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Method to Estimate the Aging of Large Rubber Marine Fender

Hitoshi Akiyama
Marine Fender Dept., Bridgestone Corporation
Totsuka, Yokohama-shi, Kanagawa, Japan
Dept. of Civil Eng., Osaka University
Teruya Shiomi
Stockpile Planning Department, Japan Oil, Gas and Metals National Corporation
Toranomon, Minato-ku, Tokyo, Japan
Atsuo Omura
Research Department, Coastal Development Institute of Technology
Nishishinbashi, Minato-ku, Tokyo, Japan
Shuji Yamamoto
Coastal Development Institute of Technology
Nishishinbashi, Minato-ku, Tokyo, Japan
Shigeru Ueda
Institute of Environment Informatics, IDEA Consultants Inc.
Hayafuchi, Tsuzuki, Yokohama, Japan
Toshiro Kamada
Dept. of Civil Eng., Osaka University
Yamadaoka, Suita-shi, Osaka, Japan

ABSTRACT

Currently, the life time of rubber marine fender (hereafter "fender") has been evaluated by the external damage but many of large size fenders are not visually deteriorated even after over 30 years of use. But, there is a concern that material and performance maybe changed even though they show no problems. Authors studied what kind of aging is happening to the material and the performance of used fenders which were picked up from the floating oil storage tanks in the NOSB and the berths of VLCC terminals and found that the reaction force increases with a year. The rubber blocks were cut off from the used fenders and sliced into the test pieces for physical properties. The remarkable drop of strength and elongation showed only in the vicinity of surface and flat and modest increase of elasticity was seen in the main body. The Finite Element Analysis with these material properties suggested that this change of material properties to be the reason of the increase of reaction force. This tendency of aging was also obtained from the accelerated aging of rubber material and scale models. The models after aging broke earlier than the less aged models in the fatigue compression cycle tests. The ultimate aging limit was assumed about 60 to 70 years due to the fact that the models were broken at the first compression.

KEY WORDS: Fender; rubber; aging; durability; mooring; life; performance.

INTRODUCTION

The large fenders have been used for very large crude oil tanker and mooring facilities such as the National Oil Storage Bases (hereafter NOSB) more than 30 years but it is difficult to know how long they can be used. Terauchi et al., (1997) reported that the service year of small or mid-size rubber fenders was from 10 to 20 years by inspecting the ports in Japan. Also "Maintenance guideline of marine fender" was published by the Coastal Development Institute of Technology (2013) to suggest how to evaluate remained functions of fender by measuring visible defects of fender body. But many of large size fenders over 2m for very large crude oil tanker and mooring facilities such as the NSOBs are not visually deteriorated even after over 30 years of use. But it does not mean that those fenders are not aged and there still is a concern about the deterioration of performance. Sueyasu (2008) studied the 14 years old large fender and reported that the deterioration stayed only near the surface and didn't penetrate into the center of rubber body. This means that inspecting the small cut sample from surface does not tell the real aging of main body of fender. On the other hands, drilling deep to get a core sample like we do to a concrete structure would damage the fender itself. So, it is important to estimate non-destructively, how much the material and performances have been changed after many years of use. Long-term durability was studied by Itoh et al., (2006) about rubber bridge bearing. Recently, more studies are being done for seismic isolators. Hamaguchi et al., (2009) studied the aging of 20 years old seismic isolator. But the study about rubber fenders is rare. In this paper, the method to estimate the change of fender performance was studied by picking up the used fenders, analyzing and comparing to the various laboratory tests of rubber material, scale models and Finite Element Analysis.

COMPRESSION TESTS OF USED FENDER

The direct way to know the fender performance after aging is to pick up the used fender from the site and test them. The NOSB in Japan have been conducting the compression tests in every 5 to 10 years for the circular shaped buckling fenders which are working for the mooring of large oil storage tanks. These fenders have not experienced the extreme deflection such as abnormal berthing which many fenders for berthing have. This is a good opportunity to study the pure aging by time and environment. The same type of circular shaped buckling fenders which had used in the offshore dolphins for the VLCC vessels also picked up and tested at the time of renewals. Fig.1 shows the example picture of circular shaped buckling fenders which is 3m high (3000H) in the VLCC dolphin.

