LABORATORY EVALUATION ON FATIGUE PERFORMANCE OF GLASS FIBER REINFORCED PLASTIC MORTAR PIPES CULVERT

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In order to investigate the fatigue performance and microstructure evolution of glass fiber reinforced plastic mortar (FRPM) pipes under cyclic loading, fatigue test was carried out. In the process of fatigue test, the deflection, crack and crack width of each feature of FRPM were observed and recorded. Then, the micro-structure of original samples was scanned by electron microscope(SEM). Mechanical properties of FRPM pipe is analyzed from the view of microstructure for the specimens before and after fatigue loading. Finally, the fatigue life of FRPM pipe under cyclic loading is predicted. The results show that the residual stiffness of FRPM pipe decreases monotonically with the increase of fatigue times, therefore the stress amplitude or stress level is the main influencing factor. The FRPM pipe has a smaller residual stiffness and shorter fatigue life when being applied higher maximum cycling stress and amplitude. The crack in the FRPM tube without fatigue occurs instantaneously and obviously larger than that after fatigue.

Keywords: *mechanic performances; FRPM; micro-structure; fatigue properties; SEM*

1. Introduction

Glass fiber reinforced plastic mortar (FRPM) pipe is a kind of new composite material using resin as matrix material, glass fiber and its products as reinforced material, and quartz sand as filling material. FRPM pipe is widely used in engineering, petroleum, electric power, agricultural irrigation, municipal administration and drainage. At present, all countries in the world are actively developing and popularizing the FRPM pipe.

There are many ways to study fatigue models. At present, the research hotspots can be summarized as cumulative damage model, fatigue residual stiffness model, fatigue residual strength model, etc. The cumulative damage model can be divided into the residual strength model with notched laminates, the residual strength model of laminates with circular holes, and the delamination damage composite laminates model.

Roham Rafiee[1] studied the failure mechanism of FRPM, introduced the continuous failure damage model (SFM) and verified the validity of the SFM damage model using different tests of the layer structure of the mechanical properties of FRPM. Z. Wang, L. Xu, X. Sun, et al.[2] investigated the tensile fatigue behavior of glass-fiber-reinforced epoxy (GF/epoxy) composites embedded with shape memory alloy (SMA) wires prepared by vacuum assisted resin infusion (VARI) processing, and revealed the damage mechanism of SMA composites under different stress levels of cyclic loadings. U. Mesut, K. Memduh, Ş. Aykut [3] studied filament wound glass fiber reinforced plastic (GRP) tubes through impact tests at 5 J and 10 J energy levels. Number of cycles occurred up to the final failure was recorded and S–N diagrams were plotted. They conclude that the burst strength and the fatigue life of the damaged GRP pipes were decreased as the impact energy increased. Also the decrease in the fatigue life was greater than that of the burst strength. Dongtao Qi, Guangxu Cheng[4] presented fatigue lives of tubular specimens under tension/torsion biaxial loading at low cycle up to 100,000 cycles. Roham Rafiee and Farshid Reshadi [5] observed the GRP tube under hydrostatic pressure and found that the first fracture (FPF) and functional failure (FF) pressure linearly increased with the increase in core thickness. H.Dong, Z.Li, J.Wang, et al [6] developed a new fatigue failure theory for multidirectional fibre-reinforced composite laminates with an arbitrary stacking sequence, by combining nonlinear residual strength and residual stiffness models with the recently improved Puck's failure theory which includes the in situ strength effect. The theoretical predictions are in good agreement with available experimental results. H. Y. Sung and O.O. Jin [7] predict the long-term performance of FRPM pipes under continuous internal pressure. The data of the continuous internal pressure test show that the linear regression analysis is suitable for predicting the

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Fig.1 - Loading device.

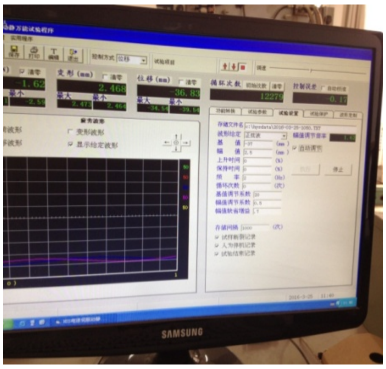


Fig.2 - Data acquisition system.


