

# Chapter 53

## Failure Behavior of Single-Lapped CFRP Plates Under Quasi-static Tensile and Fatigue Loading



Yang Yang, Wenguang Liu, Xiaoting Wang, and Mingguang Gong

**Abstract** The purpose of this article is to analyze the failure behavior of single-lapped carbon fiber-reinforced polymer (CFRP) plates under quasi-static tensile and fatigue loading. Firstly, some bolted joints of T300 fiber reinforced polymer laminates with different torque are designed. Subsequently, the quasi-static tensile test and fatigue test are carried out and the displacement-loading curves are obtained. Based on the displacement-loading curves and failure situation, the failure behavior is analyzed. The results show that after changing the preload, the maximum load and average stiffness of the quasi-linear stage can be increased by 86.92% and 98.56%, respectively; the fatigue stiffness of connecting plates can add to 31.24% and 30.66% respectively when the load ratio is 0.8 and 0.5. The study reveals conclusions and suggestions on the application of bolt torque tightening in relation to the stiffness, fatigue life and damage tolerance characteristics of joints on CFRP composite material systems.

**Keywords** Carbon fiber reinforced polymer (CFRP) · Bolted joints · Failure mode · mechanical testing

### 53.1 Introduction

Fiber reinforced composite is usually employed as the substitute of the traditional materials. Because of their high specific stiffness and strength, low mass and design-ability, they are widely used in the field of aerospace engineering. However, composite bolted joints are always the weak links in the structure due to the high stress concentration caused by drilling and anisotropy. Their failure breaks the safety and integrity of the structure. And the stiffness of composite with bolted joint is affected by many factors, such as size, laying method, bolt-hole clearance and friction, and so on. Therefore, it is of great significance to study the failure mode and stiffness of bolted joints.

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In recent years, the strength and stiffness of composite connections with bolted joint have also been widely concerned. It was reported that common failure modes of FRP bolted connections are bearing failure, shear-out failure, net tension failure, cleavage failure, bolt failure, and punching failure [1]. So engineers need to avoid the occurrence of brittle failure. On the other hand, bearing failure, which was characterized by elongation of the bolt hole in the load direction, was preferable because it occurred slowly and provided sufficient warning before the final failure [2]. The clamping force induced by tightening torque also altered the mechanism and sequence of failure in bolted joints of composite laminates [3]. Besides, It was found that the static strength and fatigue performance of AS7/8552 composite bolt laminates can be enhanced by increasing the preload under the load environment [4]. Taking the double lap bolted connection structure as the object, Diana et al. studied the mechanical properties and failure modes of bolted joints through static tensile tests, and analyzed the influence of fatigue load on the stiffness degradation behavior of composite joints [5]. Through the experimental research, the influence of interference fit and stacking sequence parameters on composite interference fit joint was discussed by Hu, meanwhile, revealed the damage mechanism of coupling interface and load-bearing interface [6]. The main concern associated with composite joints was the bearing performance, which was often evaluated by bearing response tests [7]. The tightening process was proved to help improve optimum bearing performance in double-lap, single-bolted joints and achieve a more evenly distributed load in multi-bolt joints [8]. McCarthy et al. proposed a method that can be used to correctly calculate of extrusion stress in the period of detecting the properties of damaged materials, and obtain redistribution of load at one or more holes after bearing failure [9]. Segalman et al. preliminarily analyzed the power-law relationship between the damping energy dissipation and modal displacement of the system, and found that the energy dissipation value strongly depended on the spatial position of the excitation [10].

It was difficult to observe the damage of composite directly, but the numerical simulation method was helpful to analyze the damage evolution process of composite better [11]. Therefore, it is very important to establish an accurate damage evolution model of composite connection structure. At present, the commonly used methods to predict the strength of composite bolted connections include analysis method, spring-based method and finite element (FE) method. Among them, the spring-based method was to model the multi-bolt connection as a series of springs, and each bolt was described by a linear or piecewise linear stiffness model, which was usually used in engineering due to its simplicity and efficiency [12]. Tate et al. first established a spring method for the analysis of double lap joints [13]. Gray et al. applied the spring method to the efficient numerical model of single lap joint, and found that the model can capture the physical deformation and load displacement response of the joint well [14]. Taheri Behrooz et al. developed a nonlinear spring mass model to consider the influence of material nonlinearity [15]. Camanho et al. established a three-dimensional finite element model to predict the damage progression and strength of fastening joints in carbon fiber reinforced materials that failed in extrusion, tension and shear modes [16]. Hu et al. proposed an explicit finite element analysis

model for single lap joints of braided fiber reinforced composites with nonlinear material properties and complex contact geometry [17].

