An Experimental Study on the Behavior Deterioration Trend of Friction Pendulum Bearings with Corrosion Time for Offshore Isolated Bridges

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Abstract: At present, the behavior deterioration trend of friction pendulum bearings (FPBs) widely used in offshore bridges under marine environment isn’t still clear. In this study, periodic-salt-spray and wetting–drying cycle accelerated corrosion tests were used to simulate the corrosion circumstances of FPBs in the splash and atmospheric zones, respectively. Eight sets of FPBs with a vertical bearing capacity of 35 t were designed as test samples. The environmental factors that affect the bearing behavior deterioration were analyzed; the test accelerated ratios of the factors were discussed; two kinds of test schemes were designed for the FPBs; and the macroscopic appearances of the FPBs at different corrosion times were observed. The trends of the initial static and dynamic friction coefficients with corrosion time were extensively analyzed, and the behavior deterioration trends of the mechanical properties of the FPBs were analyzed. The results show that in both the splash and atmospheric zones, the initial static and dynamic friction coefficients with corrosion time show an increasing periodic curve, but the behavior deterioration trend and period of FPBs in different locations are different. The vertical and horizontal stiffness of FPBs almost did not change with the corrosion time. The trends of equivalent damping ratio with the corrosion time are consistent with the dynamic friction coefficient. Based on the experimental results, the behavior deterioration trends of the initial static and dynamic friction coefficients of FPBs with corrosion time were obtained, which provides a basis for the seismic performance evaluations of offshore isolated bridges in their entire service lifetime.

1. Introduction
Currently, the seismic isolation technology has become one of the most promising structural seismic protection technologies owing to its reliability, efficiency, and reasonable cost. In recent years, friction pendulum bearings (FPBs) have been widely used in offshore isolated bridges because of their excellent performance such as automatic recovery function and great bearing capacity. The long-term effects of complex marine environment factors such as humidity, acid rain, and temperature may deteriorate the performance of offshore bridges; therefore, extensive and in-depth studies have been performed on the durability of bridge construction and concrete materials. However, the durability of
FPBs, the key component connecting the upper and lower parts of a bridge, has been rarely investigated. The deterioration trend of FPB's mechanical properties under long-term marine environment is not clear. Therefore, it is impossible to accurately evaluate the seismic performance of an offshore seismic isolated bridge during its entire lifetime.

At present, in the civil engineering field, studies on FPBs mainly focused on the analysis of mechanical properties and the corresponding structure by conducting experiments such as static test\(^1\), shaking table test\(^2,3\) seismic response analysis of bridges with FPBs\(^4,5,6\). Experimental and analytical study of the behavior of the friction pendulum system (FPS) in bridge seismic isolation were conducted. The experimental results demonstrate a marked increase of the capacity of the isolated bridge to withstand earthquake forces under all conditions. And the analytical results are agreement with the experimental results well\(^7\). The report presents a comprehensive description of the current stage of knowledge on the behavior of hardware used in seismic isolation and in seismic damping systems\(^8\). And the information presented by this report may represent the basis for the development of contemporary guide specifications for seismic isolation design. Xiong et al\(^9\) introduce an innovative seismic isolation system named the convex friction system (CFS) and a series of comprehensive analytical and numerical investigations are performed to verify these features of the CFS. The analytical and numerical results show that the CFS performs well in seismic isolation applications. Three different systems (IS’s) for bridges and viaducts are considered and an extensive numerical investigation has been carried out in order to assess the reliability of different design approaches\(^10\), compare the response of different types of IS’s, evaluate the sensitivity of the structural response to the friction variability due to bearing pressure and identify the response variations caused by changes in the ground motion, bridge and isolation characteristics. Castaldo et al\(^11\) researched the seismic reliability of base-isolated structures with friction pendulum bearings in order to evaluate the seismic reliability of a base-isolated structure with FP isolators considering both isolator properties and earthquake main characteristics as random variables. You et al\(^12\) reported the test results of stainless steel corrosion for up to 16 years in the wetting–drying cycle, tide, and splash zones of Qingdao sea of China. They found that stainless steel can be damaged due to pitting and crevice corrosion. The corrosion resistance of stainless steels differs because of different types of stainless steel and different regions in the ocean, but when the chrome content of stainless steel is >17%, the stainless steel has a good corrosion resistance. Liang et al\(^13,14\) performed a corrosion study with 12 years of atmospheric exposure and found that the most harmful factor for stainless steel is chloride ions, while heat and humidity cause more severe corrosion. Fan et al\(^15\) and You et al\(^12\) found that the higher the concentration of chloride ions, the higher the corrosion rate of stainless steel. Atashin et al\(^16\) and Liang et al\(^13\) studied the effects of temperature, salinity, flow rate, and pH on the corrosion rate of stainless steel. Lothongkum et al\(^17\) and Fan et al\(^15\) reported the corrosion trend of stainless steel at different pH values under 27 °C and 3.5% NaCl solution. Dolce et al\(^18\) summaries the results of a large experimental investigation on steel-PTFE interfaces in order to evaluate the effects of sliding velocity, contact pressure and so on. And two different mathematical models have been calibrated, which are capable of accounting for the investigated parameters in the evaluation of the sliding friction coefficient, based on the experimental outcomes. Zhao et al\(^19\) investigate the change law of seismic behavior of Hong Kong-Zhuhai-Macao Bridge isolated bridge using the friction pendulum bearings under the chloride ions corrosion with time, based on artificial accelerated corrosion test on the bearing in previous tests, and the fitting change curves of friction coefficient of isolation bearing were obtained. Most of the reported studies focused on the corrosion rate of stainless steel and corrosion characteristics; studies on the corrosion trend of static and dynamic friction coefficients or the variation in mechanical properties with corrosion time for FPBs have been rarely reported. It is difficult to directly use the study results to evaluate the seismic performance of offshore seismic isolated bridges during their entire life cycle. Thus, it is important to study the behavior deterioration trend of FPBs under a complex offshore marine environment. This can provide a basis for the seismic performance analysis and safety assessment of offshore bridges during the entire life cycle and further promote the application of friction pendulum isolation technology in China.
2. Establishment of behavior deterioration test schemes for FPBs