Fig. 1 Circular shaped buckling fender: 3000H

"Guideline for the Design of Fender Systems" by PIANC (2002) advised that fenders which have the reaction force more than 1MN have to have the compression at the time of delivery. So, those fenders should have the initial performance for reference. Fig. 2 shows the example of fender performance before and after 28 years of use in the Kamigoto National Oil Storage Base (NOSB-Kamigoto). In the deflection from 0 to 20%, the cylindrical body is compressed with its shape but it buckles and reaction force becomes flat when the cylindrical body swells radially. Then after 45%, the reaction force steeply goes up when the cylindrical shape is almost crashed. This is the typical characteristics of this fender to absorb as much kinetic energy which is the area between the curve and x-axis within the smallest reaction force. In order to see the tendency, the aging rate of reaction force is defined as the reaction force at 35% compression divided by the initial value at 35%. The aging rate of reaction force by years is shown in Fig. 3. The regression line increases roughly 0.3% per year and the upper and lower limits of confidence interval are shown in red broken lines.

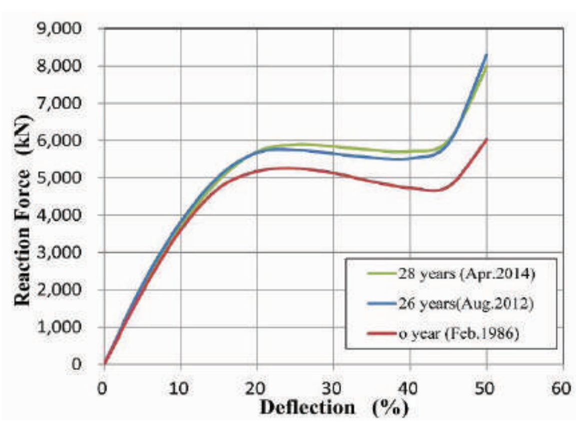

Fig. 2 Aging of fender performance: 3000H

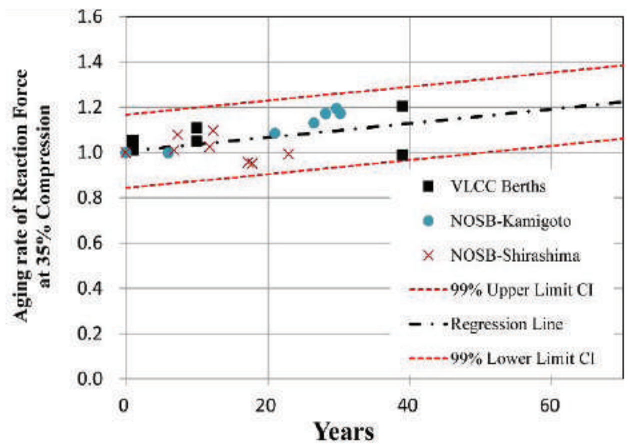

Fig. 3 The aging rate of performance by years

Fig. 4 shows the surface cracks under compression of the VLCC fender. Fig. 5 is the close up photo of cracked surface after compression. The cracks are limited in the skin rubber and do not look extending to the inner body.

Fig. 4 Surface cracks under compression (3000H, 39 years)

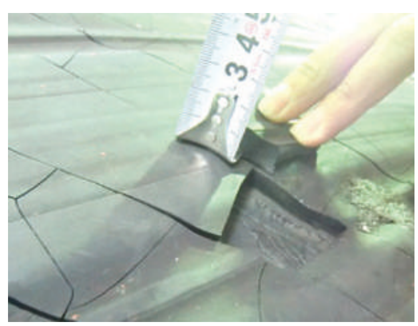

Fig.5 Broken skin after compression

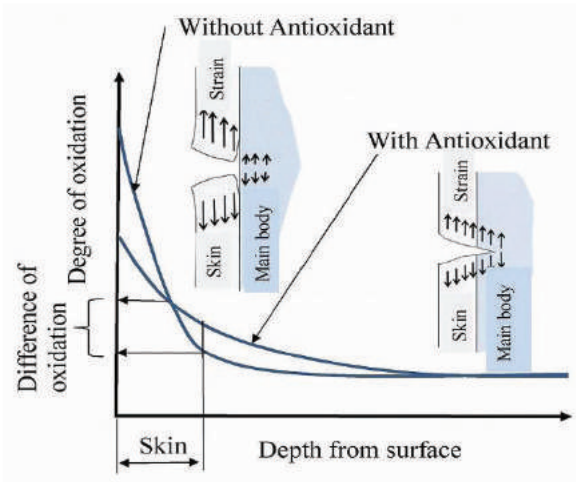

Fig. 6 Surface aging of fender (Conceptual)

Itoh et al., (2006) divided two regions of rubber: outer region and inner region, and the property in the outer region changes but does not extend to the inner region. Akiba et al., (2003) illustrated that the surface region oxidases first and impede oxidant to penetrate further inside so the antioxidant in skin rubber may not protect main body efficiently. Fig. 6 explains the concept of this phenomenon that the surface crack does not penetrate to the main body. The boundary between skin and main body has the separation and prevent the crack to extend further inside.