In order to accurately predict the failure mode and failure loading of T300 carbon/epoxy composite bolted connection, and better study the whole process of stiffness degradation, this paper makes the research object of T300 CFRP single lap bolted connection with [90/0] alternate ply, and obtains its displacement load response under different preload through static tensile and fatigue tests. At the same time, it is discussed that the preload has an influence on the shear stiffness and fatigue stiffness of the connecting plates.

### 53.2 Experiment

#### 53.2.1 Specimen Descriptions

A single lap joint structure is chosen for testing the effects of the bolt preload on the static strength and fatigue load as shown in Fig. 53.1. The composite laminates are prepared with carbon fiber/epoxy resin prepreg by hand laid autoclave molding process. Each pair of laminates is made from T300 carbon fiber reinforced polymer (CFRP) composites with lay-ups of [0/90] and the outermost layer is 0°. Each ply had a thickness of 0.135 mm and the number of laminate is 37. The dimensions are as follows:  $L_1 = L_2 = 159$  mm,  $W = 48$  mm,  $t = 5$  mm and the bolt hole diameter  $D = 8$  mm. The diameter  $d$  of bolt is 8 mm, and the distance from the center of the plate hole to the end of the plate  $e$  and  $l_3$  is 24 mm and 112 mm respectively. And distance between the center of the two holes  $l_1$  and  $l_2$  is both 32 mm. In addition, the

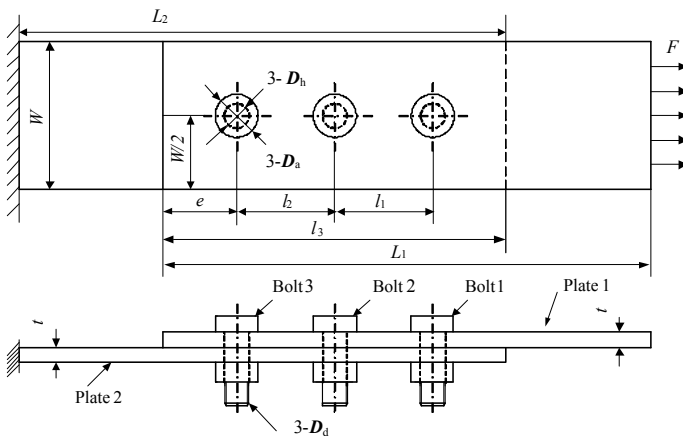


Fig. 53.1 Specimen configuration and dimensions

**Table 53.1** Mechanical properties of CFRP

Material parameters			
$E_1$ (GPa)	145	$S_{12}$ (MPa)	90
$E_2$ (GPa)	8.66	$S_{13}$ (MPa)	90
$E_3$ (GPa)	8.66	$S_{23}$ (MPa)	40
$G_{12}$ (GPa)	4.5	$X_t$ (MPa)	2400
$G_{13}$ (GPa)	4.5	$X_c$ (MPa)	1600
$G_{23}$ (GPa)	3.5	$Y_t$ (MPa)	69.5
$\nu_{12}$	0.3	$Y_c$ (MPa)	236
$\nu_{13}$	0.47	$Z_t$ (MPa)	69.5
$\nu_{23}$	0.47	$Z_c$ (MPa)	236

grip length is selected as 48 mm on each side for both the static and fatigue tests to prevent any slippage between the clamps and the specimen.

The mechanical properties of the carbon fibers are presented in Table 53.1.

