Experimental Investigation of Fatigue Quality of Structure Under Tensile Load with Unloaded Fasteners Which Rivet Bucktail Overrides Bend Radius (Parallel to Load) in Civil Aircraft

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Abstract. In the process of civil aircraft production, there will exist such a situation that the fasteners interfere with bend radius and it is hard to replace the structure element because of some limits of objective condition. This article investigates the fatigue quality of structure under tensile load with unloaded fasteners which rivet bucktail overrides bend radius (parallel to load) in civil aircraft by fatigue tests based on DFR method. The results show that the DFR value will not decrease if the fastener interferes with bend radius is not as serious as the situation that the No.6 rivet hole of the structure under tensile load with R5 invases bend radius 1.0mm.

1. Introduction
A single complete unit is relatively light due to no connection details, so it is an ideal airframe for the aircraft structural designer. However, considering the requirements of manufacture and maintenance, the majority of metal airframe structures consist of built-up construction. There are a lot of structures under tensile road with unloaded fasteners which bend radius parallels to load in built-up construction of civil aircraft, as shown in Figure 1.

In the process of civil aircraft production, a variety of unforeseen causes will make the product and design configuration not completely consistent[1]. And there are many factors leading the fasteners interfering with bend radius, for example, lacking of space, occlusion of sight, human error. Under these circumstances, the fasteners cannot be installed according to the design requirements. If it is difficult to replace the parts that do not meet the design requirement because of economic cost or schedules, the procedure that rivet bucktail overrides bend radius is recommended for the structure of several units held together by rivets[2], as shown in Figure 2. There would be high local stress in the area of bend radius, and the fastener hole would occur stress concentration when the structure are subjected to load. The superposition effect of these two factors would make the local stress higher. On the other hand, the short edge distance for end fastener leading the non-standard installation of fastener, would have an impact on the fatigue quality of the connection details. For this situation, we have not found a quantitative fatigue assessment method at present. In order to improve the ability of engineering support in the batch production of civil aircraft, it is necessary to study this issue.
This article investigates the fatigue quality of structure under tensile road with unloaded fasteners which rivet bucktail overrides bend radius (parallel to load) in civil aircraft by fatigue tests based on DFR method, expecting to provide reference for the evaluation of such engineering problems.

2. Test design

2.1. Configuration of specimen
The specimen consists of a plate and a stiffened plate, and it is held together by 6 rivets, as shown in Figure 3.

After analysing several types of specimen based on the finite element analysis, we know that this configuration of specimen has good symmetry. Also, the eccentricities between the test section and the end is relatively small. So, the stress distribution in the test section is uniform and it can avoid the secondary bending stress ideally. This is helpful to reduce the interference of manufacturing error and other factors on the test results, and is helpful to reduce the dispersion of test data.

To ensure the failure occurs in the test section of the stiffened plate with bend radius, the plate without bend radius is made of 2000 series aluminum alloy, and the stiffened plate is made of 7000 series aluminum alloy which the fatigue performance is worse than the 2000 series aluminum alloy.
2.2. Parameter of specimen

We analyze the influence of the size of bend radius, the diameter of rivet, the thickness of plate on the stress concentration of the structure with unloaded fasteners which rivets interfere with bend radius (parallel to load). The size of bend radius take 3 levels: R3, R4, R5. The diameter of rivet take 3 levels: 4.0mm, 5.0mm, 5.5mm. The thickness of plate take 3 levels: 1.6mm, 2.0mm, 2.5mm. And the hole of rivet invases bend radius 1.0mm.

In order to get scientific and reasonable conclusions through a small amount of calculation, we choose orthogonal test design [3] to determine the case to be calculated. The factors and levels to be analyzed is shown in Table 1.

Considering the factors and levels in Table 1, the orthogonal table $L_9(3^4)$ can meet the analysis requirement. The stress concentration factor of each group utilizing the finite element analysis is shown in Table 2.

**Table 1. Factor level table.**

| Level | Factor          | Size of Bend Radius | Diameter of Rivet | Thickness of Plate |
|-------|-----------------|---------------------|-------------------|--------------------|
| 1     |                 | R3                  | 4.0mm             | 1.6mm              |
| 2     |                 | R4                  | 5.0mm             | 2.0mm              |
| 3     |                 | R5                  | 5.5mm             | 2.5mm              |

**Table 2. Stress concentration factor(Ktg).**

| No. | Ktg  | No. | Ktg  | No. | Ktg  |
|-----|------|-----|------|-----|------|
| 1   | 3.26 | 4   | 3.25 | 7   | 3.20 |
| 2   | 3.23 | 5   | 3.32 | 8   | 3.26 |
| 3   | 3.32 | 6   | 3.28 | 9   | 3.26 |

Based on Table 2, we judge that the influence of the size of bend radius, the diameter of rivet, the thickness of plate on the stress concentration is not significant, the maximum difference is less than 3.61%. In the case of the same invasion of the rivet hole to the bend radius, the general trend is as follows: the stress concentration factor will decrease as the size of bend radius increase; the stress...
concentration factor is random as the diameter of rivet increase (the decrease of net section area will increase the stress, however, the increase of distance between the center of rivet hole and the bend radius will make the stress gradient smaller, as the diameter of rivet increase); the thickness of plate has little effect on the stress concentration factor as the thickness of plate increase.

