Static and Fatigue Properties of Scarf Patch Repaired Composite Laminates: An Experimental Study

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Abstract. In this paper, the static and fatigue properties of prepreg scarf-repaired composite laminates and wet layup scarf-repaired composite laminates are investigated experimentally. The results show that the patch debonding of the specimens with prepreg scarf-repaired is less than that of wet layup scarf-repaired. At the average strength of prepreg scarf-repaired specimens is higher than that of wet layup scarf-repaired. The strength of specimens is heavily influenced by the failure mode. The strength of the specimens with a same fracture surface on the upper and lower surface in test region is highest while strength is slightly decreased when the fracture surface is different on the upper and lower surface, and the strength is lowest when the specimens fail in the clamping area or near the clamping area. Fatigue has little effect on the specimen stiffness, failure strain, failure strength, debonding of repaired patch and failure mode of specimens.

1. Introduction
With the rapid development of China's aerospace, automobile industry, high-speed train and other industries, advanced composite materials with high specific strength, high specific stiffness, strong designability and good fatigue resistance have been more and more widely used [1,2]. Defects and damages will inevitably occur in the process of production, manufacture and use of composite structures [3-6].

Composite material structure repair is gradually developed on the premise that composite materials are widely used in military and civil fields. The repairing technology of composite structures has been relatively mature since the early 1980s. However, with the application of new materials and structures, the technology still needs to be developed and improved. In our country, the repair technology of composite materials started late and lacked practical application experience. Many problems need to be further studied [7].

The repair of composite structures can be classified into several categories according to the site and condition of repair shop, the different repair methods and the characteristics of the parts to be repaired. Generally, it can be divided into bonding repair machine and mechanical connection repair [8]. Bonding repair is the main common repair method, and bonding repair is divided into patching repair method and digging repair method. The repair method studied in this paper is digging repair. Digging
and repairing is suitable for repairing damages with large damage area and serious situation. Because this method generally uses prepreg as repairing material, it has certain advantages for repairing surfaces with large curvature or strict aerodynamic shape. It can obtain maximum structural recovery strength with minimum weight gain.

At present, the research on material repair mainly focuses on oblique repair configuration [9], while the research on the axial tension behavior of prepreg after permanent repair and wet paving repair is relatively less [10]. In this paper, an experimental study on composite laminate specimens repaired by digging and repairing is carried out. The effects of two repairing processes, permanent repairing with prepreg and time-limited repairing with wet paving, on the load-carrying capacity of the repaired specimens are studied. At the same time, the tensile-tensile fatigue test is carried out on the specimens to study the fatigue performance of the bonded repair specimens

2. Test

2.1. Test piece
The material of the test piece is M21E/IMA, the material specification is CMS-CP-309, and the thickness of the single layer is 0.1868 mm. The layers of the test piece are shown in Table 1. The dimension of the tensile test piece is 525 x 145 mm, and the length of the clamping section is 155 mm at both ends. The damage depth of all specimens is 5 layers, and the excavation and repair slope is 1:30. The test piece is shown in Figure 1. The test matrix of the test items is shown in Table 2. Among them, RP represents repair test, BR is prepreg bonding repair method, WLM is wet paving material repair method, FT and ST represent tension-tension fatigue test and static tension test respectively, CP represents test piece, a represents opening damage diameter of 13 mm.

![Figure 1. Tensile test piece.](image)

![Figure 2. Test piece clamping scheme.](image)
Table 1. Test piece layup information.

| Test project | Typical layup | thickness |
|--------------|---------------|-----------|
| Tensile test | [45/-45/-45/90/45/0]s | 12 layers(2.242mm) |

Table 2. Repair plate tensile test matrix.

| Repair method       | Damage type /mm | Test piece            | Test type                  |
|---------------------|-----------------|-----------------------|----------------------------|
| Permanent repair     | Opening diameter | RP- BR -FT-CP-A-1     | Tension-tension fatigue test  |
|                     | 13              | RP- BR -ST-CP-A-2     | Static tensile test         |
|                     |                 | RP- BR -ST-CP-A-3     | Static tensile test         |
| Limited time repair  | Opening diameter | RP-WLM-FT-CP-A-1      | Tension-tension fatigue test  |
|                     | 13              | RP-WLM-ST-CP-A-2      | Static tensile test         |
|                     |                 | RP-WLM-ST-CP-A-3      | Static tensile test         |

