DURABILITY TEST AND STATISTICAL EVALUATION OF RUBBER FENDERS FOR VESSEL BERTHING

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The fender is part of the ancillary equipment of mooring facilities and plays an important role in safe vessel berthing and smooth cargo handling. If fenders are damaged, economic loss will occur due to the suspension of service or restriction of operation of the mooring facility, and the operation and maintenance of the entire facility may be affected. Since fenders are used for a long time, it is necessary to ensure their durability. In 2002, the International Navigation Association (PIANC) published the “Guidelines for the Design of Fender System” and proposed a new method for confirming the durability of rubber fenders. In Japan, in 2010, consistent with the PIANC guidelines, a description of the durability of rubber fenders was added to the Standard Specifications for Port and Harbour Works of the Ports and Harbours Bureau of the Ministry of Land, Infrastructure, Transport and Tourism. In this study, the data of durability tests conducted by rubber fender manufacturers were statistically analyzed. From the results of the durability tests, a long-term performance criterion for rubber fenders was proposed.

Key Words: rubber fender, durability test, energy absorption, residual strain, statistical analysis

1. INTRODUCTION

In recent years, the size of vessels has been increasing internationally to improve the efficiency of marine logistics. On the other hand, there are some cases in which many port facilities have become obsolete or have deteriorated and cannot cope with the increase in the size of vessels. As part of the ancillary equipment of mooring facilities, fenders play an important role in safe vessel berthing and smooth cargo handling. Thus, if a fender is damaged, it may cause economic loss due to suspension of service or the restriction of mooring facilities and may affect the operation of the entire port. Therefore, it is necessary to detect damage and deterioration of the fenders at an early stage and to take measures based on an appropriate functional evaluation. Today, fenders are mainly made of rubber. Rubber deterioration factors include natural environmental factors, chemical factors, fatigue factors, and external force factors.

Since fenders are used for a long time, it is necessary to ensure their durability taking the above factors into account.

However, evaluation criteria for the long-term durability of rubber fenders have not been established. After five years of deliberation at WG33/PTC II, the International Navigation Association (PIANC) published guidelines (hereafter referred to as PIANC guidelines) for the design of fenders in 2002, and a new test method for the durability of rubber fenders was proposed. In Japan, the Ports and Harbours Bureau of the Ministry of Land, Infrastructure, Transport and Tourism revised the Standard Specifications for Port and Harbour Works, and durability tests have been carried out since 2010.

Shiraishi and Nakashima investigated the changes in the properties of rubber fenders after durability tests based on the data collected by rubber fender manufacturers (five Japanese companies and two overseas companies). The supply of products to
one Japanese company and one overseas company was subsequently discontinued, but they are also included in the analysis of this study. In this report, a statistical interpretation of the test results in the report of Shiraishi et al., including recent additional test data, is carried out, and future improvements of the test method and statistical evaluation are discussed.

2. BACKGROUND OF THE DESIGN AND DURABILITY TESTS

(1) Design method of rubber fenders

Fenders are designed so that the energy absorption $E_a$ exceeds the vessel’s effective berthing energy $E_f$, determined by equation (1)\(^5\).

$$E_f = \frac{1}{2} M_s V_b^2 C_e C_m C_s C_c$$

Here, $M_s$ is the vessel mass, $V_b$ is the berthing velocity, $C_e$ is the eccentricity factor, $C_m$ is the virtual mass factor, $C_s$ is the softness factor, and $C_c$ is the berth configuration factor.

When the energy absorption up to the allowable strain (hereafter referred to as the rated strain) of the fender is assumed to be $E_a$, the fender is determined to meet the condition of equation (2). Here, 0.9 is a factor representing the manufacturing tolerance.

$$E_a \times 0.9 > E_f$$

The energy absorption $E_a$ used for the design of the fender is the catalog value provided by the manufacturer. $E_a$ is obtained under standard temperature (23°C) and standard compression velocity. According to the PIANC guidelines, the energy absorption of rubber fenders is affected by the temperature and berthing velocity, and a design method using these coefficients is defined. In Japan, although the effects of velocity and temperature are described in the Technical Standards and Commentaries for Port and Harbour Facilities\(^5\), they have not been introduced as standard design methods at present. From the perspective of future design method changes in Japan and maintaining consistency with the PIANC guidelines, the “Guidelines for the Design and Testing of Rubber Fenders” were published in 2018\(^6\). In these guidelines, the factors affecting the performance of rubber fenders are the (a) manufacturing tolerance, (b) angular factor, (c) velocity factor, (d) temperature factor, (e) aging factor, (f) repetition factor, and (g) creep characteristics. Examples of how to consider these factors in fender design are given.

