# Experimental study on repairing of fatigue-cracked steel plates using high strength bolts and CFRP strips

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ABSTRACT: Nowadays, there are a large number of aging steel bridges producing the fatigue cracks under the fatigue loading. It is quite necessary to adopt appropriate repair methods to ensure the safe operation of the bridges. The fatigue performance of precracked steel plates using various repair methods was experimentally studied in this work. The test specimens included four main groups: reference unstrengthened group, repaired group using only stop-hole method, high strength bolt stop-hole group and high modulus CFRP strips repaired group. Under the high cycle tension-tension fatigue loading, the failure mode and fatigue life of all groups were obtained. Moreover, the effectiveness of the strengthened steel plates was investigated. Experimental results reveal that the methods of high-strength bolt stop-hole repairing and the high modulus CFRP repairing have significant effects. In addition, high strength bolt stop-hole repairing method is slightly better than high elastic modulus CFRP repairing method.

## 1 INTRODUCTION

Steel bridges are always prone to fatigue cracking under the continuously repeated loads, especially in orthotropic steel bridge decks affected by heavy traffic lines. Fatigue cracking can significantly lead to the loss of integral rigidity and the reduction of the bearing capacity of structures, and then affect the smooth driving and traffic safety in modern steel bridges. Thus there is urgent need for strengthening of aging steel structures. In order to repair the existing fatigue cracks in the steel bridges, several repair methods include stop hole method, adding doubler plates method, bolting, welding, etc, and these methods are applicable to certain occasions. The use of carbon fiber reinforcement polymer(CFRP) has a wide prospect for strengthening the steel structures because of its unique properties such as high strength-to-weight ratio, high corrosion resistance, and good anti-fatigue performance(Zhao, 2013; Ghafoori et al. 2015; Hosseini et al. 2019). These qualities make CFRP to be beneficial to repair, retrofit and rehabilitation of civil engineering structures. In addition, high elastic modulus CFRP has also been shown to have better repair effects(Wu et al. 2012).

In this paper, a set of experimental tests on strengthening of cracked steel plates are conducted to determine the fatigue performance of structures under various repair methods. The stop-hole repair method means that drilling a hole at the crack tip turns the crack into a notch and diminishes the crack tip stress singularity(Song et al.2004).The high strength bolt stop-hole method is to tighten the stop hole in structures with the high strength bolts and gaskets(Uchida 2007).The high modulus CFRP repair method is to increase the structural stiffness by pasting high modulus CFRP strips, which could also prolong the fatigue life of the structures. Through the fatigue crack repair tests of steel plates, the failure mode and fatigue life are obtained. Also, the repair efficiency of different methods is determined.

## 2 EXPERIMENT

### *2.1 Test specimens*

A total of twelve precracked standard steel plates were designed and tested under fatigue tensile loading. The test specimens were divided into four groups with different repair methods, including one group of unstrengthened steel plates, one group of steel plates repaired by stop-hole method, one group of steel plates repaired by high strength bolt stop-hole method and one group of steel plates repaired by high modulus CFRP. As is shown in the Figure 1, the standard steel plate specimen with overall dimensions of 620mm × 230mm × 12mm (length × width × thickness) is like dumbbell-shaped, and each steel plate has a initial artificial notch. Three unstrengthened notched steel plates were prepared as control specimens. The other strengthened specimens are shown in the Figure 2. In particular, the pretightening force of high strength bolts was set at 30kN for the high strength bolt stop-hole group.