### 53.2.2 Experimental Setup

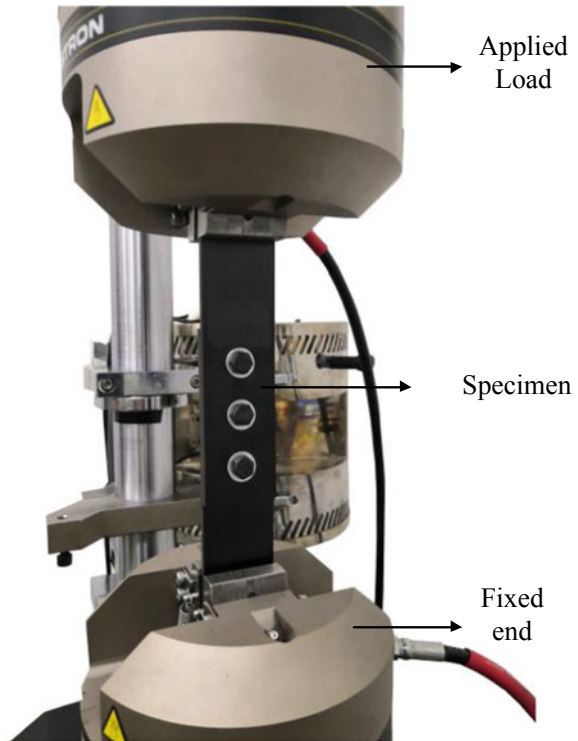
The test is divided into two groups: quasi-static tensile test and fatigue test. In order to facilitate the analysis and research, several test pieces are made for each experimental design. Number of quasi-static tensile test pieces are T1, T2, T3, T4, T5 and T6, and the corresponding pre-torque is 10 N m, 5 N m and 0.5 N m respectively. The fatigue test pieces are numbered FT1, FT2, FT3, FT4, FT5, FT6, FT7, FT8 and FT9 respectively. Corresponding pre-torque and load ratio is shown in Table 53.2.

Tensile tests of the CFRP plates are conducted according to the guidelines of ASTM D5961. The static and fatigue tests are performed using 100 kN servohydraulic fatigue test machine. In the static tests, the tensile load is applied using displacement-controlled protocol at a constant rate of 2 mm/min until failure. Figure 53.2 shows the experimental setup for a typical specimen under static or fatigue tests.

**Table 53.2** Fatigue test specimens

Specimens	$T_0$ (N m)	Load ratio
FT1	0.5	0.8
FT2	5	0.8
FT3	10	0.8
FT4	0.5	0.5
FT5	5	0.5
FT6	10	0.5
FT7	0.5	0.3
FT8	5	0.3
FT9	10	0.3

**Fig. 53.2** The system of testing machine



For the fatigue tests, specimens are subjected to tension-tension cyclic loading at a loading frequency of 10 Hz with a constant fatigue ratio of 0.1. For each type of bolt, the connections are subjected to three fatigue load ratios: 0.3, 0.5, and 0.8 of the static failure load. If number of load cycles are equal to  $10^6$  and specimens do not appear failure, the fatigue test is stopped automatically.

### 53.3 Results and Discussion

The aim of this section is to describe the behavior of the proposed bolts in steel three-bolted single-lap shear connections under the effect of axial preload loading. The failure modes and the load–displacement curves are discussed in detail.

### 53.3.1 *Quasi-static Tensile Tests*

#### 53.3.1.1 Failure Modes

Figure 53.3 shows the failure modes of the connecting plate and bolt under quasi-static tensile test. They include tensile failure and shear failure, accompanying with a certain degree of compression damage. The failure modes of laminates are out of plane, fiber matrix fracture and delamination.

The failure of the connecting plate begins with a slight brittle collision, which indicates the beginning of the pressure bearing damage of the bolt hole of the laminated plate. With the increase of external load, the micro cracks begin to sprout along the direction of plate thickness. The shear failure and tensile failure occur with the crack formation and the continuous and high volume brittle fracture sound. Due to some asymmetry factors, for instance, the verticality of the test piece installation cannot reach the ideal state, shear failure often occurs on the connection with single lap bolt. The tensile and shear failure of T1, T3, T4 and T6 occur at the “1” hole of plate 1; the tensile and shear failure of T2 occur at the “3” hole of plate 2 the tensile and shear failure of T5 occur at “3” hole of plate 2, and shear failure occur at “1” hole of plate 1. All specimens failed in “1” or “3” hole. Because they are closer to the applied load end.

#### 53.3.1.2 Load–Displacement Curves

Table 53.3 and Fig. 53.4 show the recorded load–displacement curves for the six specimens. The maximum load in the linear stage increases with the increase of the preload, and the maximum value increases 73.62% when the preload increases from 0.5 to 5 N m. When the preload increases from 0.5 to 10 N m, it increased by 86.92%. This shows that the preload has a very important influence on alignment linear phase response. Bolt connection mainly relies on the friction force generated by preload to resist the transverse load.

For the ultimate load of the connecting plate, the experimental data shows that the ultimate load of the connecting plate does not show obvious rule with the change of the preload. When the preload changes from 0.5 to 10 N m, the maximum change of the ultimate load is only 1.11%. Because the ultimate load is the overall evaluation of the whole connection structure, main influencing factors include shear deformation of bolt rod and internal tension of plate and so on.