(2) Background of the durability test

The Ports and Harbours Bureau of the Ministry of Land, Infrastructure, Transport and Tourism stipulates specifications for the rubber fenders used for port construction in the Standard Specifications for Port and Harbour Works (hereafter referred to as the Standard Specifications). The previous specifications did not have provisions for durability confirmation, and there was a difference from the PIANC guidelines. To ensure consistency, a description of the durability test was added to the Standard Specifications after 2010. The Ministry of Land, Infrastructure, Transport and Tourism has designated the Specialists Center of Port and Airport Engineering (SCOPE) as the organization for this authentication. SCOPE issues a certificate based on the results of the durability tests conducted by fender manufacturers (five companies in Japan) and reviews and deliberates on the results determined by the committee before authentication. SCOPE also examines the imported materials used for port construction in Japan, and the same certificate is required for fenders produced by foreign manufacturers (two companies in 2019) that have applied for authentication. This study analyzes the data of the test results collected so far with the consent of these fender manufacturers.

3. DURABILITY TEST

(1) Test method

A durability test for rubber fenders was not specified in the PIANC guidelines. These guidelines only stipulate the basic items of test specifications. Therefore, SCOPE established the details of the test method (hereafter referred to as test regulations) with the “Committee for Rubber Fender Durability Certification Standard” composed of experts. In addition, it has been revised based on the implementation status.

Table 1 Measurement items in each test.

| Test | Items |
|------|-------|
| A: Static compression test (pre-test) | Height (pretest) $H_1$, Reaction force $R_1$, Energy absorption $E_1$ |
| B: Durability test | Specimen temperature (pretest) $T_1$, Ambient temperature (during test) $T_S$, Specimen temperature (posttest) $T_2$ |
| C: Static compression test (post-test) | Height $H_2$, Residual strain $\delta_R$ ($\delta_R = H_1 - H_2$), Reaction force $R_2$, Energy absorption $E_2$ |

* Ambient temperature: Temperature within 3 m from the specimen
Table 1 shows the measurement items in the durability test and the static compression tests performed before and after the durability test.

The test rules stipulate the following:
(a) The specimen used for the durability test should be a fender that is at least the minimum size of a commercially available product. This means that the size of the fender is the minimum size or more described in the product catalog by rubber fender manufacturers.
(b) In the durability test, compression is repeated 3,000 times with a cycle of 150 s or less until the rated strain specified by the manufacturer is reached or exceeded. After the durability test, it is confirmed that there are no cracks, defects, or significant performance degradation. Regarding the cycle and the number of times compression is repeated, the tendency of the fender performance to decline due to past test results, the number of times vessels berth at port facilities within their service life, the performance of the testing machine used for durability tests, etc., are taken into account.
(c) The specimen temperature at the start of the durability test must be 23°C±5°C, and the specimen must not be artificially cooled before or during the test.
(d) Although the test room temperature is not specified, continuous measurement is required.
(e) A static compression test (pretest) before the durability test is performed to determine the energy absorption $E_1$ and reaction force value $R_1$. In addition, a static compression test (posttest) after the durability test is performed to obtain the energy absorption $E_2$ and reaction force value $R_2$.
(f) The static compression test must be performed within 24 hours of the durability test. This is a regulation established for the reason that the heat generated during the durability test dissipates over time and that the rubber fender’s performance is affected.

Several types of rubber properties, ranging from soft to hard for a fender of the same shape and size, are listed in the manufacturer’s catalog. By selecting these materials appropriately, it is possible to consider the structure of the mooring facility and the vessel’s hull structure by adjusting the rubber grades. The durability test was specified to be performed on the hardest and softest of these materials. The values of the reaction force and energy absorption for the same shape and dimensions vary depending on the manufacturer and the fender shape, but most of them range from 0.6 to 2.0.

(2) Evaluation of the durability test result
The result of the durability test is judged to pass if the following requirements are met:
a. No cracks are observed visually.
b. The energy absorption and reaction force values in the static compression posttest are not significantly lower than those in the static compression pretest.
Since the above requirements are qualitative expressions and cannot be used in pass/fail judgments, the purpose of this study is to propose an appropriate threshold value for condition b on the basis of the past results.