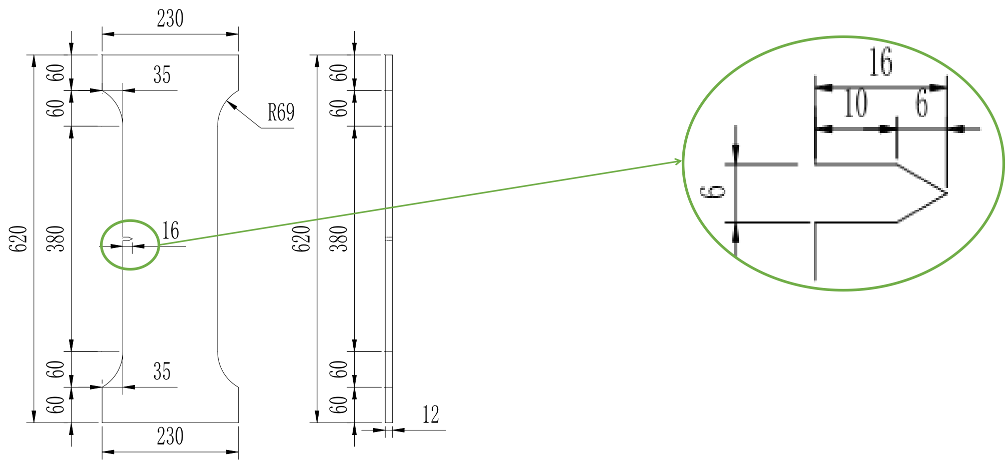
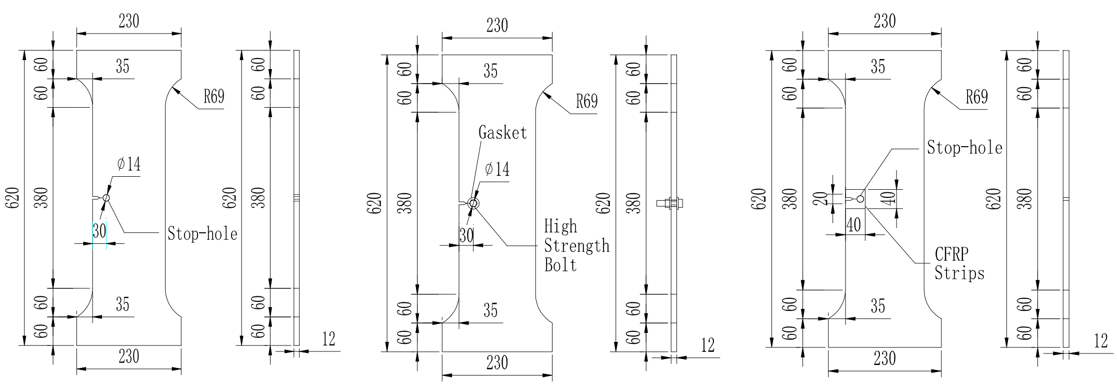



Figure 1. Control group of standard steel plate (mm)




a) Stop-hole repair group b) High strength bolt stop-hole group c) High modulus CFRP repair group

Figure 2. Dimensions of strengthened steel plates with various repair methods(mm)

### 2.2 Material properties

The utilized steel plates in all experiments were of type Q345 with a nominal yield strength of 345MPa. Furthermore, material experimental tests of three steel plates were conducted and the mechanical properties of steel plates were provided in Table 1.And the mechanical properties of structural adhesive and CFRP strips were present in Table 2.

Table 1. Mechanical properties of steel plates

| Elastic modulus(MPa) | Yield strength(MPa) | Tensile strength(MPa) |
|---|---|---|
| 210501 | 418 | 541 |

Table 2. Material properties of structural adhesive and CFRP strips

| Material | Tensile Strength(MPa) | Tensile elastic modulus(MPa) |
|---|---|---|
| Structural Adhesive | 53.1 | 2490 |
| CFRP strips | 4216 | 252000 |

### 2.3 Test set-up and instrumentation

All the fatigue test were performed in a static/fatigue servo-hydraulic machine named MTS647 Test Frame System. As depicted in Figure 3, the specimens were loaded symmetrically at the middle point. The clamping area of the upper and lower clamps was 100mm × 126mm. The lower end was fixed and the upper end actuator applied the load.

The specimen loading is divided into two stages: precracked stage and formal fatigue stage. In each stage, the specimen is preloaded with 60kN tensile force to ensure the normal operation of strain gauges and verify the reliability of finite element calculation results. The effectiveness of the strengthened steel plates was tested under high cycle tension-tension fatigue loading tests with a load frequency of 10 Hz and a stress ratio R=0.1. The specific load range is shown in Table 3. Considering the crack uniformity, precision of control and practical maneuverability, CNC wire-cutting machine was finally chosen to produce the crack. In precracked stage, the prefabricated crack length of unstrengthened group is 30mm, while the others are 37mm because of the increase of stop-hole radius.

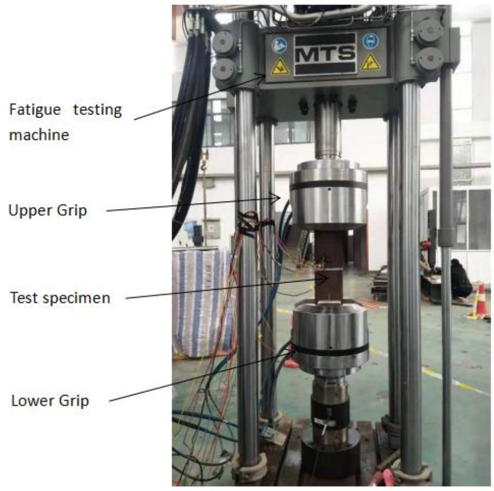
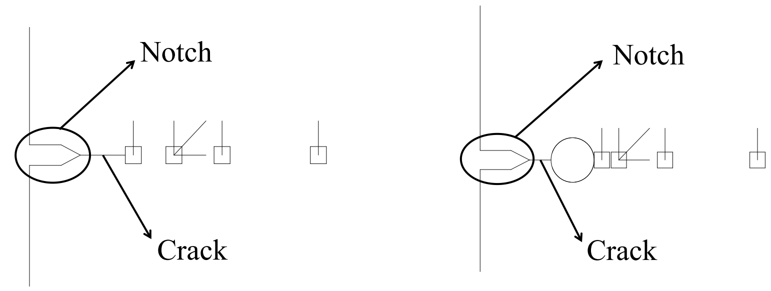