Fig.3 - Static loading.

failure pressure of FRPM after 50 years. R. Rafiee, et al [8-10] considered fatigue lifetime of composite pipe subjected to cyclic internal hydrostatic pressure with variable amplitudes.

According to the references in recent years, the fatigue performance of fiber reinforced composites is the research focuses in recent years. However, there is not much research reports on the fatigue performance of FRPM pipe. Moreover, the stress analysis of FRPM pipe by field experiment is not only heavy workload, but also constrained by various conditions such as funds, manpower and experimental environment, which is difficult to realize. Based on the experimental and numerical simulation analysis, this paper studied the fatigue properties of the FRPM pipe and forecast the fatigue lifetime for FRPM pipe.

2. Materials and test procedures

The fatigue test was carried out in the laboratory of mechanics and structure of Hebei University of Engineering. The loading equipment was a customized MTS fatigue tester. The pipe length is 40mm, the diameter is 1500mm, and the wall thickness is 5mm. Tests adopting the deformation control loading method were performed according to the standard [11,12]. The initial deformation was applied to the specimen, the contact condition between the counterforce wall, the test piece and the loading device was checked and the readings of the test instrument are normal, etc before the formal test. The loading frequency of fatigue test should not cause resonance between components and load frame. At the same time, the test specimen should be consistent with the actual working condition. The fatigue test device and data acquisition system are shown in Fig.1 and Fig. 2 respectively.

3. Experimental procedures

The constant-amplitude fatigue test (CAFT) is an effective method that has been used in many studies, so this method was used to investigate the fatigue property of FRPM pipes. Prior to performing the fatigue test, the failure pressure of investigated FRPM pipe is estimated using static test. In the process of fatigue test, respectively in cyclic times at: 0.5 million, 1 million, 1.5 million, 2 million and 2.6 million loading cycles respectively, a static load test was done at the time of cyclic loading, and the deflection - load data of the tube were recorded and the residual stiffness data were calculated as in Table1-3. After static loading, restart the fatigue test machine and continue the fatigue test. If the fatigue loading cycle times reaches to 2.6 million, the specimen did not fracture, the static load failure test is operated as shown in Fig.3, which the ultimate bearing capacity after fatigue was obtained.

The representative test procedure is shown in Fig.4.

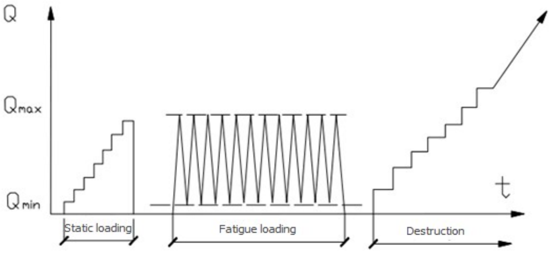


Fig.4 Fatigue test procedure.

As shown in Fig.4, the first test procedure is static loading test taken placed as in Fig.3. Then the fatigue test is carried out in the second procedure as shown in Fig.1. Finally, the specimen is loaded to damage. This test was conducted at a room temperature of 23.5℃. A stress-control mode was applied. As shown in Fig.4, this loading mode is characterized as[13,14]:

$$r = 0, S_{\min} = 0, S_m = S_a = \frac{1}{2} S_{\max}$$

Where, $S_{\max}$ is maximum loading amplitude, $S_{\min}$ is minimum loading amplitude. In this experiment: $S_{\max 1}$ = 4.12kN, $S_{\max 2}$ = 7.1kN.

