UHPFRC on the OSD and combining with the cold connection, it can reduce the stress, improve the stiffness, and expand the life of the bridge. The structure can be seen in Figure 2. Studies indicated that stress was reduced by at least 60 percent.[3]

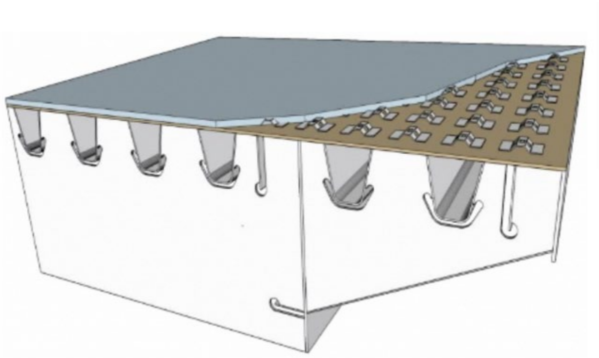
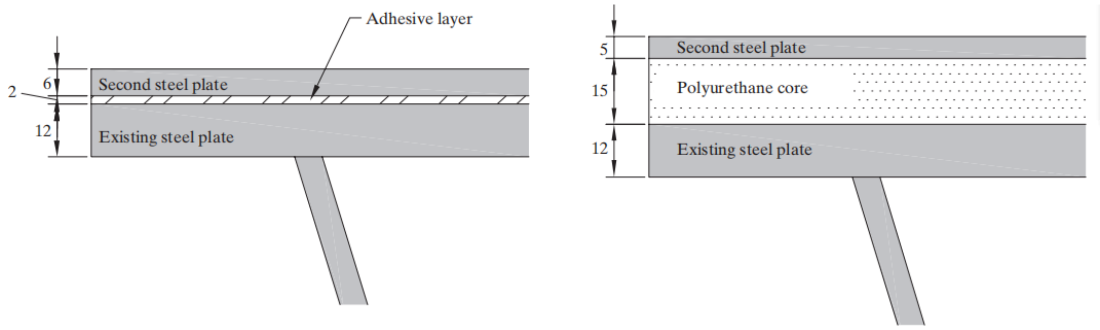


Figure 2. Ultra-high-performance fiber reinforced concrete - OSD composite system [3]

2.1.2 Bonding system and SPS technology

Both bonding system and SPS are based on OSDs, and use an additional steel plate to improve the property of cracks. Although adding a steel plate to reinforce the damaged part of OSD is the same procedure, there are still some differences. The connections in the middle of the bonding system use adhesive material, as shown in Figure 3(a), while the connections in the middle of the SPS use polyurethane, as shown in Figure 3(b). In the bonding system, reinforcing plates need to be cleaned and then coated with primer at first. Then workers will use corresponding equipment to install the plate on the original board. After that, adhesive materials will be added to the middle of two boards under vacuum ambience. Then the adhesive materials will be solidified under 50 ℃. The last procedure is to check whether there is a defect in the process of bonding using the scanner. If it is detected that defects exist, repairment will take place on time. The method of SPS has similarities to the bonding system, but the material in the middle is different. Sofia et al. [4], who studied Scharsterrijn Bridge in the Netherlands and Schonwasserpark Bridge in Germany, came up with tests about the two techniques of bonding and SPS, respectively. According to the experiment, the method of bonding will be affected by the bonding material or the gap in the middle of the bonding layer. However, before the failure of the bonding layer, its stiffness will not decrease significantly. For SPS, if the thickness of the core material is more than 30mm, the fatigue life of the sandwich beam will not be prolonged. Sofia et al. [5] also mentioned that in a real wheel loading experiment by using the finite element modelling and analysis of the panel static experiment, the stress in different parts of the bridge have a different degree of reduction. Using the method of bonding steel plate can reduce the stress by at least 45%. It also can prolong the fatigue life of welding up to 6 - 15 years. The method of using SPS can reduce stress up to 40% at least and it can extend fatigue life by 4-7 times. The article of Feldmann et al. [6] referred to an experiment in a SPS practical applicability test under the background of an expressway bridge in Germany. The results suggested that bonding system and SPS are an efficient technique for OSD maintenance, and they need light equipment. Moreover, it is easy to install when under construction. Most importantly, bonding system and SPS can enhance the stiffness of OSD structure and expand the fatigue life.