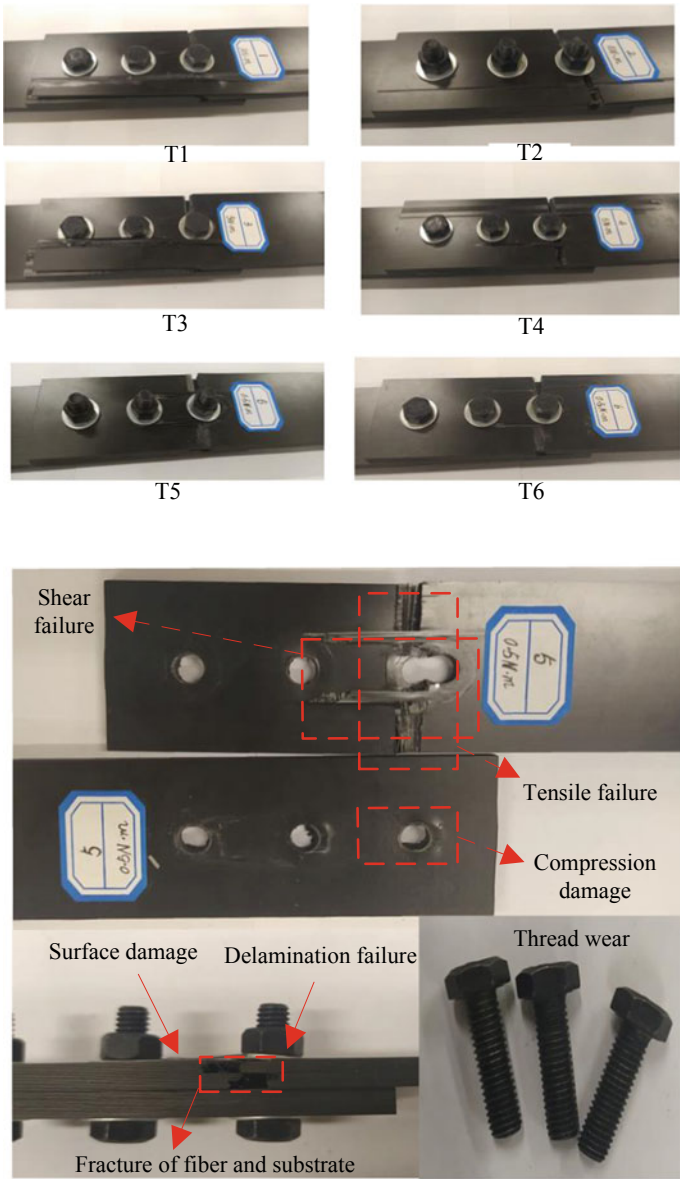
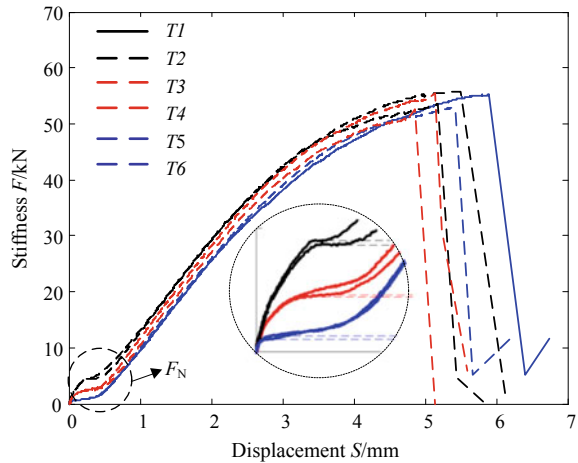


Fig. 53.3 Failure modes of quasi-static tensile tests

**Table 53.3** Tensile test results

Specimens	$F_N$ (kN)	$\bar{F}_N$	$F_{max}$ (kN)	$\bar{F}_{max}$
T1	4.342	4.397	53.53	54.63
T2	4.452		55.73	
T3	2.203	2.18	52.56	54.025
T4	2.157		55.49	
T5	0.632	0.575	52.92	54.055
T6	0.518		55.19	

