Experimental and modelling research on fatigue life of GFRP composite materials

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Experimental and modelling research on fatigue life of GFRP composite materials

J W Liu[1], Q Sun[2], X Wang[1], Y L Peng[1] and J T Wang[2,*]

[1]Henan Electric Power Survey & Design Institute, West Zhongyuan Road No. 212, 450007, Zhengzhou, Henan Province, China
[2]Department of Civil Engineering, Xi'an Jiaotong University, West Xianning Road No. 28, 710049, Xi'an, Shaanxi Province, China

Corresponding author and e-mail: J T Wang, wangjiantao@stu.xjtu.edu.cn

Abstract. To evaluate the fatigue behaviour of glass-fiber-reinforced polymers (GFRP), an experimental study was firstly carried out based on the up-down method. Then, the different prediction models, including linear model, nonlinear model and accumulated model, were utilized to modelling the fatigue life of GFRP composite materials, where the genetic algorithm (GA) was combined in the modelling procedure. The result reveals that the bond connecting the specimen with the clamp is the weakness under fatigue loading, thus the bond connecting the construction member in lattice tower with the fitting part in nodal points is the essential part that must be paid close attention to; the simulation results show that these three models whose parameters are assigned by using GA are satisfied well with the experimental data.

1. Introduction

Glass-fiber-reinforced polymers (GFRP) composite materials display high specific stiffness and strength, so it is widely used in automotive, aerospace and civil engineering applications [1]. Recently, its unique characteristic, namely, high strength-to-weight ratio, resistance to corrosion, and lower transportation and maintenance costs, have made them suitable to use for manufacturing power transmission poles as a replacement of conventional materials (wood and steel). Moreover, owing to the lofty-soft feature and strong geometrical nonlinearity of transmission tower line coupling system, the wind-induced vibration response of the coupling system can result in the fatigue failure of the local components, and finally lead to the overall collapse phenomenon. Therefore, the fatigue failure of the GFRP in transmission towers caused by wind-induced vibration is a safety problem that cannot be neglected in the design period [2]. So far, although GFRPs have been successfully employed in major structural applications, the use of the material is relatively new and there is lack of information on its behavior and design [3].

Early researchers have conducted detailed studies on the fatigue life problem. A new linear damage summation model was first used to evaluate the fatigue behavior of composite materials by Nicholas and Russ [4]. Mao and Mahadevan [5] developed a damage accumulation model to describe the degradation of composite materials. A drawback of the methods aforesaid is that they are case-sensitive, because they may provide accurate simulation results for one material system, but very poor for another. Recently methods of intelligent algorithms have been employed for interpretation of fatigue data of composite materials. For example, artificial neural networks (ANN) have proved to be

very good tools to simulate the fatigue life of composite materials [6-9]. That new intelligent methods inspire us to simulate the fatigue life based on the conventional prediction models. Hence, in this paper, an experimental study was firstly carried out to examine the fatigue behaviour based on the up-down method. Then, the different prediction models, including linear model, nonlinear model and accumulated model, were utilized to modelling the fatigue life of GFRP composite materials, where the genetic algorithm (GA) was combined in the simulation procedure.

2. Experimental programme

2.1. Material properties

The mechanical characteristic test is to obtain the relative mechanical parameters such as tensile strength, elastic modulus and Poisson's ratio. In this study, the tensile machine WDW-300D was utilized to stretch the specimens whose loading rate was set by 2mm/min. A total of six tensile bars, for which the diameter and length were 22 mm and 750 mm, respectively, as shown in Figure 1. After collecting and processing the test data, the results of mechanical property for the composite material was summarized in Table 1, where the averaged elastic modulus, Poisson's ration and ultimate load are 48.495 GPa, 0.291 and 227.6 kN respectively.

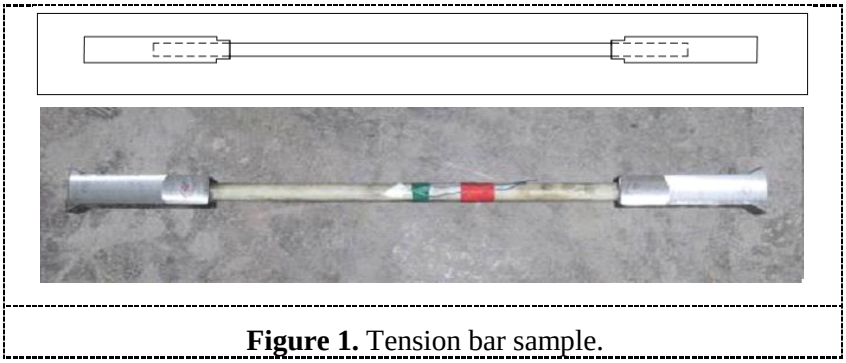


Figure 1. Tension bar sample.