MATERIAL SAMPLING TEST FROM USED FENDER

After the compression performance was demonstrated in the last section, the change of material properties was studied in this section. The material aging of bridge bearing was studied by Itoh et al., (2006) about the long-term deterioration. But the number of this kind of study is limited about the fender which is in the marine environment with direct sunlight. After the compression test shown in Fig. 2, the fender was dissected and blocks of rubber was cut out from the upper, lower and right side of body as shown in Fig. 7. The sheets of rubber were sliced from each block and tested as described in "Handbook for Execution of Port & Harbor Works" by SCOPE (2016). The hardness, tensile strength and elongation at break were measured being based on

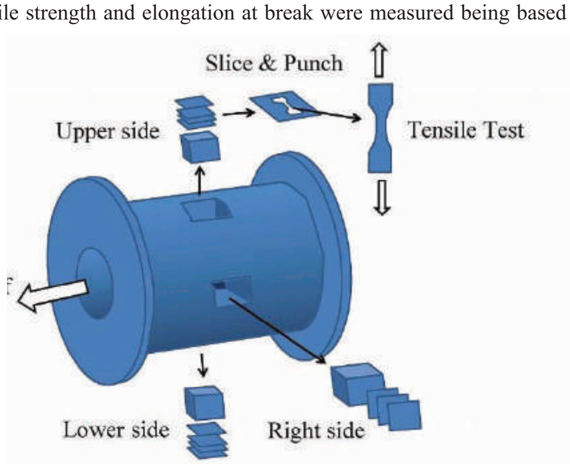

Fig. 7 Rubber sampling from fender

the procedure of JIS Standards; K6250 (2006), K6251 (2010) and K6253-3 (2012). The example of result is shown in Fig. 8. The samples were 2mm thick and the median of three specimens were used to determine the tensile strength and elongation at break. The skin rubber was at the depth of 5.12mm and the main rubber sample is at the depth of 254mm. The tensile strength and elongation at break are defined as shown in Fig. 8. The elasticity seems to reflect the performance most but the stress-strain relation is non-linear as shown in Fig. 8. So, the stress at the 100% strain (Md100) is defined as in Fig. 8.

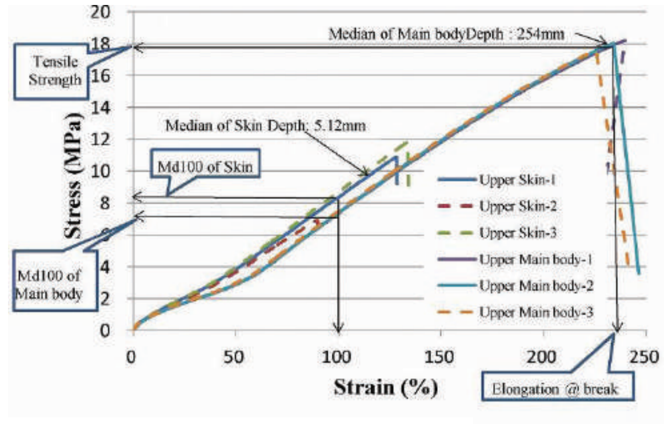

Fig. 8 Example of material test data

The distribution of Md100 in each depth from the outer surface is shown in Fig. 9. While the sharp increase of Md100 is shown near the surface, the Md100 in the main body is flat. This is a similar phenomenon as explained in Fig. 6. Itoh et al., (2006) defined the critical depth where the rubber deteriorates quickly and prevent the further deterioration of the inner rubber. They explained "When the vulcanizing sulfur crosslinks are subjected to oxidation, the crosslinks will break up , the chains will re-entangle and form more new crosslinks which makes the motion of chains impeded and results in high hardness, low elongation and brittle fracture of the material".

The flat and moderate increase of Md100 in the inner part is a different chemical reaction of oxidation but looks like a slow vulcanizing of sulfur crosslinking in normal temperature.