The marine environment is very complex and harsh; therefore, many factors lead to the behavior deterioration of FPBs. To determine the behavior deterioration trend of FPBs, the best method is to perform a long-term performance monitoring and testing for bearings used in practical engineering, but nowadays it is impossible because this method requires a lot of time, manpower, and material resources. Laboratory accelerated tests should be used to evaluate the main factors affecting behavior deterioration according to the position of FPBs. Most FPBs of offshore bridges are located in the marine atmospheric region, while some FPBs are placed in non-navigable or lower parts of bridges, probably in the splash zone. The environment of a splash zone is consistent with the salt fog test box; therefore, the accelerated periodic-salt-spray test can be used to simulate the environment of a splash zone. The wetting–drying cycle test can be used to simulate the environment of an atmospheric zone; FPBs can be directly immersed in the artificial seawater of a constant-temperature test chamber. In this paper, periodic-salt-spray and wetting–drying cycle tests were performed.

2.1. Design of test specimens

Simple FPBs were selected as the test objects. The design parameters of FPBs mainly include the vertical reaction force $W$, designed isolation period $T = \frac{2\pi}{\sqrt{gR}}$, radius of curvature $R$ of bearing sphere, ultimate displacement $D_u$, and friction factor $\mu$ of a sliding surface. The plane dimension of the spherical sliding surface is usually determined from the vertical reaction force $W$. Designed isolation period $T$ is usually equal to or greater than the natural vibration period of the structure.

Then, the radius of curvature $R$, horizontal post-yielding stiffness $K_{fy} = \frac{W}{R}$, and equivalent stiffness $K_{ef} = \frac{F}{D_u} = \frac{W}{R + \mu W/D_u}$ can be calculated. Eight FPBs with upper and lower bearing plate sizes of 200×200 mm$^2$ and 320×320 mm$^2$ were designed; these plates are made of steel Q345B. The spherical wear-resistant plates of FPBs are made of PTFE, and the sliding surface is made of chrome-plated stainless steel. The height of an FPB is 105 mm, and the vertical bearing capacity is 350 kN. The friction coefficient is 0.03, and the horizontal displacement is 80 mm. The radius of curvature is 1500 mm, as shown in figure 1. The period of isolation structure is 2.43 s, and the design values of $K_{fy}$ and $K_{ef}$ are 0.23 kN/mm and 0.36 kN/mm, respectively.

![Figure 1. Dimensions of FPBs](image)

2.2. Parameters of artificial accelerated corrosion tests

The main factors affecting the corrosion of stainless steel are the temperature, humidity, salt concentration, pH, time ratio of wetting–drying cycle test, spray pattern of periodic-salt-spray test, and placement angle of sample. To obtain the behavior deterioration trend of FPBs with corrosion time, the accelerated rate of each corrosion factor in the laboratory environment and that in the actual marine environment should be determined.