2.2. Test Scheme
Before the test, ultrasonic nondestructive testing is carried out to ensure that there are no defects such as delamination in the test piece. Static and fatigue tests were carried out using INSTRON 8802 25t static-fatigue testing machine. The clamping scheme is shown in Figure 2. The peak and valley values of the equal-amplitude spectrum of fatigue test are 31.6 KN and 3.16 KN, respectively. The stress ratio is 0.1 and the loading frequency is 2 Hz. A total of 1 million cycles are carried out. During the fatigue period, ultrasonic nondestructive testing is carried out after 100,000, 200,000, 500,000 and 1 million cycles, respectively, to detect the initiation and expansion of fatigue damage. After the fatigue test, if the specimen is not invalid, the static test will continue. The loading rate of 1 mm/min is used in both static test and post-fatigue static test.

![Figure 3. Numbering scheme of strain gauge for load-strain curve of tensile specimens](image)

The layout and numbering of strain gauges are shown in Fig. 3. Each specimen consists of 8 unidirectional sheets and 6 triaxial strain gauges. The strain gauge is symmetrical with respect to the center of the plate. The strain gauge in parentheses is attached to the non-repaired surface, and the position of the positive and negative side is the same. The repair surface strain gauge number is Ai
(i=1~13), the intact surface strain gauge number is Bi (i=1~13), of which 1, 2, 3 and 4 are medium, 5, 8 and 11 are strain gauges along the loading direction, 6, 9 and 12 are strain gauges along the 45 degree direction, 7, 10 and 13 are strain gauges perpendicular to the loading direction.

3. Test results and analysis

3.1. Load-Strain Curve

The load-strain curves of the six specimens included in this test can be divided into two situations, general situation and patch debonding situation.

Generally speaking, in the initial stage of loading, the strain increases linearly with the load and disturbs the curve around 100kN, but the strain distribution remains unchanged. That is to say, there is no damage near the measuring point, which the load disturbance is caused by the debonding of the reinforcing plate. The load-strain curve of RP-BR-FT-CP-A-1 is generally represented, as shown in Figure 4 below. Such cases include RP-BR-FT-CP-A-1, RP-BR-ST-CP-A-3, and RP-WLM-ST-CP-A-3.

In the initial stage of loading, the strain increases linearly with the load and disturbs the curve around 100kN, but the strain distribution remains unchanged. That is to say, there is no damage near the measuring point. For the load disturbance caused by the partial debonding of the reinforcing patch, the strain distribution changes when the load is loaded to a larger load, which shows that the A5 strain on the repairing side decreases greatly and the B5 on the intact side increases, which is the patch Debonding. The debonding of the patch represents the load-strain curve of RP-BR-ST-CP-A-2, as shown in Figure 5 below. Additionally, there are RP-BR-ST-CP-A-2, RP-WLM-FT-CP-A-1, and RP-WLM-ST-CP-A-2.

After analyzing the load-strain curves, the debonding of patches occurred in some specimens during static tension. The debonding conditions and debonding loads are shown in Table 3. It can be seen that the debonding of patches repaired with wet paving time limit is more than that repaired with prepreg permanently. One million fatigue cycles have no effect on the debonding of patches repaired with two repair methods.

### Table 3. Patch debonding.

| Number | RP-BR-F(S)T-CP-A | RP-WLM-F(S)T-CP-A |
|--------|------------------|------------------|
| 1      | /                | 114.8KN          |
| 2      | 168.4KN          | 167.9KN          |
| 3      | /                | /                |

Figure 4. Load-strain curve of RP-BR-FT-CP-A-1.
The failure load and strength of the two groups of specimens are shown in Table 4. The average strength of prepreg repaired specimens was 645.5 MPa, and that of wet paving repaired specimens was 607.2 MPa. It can be concluded that the repairing strength of prepreg is higher than that of wet paving repair by 6% and the peak and valley values of fatigue load spectrum are 4.9% and 0.5% of the failure load respectively. The peak and valley values of fatigue load spectrum are about 5% and 0.5% of the failure load, respectively. Under this fatigue spectrum, 1 million fatigue cycles have no effect on the strength of repaired specimens.

