Study on application of adhesives for Carbon Fiber Composites connection in High-speed Rail

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Abstract. At present, the high-speed train mainly made up of carbon fiber composites adopts a new flame-retardant multi-material system. It is necessary to select adhesives for the Adhesive bonding structures of different materials in order to meet the overall technical and performance requirements of high-speed trains. Through this research, mechanical performance data of several structural adhesives and sealant adhesives are obtained when they are bonded to the high-speed trains with carbon fiber composite material as the main body. Finally, the optimum adhesives for bonding different material systems in the high-speed trains are determined under different operational aging environments, which also provides data support for the formulation of connection specifications for carbon fiber reinforced composites in the field of high-speed railway. In addition, a multi-dimensional data reduction method is proposed for the analysis of sealant performance data, which is very helpful for the future analysis of big data of adhesives.

1. Introduction

Integral High-speed trains are facing many problems, such as harsh service environment, complex coupling effect, improvement of operation speed and service quality, and lightweight is the key to solve these problems. As one of the latest fiber reinforced composites, Carbon Fiber Reinforced Composites (CFRP) have become the best choice for high-speed trains to solve the problem of lightweight due to their excellent comprehensive performance of lightweight, high strength and high weather resistance, and their mature application in aviation, aerospace, ship, automobile and sports medical fields[1-5]. However, CFRP is anisotropic: its interlaminar strength is low and ductility is small. Consequently, the connection is the weak link of performance[6-7]. At present, the bonding mode of CFRP is mainly bonded by different kinds of adhesives. Adhesive bonding refers to bonding two or more components through adhesives, it can avoid the stress concentration caused by hole-making, and it has the advantages of high bonding efficiency and light structure[8-10]. As a result, it has become a common connection mode in CFRP.

At present, the high-speed train mainly made up of carbon fiber composites adopts a new flame retardant multi-material system. Based on the diversity of its structure, materials and service conditions, it is necessary to select a variety of adhesives to meet the performance requirements of different parts of high-speed trains.

2. Experimental
Generally speaking, the selection of adhesives for high-speed trains made up of carbon fiber composites is mainly divided into two aspects. One is to select the best structural adhesives for bonding different materials in the high-speed train, and the other is to select the best sealant for specific materials in the high-speed train.

2.1 Tensile shear property test of structural adhesives
The tensile shear property test of structural adhesives is mainly to select the best structural adhesive for the adhesion between two different materials in the high-speed train. It is mainly to select by testing and comparing the tensile shear strength of the adhesive samples with different adhesives under the standard tensile shear aging environment[11]. The test standard that Adhesives-Determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies (GB/T 7124-2008 of China, idt ISO 4587:2003) is followed to test the lap-shear, and the whole shear tests were tested at room temperature(23℃). Among them, the bonding between the two materials adopts the way of single lap. The specific lapping mode is shown in Figure 1:

![Figure 1. Single lap bonding between Carbon Fiber Composites](image)

The structural adhesives selected in this study are mainly as follows:

1. Polyurethane structural adhesives: UK1351 (1351), TS845(845) and 8100, suitable for assembling aluminum plates, steel plates and plastic part;
2. Modified polyurethane structural adhesive: 3381, mainly used for bonding polypropylene(PP), polyvinyl chloride(PVC), polyethylene(PE), engineering plastics(ABS) and other plastics;
3. Acrylic structural adhesive: 880, suitable for bonding plastics, glass and rubber.

There are four kinds of plates that need to be bonded with adhesives as a whole: stainless steel, CFRP, PVC and bakelite.

The types and sizes of adhesive samples with different adhesives are as follows:

1. Adhesive 1351/845/8100:
   ① Bakelite 25×100×2(mm) + Stainless steel 25×100×1(mm)
   ② CFRP 25×100×2(mm) + PVC 25×100×2(mm)
   ③ CFRP 25×100×2(mm) + CFRP 25×100×2(mm)
2. Adhesive 880/3381: ① CFRP 25×100×2(mm) + PE 25×100×1(mm)

The standard test environment for aging is ISO9142D3 High and Low Temperature Cycle Curve with 14 cycles (seven days in total). The temperature change curve of a specific cycle is shown as Figure 2:

![Figure 2. ISO9142D3 High and Low Temperature Cycle Curve](image)
The test process of structural adhesive tensile shear property test mainly includes plate sample grinding, alcohol cleaning, drying, adhesive tape, curing, tensile shear aging environment treatment and tensile shear strength test.