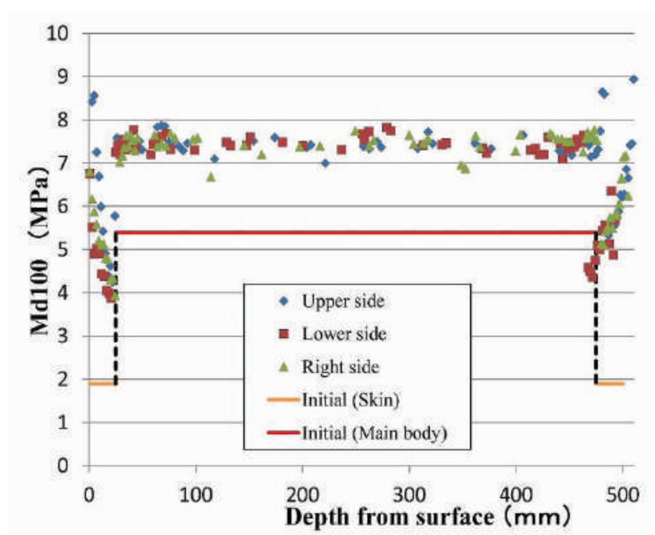

Fig. 9 Distribution of stress at 100% strain: Md100

The circular shaped buckling fender has an outer skin of different material to the main body. The skin rubber is designed softer than the main body. The sharp step of elasticity between the skin and main body assumed to prevent the cracks extend deeper to the main body. Note that it is not easy to obtain the actual initial values of the same material of old fenders. Especially, we should be careful that the physical properties of thick products and thin test material sheets may not be same due to the different vulcanizing condition. Here, the sample sheets were vulcanized carefully to have the similar temperature history of real size product.

FINITE ELEMENT ANALYSIS FOR MECHANICAL BEHAVIOR OF USED FENDER

The material properties obtained in the previous section are used to estimate the fender performance before and after aging. The commercially available FEM software called ABAQUS is used for the analysis. Yeoh's theory (1997) was chosen as the constitutive model. The element model is shown in Fig. 10. The fender is axisymmetric around the center rotation axis and plane symmetric vertically so only one quarter of body needs to be defined. Section 1 and section 10 are skin rubbers and sections from 02 to 09 are main body.

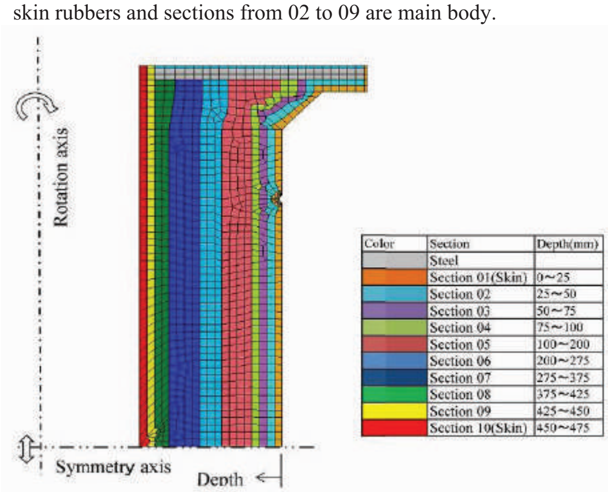

Fig. 10 Element layers for FEM

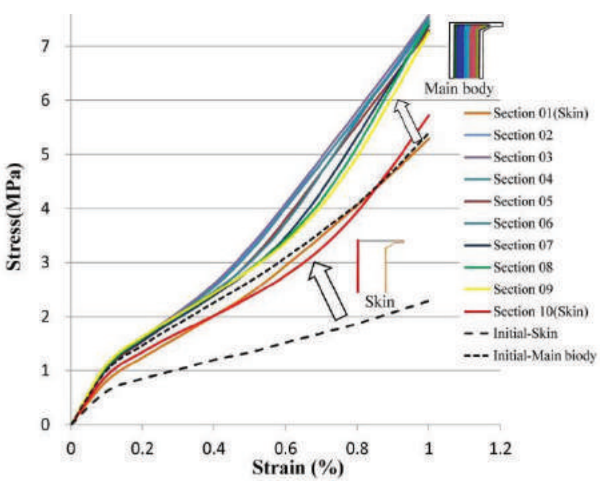

Fig. 11 Material property for FEM

The properties after aging are distributed as shown in Fig. 10. The viscosity is ignored so only stress-strain relations in Fig. 11 are defined. In Fig. 11, the color solid lines are the properties of aged rubber at the different depth. The black broken line shows the initial properties before aging. The calculated reaction force at each deflection is shown in Fig. 12. Comparing to the actual compression in Fig. 2, the reaction forces both before and after aging is higher. The several reasons can be considered for this difference. The performance in Fig. 2 is the average of 2nd and 3rd compression where the FEM result in Fig. 12 does not consider the compression history. Also the viscosity of rubber is ignored. We have the initial performance before aging and the purpose of this analysis is to estimate the effect of aging to the initial performance. So, we estimate the performance after aging by multiplying the rate between before and after aging of FEM results. The result is shown in Fig. 13. The after aging (Green line) and estimated by FEM (Blue line) matched well to the test result.