Combining the requirements of a periodic-salt-spray test and those reported in the literature, the control parameters and accelerated rate of each influencing factor were determined based on the analysis of the actual marine environment as shown in table 1. There is no relationship between the
concentration of chloride ion and accelerated rate of pH, and the test temperature of 35 °C neither makes the salt mist condense, nor makes the salt fog sublimate. Therefore, it is unnecessary to consider the combined effect of temperature and humidity on the accelerated corrosion rate. Assuming that these four factors affecting the accelerated corrosion rate are independent, the total accelerated corrosion rate is a product of the accelerate rates of these four factors. Therefore, the rate of artificial accelerated time in an FPB corrosion experiment is equal to the product of temperature, humidity, chloride ion concentration, and pH ratios, which is finally equivalent to 196.8 times. Given that the service life of a bridge bearing is 60 years, the total time of an artificial accelerated corrosion test was determined to be 2664 h, i.e., 111 days.

| Influencing factor | Salinity (%) | Temperature (°C) | pH value | Humidity (%) | Time ratio of wetting–drying cycle |
|--------------------|--------------|------------------|----------|--------------|----------------------------------|
| Actual marine environment | 3.5 | 20 | 8–8.2 | 50 | 2 : 1 |
| Reason | According to the salt composition of natural seawater, the salinity of different sea areas and specific environmental parameters in four seawater corrosion stations of China. | | | | |
| Artificially accelerated corrosion environment | (5±1) % | 35 | 6.5–7.2 | 95 | 2 : 1 |
| Reasons | According to the relationship between the weight loss of metal and the concentration of a salt solution, it was found that the corrosion rate of NaCl is the fastest when the salt concentration is ~5%, and the salt spray nozzle is easily blocked by the high-concentration salt solution[14]. | The higher the temperature, the faster the chemical reaction, and the lower the solubility of oxygen. The reaction rate increased 2 to 4 times when the temperature was increased by 10 °C [21]. The value is determined considering the dual role of dissolved oxygen and corrosion rate. | Generally, the pH is determined according to the periodic-salt–spray test. The narrower the pH range, the better the reproducibility of the tests. | The salt spray test box is in the state of saturated humidity; therefore, it can be assumed that the relative humidity is 95%. | Taking the time ratio of wetting–drying cycle in the actual marine environment as the test ratio, which is consistent with the correlation requirement. |

2.3. Test conditions
FPBs #1–4 were selected to perform the periodic-salt-spray test, and FPBs #5–8 were selected to perform the wetting–drying cycle test. The FPBs were taken out at certain intervals to test the mechanical properties including the vertical bearing capacity and horizontal hysteric behavior. Because marine corrosion may slightly affect the vertical bearing capacity, FPBs #1–8 were subjected to a horizontal hysteric performance test, but only #1 and #5 FPBs were tested to determine the vertical bearing capacity. By conducting the horizontal performance tests, the deterioration trends of static and dynamic friction coefficients, equivalent stiffness, and damping ratio with corrosion time were obtained. The test time intervals mainly simulate the actual marine corrosion environment in 5 years, 10 years, 20 years, 30 years, 45 years, and 60 years; according to the accelerated ratios, the
corresponding accelerated corrosion times were obtained: 222 h, 444 h, 888 h, 1332 h, 1998 h, and 2664 h, respectively. The main test conditions are shown in Table 2.

Table 2. Test conditions of periodic-salt-spray test and wetting–drying cycle tests for FPBs

| No. | Test conditions | Test time (h) | Test item | Test objects |
|-----|----------------|--------------|-----------|--------------|
|     | Before test    | 0            | Vertical bearing capacity | #1 and #5 |
|     | Periodic-salt-spray test / wetting–drying cycle test | 222 h (5 years) | Horizontal hysteretic behavior | #1 and #5 |
|     |               | (Spray 74 h, dry 148 h)/ (Full immersion 74 h, dry 148 h) |             | #1–4/ #5–8 |
|     | Periodic-salt-spray test / wetting–drying cycle test | 444 h (10 years) | Vertical bearing capacity | #1 and #5 |
|     |               | (Spray 148 h, dry 296 h)/ (Full immersion 148 h, dry 296 h) | Horizontal hysteretic behavior | #1–4/ #5–8 |
|     | Periodic-salt-spray test / wetting–drying cycle test | 888 h (20 years) | Vertical bearing capacity | #1 and #5 |
|     |               | (Spray 296 h, dry 592 h)/ (Full immersion 296 h, dry 592 h) | Horizontal hysteretic behavior | #1–4/ #5–8 |
|     | Periodic-salt-spray test / wetting–drying cycle test | 1332 h (30 years) | Vertical bearing capacity | #1 and #5 |
|     |               | (Spray 444 h, dry 888 h)/ (Full immersion 444 h, dry 888 h) | Horizontal hysteretic behavior | #1–4/ #5–8 |
|     | Periodic-salt-spray test / wetting–drying cycle test | 1998 h (45 years) | Vertical bearing capacity | #1 and #5 |
|     |               | (Spray 666 h, dry 1332 h)/ (Full immersion 1332 h, dry 666 h) | Horizontal hysteretic behavior | #1–4/ #5–8 |
|     | Periodic-salt-spray test / wetting–drying cycle test | 2664 h (60 years) | Vertical bearing capacity | #1 and #5 |
|     |               | (Spray 888 h, dry 1776 h)/ (Full immersion 888 h, dry 1776 h) | Horizontal hysteretic behavior | #1–4/ #5–8 |

