Experimental study on bond strength failure of GFRP lap joints

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Abstract—Bonding has many advantages such as high adhesive strength, peel resistance, good toughness, shrinkage and corrosion-resistance, compared with bolting, welding and other connection patterns, which is the basic connection of the composite materials. The mechanical properties of the bond depend on the type and geometric parameters of the bond. In this paper, experiments were conducted to study the bond strength failure of GFRP single and double lap joints and explore related influencing factors. The variable factors of test specimens include bond type, length and thickness. The quasi-static tensile test was carried out at room temperature to analyze multiple influencing factors of lap joints and characteristic of GFRP bond failure strength. The results showed that the failure of the bond usually occurred at the interface of bond, and bond types, length and thickness have significant effects on the failure of bond. Failure strength increased firstly and then decreased with the increase of adhesive thickness. With the increase of bonding length, the failure mode of the double-lap joint become complex failure mode, which is accompanied by GFRP delamination near the surface of fiber of the bonding.

1. Introduction
Glass fiber reinforced polymer (GFRP) composite materials have been recognized and gradually promoted in aerospace, aviation, architecture and other fields due to the specific durability, specific modulus and geometry\cite{1}. In order to maintain the integrity of the structure, bonding has many advantages such as high adhesive strength, peel resistance, good toughness, shrinkage and corrosion-resistance, compared with bolting, welding and other connection patterns. Bonding is the most essential connection of the composite materials though there are many combination patterns of composites\cite{2-3}.

Over the years, many scholars had propose many theories to explore the property of the bonding such as mechanical interlocking theory, bonding adsorption theory, chemical bond theory, diffusion theory and so on\cite{4}. In fact, the complex mechanical phenomena in the bond structure system could not be explained by only one theory. It was found that for the double lap joints with ladder-like slot lap plate end, sub-maximum shear stress and peel stress were significantly decreased at overlapping end, joint static strength and fatigue strength were improved significantly compared with the traditional double lap joints\cite{5}. Based on the existing main failure criteria of adhesive, the maximum stress or maximum strain criterion was applied to the composite failure criterion. But for composite material, the maximum stress or maximum strain criterion is unsuitable actually because the failure of molecular cohesive force at the interface should be considered to be combined with the failure of adhesive force at the interface.
As for the double-lap bonded components, it was found that the material properties, geometric parameters of the adhesive and the bonding form have a great influence on the stress of the bonded structure, as well as the strength performance of the bonded structure. Obtaining structural stress distribution accurately is one of the preconditions for predicting bond strength. In this paper, the bond strength performance of GFRP lap joints under different adhesives type, lapping form, bond length and bond thickness were studied. Meanwhile, the stress-strain relationship and failure mode of bonding were analyzed. The aim of this study is to provide a more suitable method for failure characteristics of ductile adhesive.

2. Experimental program

2.1 Materials

The single and double lap joints were included in GFRP lap joints as the specimens in this test. All specimens were made of pultruded GFRP composite material. Araldite epoxy resin adhesive (AE) and Hysol E-20HP adhesive (HE) were used respectively. The mechanical properties of GFRP materials and adhesive were summarized in Table 1 according to the manufacturer provided. These specimens were divided into two groups, namely, 8 GFRP single lap joints and 32 GFRP double lap joints. The details of some specimens are showed in Table 2.

| Material name             | Properties      | Value   |
|---------------------------|-----------------|---------|
| GFRP                      | Young’s modulus $E_G$ (GPa) | 32.2    |
|                           | Poisson’s ratio $\mu_G$ | 0.32    |
|                           | Tensile Strength $f_{ut}$ (MPa) | 307     |
|                           | Shear strength $f_{s1}$ (MPa) | 26.7    |
| Araldite epoxy resin      | Young’s modulus $E_{AB}$ (GPa) | 1850    |
| adhesive                  | Poisson’s ratio $\mu_{AB}$ | 0.33    |
|                           | Shear strength $f_{s2}$ (MPa) | 560     |
| Hysol E-20HP               | Tensile Strength $f_{ut}$ (MPa) | 5700    |
|                           | Poisson’s ratio $\mu_{HP}$ | 0.35    |
|                           | Ductility (%)    | 8       |