Table 1

Stiffness declining test data of GH1

Fatigue loading cycles	1	0.5 Million	1 Million	1.5 Million	2 Million	2.6 Million
E_n/E_0	1.000	0.988	0.984	0.978	0.973	0.968

Table 2

Stiffness declining test data of GH2

Fatigue loading cycles	1	0.5 Million	1 Million	1.5 Million	2 Million	2.6 Million
E_n/E_0	1.000	0.986	0.980	0.975	0.971	0.956

Table 3

Stiffness declining test data of GH3

Fatigue loading cycles	1	0.5 Million	1 Million	1.5 Million	2 Million	2.6 Million
E_n/E_0	1.000	0.976	0.968	0.957	0.932	0.919

4. Results and discussion

4.1. Residual stiffness *of* FRPM

The residual stiffness can be used to measure the fatigue damage of FRPM structure which is superiority compared with residual strength: it can be continuously measured during fatigue test, the measurement is simple and time-saving, and the damage state of two experimental samples can be compared. It is also a macroscopic phenomenological testing parameter of nondestructive examination (NDE), which can reflect the evolution state of the microscopic damage in the material. It can describe the fatigue damage state of the structure in use, and can further describe and predict the residual strength and fatigue life of the component [15,16].

Taking the same production batch and the same size specimen of GH_1 and GH_2 (FRPM pipe test sample) as an example, the first loading force amplitude is S_{max1}=4.12KN and the second loading force amplitude is S_{max2} =7.1K. The maximum stress level is 0.1 and 0.172 respectively during the fatigue test. Table 1 and Table 2 show the change of residual stiffness of FRPM pipe at different fatigue times. It can be seen from the table that the residual stiffness of pipes decreases monotonously with the increase of fatigue loading cycles, which reflects the accumulation process of internal damage with fatigue loading.

Moreover, the comparison Table 1, Table 2 and Table 3 show that the residual ring stiffness ratio of GH3 after 2.6 million fatigue is 0.919, and the ring stiffness of GH2 and GH1 is respectively 0.956, 0.968 after the same fatigue loading cycles. The reason is that the stress amplitude of GH3 is greater than GH2, and GH2 greater than GH1, or the stress level GH3 is greater than GH2, and GH2 greater than GH1. Therefore, the stress amplitude or stress level is inversely proportional to the residual ring stiffness and fatigue life in the absence of other factors.

4.2. Destructive feature *of* FRPM

The FRPM pipe after 2.6 million fatigue loading cycles, and the FRPM pipe without experienced fatigue is loaded to failure, therefore, the cracks are obtained as shown in Figure 5 and Figure 6. As shown in the picture, the failure crack of FRPM pipe without fatigue is obviously greater than that of the crack after the fatigue. It shows that the fatigue process is also the process of the internal structure internal force and the redistribution of the microstructure in the inner layer of the FRPM tube. The mechanism of destroy development is that the inner gap decreases, but a large number of micro cracks developed in the matrix, therefore the fiber is fractured. When the damage accumulates to a certain range, the micro cracks interact with each other, then the main cracks appear together and expand rapidly, resulting in fracture.

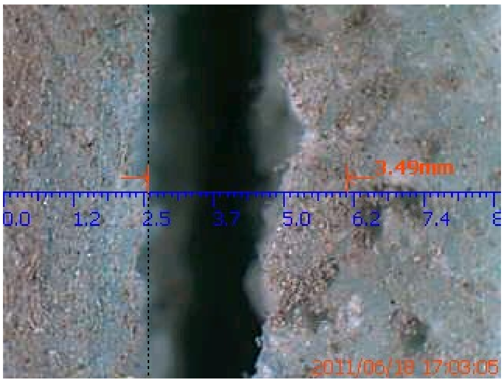


Fig.5 - Crack without fatigue.

