Experimental study on fatigue performance of bushing repair with different fasteners

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Abstract. Based on the fatigue theory, the main influencing parameters of bushing repair are qualitatively analyzed. The specimen-level fatigue test is carried out to quantitatively analyze the changes in the fatigue quality of metal structures connected by different fasteners before and after the bushing repair. The result suggests that: The DFR of the high-lock bolt connection after bushing repair is basically the same as the engineering calculation result, and the DFR of rivet connection after bushing repair is steadily lower than the engineering calculation result; Under a certain bushing interference, as the outer diameter of the bushing increases, the fatigue quality of the bushing repair structure of the high-lock bolt connection and the rivet connection shows a tendency to decrease and then increase. The experimental research provides reference for the application of civil aircraft bushing repair technology.

1. Introduction
In the manufacturing process of civil aircraft, manufacturing deviations such as deviation of fastener diameters, singular holes, and dislocation of assembly holes often occur. Using bushings to repair fastener holes is one of the treatment methods. The use of bushings to repair fastener holes has an impact on the fatigue quality of the structure, and quantitative evaluation of its impact is critical to the determination of the treatment plan. At present, the bushing repair of fastener holes has been widely used in the mainstream manufacture of civil aircraft, but there are very few relevant technical data[1], and relevant technical research has also been carried out in China[2-9], but mainly concentrate on the interference matching process of bushing and hole, qualitative analysis of bushing repair and engineering evaluation.

Based on the engineering theoretical analysis of bushing repair, this paper adopts experimental methods to carry out a quantitative analysis of the impact of bushing repair on the fatigue quality of metal structures when different fasteners are connected, aiming to provide guidance to engineering treatment and evaluation.

2. Engineering theoretical analysis
According to the analysis of fatigue theory, the fastener hole edge is more prone to cracks, and the fatigue quality is affected by the stress concentration caused by the bypass load Fa and the fastener load P, the surface quality of the hole, and the connection. The fatigue risk parts before and after the bushing repair are all located at the minimum section, as shown in Figure 1.
Two factors determine the impact of bushing repair on structural fatigue quality: one is the stress concentration of the bushing repair hole, which is related to the outer diameter of the bushing and the hole edge distance; the other is the assembly of the bushing hole, that is, the initial stress state, related to the bushing interference and the fit of fasteners.

Based on the qualitative analysis of the above-mentioned parameters, the benefits of bushing repair to structural fatigue include\cite{3,9}: 1) Increasing the outer diameter of the bushing can reduce the extrusion stress of the bushing hole edge and the additional stress of the hole edge caused by the local bending of the fastener, and reduce the stress concentration caused by the fastener load; 2) The bushing adopts freezing installation method, which can avoid damage to the hole wall and ensure the surface quality. The aspects of bushing repair that are not conducive to structural fatigue include: 1) Increasing the outer diameter of the bushing will reduce the edge distance of the bushing hole and increase the stress concentration caused by the bypass load; 2) If the initial interference of the bushing is small, after the fastener is installed, the interference of the bushing hole will be reduced compared with the interference of the fastener hole, thereby reducing the initial fit of the fastener hole.

3. Experimental Research
The method of numerical simulation alone cannot accurately incorporate the influencing of the process. Therefore, the bush repair fatigue test of different fasteners is carried out, and the test results are comparatively analyzed with the engineering values.

The test adopts the double-shear and double-row structure. The base material is 2524-T3, the thickness is 1.6mm, the bushing material is 7075-T651, the thickness is 1.6mm, and the diameter of the bushing is 1.0030 to 1.0045 times the hole diameter. Fasteners are titanium high-lock bolts HST10AG6 and aluminum alloy rivets MS20470AD6. The test mainly considers the structural fatigue quality of different bushing diameters under the connection of two different fasteners. The parameters are shown in Table 1.

| Group | Fastener type   | Bushing diameter(mm) | Bushing diameter/fastener diameter |
|-------|-----------------|-----------------------|-----------------------------------|
| 0-1   | HST10AG6        | Control group         | Control group                      |
| 1-1   | HST10AG6        | 6.5                   | 1.365                              |
| 1-2   | HST10AG6        | 7.8                   | 1.638                              |
| 1-3   | HST10AG6        | 9.1                   | 1.911                              |
| 1-4   | HST10AG6        | 10.4                  | 2.184                              |
| 0-2   | MS20470AD6      | Control group         | Control group                      |
| 2-1   | MS20470AD6      | 6.5                   | 1.365                              |
| 2-2   | MS20470AD6      | 7.8                   | 1.638                              |
| 2-3   | MS20470AD6      | 9.1                   | 1.911                              |
| 2-4   | MS20470AD6      | 10.4                  | 2.184                              |
4. Result analysis
The fatigue test results of each group are shown in Figure 2. The fracture positions of the test pieces are similar. The cracks sprouted from the edge of the hole where the bushing was installed and expanded to the edge of the plate along the direction perpendicular to the load. The fracture of some test pieces is shown in Figure 3.