Table 4. Failure Load and Ultimate Strength of Test Piece

| Test pieces Name | Destructive load /KN | average value /KN | strength /MPa | average value /MPa |
|------------------|----------------------|------------------|---------------|------------------|
| RP-BR-F(S)T-CP-A-1 | 199.1                |                  | 627.5         |                  |
| RP-BR-F(S)T-CP-A-2 | 208.1                | 205.2            | 651.7         | 645.5            |
| RP-BR-F(S)T-CP-A-3 | 208.4                |                  | 657.5         |                  |
| RP-WLM-F(S)T-CP-A-1 | 195.7                |                  | 590.1         |                  |
| RP-WLM-F(S)T-CP-A-2 | 212.2                | 194.3            | 653.3         | 607.2            |
| RP-WLM-F(S)T-CP-A-3 | 175.1                |                  | 578.2         |                  |

3.2. Failure Mode
The ultimate failure modes of the permanent prepreg repair specimens and wet paving time-limited repair specimens are shown in Fig. 6 and Fig. 7 below. During the static loading, all the six specimens were loaded to about 100 kN, and the load drop was abrupt. According to the test observation and strain data, it was judged that the reinforcing sheet had a large area of debonding, which affected the subsequent loading of the failure mode. The prepreg permanent repair A-2 and wet-paving repair A-1 and A-2 patches had a large area of debonding, but debonding did not lead to the final failure of the specimens.

The failure modes of A-2, A-3 and wet paving repair A-2 in the prepreg repair group are the failure in the clamping zone, and the delamination damage near the clamping zone extends from the clamping zone to the middle side of the test section, which results in slippage and dislocation of the
test piece. The positive and negative fracture surfaces are the same, and the strength is the highest in the same group. Prepreg A-1 and wet paving repair group A-1 were damaged in the test area, but the positive and negative fracture surfaces were different, that is, there was a large area of delamination in the test area, and the strength was lower in the same group of specimens. The strength of wet paving repair group A-3 was the lowest near the clamping area.

![Figure 6. RP-BR-F(S) T-CP-A failure mode.](image1)

![Figure 7. RP-WLM-F(S) T-CP-A failure mode.](image2)

3.3. Nondestructive Testing of Fatigue Process

During the test, 1000000 cycles were carried out, and nondestructive testing was carried out after 10000, 200000, 500000 cycles and fatigue tests respectively to determine whether there was fatigue damage initiation and expansion. The scanning images of the testing were shown in Fig. 8 and Fig. 9. From left to right and from top to bottom are the C-scan images of the specimen before test, 100,000 times of fatigue, 200,000 times of fatigue, 500,000 times of fatigue, 1 million times of fatigue and tensile test after fatigue. From the image, it can be seen that no damage and expansion of specimens occur during fatigue.

![Figure 8. RP-BR-FT-CP-A-1](image3)
3.5. Fatigue Stiffness Comparison

The samples before and after fatigue were loaded, and the load-strain curves were drawn by taking the average values of the two sections (upper section 1: A1, A4, B1, B4 and lower section 2: A2, A3, B2, and B3). The stiffness of fatigue specimens before and after the comparison, as shown in Figure 10 and Figure 11 below. It can be seen that the load-strain curves before and after fatigue are consistent, that is, the overall stiffness of the structure is basically the same as before fatigue. It can be considered that the fatigue test has no effect on the repair effect. The results show that the repaired composite plate has good tensile-tensile fatigue load resistance.
4. conclusion

After permanent repair and tension-tension fatigue and static tension tests of composite prepreg, the following conclusions are drawn according to the test results of load-strain curve, failure strength and ultimate failure mode.

1) The debonding condition of wet patch repair patch is more than that of permanent repair of prepreg, indicating that the bonding between wet patch repair patch and motherboard is weaker.

2) The average strength of composite laminates repaired permanently with prepreg is 645.5 MPa. The average strength of composite laminates repaired with wet paving time limit is 607.2 MPa. The repairing strength of prepreg is 6% higher than that of wet paving repair.

3) The failure mode affects the failure strength of specimens. The strength of the specimens with the same fracture surface is higher in the test area, while the strength of the specimens with different fracture surface, in the clamping area or near the clamping area is lower.

4) The peak and valley values of fatigue load spectrum are about 5.0% and 0.5% of the failure load. Under this fatigue spectrum, no damage and expansion of the specimens occurred during 1 million fatigue cycles.

5) 1 million fatigue cycles have no effect on the debonding, failure strength and stiffness of patches for bonded excavation and repair specimens.

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