(a) (b)

Figure 3. (a) The structure of bonding system. (b) The structure of SPS. (Units: mm).[5]

2.1.3 Using Fe-SMA for strength

Fe-SMA is a material with the capacity of shape memory, and it has an active reinforcement ability for the welded crack part of the steel bridge deck. Fe-SMA is pulled up to a certain state and fixed on the surface of OSD. When the material is heated by an external power supplement through resistance, then it will automatically dissipate heat. After cooling, it will shrink and return to its original appearance, generating prestress to reinforce the bridge. In the study of Zhang Qinghua et al. [7], they took Hong Kong-Zhuhai-Macao Bridge as the background, and used ANSYS software to establish the finite element model, as shown in Figure 4. Through the study, it is found that Fe-SMA has a certain effect on fatigue reinforcement. The greater the depth of the crack, the higher the level of prestress should be loaded. In order to achieve the ideal state, the level of prestress must reach at least 300MPa.

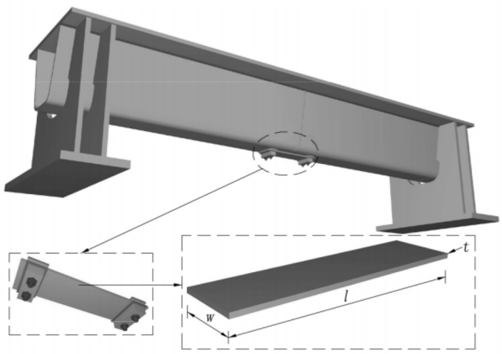


Figure 4. The details of bolting Fe-SMA [7]

1.2 Integral reinforcement measures

Integral reinforcement method means improving the whole pavement structure of OSD bridges by replacing the previous traditional layer with other materials to boost the behavior of OSD fatigue. During this reinforcement process, materials applied in mainly include using UHPC, SFRC as well as other innovative materials such as NWF and UTAO. These materials show good properties in fatigue resistance. These years, quantities of related research on new materials have been carried out.

2.2.1 Application of UHPC in the OSD fatigue reinforcement

UHPC is a kind of concrete showing high compressive strength and good durability [8]. By combining this UHPC layer with the existing orthotropic steel decks, the stress under the action of wheel loads can be greatly reduced, thus expanding the lifetime of the overall system. According to Benjamin et al. [8], many bridges have used UHPC for maintenance and reinforcement, involving the road bridge across the Rhine River at Kreissern and the Rantau-Siliau Bridge where five UHPC beams are applied.

To avoid high tensile stress at the bottom of UHPC layer [9], as shown in Figure 5, steel strips welded with studs will be firstly installed on OSD layer by fixing the strips at both ends for construction convenience. The steel bars will be put on in a reticular structure. When these processes have been done, UHPC will be poured on. The surface layer is a bearing layer in order to avoid abrasions of UHPC layer.

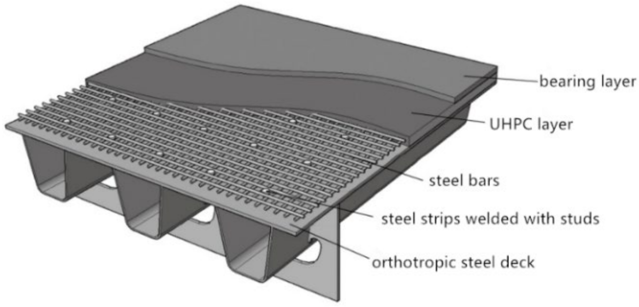


Figure 5. Cross-sectional view of the pavement [9]

Wang et al. [9] concluded that UHPC greatly decreases the stress domain under the wheel load. By evaluating the case of Fochen West Bridge in China, Zhu et al. [10] believed that UHPC-OSD system presents adequate anti-fatigue capability, and that much smaller maximal stress can be expected in all details compared with the previous one. Also, Xu et al. [11] concluded that the orthotropic steel deck bridge after the reinforcement of UHPC layer can last for more than 100 years. Hesham et al. [12] suggested that the crack formation life rises 236% while applying the UHPC overlayer. They also claimed that a 60mm thick layer is advisable for lessening hot spot stress.