2.2 Specimens

The specimens of the lap joint for tensile test are shown in Fig.1. The thickness of the lap plate is equal to that of the GFRP laminates bonded. According to the literature[6], sandpaper was used to polish the bonding surface and anhydrous alcohol was used to clean the impurities on the bonding surface to ensure the cleanliness of the bonding surface. The gasket was used to control the thickness of the adhesive, whose thickness is 0.1mm. The adhesive was evenly distributed in the overlapping area of GFRP laminates, and cured at room temperature for more than 12 hours, so that the bond strength of the samples reached the test conditions, which indicated that the specimens were made and formed[7].

| Specimen number | Adhesive          | Size(mm) | Effective bond length (mm) | Effective bond thickness (mm) |
|-----------------|-------------------|----------|---------------------------|-------------------------------|
| S-1-40          |                   | 200×20×5 | 40                        | 0.5                           |
| S-2-50          |                   | 200×20×5 | 50                        | 0.5                           |
| S-3-60          | Epoxy resin AB Adhesive | 200×20×5 | 60                        | 0.5                           |
| S-4-70          |                   | 200×20×5 | 70                        | 0.5                           |
| S-5-0.5         | Hysol loctite E-20 HP | 200×20×5 | 60                        | 0.5                           |
2.3. Test equipment and loading
In order to test the tensile strength of specimens and the energy dissipation performance of adhesive in bonding, electrohydraulic servo universal testing machine WA-FY600C controlled by microcomputer was used to test the tensile properties according to ISO 527-1. Firstly, the upper end of the test specimen was clamped and fixed completely. Then, the lower end was clamped as well. A uniformly stretching along the longitudinal direction at a constant speed of 0.5mm/min until failure was conducted[8-9], as shown in Fig.2. The failure strength of the bond joints was obtained by dividing the failure load $F$ by $S$ of the bond area. The failure modes of the joints and the curves of the tensile force changing with the displacement were also obtained, as shown in Fig.3 and 4.

Three sets of experiments, which variable factors composed of adhesive, bond length and bond thickness, were conducted respectively. The single-variable control method was adopted and each variable was repeated three times during the experiment.

3. Results and Discussion
3.1. Failure mode
Tensile failure modes for GFRP lap joints are different because of using different adhesive and geometry of laps. The failure failure of specimens with Araldite epoxy resin adhesive (AE) is mainly caused by cohesion failure and adhesion failure. When the thickness of the adhesive layer is maintained at 0.5mm, adhesion failure occurred in the peeling way, as shown in Fig.3 (a) and (b). However, the failure failure of the specimens with Hysol loctite E-20 HP Adhesive( HE) mainly occurred in the form of cohesion failure, adhesion failure, substrate stratification failure and mixed
failure, as shown in Fig.3 (c) and (d). The reason of brittle failure is that the clamping force was too large, which made the bond stress mutation and affected the stress distribution of specimens.

![Failure modes](image)

Fig. 3 Failure mode of specimens

3.2 Load-displacement curves
The force-displacement curves of the single-lap joints were obtained, as shown in Fig.4 (a). The results showed that the force increases with the increase of bonding length. The force increases by 1.08kN, 0.66kN, 0.48kN, respectively. For specimen S-4-70, capacity force increased by 2.27kN, which was more than half of that for specimen S-1-40. When the bonding thickness increases by 0.1mm, the applied load increases by 0.336kN on average. Kept the loading rate of specimens of S-5-0.5, S-6-0.6, S-7-0.7 and adhesive layer length of 60mm the same, there can be found a force drop appeared in the middle. The reason that is the internal bond changed with a slight sound in the process of the experiment, resulted to stress redistribution. Furthermore, when thickness is between 0.6mm and 0.7mm, the failure load increased almost 0.794kN, experimental results are shown in Fig.4(b).
3.3. Stress-strain analysis