Table 1. Results of mechanical characteristic test.

Specimen No.	Diameter/mm	Elastic modulus/GPa	Poisson's ration	Ultimate load/kN	Nominal stress/MPa
1	22.26	48.001	0.26769	232.4	597.17
2	22.36	47.756	0.27527	233.1	593.62
3	22.36	50.033	0.35862	219.8	559.75
4	22.40	48.188	0.26295	225.2	571.46
Average	22.345	48.495	0.29113	227.6	580.50

2.2. Loading protocol and test results

During the fatigue loading, a total of eight specimens were subjected to the cyclic fatigue loads to obtain the ultimate fatigue bearing capacity, where the up-down method was applied to conduct the experimental design and to predict the material's fatigue life. Considering that, the loading protocol was designed as follows: the first specimen was imposed by a starting level of test loading amplitude (50 kN) and a proper stress amplitude increment ΔF (12.5 kN) was determined; if the first specimen failed prior to the expected life of 100000 cycles, then the second specimen would be tested at a lower loading amplitude level by decreasing $4\Delta F$, otherwise, the test loading amplitude was exerted at a higher stress level by increasing $2\Delta F$; regarding the third specimen to eighth specimen, if the previous specimen failed prior to the expected loading cycles, the third specimen would be tested at a

lower loading amplitude level by decreasing ΔF, otherwise, the third specimen would be tested at a higher loading level by increasing ΔF. In this part, the apparatus (MTS810 $\pm$ 250) shown in Figure 2 was employed to carry out fatigue loading. The test frequency was set as 1 Hz, and meanwhile the tension-tension test was conducted in 0.1 stress ratio control under 100000 loading cycles. After the test, the fatigue failure mode, shown in Figure 3, revealed that the bond connecting the specimen with the clamp broke down, reflecting the fact that the quality of the connection is essential to the GFRP specimens so that must be paid high attention to.

Figure 2. Loading setup.

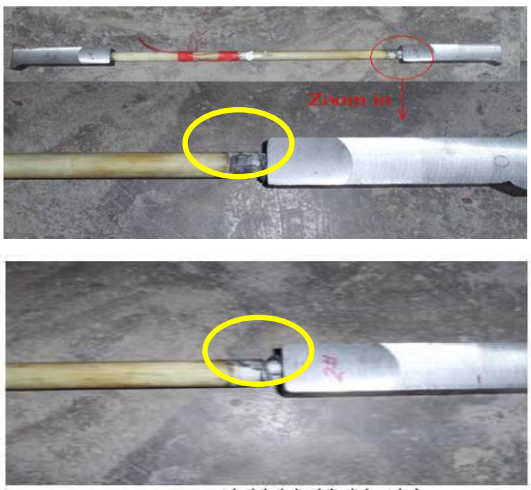


Figure 3. Fatigue damage characteristics.

Through the sequence test, a summary of the test result is provided in Table 2.

Table 2. Results of fatigue test.

No.	Load /kN		Stress /MPa		Fatigue life/cycles	State
	Max	Min	Max	min		
1	50.00	5.00	131.60	13.16	10^5	Intact
2	100.00	10.00	263.20	26.32	16617	Failure
3	75.00	7.50	197.40	19.74	10^5	Intact
4	87.50	8.75	230.30	23.03	10^5	Failure
5	100.00	10.00	263.20	26.32	25624	Intact
6	87.50	8.75	230.30	23.03	10^5	Intact
7	100.00	10.00	263.20	26.32	22421	Failure
8	87.50	8.75	230.30	23.03	97301	Failure

2.3. The up-down method to determine ultimate fatigue bearing capacity

The up-down diagram can be executed and revealed in Figure 4 [10], where the symbol "$\times$" and "$\bigcirc$" denote the failure and survival specimens, respectively. Using S_f and S_s to represent the test stress amplitudes of paired failure and survival specimens, respectively. The average paired stress amplitudes S_l is

$$S_l = \frac{S_f + S_s}{2} \tag{1}$$

where S_f , S_s represent failure stress and survival amplitude respectively. S_l denotes fatigue limit that was obtained from the four paired specimens.

Based on the result of fatigue limit, the average value limit S_{lm} and standard deviation $S_{l\sigma}$ can be estimated by the following equation

$$S_{lm} = \frac{1}{k}\sum_{i=1}^{k} S_{li} \tag{2}$$

$$S_{l\sigma} = \sqrt{\frac{1}{k-1}\sum_{i=1}^{k}(S_{li} - S_{lm})^2} \tag{3}$$

where k is number of paired data. Thus, the statistical parameters of normal distribution, S_{lm} and $S_{l\sigma}$ were 226.1875MPa and 20.6991, respectively.