2.2 The stripping performance test of sealant

The stripping performance test of sealant is mainly to select the best sealant adhesive for a specific material in the high-speed train made up of CFRP. It is mainly to select by testing and comparing the stripping performance of different adhesives in different standard aging environment. The test standard that Structural adhesives-Testing of adhesively bonded joints-Grub peel test (DIN54457-2007) is followed to perform 180° stripping test. The sealants selected in this study are mainly silane modified polymers, which mainly include the following three types: Terostat MS 939 FR(939), MS1939(1939) and ISR 70-03 SSKF (7003). And there are three kinds of materials that need to be tested for adhesive stripping performance: stainless steel, CFRP, PVC. For each type of sealant, the adhesive sample type and size are as follows:

(1) Stainless steel 150 x 300 x 2 (mm); (2) CFRP 150 x 300 x 2 (mm); (3) PVC 150 x 300 x 2 (mm)

The standard aging treatment test environment for the stripping performance test of sealed adhesives mainly includes four types: (1) solidification for 168 hours; (2) solidification for 168 hours + soaking water for 168 hours; (3) solidification for 168 hours + soaking water for 168 hours + 80°C high temperature for 24h; (4) solidification for 168 hours + soaking water for 168 hours + 80°C high temperature for 24 hours + high temperature and humidity 168 hours.

In general, the stripping performance test process of sealant mainly includes plate sample grinding, alcohol cleaning, drying, coating adhesive in surface, curing, different aging environment treatment and stripping performance test[12-13]. Figure 3 is a sealant bonded to the surface of CFRP. The stripping performance test of sealant is mainly through 180° stripping experiment to measure the ratio of the stripping cohesive failure of each adhesive, that is, the ratio of the adhesive cohesive failure surface to the total coating area when the bond sample is strippinged off. The higher the value is, the better the adhesion performance is. Figure 4 is the stripping performance test of stainless steel for different adhesives, and the stripping cohesion failure ratio on the left is 98%, and the right is 10%.

2.3 Experimental Equipment

The main experimental equipments needed in this research are as follows: Aging Testing Machine, Programmable constant temperature and humidity testing machine, Commercial compressed air gun, Static screw mixer, Beaker, glass rod, sandpaper, tape, etc.

3. Results and discussions
3.1 Tensile shear properties of structural adhesives

By testing the tensile shear properties of adhesive specimens with different structures, the tensile shear strength of different adhesives treated under standard tensile shear aging environment is finally obtained, and the error bar for the test data is ± 0.1Mpa, as shown in Table 1 below:

Table 1. Tensile shear strength after aging treatment of different adhesives bonding plates(MPa)

| Aging condition | Bakelite+Stainless steel | CFRP+PVC | CFRP+CFRP | CFRP+PE |
|-----------------|--------------------------|----------|-----------|---------|
| Adhesive type   | 8100 845 1351 8100 845 1351 8100 845 1351 8100 845 1351 880 3381 |
| Tensile shear strength/MPa | 1.2 0.7 0.9 5.7 5.8 ∞ 13.7 7.4 17.0 3.1 0.9 |

Structural adhesives are shown in Figure 5. Obviously, the following conclusions can be drawn:

1) For bonding stainless steel and bakelite, the order of tensile shear strength of different adhesives from high to low is adhesive 8100>1351>845, so 8100 can be preferred from the performance of tensile shear properties.

2) Adhesive 1351 has the strongest tensile shear strength when bonding CFRP and PVC, because the PVC sheet has been damaged before the adhesive bonding site is damaged during the tensile shear performance test. The tensile shear performance of adhesive 8100 and 845 are not much different, and their tensile shear strength is around 5.7MPa.

3) The tensile shear strength is adhesive 1351>8100>845 when CFRP is bonded to each other from high to low, and the tensile shear strength of adhesive 1351 reaches 17MPa, indicating that the tensile shear performance of adhesive 1351 for bonding CFRP is very good, so adhesive 1351 is preferred.