4. EVALUATION OF TEST RESULTS
(1) Evaluation of test data
The reaction force ratio $(R_2/R_1)$ and energy absorption ratio $(E_2/E_1)$ were obtained from the results measured in the static compression tests, the pretest, and posttest. The relationship between them, and the residual strain $\delta_R$ of the fender, ambient temperature $T_A$, and specimen temperatures $T_1$, $T_2$, etc., were analyzed.

Rubber fenders are classified into the three categories below according to their shape and how they deform when loaded. Figure 1 shows examples of typical shapes for each classification.

G-A: V-type, etc. (When the strain reaches approximately 10%–20% of the height of the fender, it undergoes overall compressive deformation when subjected to a load. If the strain exceeds 20%–30%, buckling deformation occurs in the legs, and the reaction force becomes almost constant).

G-B: Vertical cylindrical type, etc. (As with shape G-A, the fender deforms as a whole up to approximately 10%–20% of its height, and the reaction force becomes almost constant due to the buckling deformation of the legs over 20%–30%. In addition, the expansion of the diameter of the rubber fender boosts the reaction force).

G-C: Planar structure, etc. (The fender is used mainly for small ships such as in fishing ports, and it absorbs energy mainly by compressive deformation of the rubber against impact).

The relationship between the strain and reaction force of rubber fenders is classified into the four patterns below, as shown in Fig. 2. Figure 2 shows the rated strain as 50%, but the rated strain of fenders varies depending on the shape and is 40% to 70% of the fender height.

P-1: The reaction force peaks at a certain strain and then decreases and increases again (Buckling type I).

P-2: As with P-1, there is buckling but no peak, and then the reaction force increases (Buckling type II).

P-3: The reaction force increases in a high-order curve with respect to the strain (Curvilinear increase type).

P-4: The reaction force increases proportionally with strain (Linear increase type).
Fig. 1 Examples of each classification of fender shape.

Fig. 2 Classification of fender types by the performance curve.

Fig. 3 Reaction forces before and after the durability test (conceptual).

The energy absorption \( E_1 \) in the static compression test (pretest) of the fender with P-1 is obtained from the area surrounded by A-B-C (the range of the solid line AB, rated strain C, and horizontal axis) in Fig. 3. The method of determining the energy absorption \( E_2 \) in the static compression test (posttest) is not consistent depending on the year of the test. In early 2010, when durability tests began in Japan, the way to handle the residual strain was not standardized in the calculation of the energy absorption \( E_2 \). Since 2012, the energy absorption \( E_2 \) has been standardized in consideration of the effect of the residual strain \( \varepsilon_R (=\delta_R/H_1) \) on the horizontal axis AA' in Fig. 3. When the residual strain in the static compression test (posttest) is not included in compression (hereafter abbreviated as “not included”), the energy absorption is the enclosed area of A'B"C' in Fig. 3, (the range of the dashed lines A'B" and C'). In this case, even if there is a residual strain, the reaction force characteristics are considered up to the same compression amount C(= C+A') as in the initial compression. On the other hand, when the residual strain is included (hereafter abbreviated as “included”), the clearance of the residual strain is included in the compression. Therefore, the energy absorption when the residual strain is included (A'B'C) is generally smaller than the value when the residual strain is not included.

Figure 4 shows examples of the relationship between the strain and reaction force before and after the durability test for P-1 to P-4 in Fig. 2. "Pretest" indicates the results before the durability test, and “Posttest” indicates the results after the durability test. In all the characteristics, the reaction force after the durability test is reduced, and the energy absorption obtained by integrating the reaction force is also reduced.

Figure 5 shows an example of a comparison of the energy absorption ratios obtained by both methods using the same test results with and without the residual strain. In this example, it can be seen that the energy absorption ratio when the residual strain is included is evaluated as 5% to 10% lower than when the residual strain is not included. Cases whose energy absorption ratio exceeds 100% correspond to the shape G-C and characteristic P-3 shown above.

(2) Analysis of the test results
a) Test results
The number of test samples subjected to the durability test is 131. Table 2 shows the number of test samples according to the classification described...
above with and without the residual strain. The sample numbers are 87 and 44, respectively. Shape G-A and shape G-B are classified as curve pattern P-1 or P-2, and shape G-C is classified as P-3 or P-4. The classifications of P-1 to P-4 in the table are based on the curve of the strain and reaction force before the durability test, but some of the characteristics change from P-1 to P-2 after the durability test.