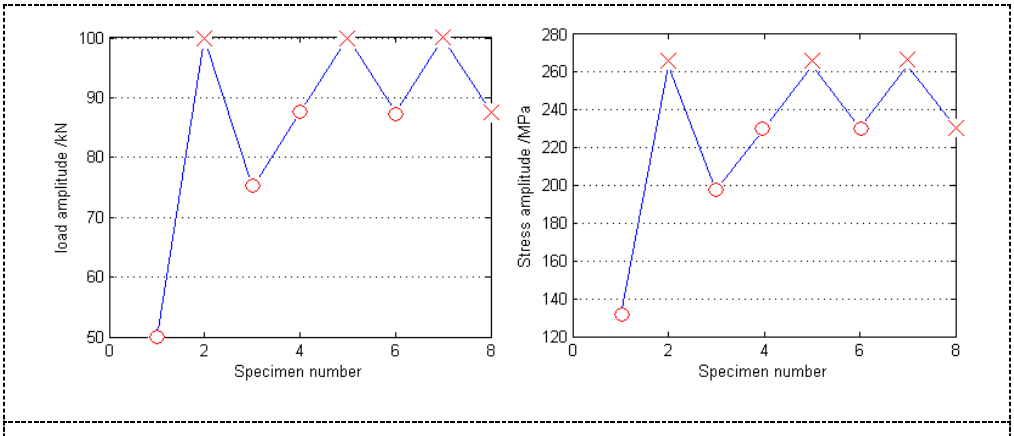


Figure 4. The up-down method.

2.4. Discussion about the fatigue limit

As shown in Figure 2, the specimens were all fixed at the top and applied to the cyclic loading at the bottom. It should be observed that the fatigue limit stress value (226.1875 MPa) is much less than the average result (580.5 MPa) of nominal stress from the mechanical test. Therefore, the fatigue damage is not dependent on the strength value but closely related to fatigue failure mode. It was because that the GFRP specimens at the joint node endured much more fatigue loads than other parts in the specimen. The bond connecting the specimen with the clamp might be the weak link during its fatigue life. For this reason, the bond connecting the construction member in lattice tower with the fitting part in nodal points (see Figure 3) is the essential part that must be paid close attention to.

3. Fatigue life prediction

Many experimental studies have been carried out for obtaining the fatigue properties of different types of composite materials. Based on these results, the different prediction models, including linear model, nonlinear model and accumulated model, were utilized to modelling the fatigue life of GFRP composite materials, where the genetic algorithm (GA) [11-12] was combined in the modelling procedure.

A linear relationship between the maximum stress S and the logarithm of N, the number of load cycles of fatigue failure, is given as

$$S = aLog(N) + b \tag{4}$$

where a and b are parameters related to material properties.

In this paper, we also designed a new model which named as nonlinear or polynomial model on the basis of linear regression model mentioned before. The number of load cycles of fatigue failure, is expressed by

$$S = c[Log(N)]^2 + dLog(N) + e \tag{5}$$

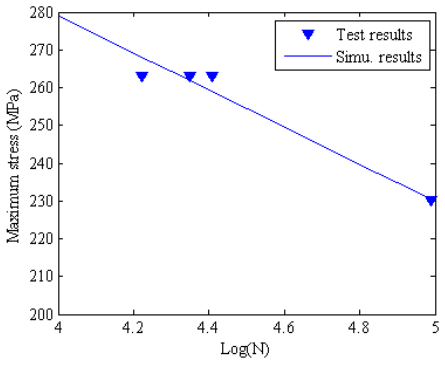
where c, d and e are the material parameters like those in Eq. (4).

Moreover, a damage accumulation model was also utilized to predict the fatigue life:

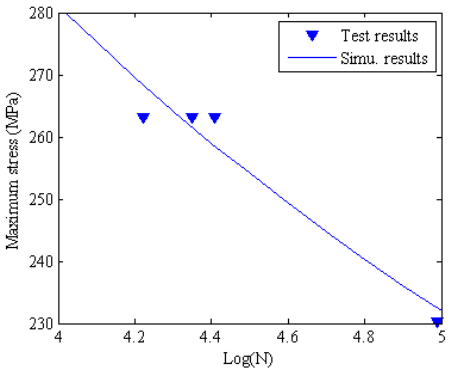
$$S = q(\frac{n}{N})^f + (1-q)(\frac{n}{N})^g \tag{6}$$

where S is the normalized accumulated damage; q, f and g are material dependent parameters; n is the number of applied loading cycles; N is the fatigue life at the corresponding applied load level.