2.2.3 SFRC application in OSD fatigue reinforcement

SFRC possesses a good durability and good resistance of chemical or biochemical erosion. It is widely used in Japan for fatigue reinforcement.

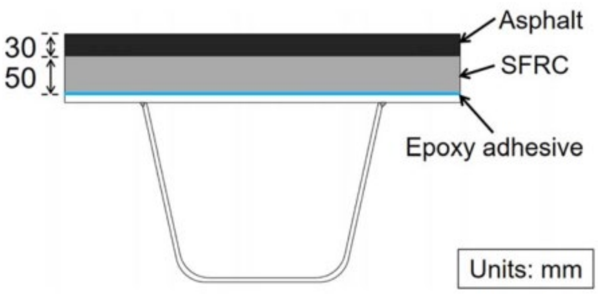


Figure 6. The structure of pavement with the application of SFRC [13]

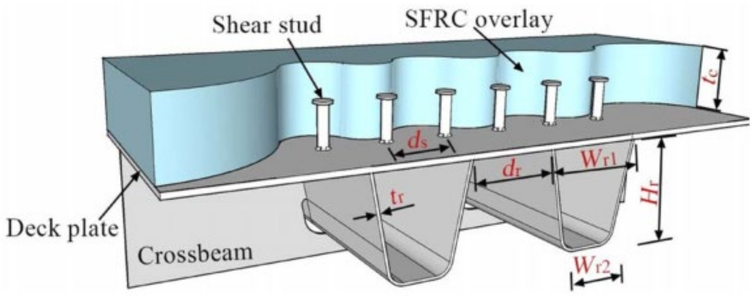


Figure 7. The structure of pavement [14]

Figure 6 shows the structure using SFRC, consisting of OSD, SFRC layer and asphalt layer. Epoxy adhesive is added between SFRC and the orthotropic steel deck to ensure unity of SFRC and OSDs. As shown in Figure 7, sometimes shear studs will be put into OSDs in order to not only combine OSD and SFRC overlayer together, but also resist the shear strain.

Ye et al. [14] stated that SFRC has a great influence on the durability of the bridge deck. And the thickness of this overlayer determines the property of the bridge deck under the vehicle load. They also stated that using high-shear-resistant SFRC is necessary for improving the fatigue propagation [14]. Concluding from the experiment, Tadashi et al. [15] suggested that applying SFRC instead of traditional pavement can greatly slow down the development of crack propagation. They claimed that using epoxy adhesive between the orthotropic steel deck and SFRC pavement can reduce the stress and enhance the capacity of anti-fatigue [15]. And SFRC is useful to control longitudinal and horizontal development of fatigue crack on the orthotropic steel deck, and it can be deduced that the degree of crack control is generally proportional to the reinforcement ratio [16].

2. Discussion

This part compares different methods of fatigue reinforcement among some important parameters. The results are shown in Table 1. From Table 1, it can be seen that cold reinforcement techniques mainly include three methods. Each method has some capacities to decrease the stress. The Cold connecting plate method can decrease by at least 10MPa, and UHPFRC can decrease by 60%.

From Table 2, it can be indicated that bonding system and SPS are both good methods for decreasing stress. Bonding system can reduce stress by 40%, and it can expand life for about 6-15 years. SPS can reduce stress by 40%, and it can elongate the fatigue life for 4-7 times.

The requirement of prestress for using Fe-SMA is usually over 300 MPa. Fe-SMA is used to provide a primary force to control the crack. Therefore, it needs to provide 300MPa prestress before used in repair.