Table 3 shows the durability test conditions (the test specimen height, specimen temperature, com-
pression cycle, and ambient temperature) and test results (residual strain \( \varepsilon_R \), reaction force ratio \( R_2/R_1 \), and energy absorption ratio \( E_2/E_1 \)) with and without the residual strain, as well as the mean value, standard deviation, and coefficient of variation of those data. The average reaction force ratio with the residual strain is 92.4%, which is approximately 1% lower than the average value without the residual strain, 93.4%. In addition, the average value of the energy absorption ratio when the residual strain is included is 86.4%, which is approximately 4% lower than the average value, 90.5%, without the residual strain.

Table 4 shows the test conditions, the average value of the test results, and the standard deviation for each shape of the fender for the test samples that include the residual strain. The average values of the energy absorption ratios are approximately the same at 86.4%, 86.0%, and 86.7% for shape G-A, shape G-B, and shape G-C, respectively, but the standard deviation is large for shape G-C.

The specimen height used for the durability test is at least the minimum size described in the catalog of the fender. Figure 6 shows the frequency distribution of the specimen heights used in the durability test. The mode value varies depending on the shape of the specimen. For shape G-A, the height is 200 mm (200 mm to less than 300 mm in the figure); for shape G-B, the height is 400 mm (400 mm to less than 500 mm in the figure); and for shape G-C, the height is 100 mm (100 mm to less than 200 mm in the figure).

The specimen temperature at the start of the durability test is specified as 23±5°C, but as shown in Fig. 7, most specimens fall into the range of 20°C to 25°C. Some specimens are close to the upper limit of 28°C and the lower limit of 18°C. On the other hand, there are cases where the ambient temperature (average) during the durability test varies greatly on the high-temperature side (maximum 33.1°C) or on the low-temperature side (minimum 14.5°C). There is no requirement for temperature control in the laboratory during the durability test, but there are provisions that the sample must not be artificially cooled. The tests on the low-temperature side may eventually cool the specimen, and the tests on the high-temperature side may accelerate the heating of the rubber surface. The effect of the ambient temperature on the specimen temperature will be described later.

b) The reaction force ratio and energy absorption ratio

Figure 8 shows the frequency distribution of the reaction force ratio. The average reaction force ratio in residual inclusions is 92.4%, as shown in Table 3. If it is not included, it is 93.4%. There are some samples with a reaction force ratio exceeding 100%, and this can be seen in the case where the reaction force value at the rated strain increases rapidly due to repeated compression. Increasing the reaction force requires caution when the reaction force affects the structural design, such as in a dolphin fender.

Figure 9 shows the frequency distribution of the energy absorption ratio. In relation to the strain and reaction force after the durability test, the reaction force tends to decrease after the durability test for the same strain, so the energy absorption ratio is less than 100%. Among both specimens with and without residual strain, many specimens had a value of 80% or more, but some specimens were below 80%. As shown in Table 3, the average absorbed energy ratio is 86.4% with the residual strain and 90.5% without the residual strain. The most frequent number is 80%–85% with the residual strain and 90%–95% without the residual strain. If the residual strain is not included, the reaction force and energy absorption are overestimated in the static compression test after the durability test, so the subsequent analysis will be limited to the data with the residual strain (87 samples). The number of samples analyzed for the specimen temperature \( T_2 \) after the test is 35.

Table 4: Conditions and results of durability tests.
(by shapes, residual strain included)

|                | G-A (n=53) | G-B (n=18) | G-C (n=16) |
|----------------|-----------|-----------|-----------|
| Specimen height (mm) |          |           |           |
| Ave             | 271       | 378       | 119       |
| SD              | 12.1      | 64.7      | 20.6      |
| Compression cycle (s) |          |           |           |
| Ave             | 54.5      | 83.2      | 15.6      |
| SD              | 38.1      | 46.7      | 8.21      |
| Specimen temperature (°C) |          |           |           |
| Ave             | 23.3      | 23.2      | 21.4      |
| SD              | 2.24      | 2.41      | 1.36      |
| Ambient temperature (°C) |          |           |           |
| Ave             | 24.0      | 30.1      | 23.8      |
| SD              | 3.43      | 3.12      | 1.79      |
| Residual strain (%) | 2.16      | 1.83      | 2.33      |
| Ave             | 1.02      | 0.94      | 1.26      |
| Reaction force ratio (%) | 93.7      | 93.0      | 87.8      |
| Ave             | 7.15      | 6.57      | 10.5      |
| Energy absorption ratio (%) | 86.4      | 86.0      | 86.7      |
| Ave             | 4.39      | 5.46      | 7.77      |

Ave: Average, SD: Standard Deviation
Fig. 7 Temperature of the specimens before the test and the ambient temperature during the test.