**Fig. 53.4** The system of testing machine



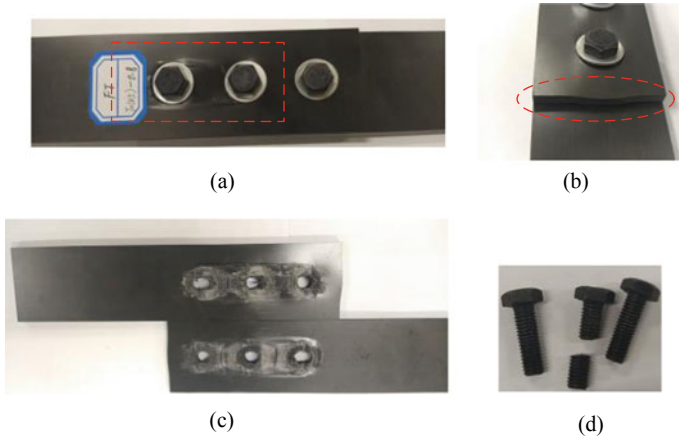
### 53.3.2 Fatigue Test

#### 53.3.2.1 Failure Modes

Compared with the failure mode under quasi-static loading, the fatigue failure was more severe, as shown in Fig. 53.5. The laminates also not only have delamination failure, fiber matrix fracture and out of plane failure under the fatigue loading, but also the serious fretting wear between the joint surfaces of the connecting plates which do not appear under the quasi-static loading, and the plate end deformation and bolt fracture occurred under the high cycle fatigue loading.

On the other hand, the specimens, with a load ratio of 0.3, reach 1 million loading cycles without experiencing any failure. It should be noted that the tests are stopped after reaching 1 million cycles, and the specimens are then tested under increasing monotonic loading until failure.



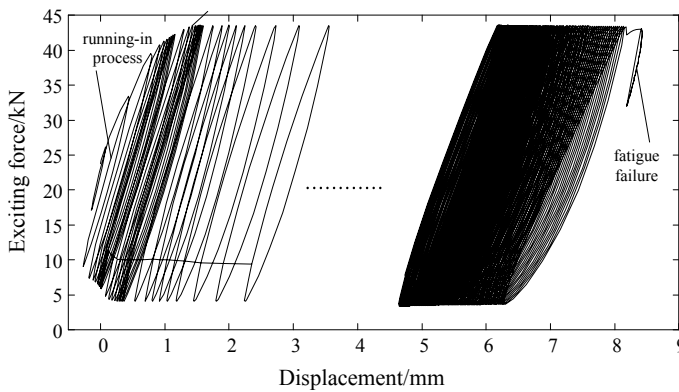


**Fig. 53.5** Failure modes of fatigue tests **a** shear-out failure **b** delamination failure **c** fretting wear failure **d** high cycle fatigue fracture of bolt

**53.3.2.2 Load–Displacement Curves**

The fatigue failure process always occurs in three sequential stages: crack initiation, crack propagation, and failure stage. With an increase in the loading cycle, cracks propagate rapidly. However, with the damage of the bolts, a redistribution of the bolt loads could occur, which leads to delay the crack propagation rate because of the reduction in the load transferred by these critical bolts.

Figure 53.6 shows the exciting force displacement curve of composite bolted plate under sinusoidal transverse exciting force. When the exciting force is applied, the exciting force fails to reach the preset value because the fatigue testing machine is in the running in stage. The exciting force reaches the available value at the 50 cycle.



**Fig. 53.6** Fatigue loading hysteresis curve

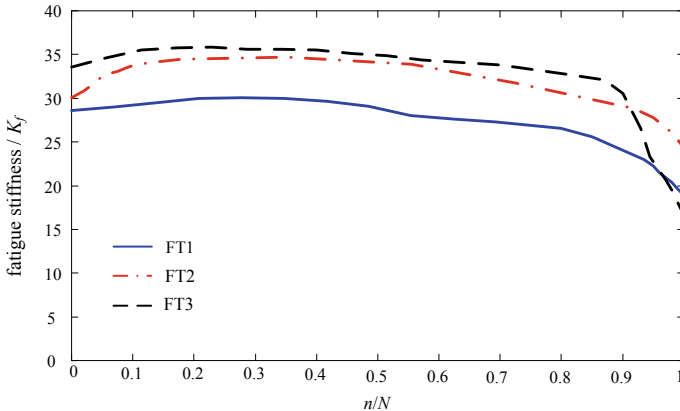
**Table 53.4** Fatigue test results of bolted plate