Table 1. Parameter comparison within cold reinforcement techniques

Parameters	Stress decrement	The range of application
Drilling stop-hole method		less than 42MPa and the out-of-plane stress is within a small range.
Cold connecting plate method	At least 10MPa	original fatigue strain range is larger than 50 micro-strains.
UHPFRC	60%	

Table 2. Parameter comparison within bonding system and SPS

Parameter	Stress decrement	The extension of life
Bonding system	45%	6-15 years
SPS	40%	4-7 times

From the information above, it can be found that local reinforcement has a good effect on the extension of bridge life in its feasible scope. Because the data is not a reduction at the same starting point, it is difficult to find which one is best. However, through the experimental data of scholars, it can be seen that the local reinforcement method can improve the fatigue of bridges to a large extent, so as to obtain longer service life.

Table 3. Parameters comparison within UHPC

parameters	Compressive stress	Tensile stress	Fatigue lifetime	Fatigue lifetime increment	Stress decrement	Applicable field
Using UHPC	>=120 MPa	>=7 MPa	8 million cycles	Over 230%	26%-83%	UHPC <100 mm
Using SFRC	>=113 MPa	>=5.2 MPa			18%-31%	SFRC >=120mm

From Table 3, it can be seen that after UHPC reinforcement, fatigue life is increased by over 230% and stress is decreased by over 25%, which shows good property of fatigue reinforcement and is good enough to suffer from wheel load for many years. And it is noticeable that the UHPC layer is only 100 millimeters in thickness. It can also be found that the stress is decreased by over 18%, but not more than 31%. And the required thickness for SFRC is over 120 millimeters, which also shows good property for fatigue reinforcement. UHPC and SFRC have similar stress lower limit, but usually UHPC can withstand much higher compressive and tensile stress. However, it is difficult to tell which one has better performance in fatigue reinforcement since the data in the table is only the lower limit, and there is accurate definition for them.

Both UHPC and SFRC layer can be taken as materials for fatigue reinforcement, but there is something to consider. First is self-weight. It seems that using UHPC layer will have lighter weight. On the one hand, using UHPC requires a thinner layer of UHPC and presents better fatigue resistance. On the other hand, using SFRC needs steel bars, which adds extra weight to the system and causes a heavier mass. Second is the cost. UHPC is a relatively high-cost material compared with conventional concrete. This will greatly increase the project expenses. In conclusion, deciding to use which type of material depends greatly on mechanical properties, total cost, environmental factors, installation equipment and so on. It would be better to have a comprehensive consideration of all factors as possible.

3. Conclusion

OSD is now widely used in Europe, America, China and other countries due to its advantages of light weight and convenient installation. In this paper, the current achievements in the reinforcement and maintenance of OSD bridges with fatigue damage are summarized, and both advantages and disadvantages of reinforcement technologies are listed. These are to facilitate readers to compare different technologies and provide a potential direction for the subsequent research of relevant scholars.

It is concluded that local reinforcement and integral reinforcement are two main methods to improve the fatigue state of orthotropic steel deck. Cold reinforcement of the drilling and sealing method should not be used alone, which means combining with other methods shows better reinforcement effects. The bonding system and SPS equipment are light in weight and easy to lay and these two methods have a good effect in reinforcement. Fe-SMA material is relatively new and needs further exploration. The overall effect of local reinforcement is better. The maintenance process will not affect the normal running of vehicles, and the cost is relatively low. However, when it is used, it will be subjected to many conditions. UHPC composite system has a good effect on improving the fatigue performance of OSDs. Its advantages lie in its high fatigue resistance, stress resistance and durability. SFRC layer can control fatigue propagation both longitudinally and laterally, which is a good fatigue reinforcement material for OSD bridges. Scholars in the field are working on other novel materials, such as NWF. However, the overall reinforcement may be complicated in operation. At the same time, normal traffic will be affected due to the overall modification in the process of modification.