We analyze the influence of the interference of fasteners with bend radius on the stress concentration of the structure with unloaded fasteners which rivets interfere with bend radius (parallel to load). The size of bend radius is R5, the diameter of rivet is 5.0 mm, the thickness of plate is 1.6 mm, the distance between bend radius and rivet take 3 levels: rivets far away from bend radius; distance between bend radius and rivet is 1.0 mm; the rivet hole invades bend radius 1.0 mm. The stress concentration factor of the 3 cases utilizing the finite element analysis is 3.13, 3.11, 3.23. Therefore, we judge that the influence of the interference of fasteners with bend radius on the stress concentration is also not significant, and the maximum difference is less than 3.72%. Besides, the high stress area of the case that rivets far away from bend radius is larger than the other 2 cases.

Intuitively, the fasteners deviate from the standard installation more serious as the size of bend radius decrease and as the distance between rivets and bend radius decrease. According to the batch production of a specific civil aircraft, the case that structure under tensile road with R5 that the hole of No.6 rivet invades bend radius 1.0 mm is a rare bad situation.

Based on the above situation, we choose 3 groups fatigue test, the parameters of specimen are as follows: the size of bend radius is R5; the diameter of rivet is 5.0 mm, the thickness of plate is 1.6 mm; the distance between bend radius and rivet take 3 levels, that is, rivets far away from bend radius, distance between bend radius and rivet is 1.0 mm, the hole of rivet invades bend radius 1.0 mm.

2.3. The load spectrum
Draw lessons from Reference [4], the load spectrum is as follows: the load applied is constant amplitude load (sinusoidal load), stress ratio is 0.06, the frequency is 500 ~ 1800 cycles/minute, the fatigue life is about 1.5 ~ 3.5 × 10^5 cycles.

For the group of rivets far away from bend radius, the theoretical load can be calculated by the following process: first, we calculate the DFR value of the test section according to the double row fastener details of structure under tensile road with unloaded fasteners; second, we reverse derive the working stress from DFR value utilizing the “single point method” of Reference [4]; last, we calculate the load according to the working stress and the cross sectional area of test section. The theoretical load can provide reference to the pretest load, and the final test load should be adjusted according to the pretest result to ensure the fatigue life of specimen is within the appropriate range.

The theoretical loads of other groups are hard to predicted because of the non-standard installation of fasteners. So, they should be adjusted according to the group of rivets far away from bend radius and the pretest result.

3. Test results

3.1. Processing data for test
For the original fatigue life of each experimental group, we use two ways to process data for outliers: first, we remove the fatigue life which are too long or too short; second, we eliminate the fatigue life which are not in the same sample utilizing the Chauvenet Criteria [5], to ensure the test results more reasonable.

Next, we can derive the DFR value of each experimental group utilizing the “single point method” of Reference [4] from the filtered fatigue life and the strain measured in the specimens.

3.2. Analysis of test results
All of the specimen failure in the expected test section. Through SEM analysis, we find the crack propagation process as follows: the crack starts first at the edge of the fastener hole of the plate, the crack initiation life is more than 70% of the total fatigue life, the life when the crack length reaches 0.5mm is more than 80% of the total fatigue life, the instability failure occurs when the crack length reaches 5.0mm. We consider that the specimen will begin to fail when the crack length reaches 0.5mm, so we derive the DFR value utilizing 80% of the total fatigue life.

For the group of rivets far away from bend radius, the test DFR value is 7.77% higher than the theoretical value. The difference is within the reasonable range, therefore, the results of this test have reference value for engineering application.

We define the ratio of the DFR value of the group which rivets interfere with bend radius to the DFR value of the group that rivets far away from bend radius as the interference factor, and the notation is R’. The factor of R’ of each group is shown in Table 3. Compared with Group 1, the DFR values of Group 2 and Group 3 do not decrease. Compared with Group 2, the DFR value of Group 3 decreases 0.07%. Combined with the stress concentration analysis in Section 2.2 of this article, we conjecture the causes are as follows: the high stress area will decrease because of strengthening of vertical edge as rivets interfere with bend radius; the non-standard installation of rivets will make the fatigue quality become worse; The effect of the 2 factors on DFR value is reverse, and which factor plays a leading role depends on the distance between rivets and bend radius.

### Table 3. The R’ value

| No. | Distance Between Rivets And Bend Radius | R’   |
|-----|----------------------------------------|------|
| 1   | Rivets far away from bend radius       | 1.00 |
| 2   | Distance between rivets and bend radius is 1.0mm | 1.02 |
| 3   | The rivet hole invades bend radius 1.0mm | 1.01 |

### 4. Conclusions

For structure under tensile road with unloaded fasteners which rivet bucktail overrides bend radius (parallel to load), the effect of short edge distance for end fasteners on stress concentration is not significant. And because of strengthening of vertical edge, the high stress area will decrease, the DFR value of the structure will increase, but the non-standard installation of fasteners will make the DFR value of the structure decrease.

The DFR value will no decrease if if the fastener interferes with bend radius is not as serious as the situation that the No.6 rivet hole of the structure under tensile load with R5 invases bend radius 1.0mm.

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