Figure 3. Fatigue test set-up

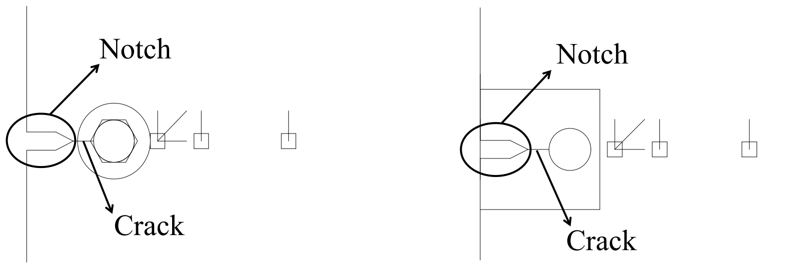
Table 3. Summary of load design of test specimens

| Strengthening method | Specimen | Load range （kN） | Designed stress amplitude （MPa） |
|---|---|---|---|
| Unstrengthened | 1-1 | 16.7～166.7 | 200 |
| | 1-2 | 19.4～194.4 | 250 |
| | 1-3 | 22.2～222.2 | 300 |
| Stop-hole | 2-1 | 16.7～166.7 | 200 |
| | 2-2 | 19.4～194.4 | 250 |
| | 2-3 | 22.2～222.2 | 300 |
| High strength bolt stop-hole | 3-1 | 16.7～166.7 | 200 |
| | 3-2 | 19.4～194.4 | 250 |
| | 3-3 | 22.2～222.2 | 300 |
| High modulus CFRP | 4-1 | 16.7～166.7 | 200 |
| | 4-2 | 19.4～194.4 | 250 |
| | 4-3 | 22.2～222.2 | 300 |

In order to monitor the strain distribution at the vicinity of crack tip on the steel plates, two strain rosettes and four strain gauges were placed at the same position for each specimens. However, the first strain rosette is far away from the crack or stop-hole tip, the strain gauge at the crack or crack stop (about 2mm away from the center of the strain gauges to the edge) was added to the unstrengthened group (group 1) and the stop-hole repair group (group 2), as shown in Figure 4(a)～(b). The distance between the strain rosettes of the four groups and the edge of the steel plate is 45mm, and the distance between the same position of strain gauges and the edge of the steel plates is 60mm or 90mm for four groups, so as to conduct horizontal comparison. In the formal fatigue stage, a temperature compensation measuring point is set at one side, as shown in Figure 5.




a) Unstrengthened group b) Stop-hole repair group




c) high strength bolt stop-hole group d) High modulus CFRP repair group

Figure 4. Specimen instrumentation

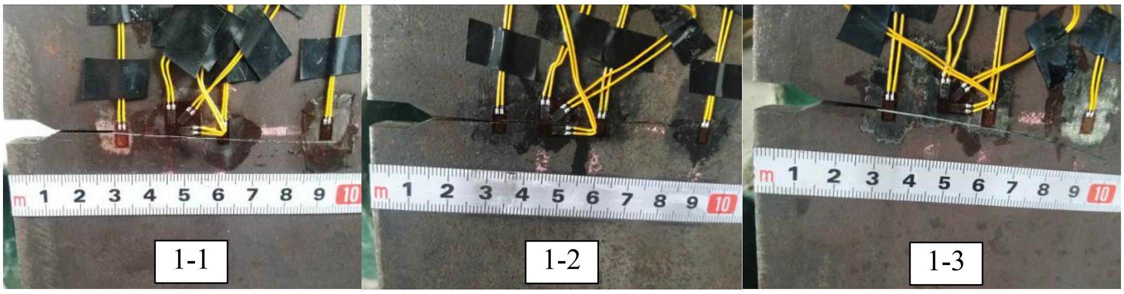
Figure 5. Layout of temperature compensation measuring points