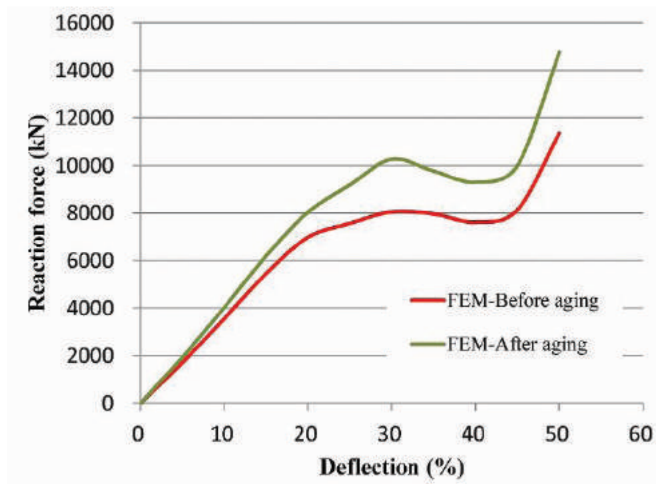

Fig. 12 Fender performance by FEM: 3000H

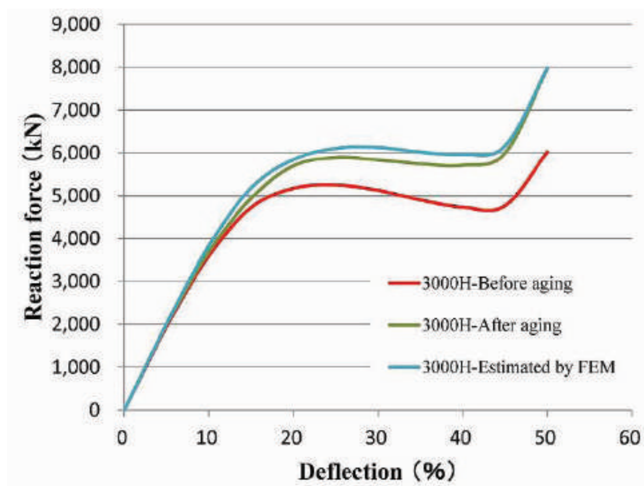

Fig. 13 Estimated performance by FEM

Fig. 14 shows the deformation of fender body comparing to the actual compression test. The orange lines are the copy of calculated deformation which matches well to the compression photo.

The maximum principal strain occurred at the buckling area in the red circle in Fig. 14 which was 106%.

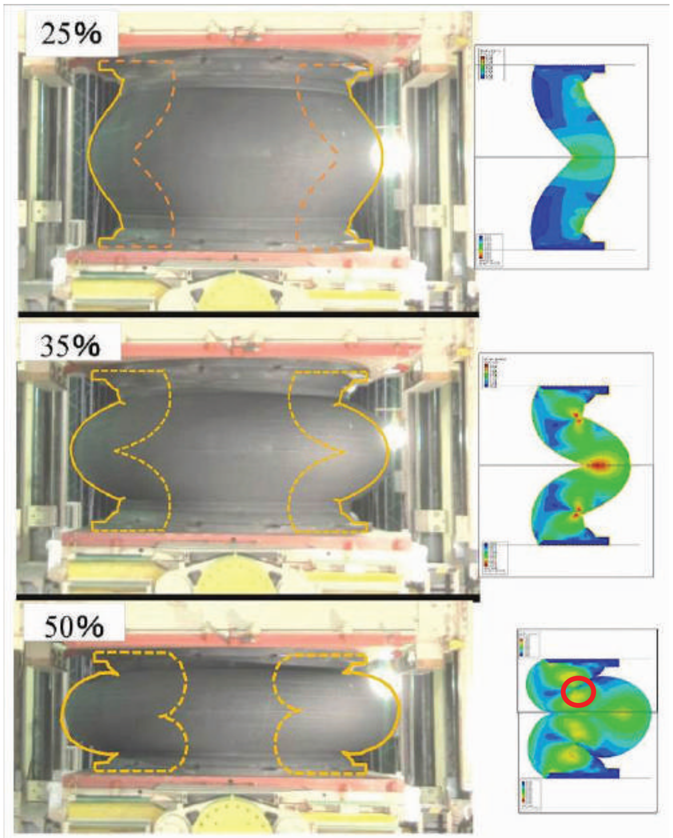

Fig. 14 Compression shape: 3000H

PREDICTION OF AGED PERFORMANCE BY THERMAL ACCERELATION

So far, the study is based on the 28 year-used fender picked up from the NOSB-Kamigoto. In this section, the prediction method of aged performance based on laboratory data is studied. There are many deterioration factors such as: oxidation, ozone, ultraviolet, temperature, acid, water, bacteria and so on. While ozone, ultraviolet, acid, water and bacteria affect only near the surface and do not affect the performance but the temperature penetrates to whole body and slowly change the polymer structure with oxygen. So, we focus on the thermal oxidation of first order which assumes the Arrhenius theory as expressed in Eq. 1.