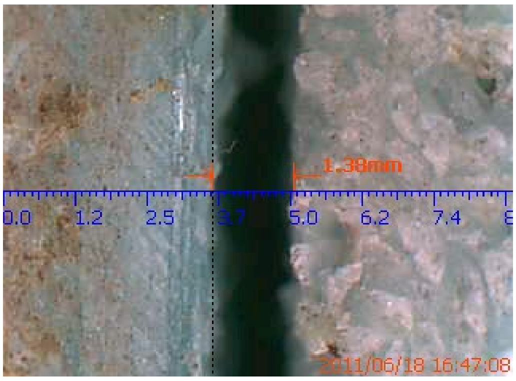
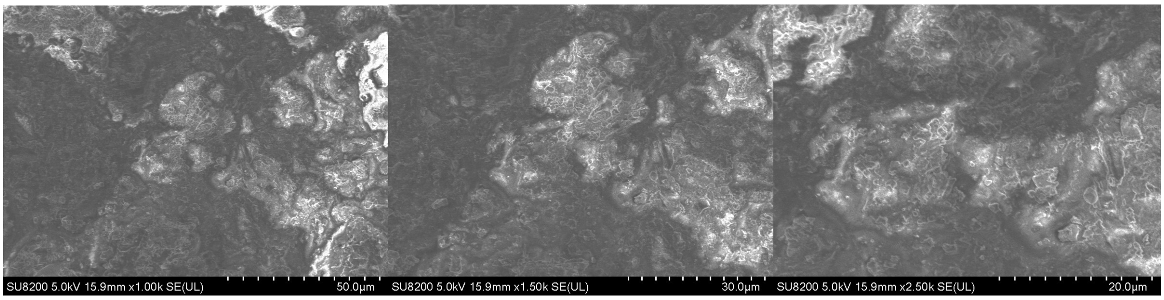
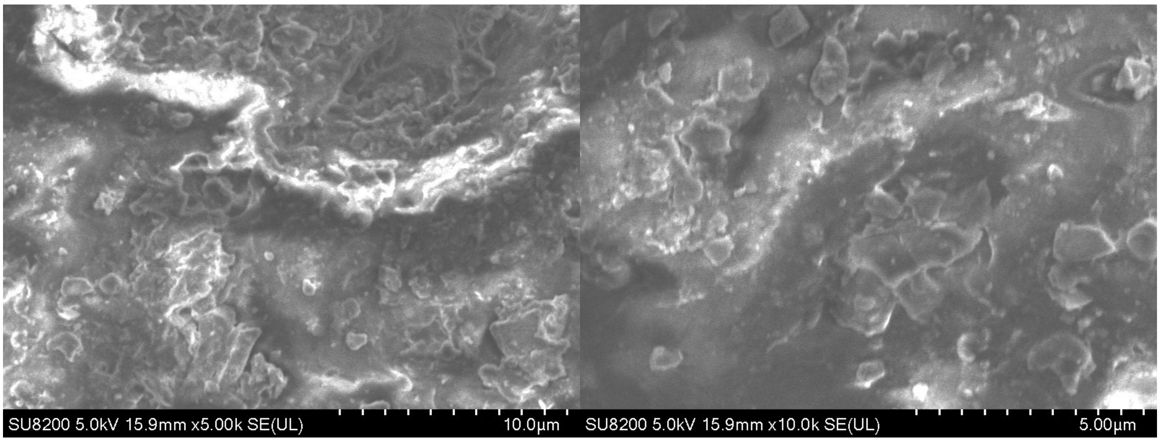


Fig.6 - Fatigue crack.