Specimens	Load ratio	$F_{\max}$ (kN)	$F_{\min}$ (kN)	$N$
T5, T6	1	54.055	–	1
T3, T4	1	54.025	–	1
T1, T2	1	54.630	–	1
FT1	0.8	44	4.4	1202
FT2	0.8	43	4.4	1443
FT3	0.8	43	4.3	1748
FT4	0.5	27	2.7	4546
FT5	0.5	27	2.7	5444
FT6	0.5	27	2.7	6556
FT7	0.3	16	1.6	$>10^6$
FT8	0.3	16	1.6	$>10^6$
FT9	0.3	16	1.6	$>10^6$

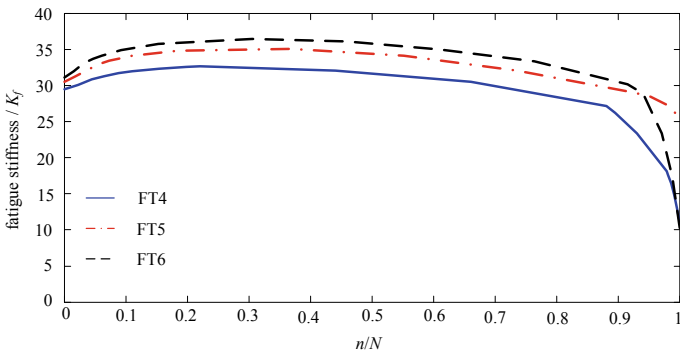
Therefore, the data before the 50 cycle is not analyzed in the following paper. It can be seen from the figure that with the progress of the experiment, the transverse displacement of each cycle increases due to the removal of the rough peak of the joint surface of the connecting plate and the plastic deformation.

The number of loading cycle reaches  $10^6$ . When the load ratio is 0.8 and the preload changes from 0 N m to 5 N m and 10 N m, the fatigue life increases by 16.7% and 31.2% respectively. When the load ratio is 0.5 and the preload changes from 0 N m to 5 N m and 10 N m, the fatigue life increases by 16.5% and 30.66% respectively. By increasing the preload, the fatigue life of the structure can be effectively improved, as shown in Table 53.4.

As can be seen from Fig. 53.7, the variation of the dynamic stiffness can be divided into three stages: slight increase of stiffness, maintenance of stiffness and sudden decrease of stiffness. The results show that the stiffness of each bolted connection plate decreases abruptly in the range of 0.85–0.95 during the loading process. When the load ratio is 0.5 and the preload is 0.5 N m, 5 N m, and 10 N m respectively, the average stiffness from the beginning of loading to the inflection point of stiffness sudden drop is 31.20 kN/mm, 32.89 kN/mm and 33.83 kN/mm respectively. The maximum increase of average fatigue stiffness is about 7.77%. When the load ratio is 0.8 and the preload is 0.5 N m, 5 N m, and 10 N m respectively, the average stiffness from the beginning of loading to the inflection point of stiffness sudden drop is 28.77, 32.57 and 34.64 kN/mm. The maximum increase of average fatigue stiffness is about 16.95%. From the above numerical analysis, it can be seen that the fatigue stiffness of bolted plate can be effectively improved by increasing the preload. Under the excitation force with load ratio of 0.3, the ultimate failure does not occur, so dynamic fatigue stiffness is not given.



(a) 0.8



(b) 0.5

Fig. 53.7 Dynamic fatigue stiffness of connecting plate

### 53.4 Conclusions

- (1) Under the action of static tensile load, the failure modes of connecting plates are tensile failure and shear failure, accompanied by bearing damage. The laminates have delamination failure, fiber matrix fracture and out of plane failure. All test pieces fail at “1” hole and “3” hole.
- (2) The stiffness of linear stage is significantly affected by preload. The preload changes from 0.5 to 10 N m, so the average stiffness increases by 98.56%. The preload has little effect on the stiffness of shear deformation stage.
- (3) Under fatigue loading, shear failure and severe fretting wear occurs in the specimens, and delamination failure, fiber matrix fracture and out of plane failure do not appear in the laminates. The deformation of the plate end and the fracture of the bolt under high cycle fatigue loading occur.

- (4) Increasing the preload can effectively improve the fatigue strength of the connecting plate. When the load ratio is 0.8 and 0.5 respectively and the preload is increased from 0.5 to 10 N m, the fatigue life increases by 31.24 and 30.66%. When the load ratio is 0.3 and the number of cyclic loading reaches  $10^6$ , the ultimate failure does not occur.

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