Note: The ratio of drying and wetting times is 2:1, and the test time equals to the drying time plus wetting time. Taking the periodic-salt-spray test of 222 h as an example, the ratio of the total drying time to the total wetting time is 148 h: 74 h. Every day, the spraying time is 8 h, and the drying time is 16 h. The temperature was maintained at 35 °C. For the wetting–drying cycle test of 222 h, the ratio of the total drying time to the total wetting time is also 148 h: 74 h, but the FPBs were first immersed in seawater for 74 h and then dried in a constant-temperature box for 148 h. The temperature was also maintained at 35 °C.

3. Experimental study on the performance of FPBs under an artificial accelerated corrosion environment

3.1. Test equipment
The tests were performed at Earthquake Engineering Research & Test Center, Key Laboratory of Seismic Control and Structural Safety, Guangzhou University. The equipment used in the test are shown in figures 2–6. The mechanical performance tests for bearings were carried out on a large-scale
A multifunction tensile-compression-shear test system equipped with an electrohydraulic servo control system developed independently. In the test system, the vertical maximum compression load was 500 t; the vertical maximum tension load was 300 t; the horizontal load was 110 t; the horizontal loading frequency was 1 Hz. The system can be used to determine the ultimate performance, compression, tension, and shear performance for isolation bearings.

(a) Salt spray test chamber.  
(b) Test specimen. 
Figure 2. Salt spray test chamber and test specimen.

(a) Constant-temperature test chamber.  
(b) Test specimen. 
Figure 3. Constant-temperature test chamber and test specimen.

Figure 4. Tensile-compression-shear test set-up
3.2 Periodic-salt-spray test

3.2.1. Experimental observation.
The experimental phenomena of FPBs #1–4 in the periodic-salt-spray test at each corrosion time are shown in figure 5.

![Figure 5. Periodic-salt-spray test of FPBs #1–4.](image)

Figure 5 shows that with the increase in the test time for the periodic-salt-spray test, increasingly more rust appeared on the bearings, and the corrosion of bearings became increasingly more severe. The most severe corrosion appeared on the steel and bolt connecting the upper and lower parts of bearings. Because of unique concave rotating surfaces of the FPBs, rust water was observed on the concave rotating surfaces after the fasteners were corroded. Although the stainless-steel material made of a sliding surface is not easily corroded, the long-stay rust water may also affect the horizontal friction isolation performance of the bearing. For the corroded FPBs, its self-restoring function may become the disadvantage affecting the bearing performance.

3.2.2. Trend of mechanical properties of FPBs

3.2.2.1. Vertical performance
Vertical loading tests were performed for the FPBs, and the compression deformation at each corrosion time was obtained when the design load was 350 kN. Furthermore, the trends of vertical stiffness with corrosion time were obtained. The compression deformation and vertical stiffness of FPB #1 are shown in table 3. The results of other FPBs are similar; to avoid repetition, they are not described.

| Corrosion time | 0 h  | 222 h | 444 h | 888 h | 1332h | 1998h | 2664h |
|---------------|------|-------|-------|-------|-------|-------|-------|
| Compression deformation (mm) | 0.876 | 0.841 | 0.933 | 0.883 | 0.740 | 0.940 | 0.898 |


As shown in table 3, when the vertical force was equal to the design load 350 kN, irrespective of the corrosion time, the vertical compression deformation of the FPB was also <1% of the total height (1.05 mm). Thus, with the increase in corrosion time, the FPBs always satisfied the requirements of vertical bearing capacity. In summary, with the change in corrosion time, deviations between the average and initial values of vertical stiffness were mostly from 1% to 8%, indicating that the corrosion environment slightly affected the vertical stiffness.

3.2.2.2. Horizontal performance

(a) Horizontal hysteresis curve

A vertical load 35 t was applied to the FPBs. The single-side slide distance of FPBs was 60 mm, and the horizontal load had five cycles. The horizontal hysteresis curves of the FPBs were recorded. Furthermore, the static and dynamic friction coefficients, post-yielding stiffness, and equivalent damping ratio were calculated, and the deterioration trend with corrosion time was obtained. Limited by the length of this paper, only the horizontal force–displacement curves of FPB #1 at different corrosion times in the periodic-salt-spray test are shown in Figure 6. With the change in corrosion time, the horizontal friction force of the FPB experienced a similar periodic trend: first decreased, then increased, and finally decreased.