## 3 RESULTS AND DISCUSSION

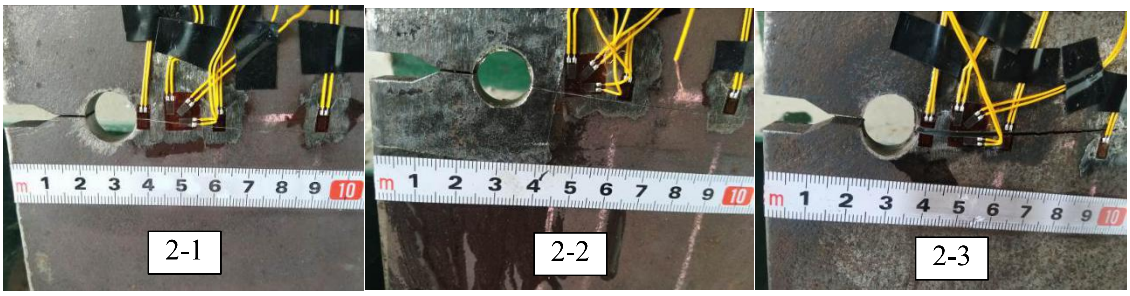
### *3.1 Failure modes*

The typical failure modes of all specimens under fatigue loading can be identified from the damaged photographs of specimens, as depicted in Figure 6(a)～(d).

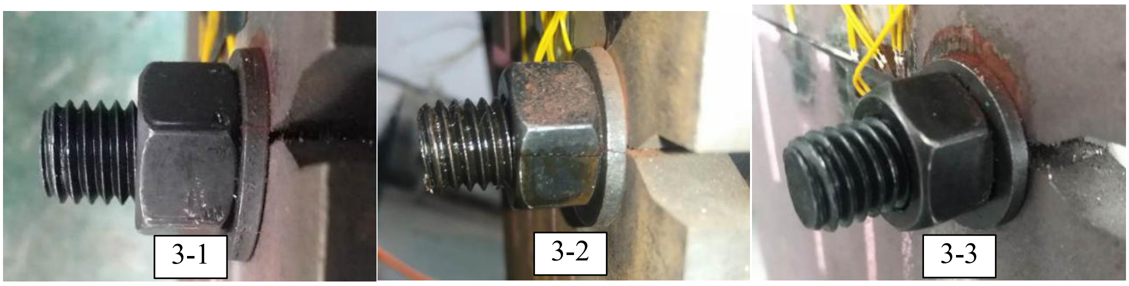
The fatigue crack initiation of specimens 1-1, 1-2 and 1-3 were occurred at the crack tip, and the others all were generated at the minimum cross-section of the stop hole. In particular, for high strength bolt stop-hole group, the gaskets and bolts were suffered from fatigue fracture under the action of friction due to the cumulative damage. At the same time, with the decrease of the preload efficiency, the failure finally happened at the minimum section of the stop-hole. However, the gaskets or bolts of test specimen 3-3 were not damaged, and the relative slip between the washers and the steel plate was obvious, indicating that the bolt pre-tightening force failed, as shown in figure Figure 6 (c), and its fatigue life did not reach the expected level. This situation should be avoided in the actual repair, and the corresponding preload should be increased when necessary. For the high modulus CFRP repair group, the failure resulted from the debonding of the interface between CFRP strips and steel plates, as shown in Figure 6(d).First of all, the test specimens 4-2 and 4-3 showed interfacial debonding shortly after the beginning of dynamic load, and the relative slip between CFRP strips and steel plates was obvious, indicating that the CFRP repair failed at an early stage and its fatigue life did not reach the expected level, which should be avoided in the practical strengthening. After fine adjustment of the pasting process, the specimen 4-1 achieved the desired effect. The final failure mode of CFRP strips in specimens 4-2 and 4-3 is the same as that of specimen 4-1.



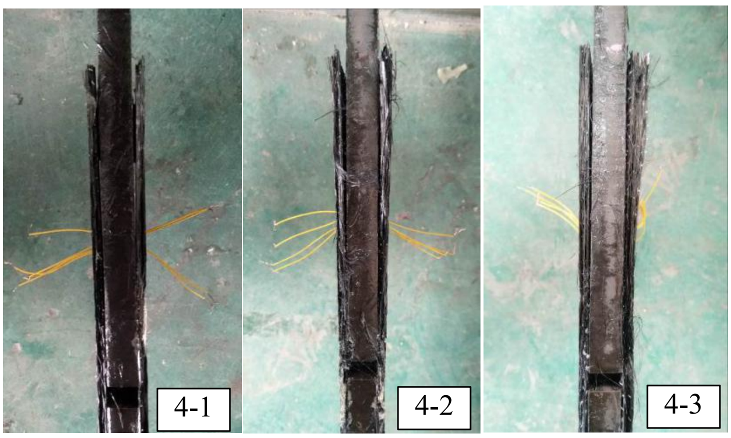

a) Failure modes of unstrengthened group




b) Failure modes of stop-hole repair group




c) Failure modes of high strength bolt stop-hole repair group




d) Failure modes of high modulus CFRP repair group

Figure 6. Failure modes of all groups

### 3.2 *Fatigue life*

The fatigue failure of the structures originates from the tiny defects of the structures themselves and the stress concentration is generated under the action of external loads. The tiny defects gradually develop into cracks and expand continuously.