4) When bonding CFRP with PE, the tensile shear performance of adhesive 880 is better than 3381, so it is preferred.

Figure 5. Bar chart of tensile shear strength when different plates are bonded with different adhesives, (a)Stainless steel+bakelite, (b)CFRP+PVC, (c)CFRP+CFRP, (d)CFRP+PE.
3.2 Stripping properties of sealants

By testing the tensile shear properties of adhesive specimens with different structures, the tensile shear strength of different adhesives treated under standard tensile shear aging environment is finally obtained, and the error bar for the test data is ± 0.1Mpa, as shown in Table 1 below:

By testing the stripping performance of the specimens bonded with different sealants, the stripping cohesive failure ratio of different adhesives after successively superimposed treatment in the standard stripping aging environment are finally obtained, and the error bar for the test data for the stripping test is ± 3%, as shown in Table 2:

| Aging conditions (Sequential superposition) | Material | Stainless steel | CFRP | PVC |
|-------------------------------------------|----------|-----------------|------|-----|
| solidification 168h                       | 939      | 1939            | 7003 |     |
| soaking water 168h                        | 85%      | 98%             | 80%  |     |
| 80℃ high temperature 24h                 | 90%      | 98%             | 80%  |     |
| high temperature and humidity 168h        | 95%      | 95%             | 90%  | 60% |

The above experimental test results are summarized to obtain the change curves of the stripping cohesion failure ratio of different adhesives after the treatment of successively superimposed aging environment, as shown in Figure 6. It is obvious that the following conclusions can be drawn:

(1) For stainless steel, adhesive 939 is highly sensitive to water when bonding, its stripping cohesion failure ratio after soaking water environment is only 10%, so the adhesion stripping performance is very poor. Adhesive 7003 and 1939 have better bonding properties overall. In addition, water will have a little impact on the stripping performance of adhesive 1939, and adhesive 7003 is more stable.

(2) For CFRP, the stripping performance of adhesive 1939 is more stable and safe, and the ratio of stripping cohesive failure under all four successively superposition aging environment treatment is higher than 90%. However, stripping performances of adhesive 7003 and 939 fluctuate greatly in different aging environments, and adhesive 939 performs poor in 80℃ high temperature environment.

(3) For PVC, the overall stripping performance of adhesive 939 is significantly lower than that of 1939 and 7003, there are safety risks in bonding. In addition, the stripping performance of adhesive 1939 and 7003 under all four successively superposition aging environment treatment is higher than 90%, the bonding is relatively safe and can be used. And, the stripping performance of adhesive 7003 is better than that of 1939.

![Figure 6](image_url)

**Figure 6.** The stripping cohesion failure radio curves of different adhesive bonding materials after the treatment of four successively superimposed aging environment(a)Stainless steel, (b)CFRP, (c)PVC.

3.3 Establishment of comprehensive stripping performance index of sealant

According to the stripping performance test of the above sealant, for each adhesive, it can be selected...
only when it shows better stripping performance under four different aging experimental environments. It has become the core problem of choosing adhesives for the high-speed train made up of CFRP that how to select the best adhesive quickly and accurately considering the stripping performance under the four different aging environments, especially when the adhesive in four different conditions show the jagged stripping performance (performances in some aging environments are good, also some are bad), this problem will become more important.

Considering the different stripping performance of different adhesives in four aging environments, a comprehensive evaluation index can be formulated to select sealants, which can solve the above problem well. And, according to the standard performance requirements of sealants, the comprehensive index needs to meet the following conditions:

1) The comprehensive stripping index must be the same as the stripping cohesion failure ratio when the stripping cohesion failure ratio in four different aging environments is the same.
2) Only when the stripping cohesion failure ratio is good in all four aging environment can the comprehensive index be good. As long as the stripping cohesion failure ratio is low in one of the circumstances, the comprehensive index will eventually be low and close to the lowest stripping cohesion failure ratio. The requirement of the comprehensive index also indicates that the average value is not satisfied;
3) According to the demand of different adhesives for different environments, a comprehensive stripping performance index focusing on one or more environments can be formulated.