At present, the fatigue damage reinforcement techniques of orthotropic deck of bridge are more and more diversified. Based on these measures, some better reinforcement measures can be further explored. The simple operation can also prolong the life of OSDs. It may also be possible to combine it with computer technology, with cooperation in areas such as electronic instruments, to promote further development of reinforcement technologies.

References

[1] Deng Wenzhong. New Idea of Orthotropic plate steel Surface Bridge [J]. Selected Edition of Bridge Journal, 2009, 38-45.

[2] Ji Bohai. Fatigue Life Evaluation of U-rib Butt Weld of Orthotropic Steel Bridge Deck [J]. Journal of Chongqing Jiaotong University, 2015, 16-21.

[3] Wang Chunsheng, Zhai Musai, Duan Lan, et al. Cold Reinforcement and Evaluation of Steel Bridges with Fatigue Cracks [J], Journal of Bridge Engineering, 2018, 23(4): 04018014.

[4] Sofia Teixeira de Freitas, Henk Kolstein, Frans Bijlaard. Fatigue behaviour of bonded and sandwich systems for strengthening orthotropic bridge decks [J], Composite Structures, 2013, 97: 117-128.

[5] Sofia Teixeira de Freitas, Henk Kolstein, Frans Bijlaard. Lightweight Reinforcement Systems for Fatigue-Cracked Orthotropic Bridge Decks [J], Structural Engineering International, 2012 23(4), 458-467.

[6] Feldmann M., Sedlacek G., Ge ler A., A System of Steel-elastom Sandwich Plates for Strengthening Orthotropic Bridge Decks [J], Mechanics of Composite Materials, 2007.

[7] Zhang Qinghua, Zhu Jinzhu, Chen Lu, et al. Research on a Positive Reinforcement Method for Fatigue Cracking in Longitudinal Rib Butt Welds of Orthotropic Steel Bridge Deck, 2021, 51(2): 18-25. (In Chinese)

[8] Benjamin G., Eugen B., Byung-Suk Kim, et al. International Perspective on UHPC in Bridge Engineering, American Society of Civil Engineering, 2020, 25(11): 1-16.

[9] Yang Wang, Xudong Shao, Jie Chen, et al. UHPC-based strengthening technique for orthotropic steel decks with significant fatigue cracking issues [J], Journal of constructional steel research, 2021, 176: 1-13.

[10] Zhu Zhiwen, Yuan Tao, Xiang Ze, et al. Behaviour and fatigue performance of details in an orthotropic steel bridge with UHPC-deck plate composite system under in-service traffic flows [J]. Journal of bridge engineering, 2017, 23: 4017142-4017163.

[11] Xu Jiang, Yuan Yuan, Chong Wu, et al. Fatigue life assessment of orthotropic steel deck with UHPC pavement [J]. Journal of engineering, 2017, 1-10.

[12] Hesham A., Bin Cheng, Liang Tian, et al. Reduce hot spot stresses in welded connections of orthotropic steel bridge decks by using UHPC layer: Experimental and numerical investigation. Engineering structure, 2020, 1-16.

[13] Mizuki Hayama, Hidehiko Sekiya, Masanobu Nagai.: Verification of the Reinforcement Effect of an SFRC Pavement under a Live Load Based on Visualization of Deformation of a Trough Rib of an Orthotropic Steel Deck Using MSMSIMUs and Contact Displacement Gauges [J]. Journal of Bridge Engineering, 2022, 1-12.

[14] Ye Huawen, Yang Zhe, Han Bing, et al. Failure mechanisms governing fatigue strength of steel-SFRC composite bridge deck with U-ribs [J]. American society of civil engineering, 2021, 1-9.

[15] Abe Tadashi, Yutaka Kawai, Takeshiy, et al. Decreasing effect of stress in orthotropic steel decks by SFRC [J]. Journal of Japan society of civil engineering, 2015, 47-62. (In Japanese)

[16] Su Qingtian, Dai Changyuan, Xu Chen. Full-scale experimental study on the negative flexural behaviour of orthotropic steel-concrete composite bridge deck [J]. American society of civil engineering, 2018, 1-14.