-80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80
-25
-20
-15
-10
-5
0
5
10
15
20
25
Horizontal Disp.(mm)
Horizontal Load(kN)

(a) Before test.
(b) After 222 hours test.
(c) After 444 hours test.
(d) After 888 hours test.
(e) After 1332 hours test.  
(f) After 1998 hours test.
(g) After 2664 hours test.

Figure 6. Hysteretic curves of FPB #1 at corrosion time.

(b) Static and dynamic friction coefficients

Figure 7 shows the static and dynamic friction coefficients of FPBs #1–4 at each corrosion time for the periodic-salt-spray test. With the increase in corrosion time, the static and dynamic friction coefficients of FPBs #1–4 clearly increased and decreased, respectively, exhibiting similar periodic wave curves. The final value of the coefficients at 60 years was less than the initial value at 0 year. The horizontal axis is the actual service time of the FPB in the actual environment corresponding to the accelerated corrosion time in the periodic-salt-spray test.

Static friction coefficients of FPBs.

Figure 7. Dynamic and static friction coefficients of FPBs #1–4 at each corrosion time in the periodic-salt-spray test.

Because the trend of the friction coefficient of a single FPB was similar except FPB #3, the trend of the friction coefficient can be obtained from the average friction coefficients of the FPBs at different corrosion times, as shown in figure 8. The test curves of FPB #3 showed the opposite phenomenon compared to the data of other bearings; therefore, these experimental data were discarded.
Figure 8. Average values of dynamic or static friction coefficients for FPBs #1–4 at each corresponding actual usage time to each accelerated corrosion time in the periodic-salt-spray test.

Figure 8 shows that the static friction coefficient increased with the corrosion time in the first 20 years in the periodic-salt-spray test. At this time, the sliding surface of the bearing was always in the wet state and gradually formed a thick rust layer. The sliding surface became rough, and the static friction coefficient increased constantly. The initial static friction needed to overcome gradually increased. From the 20th years to the 40th years, with the increase in the number of friction action, the surface of the corrosion layer gradually became wet or damaged, and the initial static friction coefficient gradually decreased. Then, the next similar periodic corrosion process started. The trend of dynamic friction coefficient also showed a similar periodic wave phenomenon, but it showed an overall downward trend. After 60 years of periodic-salt-spray corrosion, the dynamic friction coefficient decreased by 65% compared to that before the corrosion, indicating that the friction energy dissipation capacity of the FPB significantly reduced.

According to the experimental results and trend of the static and dynamic friction coefficients of the FPBs with corrosion time, the periodic and linear functions were used to fit the friction coefficients. The fitting formulas are as follows:

\[
\mu_s(t) = [0.1748 \sin(0.1096t - 0.7987) + 0.0016t + 1.1007] \mu_{s0} \\
\mu_d(t) = [0.0978 \sin(0.1390t - 2.4965) - 0.0112t + 1.0594] \mu_{d0} 
\]

(1) \( \mu_{s0} \) and \( \mu_{d0} \) are the initial static and dynamic friction coefficients of FPBs, respectively; the unit of friction coefficient is %; the unit of time \( t \) is year; the correlation coefficients of the fitting formulas for the static and dynamic friction coefficients are 0.76 and 0.93, respectively.

The static and dynamic friction coefficients at each corrosion time were calculated using the fitting formulas. The errors of the calculation and test average values are shown in Table 4. Clearly, the error is <10%.

| Corrosion time/year | Static friction coefficient | Dynamic friction coefficient |
|---------------------|-----------------------------|-----------------------------|
|                     | Test average value           | Calculated value            | Error (%) | Test average value | Calculated value | Error (%) |
| 0                   | 0.0337                      | 0.0329                      | 2.43      | 0.0273            | 0.0273           | 0.00      |
| 5                   | 0.0337                      | 0.0359                      | -6.13     | 0.0257            | 0.0248           | 3.63      |
| 10                  | 0.0409                      | 0.0394                      | 3.81      | 0.0218            | 0.0235           | -7.23     |
| 20                  | 0.0443                      | 0.0440                      | 0.68      | 0.0249            | 0.0235           | 5.96      |
| 30                  | 0.0417                      | 0.0423                      | -1.42     | 0.0216            | 0.0224           | -3.57     |
| 45                  | 0.0351                      | 0.0346                      | 1.45      | 0.0140            | 0.0136           | 2.94      |
| 60                  | 0.0373                      | 0.0375                      | -0.53     | 0.0093            | 0.0094           | -1.06     |
(c) Horizontal post-yielding stiffness and equivalent damping ratio

Using the slope of the third-circle hysteresis curve, the horizontal post-yielding stiffness of the FPBs at different service times in the periodic-salt-spray test were obtained, as shown in table 5. Clearly, with the change in corrosion time, the horizontal stiffness slightly changed, indicating that a marine environment has less effect on the horizontal stiffness of FPBs. The formulas of horizontal post-yielding stiffness $K_{hp}$ show that $K_{hp}$ is related to the vertical force and radius of curvature, and basically not affected by the marine environment.