Fig. 8 Distribution of the reaction force ratio.

Fig. 9 Distribution of the energy absorption ratio.

**Figure 10** shows the relationship between the reaction force ratio and the energy absorption ratio when the residual strain is included. There are cases where the reaction force ratio exceeds 100%, but the energy absorption ratio is less than 100%. A reaction force ratio exceeding 100% can be seen in the examples where the fender material undergoes residual strain, the fender material height decreases, and the reaction force increases near the rated strain.

c) **Effect of the compression cycle**

Each manufacturer’s test was conducted over a wide range of compression cycles, 150 s or less. The minimum compression cycle was 7.9 s (test time 6.6 h), and the maximum compression cycle was 146.5 s (test time 122.1 h). **Figure 11** shows the relationship between the compression cycle and the energy absorption ratio when the residual strain is included. Shape G-C has a small compression cycle due to the small height of the test specimen, as shown in **Fig. 6**. The figure shows that the compression cycle has little effect on the energy absorption ratio.

d) **Specimen temperature after the durability test**

The temperature of the fender specimen $T_1$ before the durability test increases after the test to $T_2$. **Figure 12** (1) and **Fig. 12** (2) show the frequency distribution of the specimen temperature before and after the durability test. Since the rubber generates heat due to the repeated compression, the specimen temperature after the test rises. In particular, shape G-B tends to have a high specimen temperature after the durability test.

**Figure 13** shows the relationship between the ambient temperature and the specimen temperature after the test. From the figure, the coefficient of determination $R^2$ of both regression equations is 0.57, but $R^2 = 0.77$ for shape G-A alone.

**Figure 14** shows the relationship between the ambient temperature and the specimen temperature increase after the test ($T_2 - T_1$). Shape G-B shows a large temperature change. From the figure, $R^2$ of both regression equations is 0.13, but $R^2 = 0.27$ for shape G-A alone.
Figure 15 shows the relationship between the rated strain of the fender and the temperature change of the specimen after the test ($T_2 - T_1$). The fenders with a higher rated strain show a greater temperature increase, especially for the shape G-B. From the figure, $R^2$ of both regression equations is 0.26.

Figure 16 shows the relationship between the fender height and specimen temperature change ($T_2 - T_1$). The higher the fender height, the larger the temperature change after the test. The $R^2$ value of both regression equations is 0.44. Tests at high ambient temperatures lead to an increase in the specimen temperature, as described later, which also leads to an increase in the residual strain of the fender and a decrease in the energy absorption ratio. Since these items are important factors in the durability evaluation, appropriate management of the ambient temperature is important.
e) Residual strain

The fenders undergo a residual strain after the durability test. If the initial height before the test is \( H_1 \) and the height after the test is \( H_2 \), the residual displacement can be calculated as \( \delta_R = H_1 - H_2 \). The value obtained by dividing the residual displacement by the initial height \( H_1 \) is the residual strain \( \varepsilon_R \).

Figure 17 shows the frequency distribution of residual strain. The average residual strain is 2.12%, as shown in Table 3, with 2%–3% being the most frequent values. Figure 18 shows the relationship between the specimen temperature \( T_2 \) after the test and the residual strain. After the durability test, the rubber was softened, and the surface temperature of the specimen increased due to the heat generated by compression. From the figure, the \( R^2 \) of the regression equation is as low as 0.04, but \( R^2 \) is 0.45 for the shape G-A alone, as shown in Fig. 19.

f) Residual strain and energy absorption

Figure 20 shows the relationship between the residual strain \( \varepsilon_R \) and the energy absorption ratio \( (E_2/E_1) \). The energy absorption ratio tends to decrease as the residual strain increases. As shown in the figure, the \( R^2 \) of the regression equation is as low as 0.10. When limited to shape G-A, \( R^2 \) is 0.19, as shown in Fig. 21. As shown in Fig. 22, \( R^2 \) is 0.24 for shape G-B. Although the PIANC guidelines do not provide a quantitative index of performance degradation, an energy absorption ratio of 80% or more and a residual strain of 5% or less may be proposed as a criterion based on many previous test results. This will be analyzed in the next section, and a criterion will be proposed based on this analysis.