The criterion of fatigue failure is that the stress amplitude measured by strain gauges 45mm away from the edge of specimens changes obviously or the strain gauge of tip is destroyed (both are basically synchronous). The results of crack initiation life (regarded as fatigue life) were summarized in Table 4. In the high elastic modulus CFRP repair group, the obvious changes of the stress amplitude measured by the strain gauge 60mm away from the edge of the specimen was taken as the criterion of fatigue failure, and the crack initiation life was obtained by corresponding reduction. Since the strain gauges at 45mm or the strain gauges at 60mm is not located at the tip of the prefabricated crack or stop hole, the measured stress amplitude should be obtained according to the data of the strain gauges at the tip or through corresponding conversion.

| Test specimen | Load range （kN） | Measured stress amplitude （MPa） | Initial change （$10^4$ times） | Specimen damage （$10^4$ times） |
|---|---|---|---|---|
| 1-1 | 16.7～166.7 | 235 | 1.0 | 8.2 |
| 1-2 | 19.4～194.4 | 284 | 0.5 | 4.6 |
| 1-3 | 22.2～222.2 | 319 | 0.4 | 3.7 |
| 2-1 | 16.7～166.7 | 330 | 20.5 | 25.2 |
| 2-2 | 19.4～194.4 | 389 | 13.5 | 17.1 |
| 2-3 | 22.2～222.2 | 459 | 5.0 | 8.1 |
| 3-1 | 16.7～166.7 | 298 | 178.5 | 180.7 |
| 3-2 | 19.4～194.4 | 357 | 139.5 | 141.9 |
| 3-3 | 22.2～222.2 | 398 | 23.5 | 26.6 |
| 4-1 | 16.7～166.7 | 275 | 172.7 | 175.7 |
| 4-2 | 19.4～194.4 | 320 | 20.0 | 24.7 |
| 4-3 | 22.2～222.2 | 381 | 13.0 | 18.2 |

*Bolt rupture occurs in 3-3 specimen, and CFRP early failures occur in 4-2 and 4-3 specimens.

## 4 CONCLUSION

In this study, fatigue tests were mainly carried out on two repair methods of high strength bolt stop hole and high modulus CFRP strips, and the reference groups of stop hole method and unrepaired method were set up by contrast. Based on the experiments and analytical modeling, the main conclusions from this study can be summarized as follows:

(1) Given the failure mode under the fatigue loading, the fatigue crack initiation of specimens 1-1, 1-2 and 1-3 were occurred at the crack tip, and the others all were generated at the minimum cross-section of the stop hole.

(2)The fatigue life of precracked steel plates reinforced by the stop-hole repair method can be extended by more than 20 times, while the fatigue life of adopting high strength bolts stop-hole repair method is more than 9 times than that of only by stop-hole repair method. Furthermore, the fatigue life of the structures with pre-tightening force failure of high-strength bolts is obviously decreased, which is 4.7 times of that of the repair with only the stop hole. And the fatigue life of the structures repaired with high elastic modulus CFRP strips is more than 8 times that of the structures repaired solely with the stop hole. Similarly, the fatigue life of the structures repaired with high modulus CFRP strips is obviously decreased when the CFRP strips fail early, which is 1.8 times that of the structures repaired with only the stop hole. These failure of pre-tightening force and early CFRP strips should be avoided during actual repair.

(3)Each repair method can effectively reduce the peak stress and plays surely the role of strengthening steel plates. The methods of high-strength bolt stop-hole repair and the high modulus CFRP repair have significant effects, which are consistent with the fatigue test results. In addition, high strength bolt stop-hole repair method is slightly better than high elastic modulus CFRP repair method.

## 5 ACKNOWLEDGMENTS

The authors acknowledge the financial support from Key Project of Chinese National Programs for Fundamental Research and Development (973 Program, Grant No: 2013CB036303), the National Natural Science Foundation of China (No. 51408424) and the Fundamental Research Funds for the Central Universities.

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