Table 5. Horizontal stiffness of FPBs #1–4 at each accelerated corrosion time

| FPB     | #1       | #2       | #3       | #4       |
|---------|----------|----------|----------|----------|
| 0h      | 0.2613   | 0.2513   | 0.2528   | 0.2549   |
| 222h(5 year) | 0.2614   | 0.2592   | 0.2665   | 0.2685   |
| 444h(10 year) | 0.2692   | 0.2580   | 0.2741   | 0.2647   |
| 888h(20 year) | 0.2658   | 0.2705   | 0.2875   | 0.2694   |
| 1332h(30 year) | 0.2652   | 0.2639   | 0.2849   | 0.2624   |
| 1998h(45 year) | 0.2607   | 0.2798   | 0.3135   | 0.2842   |
| 2664h(60 year) | 0.2614   | 0.2649   | 0.2815   | 0.2690   |

Equivalent damping ratio is an important parameter reflecting the energy dissipation performance of FPB; it can be calculated from the area of hysteresis curve. The trend of equivalent damping ratio with corrosion time in the periodic-salt-spray test is shown in figure 9. The trend of equivalent damping ratio is similar to that of dynamic friction coefficient. According to the theoretical formulas of equivalent damping ratio for FPBs, $\xi_{eq} = \frac{2\mu D}{\pi(\mu D + D/\rho)}$, when the maximum horizontal displacement $D$ and curvature radius of bearing $\rho$ are determined, the only influencing factor of equivalent damping ratio is the dynamic friction coefficient. The theoretical equivalent damping ratio calculated using the test value of dynamic friction coefficient in the theoretical formulas is very close to the calculated value using the area of hysteretic curves.

![Figure 9. Equivalent damping ratio of FPBs #1–4 at each corrosion time.](image)

3.3. Wetting–drying cycle test

3.3.1. Experimental phenomena

In the wetting–drying cycle test, the comparisons of experimental phenomena among FPBs #5–8 with corrosion time are shown in figure 10.
Figure 10 shows that with the increase in corrosion time, increasingly more salt crystallization and rust appeared on the sliding surface of FPBs; the most easily eroded are still the steel and bolt fastener. Compared to the periodic-salt-spray test, the corrosion situations of the FPBs in the wetting–drying cycle test were lighter, and the rust on the surface was no more severe. This indicates that under the marine environment, the corrosion of bearings in the splash zone is more severe than that in the atmospheric zone. Much attention should be paid to the corrosion of FPBs in the non-navigable or lower part of bridges.

### 3.3.2. Mechanical properties of FPBs

#### 3.3.2.1. Vertical performance

In the wetting–drying cycle test, the trends of vertical compression deformation and average vertical stiffness of FPB #5 with the corrosion time are shown in table 6. The results of other FPBs are similar. The average vertical compression deformation of FPB #5 at each corrosion time was <1.05 mm. In other words, when the FPB was corroded for 2664 h in the artificial accelerated corrosion test, which is equivalent to 60 years of the actual usage time in the marine environment, the vertical bearing capacity of the FPB always satisfies the design requirements. Similarly, with the increase in corrosion time, the average vertical stiffness slightly changed, i.e., the marine corrosion environment slightly affected the vertical stiffness of the FPBs.

| Corrosion time (h) | Compression deformation (mm) | Vertical stiffness (kN/mm) |
|--------------------|-------------------------------|----------------------------|
| 0                  | 0.940                         | 425.07                     |
| 222                | 0.962                         | 449.68                     |
| 444                | 0.993                         | 434.11                     |
| 888                | 0.961                         | 449.26                     |
| 1332               | 0.862                         | 489.68                     |
| 1998               | 0.805                         | 413.07                     |
| 2664               | 0.975                         | 401.48                     |

#### 3.3.2.2. Horizontal performance

(a) Static and dynamic friction coefficients
The trends of static and dynamic friction coefficients of FPBs #5–8 with corrosion time are shown in figure 11. The deterioration trend of the static or dynamic friction coefficients with the corrosion time for different FPBs are similar. The static and dynamic friction coefficients showed a general periodic wave-shape changes. The horizontal axis shows the actual service time of the FPBs in the actual environment corresponding to the accelerated corrosion time in the wetting–drying cycle test.