g) Consideration on test results

Statistical analysis of test results and correlation analysis of parameters were performed for reaction force, absorbed energy, etc. in the static compression test (pretest and posttest) conducted before and after the durability test. In the test results, the coefficient of variation of the data was large for some parameters, and the coefficient of determination \( R^2 \) was low for the correlation between the variables. The reasons are as follows:

a. As mentioned above, the test specimens of rubber fenders were made larger than the minimum size shown in the manufacturer’s catalog. Therefore, the shape and size of the test specimen were different for each specimen.

b. The reaction force and absorbed energy of the rubber fender were temperature-dependent, but in the durability test, there was no temperature regulation in the test room during the durability tests, and the test was conducted at different ambient temperatures for each test piece.

c. The posttests were performed within 24 hours after durability test, then, there were different heat dissipation conditions after durability tests.

Due to the nature of this test, the shape and size of the test piece cannot be unified, but in the future, it is considered that the above-mentioned variation can be reduced by making the test environment temperature condition and so on.
5. STATISTICAL EVALUATION OF THE DURABILITY TEST RESULTS

(1) Reduction in the reaction force and energy absorption after the durability tests

In the durability test, 3,000 loadings were performed up to the rated strain. As described above, the pass/fail judgment of the durability performance is based on the following: (a) no cracks are observed visually; (b) the reaction force ratio \( R_2/R_1 \) and energy absorption ratio \( E_2/E_1 \) before and after the durability test are not significantly reduced. Here, the reaction force ratio, energy absorption ratio and residual strain are evaluated statistically based on the results of the durability tests. The load conditions of this durability test, which repeatedly compresses fenders to the rated deflection, seem much more severe than actual berthing conditions, for instance, as in the results from the survey\(^7\). In addition, the berthing interval of an actual vessel differs from several hours to several days according to the mooring facility, but it must be much larger than the loading cycle of this test (150 s or less).

In addition, regarding the relationship between the number of vessel berthings and years, if the ship berthing interval is one day, then \( 10^3, 3 \times 10^3, 10^4, \) and \( 10^5 \) vessel berthing events correspond to 2.7, 8.2, 27.4, and 274 years, respectively. If it is one week, they correspond to 19.2, 57.5, 192, and 1918 years, respectively. The regulation of the number of durability tests is not based on the number of vessel berthings, but is rather an index of the durability of rubber fenders.

A reduction in the reaction force due to repeated compression has been reported for fenders used in the mooring of floating bridges\(^8\). Although it depends on the strain amplitude, the decreasing tendency at 3,000 compressions is almost the same as in the test results. In addition, for berths where several vessels berth a day, 3,000 repeated tests may be considered insufficient, but as shown in Fig. 23, the decrease in the reaction force hardly changes up to tens of thousands of compressions.
of compressions. This indicates that there is no significant difference between 3,000 compressions and tens of thousands of compressions in terms of durability. Therefore, when the performance degradation after 3,000 repeated compression tests is within a certain value, the fender can be expected to maintain its durability against tens of thousands of compressions. From this point of view, an index for the durability evaluation can be obtained based on the statistical analysis of the results of the durability tests that have been conducted so far.

In the durability test, as shown in Table 1, \( R_1 \) and \( E_1 \) are obtained in the static compression pretest, and \( R_2 \) and \( E_2 \) are obtained in the static compression posttest. Therefore, the values of \( R_2/R_1 \) and \( E_2/E_1 \) are obtained for each test specimen. Since these contain samples of various shapes and dimensions, we will investigate the statistical distribution properties of \( R_2/R_1 \) and \( E_2/E_1 \) for each shape and classification shown in Fig. 1.

Figure 24 (1) shows the distribution of the reaction force ratio \( R_2/R_1 \) in the durability test, and Fig. 24 (2) shows the distribution of the energy absorption ratio \( E_2/E_1 \). Shape G-A and shape G-B have similar distributions of the reaction force ratio and absorbed energy ratio. In contrast, shape G-C has a different distribution shape. Shape G-A and shape G-B are fenders targeted by the PIANC guidelines, while shape G-C is a small fender that is mainly used in fishing ports. Therefore, statistical analysis is performed separately.