![Figure 2 fatigue test results](image1)

![Figure 3 fracture of some test pieces](image2)

The Chauvenet criterion is used to eliminate the abnormal test data, and the valid data is processed by the standard S-N curve method. The characteristic life is first obtained, and then the reliability life \( N_{95,95} \) is calculated from the specimen coefficient, the confidence coefficient and the reliability coefficient, and finally solve the detailed fatigue rating (DFR) of the test piece according to the standard SN curve equation. Calculate engineering DFR according to "Civil Aircraft Structure Durability and Damage Tolerance Design Manual"[10]. Test DFR and engineering DFR are shown in Table 2.

| Group | TEST DFR (MPa) | Compare with no bushing | Engineering DFR (MPa) | deviation |
|-------|----------------|-------------------------|----------------------|-----------|
| 0-1   | 209.94         | -                       | 155.73               | 34.81%    |
| 1-1   | 184.05         | -12.33%                 | 155.73               | 18.19%    |
|   | DFR (mm) | % Change | DFR (mm) | % Change |
|---|---------|----------|---------|----------|
| 1-2 | 154.91 | -26.21% | 155.73 | -0.53% |
| 1-3 | 149.67 | -28.71% | 155.73 | -3.89% |
| 1-4 | 163.42 | -22.16% | 155.73 | 4.94% |
| 0-2 | 131.09 | -131.66 | -0.43% | 131.66 |
| 2-1 | 112.60 | -14.10% | 131.66 | -14.48% |
| 2-2 | 116.78 | -10.92% | 131.66 | -11.30% |
| 2-3 | 110.95 | -15.36% | 131.66 | -15.73% |
| 2-4 | 117.04 | -10.72% | 131.66 | -11.10% |

It can be obtained from the test results that the DFR of the two types of fastener connection structures decreased after bushing repair. For high-lock bolts, the increase in the hole diameter of the bush reduces the compression stress at the edge of the bush hole and the stress concentration caused by the load transmitted by the fastener, and as the ratio of the plate thickness to the hole diameter of the bush decreases, that reduces the additional stress of the hole edge caused by the local bending of the high-lock bolt, which is beneficial to the fatigue quality; but on the other hand, as the bushing hole diameter increases, the bushing hole edge distance decreases, which increases the stress of the bypass load concentration, and the increase of the bushing hole diameter will reduce the initial matching effect of the fastener hole, and will have an adverse effect on the fatigue quality. Considering the comprehensive influence of the above-mentioned factors, the DFR of the structure does not show a monotonic characteristic as the outer diameter of the bushing increases.

The test results of rivets are similar to that of high-lock bolts. Under the influence of multiple factors, the DFR of the structure does not show the monotonic characteristics of increasing the outer diameter of the bushing. The difference is that the test value of the high lock bolt is higher than the engineering value when the hole is small, while the test value of the rivet is lower than the engineering value. Except for the cracks in the bushing hole, the rivet test piece is cracked in the other row of rivet holes.

5. Conclusion

Based on the fatigue theory, the main influencing parameters of bushing repair are qualitatively analyzed, and the specimen-level fatigue test is carried out to quantitatively analyze the changes in the fatigue quality of metal structures before and after the bushing repair with different fasteners. The study came to the following conclusions:

1) Under certain parameters for high-lock bolt connection, bushing repair will not reduce structural fatigue strength.

2) The DFR of the high-lock bolt connection after bushing repair is basically the same as the engineering calculation result, and the rivet connection after bushing repair is steadily lower than the engineering calculation result.

3) Under a certain bushing interference, as the outer diameter of the bushing increases, the fatigue quality of the bushing repair structure of the high-lock bolt and the rivet connection shows a tendency to decrease and then increase.

The experimental research provides reference for the application of bushing repair technology on civil aircraft.

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