Similarly, the average static or dynamic friction coefficients of FPBs #5–8 were obtained. According to the overall experimental results and corrosion states of bearings, trends of the static and dynamic friction coefficients of the bearings in the actual marine environment with the corrosion time were obtained, as shown in figure 12.

Figure 12 shows that the static friction coefficient gradually increased with the corrosion time in the first 15 years in the wetting–drying cycle test. From the 15th to the 30th years, the static friction coefficient constantly decreased. From the 30th to the 45th years, the static friction coefficient constantly increased, and in the next 15 years, the static friction coefficient decreased. In general, the static friction coefficient showed a similar periodic wave change, as well as a gradually increasing trend. This is probably because in the wetting–drying cycle test, the corrosion degree of a sliding surface depends on the salt crystal number. In the first 15 years, the number of salt crystals on the sliding surface constantly increased, and the sliding surface became increasing more rough. Therefore, the static friction coefficient increased. From the 15th to the 30th years, the salt crystals became increasingly denser, and a layer of smooth passive film was formed. Therefore, the static friction
coefficient decreased. From the 30th to the 45th years, the passive film was destroyed, and the sliding surface became rough. Therefore, the static friction coefficient increased. Then, the next similar periodic corrosion process started. After 60 years of wetting–drying cycle corrosion, the static friction coefficient of the FPBs increased by ~94% compared to that before the corrosion, and the dynamic friction coefficient of the FPBs increased by ~37% compared to that before the corrosion. The trend of the dynamic friction coefficient is similar to that of the static friction coefficient, but the static friction coefficient showed a larger variation.

The trend of the average static and dynamic friction coefficients of FPBs #5–8 with the corrosion time, shows that the friction coefficient of the bearing first increased and then decreased, then increased, and finally decreased after a certain number of years. At the same time, an upward trend was observed in the entire lifetime; therefore, the periodic and linear functions were used to fit the friction coefficients. The fitting formulas are as follows:

\[
\mu_s(t) = -0.3731 \sin(-0.2214 t + 8.2942) + 0.0208 t + 1.2197 \mu_{s0}
\]

\[
\mu_d(t) = 0.1717 \sin(0.1922 t - 0.3199) + 0.0096 t + 1.0659 \mu_{d0}
\]

\(\mu_{s0}\) and \(\mu_{d0}\) are the static and dynamic friction coefficients of the FPB before it was corroded, respectively; the unit of friction coefficient is %; the unit of time is year; the correlation coefficient \(R^2\) of the static and dynamic friction coefficients in the fitting formula are 0.71 and 0.65, respectively.

The calculated value of the fitting curve, average value of the test, and error between them for the FPBs used in the wetting–drying cycle test are shown in table 7. The error of dynamic friction coefficient was <10%, but the error of the initial static friction coefficient in some parts was >10%, even up to 18.48%, but <20% basically.

Table 7. Errors between the calculated friction coefficients with the experimental data of the FPBs used in the wetting–drying cycle test

| Corrosion time (year) | Static friction coefficient | Dynamic friction coefficient |
|-----------------------|----------------------------|----------------------------|
|                       | Average value of test      | Calculated value           | Error (%) | Average value of test | Calculated value | Error (%) |
| 0                     | 0.0357                     | 0.0313                     | 14.06     | 0.0228               | 0.0231         | -1.30     |
| 5                     | 0.0300                     | 0.0368                     | -18.48    | 0.0268               | 0.0277         | -3.25     |
| 10                    | 0.0561                     | 0.0536                     | 4.66      | 0.0297               | 0.0304         | -2.30     |
| 20                    | 0.0586                     | 0.0670                     | -12.54    | 0.0272               | 0.0273         | -0.37     |
| 30                    | 0.0605                     | 0.0526                     | 15.02     | 0.0310               | 0.0283         | 9.54      |
| 45                    | 0.0963                     | 0.0901                     | 6.88      | 0.0390               | 0.0377         | 3.45      |
| 60                    | 0.0696                     | 0.0753                     | -7.57     | 0.0313               | 0.0336         | -6.85     |

(b) Horizontal post-yield stiffness and equivalent damping ratio

Table 8 shows the trends of horizontal post-yield stiffness of FPBs #5–8 with the corrosion time in the wetting–drying cycle test. Similar to the trends of periodic-salt-spray test, the corrosion time slightly affected the horizontal stiffness.