Influence of bond thickness of double-lap bond strength failure were conducted by testing D-AE-1, D-AE-2, D-AE-4 and D-AE-5 with AE adhesive. The stress-strain curves of tensile test are shown as Fig. 5(a). Compared D-AE-1 to D-AE-5, it is found that the slope of D-AE-5 curve is higher at the beginning of loading to the failure. The final failure load is also higher and increasing by about 25%. Compared with D-AE-2 and D-AE-4, it is found that the change rate of D-AE-4 curve decreased at the beginning of loading and increased until failure, compared with D-AE-2. The failure load increased by about 12.5%.

In order to test effect of bond length of double lap on the failure, the specimens of D-HE-5, D-HE-6, D-HE-7 and D-HE-8 were selected, the experiment results are showed in Fig. 5(b). when bonding length kept at 70mm, the maximum stress value was 101.97MPa and the minimum stress value was 77.63MPa. The reason why the curve is different is that the center line of the bonding member for D-HE-5 was offset. It can be seen that the initial slope (elastic modulus) of four specimens is very close, indicated that bond performance with HE adhesive is reliable.
4. Conclusions
In this paper, tensile experiments were conducted to analyze several characteristics of bond failure and feasibility, including GFRP single and double lap bonding. The results showed that the double-lap bonding was effective for GFRP, which verified the effectiveness of the proposed method. The following conclusions were drawn:

(1) According to the comparative analysis of the experiments, the failure modes of specimens mainly occurred at the bond interface, failure mode was mainly adhesion failure, cohesion failure and the superposition mode of the two failure.

(2) Through the comparison of GFRP single and double lap bonding performance it was found that bond strength using double lap for GFRP members was larger than that using single lap method.

(3) By comparison of AE and HE adhesive, it was found that HE adhesive had better bond performance and pseudo ductility under the same experimental conditions due to the fiber on the bonding surface of GFRP plate was delamination, and the tensile failure mode was occurred.

(4) Bond performance of GFRP double lap was closely related to bond thickness. The optimal bonding thickness was 0.6mm. With increasing of bond thickness, the bond strength increased, then decreased slightly. The failure strength also increased linearly with increasing of bond length.

Acknowledgements
The authors gratefully acknowledge the financial support provided by key scientific research project of Education Department of Hunan Province (grant No: 20A426) and Natural Science Foundation of Hunan Provincial (grant No: 2021JJ50015). The experimental work was conducted in the Department of Civil Engineering at University of South China, and the technical support from Mr. Zhenfu Chen and Mr. Zhiheng Zhang (Structural Laboratory of University of South China) is acknowledged.

References
[1] Ku H and Wang H, 2011, A review on the tensile properties of natural fiber reinforced polymer composites, Compos. Pt. B-Eng. 42(4):856-873.
[2] Petrie E M. Handbook of adhesives and sealants[M]. McGraw-Hill Education, 2007.
[3] Yanhua Zhang, Zhu Libin, Tan Haiyan, et al. Adhesives and bonding technology [M]. Beijing: Chemical Industry Press, 2018.
[4] D5573-99 Standard practice for classifying failure modes in (FRP) joints.
[5] Chuang W Y, Tsai J L. Investigating the performances of stepwise patched double lap joint[J]. International Journal of Adhesion & Adhesives,2013, 42:44-50.
[6] Guan-xia Yang. Study on bonding repair and reinforcement technology and mechanical properties of composite materials [D]. Tianjin Polytechnic University,2019.
[7] D3164-03 Standard test method for strength properties of adhesively bonded plastic lap-shear sandwich joint in shear by tension loading.
[8] ISO 527–1 Determination of tensile properties.
[9] Pascoe J A, Zavatta N, Troiani E, et al. The effect of bond-line thickness on fatigue crack growth rate in adhesively bonded joints[J]. Engineering Fracture Mechanics, 2020, 229: 106959.