(2) Regression curves used in the analysis

As shown in Fig. 24(1) and Fig. 24(2), \( R_2/R_1 \) and \( E_2/E_1 \) show different distribution shapes for each fender sample. In addition, as shown in Fig. 6, the size of the specimen also varies from product to product. Therefore, it should be noted that the distribution properties shown here are not variations in performance for standard specimens such as steel and concrete. Here, we analyze the performance change of rubber fenders. Various factors are involved in the performance of the fender due to repeated loading, and it is difficult to identify the performance with a specific probability distribution model. Therefore, here, we will compare the distribution functions used for the probability distributions of materials and examine them with the goal of identifying the distribution shape and the shape parameter with the best fit.

Regression curves with a normal distribution, lognormal distribution, and Weibull distribution \((k = 2.0, 3.0, 4.0, 5.0)\) were fitted to the test data. The coefficients of the plotting formula in equation (3) were normalized with reference to Goda\(^9\), and the lognormal distribution was set to \( \alpha = 0.375 \) and \( \beta = 0.25 \) according to Blom\(^10\). For the Weibull distribution,
equation (4), modified by Goda\textsuperscript{12) from Petruasks and Aagaard\textsuperscript{11}), was used.\n
\[ F(x) = 1 - \exp \left[-\left(\frac{x-B}{A}\right)^k\right] \quad B < x < \infty \quad (3) \]

\[ F_m = 1 - \left(\frac{m-a}{n+b}\right) \quad m = 1, 2, \ldots, N \quad (4) \]

\[ \alpha = 0.20 + 0.27/\sqrt{k}, \quad \beta = 0.20 + 0.23/\sqrt{k} \quad (5) \]

Here, \( A \) is the scale parameter, \( B \) is the position parameter, \( k \) is the shape factor, \( m \) is the sample number, and \( N \) is the sample size.

\section*{(3) Results by regression analysis}

\textbf{Figure 25} shows the distribution function for the reaction force ratio. \textbf{Table 5} shows the regression estimates of the reaction force ratios for \( R^2 \) and the nonexceedance probabilities of 0.05, 0.025, and 0.01 for each probability distribution of the reaction force ratios in shape G-A and shape G-B. If the level of the probability of nonexceedance is set to 0.025, then \( R_2/R_1 = 83\% \) (Weibull distribution, \( k=2.0 \)).

\textbf{Table 6} shows the regression estimates of the reaction force ratios for \( R^2 \) and the nonexceedance probabilities of 0.05, 0.025, and 0.01 for each probability distribution of the reaction force ratios in the durability test for shape G-C. If the nonexceedance probability is set to 0.025, then \( R_2/R_1 = 70\% \) (lognormal distribution). However, for shape G-C, the number of test samples is small, and \( R^2 \) of the regression equation is small compared to those of shape G-A and shape G-B; therefore, it is desirable to re-evaluate these equations with accumulated future data.