Table 8. Horizontal stiffness of FPBs #5–8 at each corrosion time

| Corrosion time (year) | #5     | #6     | #7     | #8     |
|-----------------------|--------|--------|--------|--------|
| 0 h                   | 0.2586 | 0.2530 | 0.2512 | 0.2509 |
| 222 h (5 years)       | 0.2991 | 0.2966 | 0.2589 | 0.2622 |
| 444 h (10 years)      | 0.2662 | 0.2747 | 0.2707 | 0.2629 |
| 888 h (20 years)      | 0.2620 | 0.2668 | 0.2568 | 0.2564 |
| 1332 h (30 years)     | 0.2655 | 0.2793 | 0.2598 | 0.2566 |
| 1998 h (45 years)     | 0.2792 | 0.3176 | 0.2989 | 0.3016 |
| 2664 h (60 years)     | 0.2923 | 0.2904 | 0.2954 | 0.2820 |

In the wetting–drying cycle test, the trends of equivalent damping ratio of FPBs with corrosion time are shown in figure 13. For the corrosion time, the trend of the equivalent damping ratio is
consistent with that of the dynamic friction coefficient.

Figure 13. Equivalent damping ratio of FPBs #5–8 at each corrosion time

3.4. Comparison of periodic-salt-spray test and wetting–drying cycle test

By comparing the test results of periodic-salt-spray and wetting–drying cycle tests, the trends of the static and dynamic friction coefficients with corrosion time in the two types of accelerated corrosion tests are shown in figure 14.

(a) Comparison of static friction coefficients of the periodic-salt-spray and wetting–drying cycle tests for the FPBs.

(b) Comparison of dynamic friction coefficients of the periodic-salt-spray and wetting–drying cycle tests for the FPBs.

Figure 14. Comparison of static and dynamic friction coefficients of the periodic-salt-spray and wetting–drying cycle tests for the FPBs.

Figure 14 shows the following:

a) During the first 15 years, all the static friction coefficients obtained by the periodic-salt-spray and wetting–drying cycle tests gradually increased, but the variation of test data in the wetting–drying cycle test was larger than that in the periodic-salt-spray test. During the second 15 years, all the static friction coefficients obtained from the two types of tests gradually decreased. However, from the 30th to the 60th years, two opposite trends were observed in the two types of tests. This is probably because the sliding surfaces of FPBs #5–8 were completely dry and had a large amount of salt crystals, unlike FPBs #1–4 in a humid environment. Therefore, the influencing mechanisms of friction coefficient in the two tests are different.

b) The trends of dynamic friction coefficients obtained from the two test methods are very different; the FPBs present in the splash zone showed completely different corrosion results compared to those in the atmospheric zone. After 60 years of marine environment corrosion, the dynamic friction coefficient in the periodic-salt-spray test decreased, whereas the dynamic friction coefficient in the wetting–drying cycle test increased. The possible reasons for this difference are as follows:
1. The corrosion environment is very different between the splash and atmospheric zones.

2. Although the total time of each test was the same, the frequency of wetting and drying cycle in the periodic-salt-spray test was much more than that in the wetting–drying cycle test.

3. During the periodic-salt-spray test, the salt crystals constantly settled on the sliding surface of the bearing, while the entire FPBs were immersed in salt water in the wetting–drying cycle test. Therefore, the corrosion rate in the wetting–drying cycle test was lower than that in the periodic-salt-spray test. Therefore, the friction coefficient still showed a small variation without substantial decrease of accelerated corrosion.

4. In the periodic-salt-spray test, the sliding surface of the FPBs was still wet, but the sliding surface was completely dry in the wetting–drying cycle test.

4. Conclusions
At present, the behavior deterioration trend of FPBs widely used in offshore bridges under the marine environment is still not clear. Periodic-salt-spray and wetting–drying cycle tests were performed on FPBs to simulate the situations of FPBs exposed to marine environment in the splash and atmospheric zones. The behavior deterioration trends of the FPBs and isolated bridge with FPBs were evaluated. The main conclusions are as follows:

1) The static and dynamic friction coefficients of FPBs showed a similar periodic wave-shape change with the corrosion time, but a large difference was observed between the periodic-salt-spray test (splash zone) and wetting–drying cycle test (atmospheric zone). The former had a longer deterioration period, while the latter had a shorter deterioration period. After 60 years of actual marine environment, the dynamic friction coefficient in the splash zone decreased and that in the atmospheric zone increased.

2) The vertical and horizontal stiffness of the FPB almost did not change with the corrosion time, and the vertical supporting capacity of the bearing always satisfied the requirement. The equivalent damping ratio of the bearing also showed a similar periodic wave-shape change with the corrosion time, consistent with the dynamic friction coefficient of the bearing.

3) Based on the above tests, the formulas for the variation law of performance of the static and dynamic friction coefficients of FPBs were obtained, which can be used to study the deterioration trend of seismic performance for the offshore isolated bridges in its entire life cycle.

Acknowledgements
This work was supported by Natural Science Fund of China (NSFC) under grant Nos. 51678173 and 51578170, and Science and Technology Program of Guangzhou, China under grant Nos. 1201421152 and 201707010295.

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