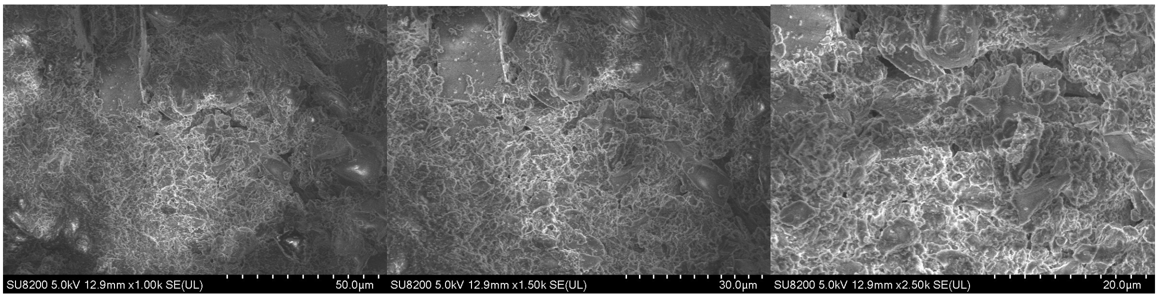


（a）1000 times （b）1500 times （c）2500 times

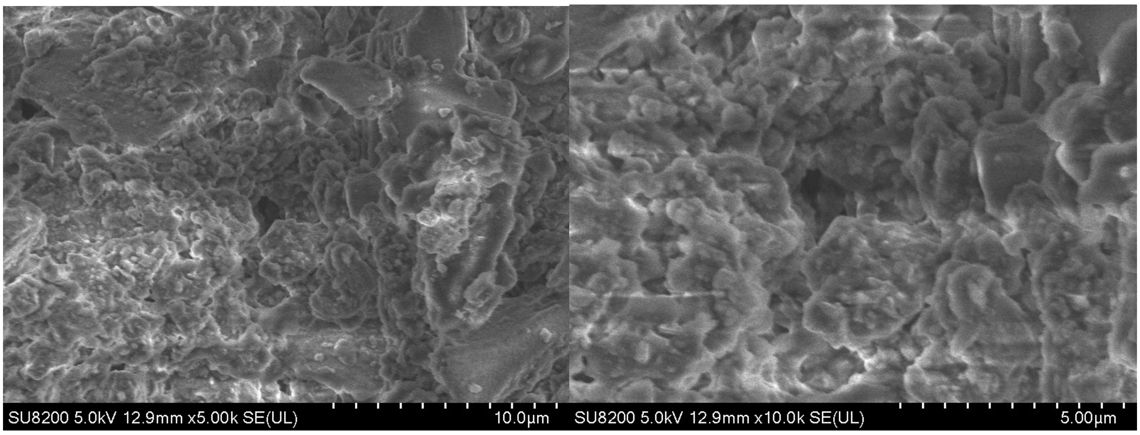


（d）5000 times （e）10000 times

Fig.7 - Microstructure without fatigue.



（a）1000 times （b）1500 times （c） 2500 times



（d）5000 times （e）10000 times

Fig.8 - Fatigue microstructure.

4.3. Microstructure of FRPM

Scanning electron microscope (SEM) device is Hitachi-SU8200. The FRPM sample of 20mm size is intercepted in the same position of FRPM pipe after fatigue and direct static load destruction.

It is polished to smooth and flattening, and the coarse particles on the surface of the specimen are cleared by the skin tearing mode. It is fixed on the sample tray with conductive adhesive and observed, which 1000 times, 1500

Table4

Mechanical properties of layers

Layer	Modulus of elasticity /Gpa	Shear modulus /Gpa	Poisson ratio/ μ
Lining layer	E=6.74		μ=0.33
Hoop winding lay	E_{11}=38	G_{12}=3.8	μ_{12}=0.3
	E_{22}=6.9	G_{23}=3.8	μ_{23}=0.158
	E_{33}=6.9	G_{31}=3.8	μ_{31}=0.158
Intertwining layer	E_{11}=70	G_{23}=3.8	μ_{12}=0.3
	E_{22}=7.5	G_{23}=3.8	μ_{23}=0.158
	E_{33}=7.5	G_{31}=3.8	μ_{3}1=0.158
Mortar layer	E=6.4		μ=0.33

Table 5

Fatigue properties

Fatigue cycle /times	Residual strength / Mpa
10	110
100	92
1000	75
10000	60
1e+5	48
1e+6	40
1e+7	26

Table 6

Fatigue life comparison

Specimen	Theoretical values / 1e+5	Simulation values /1e+5	Error/%
GH1	554.02	570.10	2.902
GH2	477.64	487.20	2.001

times, 2500 times, 5000 times and 10000 times of 5 kinds of observation times were selected. The microstructure comparison of the specimens without fatigue and after 2.6 million fatigue cycles is compared in different magnification times, as shown in Figure 7 and Figure 8.