$$K = A \cdot \exp\left(-\frac{E}{RT}\right) \tag{1}$$

K : Rate constant
A : Pre-exponential factor
E : Activation energy (kj/mol/K)
R : Gas constant (=0.008315 kj/mol/K)
T : Kelvin temperature (K)

The prediction by Arrhenius formula is a logarithmic extrapolation so it contains a variance. In order to minimize the error of prediction, the conditions were recommended by IEC publication (1974). The IEC's recommendation and the condition used here are as follows:

- Number of temperature levels should be ≧3: 3 levels (80, 90, 100 deg.) in this study
- Time at highest temperature should be ≧ 100h: 120h (5 days)
- Time at the lowest temperature should be ≧5000h: 8400h (350 days)
- Increment of temperature levels should be from 10 to 25deg: 10deg.

Accelerated Thermal Oxidation of Material Sheet

The thermal oxidation was given to the rubber material to accelerate the aging and to obtain the relations among the different temperature by calculating the activation energy assuming the Arrhenius's law. The 2mm thick sheets made of same rubber used for the fender were put in the oven which was controlled at 80, 90 and 100 degree Celsius for the duration from 1 to 350 days. The hardness, tensile strength and elongation at break were tested. The activation energy differs depending on which character is chosen. Here again, considering the purpose is discussing the performance of fender, Md100 was chosen. The values of Md100 of main body and skin rubber are shown in Fig. 15 and Fig. 16, respectively.

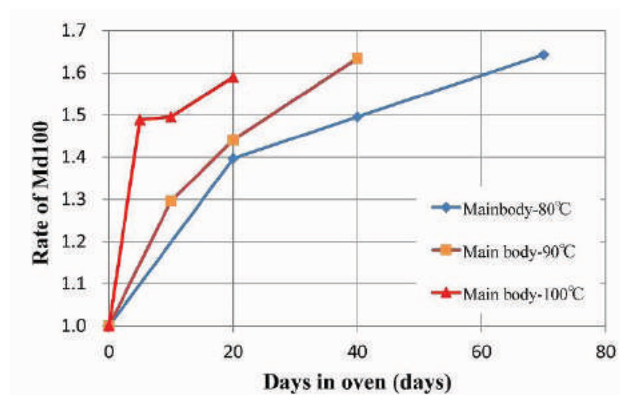

Fig. 15 Accelerated aging of Stress at 100% strain (Md100) –Main body

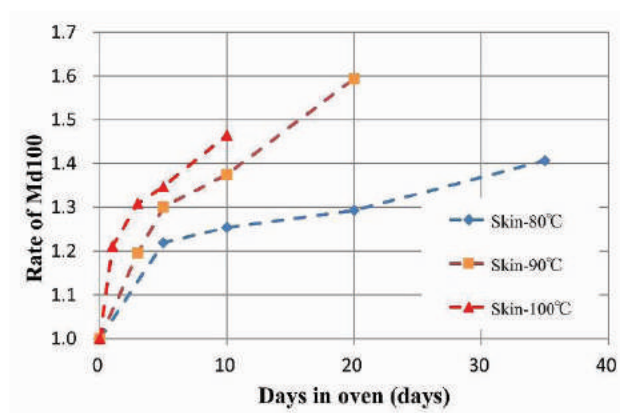

Fig. 16 Accelerated aging of Stress at 100% strain (Md100) -Skin

The activation energy is obtained as shown in Table. 1. The values differ depending on the rate of Md100. The skin rubber broke before being stretched to 100% strain at the rate of 1.5 so there is no data of skin rubber at 1.5 in Table. 1.

Table 1. Activation Energy of rubbers

Main body		Skin	
Rate of Md100	Activation Energy :E (kj/mol/K)	Rate of Md100	Activation Energy :E (kj/mol/K)
1.2	86.95	1.1	85.76
1.3	86.94	1.2	85.76
1.4	87.98	1.3	110.14
1.5	74.41	1.4	85.39
1.6	58.49	1.5	-
Average	78.96	Average	91.77

Accelerated Thermal Oxidation of Scale Models

The models of circular shaped buckling fender which are 100mm high (100H) of same material are made and put in the oven for accelerated thermal oxidation. The average activation energy in Table.1 (=78.96 kj/mol/K) was used to convert the time at the room temperature (23deg) by the following Eq. 2.

$$t = t_y \cdot \exp\left(\frac{E}{R}\left(\frac{1}{T_0} - \frac{1}{T_y}\right)\right) \tag{2}$$

t ：Equivalent aging time at room temperature:T_0

t_y : The time in oven

T_0 : Room temperature (=23+237.15 K)

T_y : Oven temperature (=80+237.15K)

E : Activation energy（kj/mol/K）

R : Gas constant（=0.008315 kj/mol/K）

The results of equivalent time calculated by Eq. 2 and the rate of reaction forces (at 35% deflection) of models before and after aging are shown in Table. 2.