\textbf{Figure 26} shows the distribution function for the energy absorption ratio. \textbf{Table 7} shows the regression estimates of the energy absorption ratios for \( R^2 \) and the nonexceedance probabilities of 0.05, 0.025, and 0.01 for each probability distribution of the energy absorption ratios for shape G-A and shape G-B. If the level of the probability of nonexceedance is set to 0.025, then \( E_2/E_1 = 77\% \) (Weibull distribution, \( k=4.0 \)).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Shape parameter & \( A \) & \( B \) & \( R^2 \) & \( R_2/R_1 \) & \( 0.05 \) & \( 0.025 \) & \( 0.01 \) \\
\hline
Normal & - & - & - & 0.916 & 70.6 & 67.3 & 63.4 \\
Lognormal & - & - & - & 0.943 & 72.6 & 70.1 & 67.3 \\
Weibull & 2.0 & 21.8 & 68.4 & 0.859 & 73.4 & 71.9 & 70.6 \\
& 3.0 & 30.4 & 60.6 & 0.825 & 71.9 & 69.5 & 67.2 \\
& 4.0 & 38.3 & 53.1 & 0.801 & 71.3 & 68.3 & 65.2 \\
& 5.0 & 45.9 & 45.7 & 0.784 & 71.0 & 67.7 & 63.9 \\
\hline
\end{tabular}
\caption{Probability distribution of the reaction force ratio (shape G-C).
}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Shape parameter & \( A \) & \( B \) & \( R^2 \) & \( E_2/E_1 \) & \( 0.05 \) & \( 0.025 \) & \( 0.01 \) \\
\hline
Normal & - & - & - & 0.972 & 78.7 & 77.2 & 75.5 \\
Lognormal & - & - & - & 0.982 & 78.9 & 77.5 & 76.0 \\
Weibull & 2.0 & 9.97 & 77.5 & 0.962 & 79.7 & 79.1 & 78.5 \\
& 3.0 & 14.4 & 73.5 & 0.987 & 78.8 & 77.7 & 76.6 \\
& 4.0 & 18.4 & 69.6 & 0.990 & 78.4 & 77.0 & 75.5 \\
& 5.0 & 22.2 & 65.9 & 0.988 & 78.2 & 76.5 & 74.8 \\
\hline
\end{tabular}
\caption{Probability distribution of the energy absorption ratio (shape G-A, shape G-B).
}
\end{table}
Table 8 shows the regression estimates of the energy absorption ratios for $R^2$ and the nonexceedance probabilities of 0.05, 0.025, and 0.01 for each probability distribution of the energy absorption ratios in the durability test for shape G-C. If the nonexceedance probability is set to 0.025, then $E_2/E_1 = 73\%$ (lognormal distribution). Again, for shape G-C-type fenders, the results should be reevaluated by future accumulated data because the number of test samples and the $R^2$ of the regression equation are small.

Figure 27 shows the distribution function for residual strain. Table 9 shows the regression estimates of residual strain for $R^2$ and the nonexceedance probabilities of 0.05, 0.025, and 0.01 for each probability distribution of residual strain in the durability tests for shape G-A and shape G-B. If the nonexceedance probability level is set to 0.025, then $\varepsilon_R = 4.2\%$ (Weibull distribution, $k = 5.0$).

Table 10 shows the regression estimates of the reaction force ratio for $R^2$ and the nonexceedance probability (0.05, 0.025, and 0.01) for each probability distribution of the residual strain in the durability test for shape G-C. If the nonexceedance probability is set to 0.025, $\varepsilon_R = 4.8\%$ (normal distribution). However, shape G-C should be reevaluated by future accumulated data because the number of test samples and the $R^2$ of the regression equation are small.

As described above, regarding the durability test results, when evaluating the performance ratio for either the reaction force or the energy absorption, the ratio does not change much. Since the evaluation is based on the absorption of the berthing energy, the energy absorption should be considered. The residual strain is considered to be an important factor that shows signs of performance degradation. Therefore, the energy absorption ratio and the residual strain are specified based on the durability test results. From the durability test results, it was estimated that the energy absorption ratio after 3,000 repeated compressions for the characteristic shapes G-A and G-B was 77% with a nonexceedance probability of 0.025, and the residual strain was 4.2%. However, considering that $R^2$ is not very high and that the difference in the estimated values is large due to the probability distri-
Table 10 Probability distribution of the residual strain (shape G-C).

| Shape parameter | $A$ | $B$  | $R^2$  | $\varepsilon_R$ (%) |
|-----------------|-----|------|--------|---------------------|
| Normal          | -   | -    | 0.923  | 4.41 4.81 5.27      |
| Lognormal       | -   | -    | 0.842  | 4.72 5.43 6.40      |
| Weibull         | 2.0 | -2.58| 4.81   | 0.821 4.03 4.20 4.35|
|                 | 3.0 | -3.75| 5.68   | 0.848 4.29 4.58 4.87|
|                 | 4.0 | -4.83| 6.71   | 0.872 4.41 4.78 5.18|
|                 | 5.0 | -5.87| 7.72   | 0.880 4.48 4.90 5.38|

7. FUTURE ISSUES

From the results of the durability test, the performance change after the repeated compression of fenders was analyzed. Among the test conditions, there were cases where the ambient temperature was not required to be constant in the test room, and it was confirmed that the effect on the test results was significant. In the future, the unification of test methods and conditions will be an issue. The analysis of the test results is based on limited data, such as the reaction force ratio, energy absorption ratio, and residual strain, before and after the durability test. Evaluation from a microscopic point of view, such as studying changes in the molecular structure of the rubber material and internal crack growth during the durability test, has not been performed. Evaluation methods based on the microscopic changes that occur along with the reduction in the reaction force are a topic for the future.

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