4.4. Fatigue lifetime of FRPM

The total number of the load is defined as the fatigue life when the specimen breaks completely[17,18]. According to the Miner fatigue damage criterion, the fatigue life of FRPM can be characterized by the following equation:

$$R(n) = R_0 - \frac{n}{N}(R_0 - S_{max}) \qquad (1)$$

Where,

$R(n)$ – Residual strength after n times fatigue cycle
R_0 – Initial ultimate strength of specimen
n – Fatigue cycle times
N – Fatigue life of equal amplitude fatigue

S_{max} – Upper limit of equal amplitude loading

The fatigue life of FRPM pipe was simulated with ANSYS 16.0 and nCode Design Life. The size of FRPM pipe model is: inner diameter of $1.4m$, external diameter of $1.5m$, length of $0.3m$, material parameters of $1800kg/m^3$, loading frequency of $2H_z$. The modulus of elasticity and other mechanical properties of layers are shown inTable 4.The tiredness is shown in Table 5.

According to the Miner criterion, the comparison between theoretical values and simulation results is shown in Table 6. From the table, it can be seen that the theoretical value of Miner criterion is in good agreement with the simulation results, and the Miner criterion is suitable for predicting the fatigue life of glass reinforced plastic sand pipe.

Based on the above experimental results of pipe culvert stress state of FRPM indoor fatigue test, it can be concluded that after 2.6 million times of fatigue, strength and stiffness of FRPM culvert were not significantly reduce, without layered peeling and brittle fracture phenomenon. According to the fatigue life prediction formula, its fatigue life completely meets to the requirements of the highway culvert application. This experiment and the further studies can be used widely in highway culverts of FRPM and it provide a reliable basis of analysis in durability design.

5. Conclusions

In this paper, based on the experimental and numerical simulation, the fatigue properties and microstructure characteristics of FRPM pipe under cyclic loading were investigated. The basic physical and mechanical properties of glass fiber reinforced plastic mortar pipe are analyzed, and the technical requirements for the structural parameters, the basic mechanical indexes and durability characteristics of FRPM pipe are analyzed. The following conclusions can be drawn.

- In the aspect of residual stiffness, the residual stiffness of the pipe decreases monotonically with the increase of fatigue times, which reflects the continuous accumulation of internal damage with fatigue loading, and the stress amplitude or stress level is inversely proportional to the residual ring stiffness and fatigue life in the case of other influencing factors.
- From the macroscopic point of view, the fracture is obviously less than that of the failure after fatigue, which indicates that the fatigue process is also the process of the internal structure internal force and the microstructure structure reorganization of the FRPM tube. With the development of the process, there will be a large number of micro cracks in the matrix and the fibers break up, when the damage accumulates to one. The degree of micro crack interaction and the aggregation of the main cracks increase rapidly and lead to fracture.
- The microstructure of materials often determines their macroscopic behavior. As a result of the comprehensive analysis, the glass fiber reinforced plastic sand pipe has been destroyed, and the whole structure of the skeleton is destroyed, the fine cracks are uneven and the debris increases, which leads to the decrease of its stiffness and life. (4.2 conclusion) the microstructure of the tube is gradually evolved from the whole structure to granular laminar structure. At this time, the microstructure of the tube is gradually evolved into a granular laminar structure. The crack width is less than the fatigue failure crack (4.3 conclusion), but with the emergence of the gap, it can be foreseen. With the development of the fatigue process, the micro crack will further develop, connect and connect, and form the main crack.
- The long term performance of FRPM pipes after 2 million fatigue load is degraded up to 25% of the initial performance. Although the ultimate bearing capacity of glass fiber reinforced plastic sand pipe under fatigue loading decreases, the failure form has the trend from brittle to plasticity.

In summary, the culverts constructed with FRPM have a better mechanics and durability performance than those with the concrete. This experiment and the following research provide a reliable basis for the design of FRPM pipe in the application of highway culvert. A trial section of FRPM should be put into effect in the future in order to determine the applicability for different regions.

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