Table. 2 Performance of models after aging ：100H (80 deg)

Days in oven: t_y (days)	Equivalent years: t (years)	Reaction force before aging (kN)	Reaction force after aging (kN)	Rate of reaction force (@35%)
0	0.0	5.24	5.24	1.00
35	17.0	4.87	5.90	1.21
70	33.9	4.88	6.30	1.29
140	67.8	4.92	6.96	1.42
210	101.8	4.92	Break	Break
280	135.7	4.94	Break	Break
350	169.6	5.30	-	-

The aging rates of reaction force which were added to Fig. 3 are now shown in Fig. 17. The curve of model (Blue solid line with triangle plots) increases to 10 to 20 % higher than the regression line of test results in the first 20 years then becomes parallel and close to the 99% upper limit CI of test results after 20 years. The test results of used fenders do not show the first increase. Possible reasons are:

A: The rubber thickness of real fender is from 400 to 500 mm when the model thickness is about 15mm. So, the oxidation could be faster in models than actual size fender. This could be improved by non-oxide environment such as nitrogen sealed both for material sheets and models.

B: The range of temperature: 80～100 degrees Celsius (℃) may be a little too high and some chemical reaction other than the 1st order oxidation might have affected. This could be improved by adding the lower temperature (70, 60℃) condition, if time allows. Although a little bigger values of reaction force should be acceptable for safety from the design point of view, the further improvements will be planned in future study.

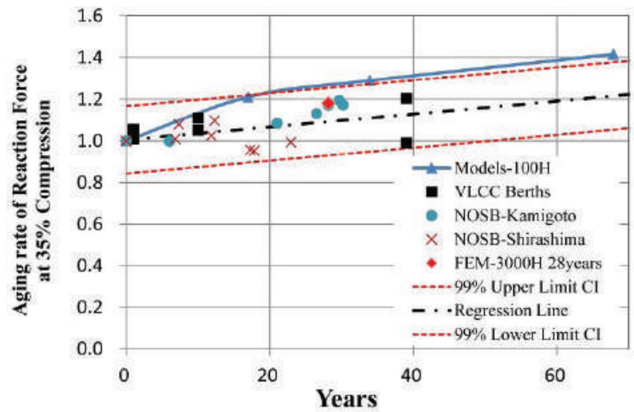

Fig. 17 Rate of reaction force (100H model & FEM)

The models aged longer than 140 days (67.8 years) were broken at the first compression due to the brittleness of rubber. It means the fender has lost its fundamental function for energy absorption. Fig. 18 shows how it looked. The vertical crack extended full body first and was torn horizontally near the upper and lower flange parts.

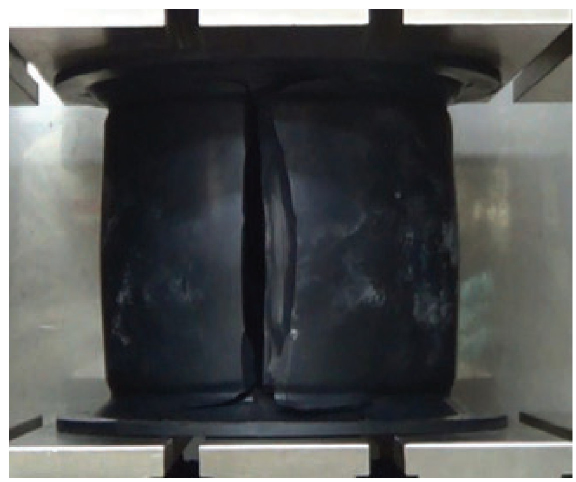

Fig. 18 Broken miniature fender: 100H (67.8 years)

A similar destruction mode was observed in South America (2012) for the 2000H (2m high) fender after 42 years of use. A large compression was seen and reported when this fender was suddenly broken. The average temperature of this area is 23.3℃. 42 years is much shorter than 67.8 years but we should be noted that this type of sudden destruction could occur even if the fenders visually look sound. Fender should be replaced before the material is deteriorated this much.