Based on the above requirements, the following function is finally selected to calculate the comprehensive stripping performance index, and its specific expression is shown as in equation (1):

\[ H_{\text{com}} = \left( \frac{1}{\sum_{i=1}^{n} m_i} \times \left( \frac{m_1}{x_1} + \frac{m_2}{x_2} + \cdots + \frac{m_n}{x_n} \right) \right)^{-1} \]  

(1)

Among them, \( H_{\text{com}} \) is the formulated comprehensive stripping performance index, \( m_i \) is the weight coefficient of each environment, \( x_n \) is the stripping cohesion failure ratio in different aging environments, and \( n \) is the number of aging test environments needed. For the above functions, the comprehensive stripping performance index focusing on different environments can be worked out by adjusting the size of each weight.

Since the consideration of the four environments in this experimental study is equivalent, that is, the weight coefficients are the same, which can be assumed to be 1. In addition, there are only four different aging environments, that is, \( n=4 \). So, the final comprehensive stripping performance index is calculated as follows equation (2):

\[ H_{\text{com}} = \left( \frac{1}{4} \times \left( \frac{1}{x_1} + \frac{1}{x_2} + \frac{1}{x_3} + \frac{1}{x_4} \right) \right)^{-1} \]  

(2)

In the above formula, \( x_1, x_2, x_3 \) and \( x_4 \) is the actual stripping cohesion failure radio in four different aging environments of this experimental study. Bring them into the above formula, we could get the final comprehensive stripping performance index as shown in Table 3.

**Table 3.** The comprehensive stripping performance index of different adhesives under four different aging environments

| Material       | Stainless steel | CFRP  | PVC  |
|----------------|-----------------|-------|------|
| Adhesives      | 939             | 1939  | 7003 |
| comprehensive stripping performance(%) | 29.7%           | 84.6% | 82.3% | 74.7% | 97.2% | 84.7% | 60.2% | 94.2% | 97% |

The above data are summarized to obtain the bar chart of the comprehensive stripping performance indexes of different adhesives, as shown in Figure 7, and the following conclusions can be drawn:

1) For stainless steel, the comprehensive stripping performance of different sealants from high to low is adhesive 1939>7003>939, of which adhesive 1939 has the highest comprehensive stripping performance, so adhesive 1939 is the best choice.
2) For CFRP, the comprehensive stripping performance of different sealants from high to low is adhesive 1939>7003>939, of which adhesive 1939 has the highest comprehensive stripping performance, so adhesive 1939 is the best choice.
adhesive 1939>7003>939, and the comprehensive stripping index of adhesive 1939 is more than 90%, the bonding is very safe and adhesive 1939 can be selected.

(3) For PVC, the comprehensive stripping performance of different sealants from high to low is adhesive 7003>1939>939, the comprehensive stripping index of adhesive 7003 and 1939 are higher than 90%, so they both can be selected.

Figure 7. Bar chart of the comprehensive stripping performance indexes of different adhesives (a) Stainless steel, (b) CFRP, (c) PVC.

It can be seen that the above conclusions are consistent with those obtained in 3.2 analysis, which also indicates the effectiveness of the calculation method to the comprehensive stripping performance index.

4. Conclusions

Through the overall project research, the following conclusions are drawn for the selection of structural and sealant adhesives for carbon fiber composites connection in High-speed Rail:

(1) Structural adhesives
   1) Adhesive 1351 is preferred when CFRP is bonded to each other;
   2) Adhesive 1351 is preferred when bonding PVC with CFRP;
   3) Adhesive 8100 is preferred when bonding stainless steel with bakelite;
   4) Adhesive 880 is preferred when bonding PE with CFRP.

(2) Sealant adhesives
   1) Adhesive 1939 is preferred for CFRP;
   2) Adhesive 7003 is preferred for PVC;
   3) Adhesive 1939 is preferred for stainless steel.

In addition, in the stripping performance analysis for sealants, a new comprehensive stripping performance index is introduced for the stripping performance of the same adhesives in various environments, the essence is to reduce the dimension of multidimensional data and improve the efficiency of data processing, especially helpful for the big data analysis of the accumulation of different adhesive properties in the future. However, it is only a preliminary calculation method, which can be continuously improved according to the actual demand and the amount of data accumulated to make it more perfect and comprehensive.

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