To determine the material parameters in the aforementioned models, the genetic algorithm (GA) was employed herein for modeling the fatigue behavior of composite materials. The process is introduced as follows: First, fatigue life cycles from experiment were collected to be incorporated into the fatigue model formulation. Then, the simulated stress was figured out. During the phase of the GA, the objective function was defined as the sum of differences between the stress of experimental results and the simulated results obtained by GA. The prediction result using GA in this test is provided in Figure 5, which has a good agreement compared to the test results.



(a) Linear model.



(b) Damage accumulation model.

Figure 5. Simulation results using GA.

In order to further testify the effectiveness of GA, fatigue data from other tests from the early literatures were retrieved to examine. A total of four tests, named Material 1 [13], Material 2 [14], Material 3 [15] and Material 4 [16], were collected to validate the effectiveness. The material parameters in the aforesaid prediction models are recommended in Table 3, and the validation results are displayed in the Figure 6 ~ Figure 8.

Table 3. Calculated fatigue parameters.

Material	Linear model		Nonlinear model			Accumulate model		
	a	*b*	*c*	*d*	*e*	*q*	*f*	*g*
Mat 1	-0.130	1.466	0.021	-0.351	2.021	0.541	-0.082	1.936
Mat 2	-0.084	1.1387	0.009	-0.164	1.315	0.503	-0.064	1.063
Mat 3	-0.123	1.219	0.003	-0.162	1.330	0.389	-0.085	10.000
Mat 4	-0.203	1.383	0.002	-0.210	1.373	0.180	-0.160	-1.624

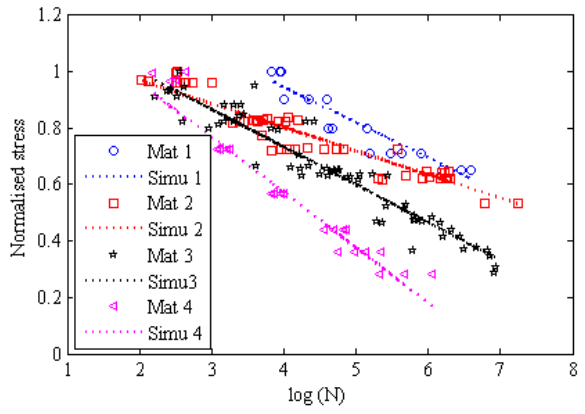


Figure 6. Linear model using GA.

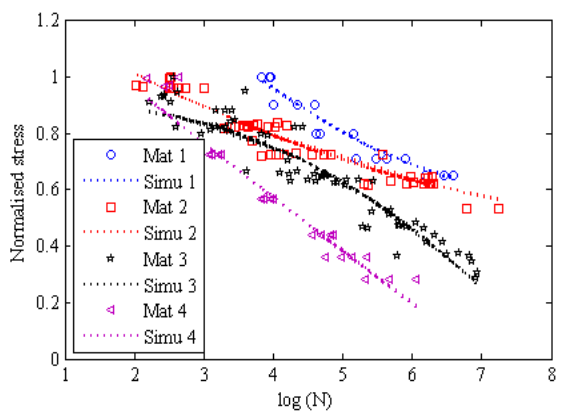


Figure 7. Nonlinear model using GA.

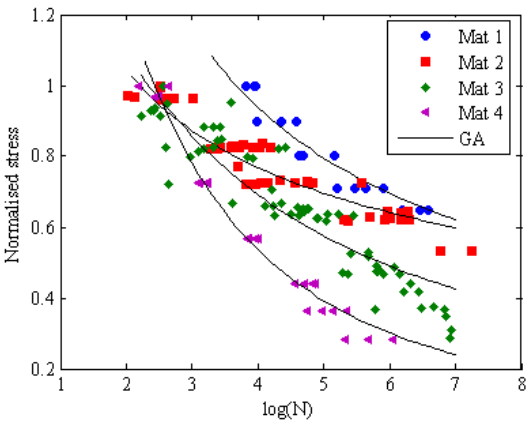


Figure 8. Damage accumulation model using GA.

The simulation results show that these three models whose parameters are assigned by using GA are satisfied well with the experimental data, which can provide some beneficial references to the fatigue life prediction and damage evaluation.

4. Conclusions

In this paper, an experimental study was carried out to investigate the fatigue behaviour based on the up-down method, and the fatigue life was predicted using different models based on the GA method. Some important conclusions can be drawn from the aforementioned research:

1) The bond connecting the specimen with the clamp is the weakness under fatigue loading. It should be observed that the fatigue limit stress value (226.1875 MPa) is much less than the average result (580.5MPa) of nominal stress from the mechanical test. Therefore, the bond connecting the construction member in lattice tower with the fitting part in nodal points is the essential part that must be paid close attention to.
2) The simulation results show that these three models whose parameters are assigned by using GA are satisfied well with the experimental data, which can provide some beneficial references to the fatigue life prediction and damage evaluation.

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