Fig. 19 Broken actual fender: 2000H (42 years)

Fatigue Tests of Aged Models

A series of fatigue tests were conducted to the models after accelerated oxidation by oven. The condition of fatigue tests is as follows:

- Fender models: Circular shaped buckling fender 100H
- Compression stroke: 35mm (35%)
- Compression speed: 12 mm/s
- Temperature: 23℃
- Tests finished when:
  - Any crack penetrates through the body,
  - Reaction force drops sharply or
  - Permanent deflection exceeds 5mm (5%)

Fig. 20 shows how the rates of reaction force at 35% drop by the number of compression cycle. The rate 1.0 is the average of 2[nd] and 3[rd] compression. Every test was finished by both the sharp drop of reaction force and the crack penetrated through body.

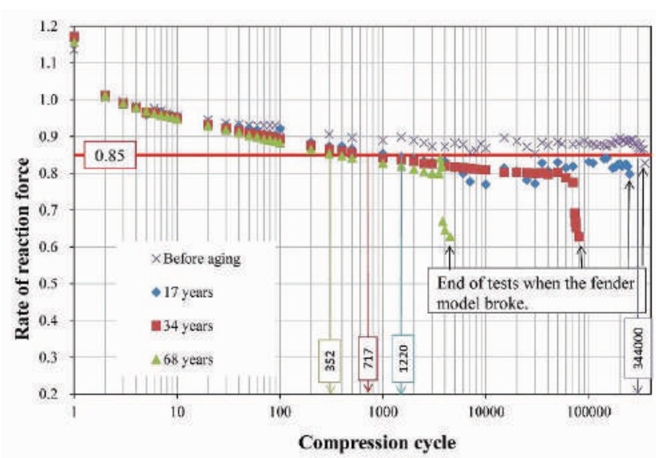

Fig. 20 Fatigue tests of model fenders

The aged fenders drop earlier and break earlier than new fender. Murata et al., (2009) suggested defining 85% of initial performance as the limit of service life. This is shown as a red line in Fig. 20. Each cycle at 85% and break are shown in Table. 3.

Table. 3 Cycle limits of model fenders

Age of fender model	Number of cycle to 85%	Break
Before aging	344000	350000
17 years	1220	250000
34 years	717	80000
68 years	352	4500

LIFE ESTIMATION FOR FENDER DESIGN

Thus, the aging of large rubber fender has been studied from three aspects; testing of used fender, FEM by material from used fender and accelerated aging of models. The possible design concept of fender aging is demonstrated in Fig. 21. Omura et al., (2014) reported that in the NOSB projects, the design range of fender was determined from 0.85 to 1.15 times of the initial performance. Assuming the upper design limit of reaction force factor is 1.15, the regression line crosses over at 47 years of use. The lower limit is described by the number of compression cycle in Fig. 20, so the years until the reaction force drops to 85% of initial performance needs to be estimated from the berthing frequency of each port. The models over 67.8 years of accelerated oxidation broke at the 1[st] compression. These limits are shown in Fig. 21 as red lines and pink area.

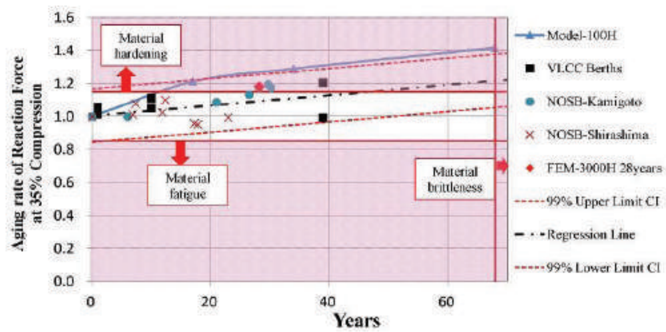

Fig. 21 Limits of fender reaction force by years

CONCLUSIONS

A series of aging study from several different aspects have led us to the following findings and conclusions.

- The reaction force of fender increases by a year.
- The aging starts at the surface of rubber and the effect decreases sharply by depth. The aging of main body is a flat increase of elasticity and the deterioration from outside is impeded by aged skin layer.
- The performance of aged fender could be predicted by Finite Element Method with Yeoh's constitutive model as far as by using the rate of performance between initial and aged.
- The accelerated thermal oxidation of scale models indicated that the ultimate limit of this fender was 67.8 years at 23 degree C. The fender model became brittle and was destroyed at the first compression when the oxidation exceeds this level.
- The fatigue tests of model indicated that the reaction force of aged fenders drops faster than newer fender and breaks earlier at less number of compression cycle.

This study is an example of the circular shaped buckling fenders and the assumption made here is considered to be in the safer side in terms of oxidation but it gives a practical method for aging estimation.

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