Approaches to Life Evaluation of Rubber Marine Fender

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Abstract
The impact of aging on the performance of rubber marine fender (hereafter fender) has been a issue for long period of time in ports and offshore facilities. In this paper, three approaches have been undertaken:

1. how the fender performance changes due to the years in service;
2. how can we predict the change of fender performance; and
3. study of the possiblity to measure the aging of fender non-destructively.

A number of used fenders were collected and the performance was measured and plotted against the number of years in service, showing a moderate increase of the reaction force over time. It was noted that the first compression cycle of the collected fenders showed a higher reaction force which could in turn become a concern for new and existing structure design.

The accelerated thermal oxidation based on the Arrhenius formula was used to predict the change of performance by means of FEM and miniature model tests, these demonstrated a moderate increase of reaction force over time. Other non-destructive measurements were also taken of the surface hardness and the internal (inside) rubber properties using ultra-sonic wave sensors to enable a better understanding to the aging process of rubber. Technical issues remain to be resolved in both techniques.

Keywords: marine fender, aging, reaction force, service life, accelerated thermal oxidation

1. Introduction

The fender is an important shock absorbing element between a vessel and the berthing structure. Although it has a history of more than sixty years, the information about the useful life is limited. Terauchi et al. [1] reported that the service life of small V-shaped fenders is 10 to 20 years from the survey of ports in Japan. The guideline of how to evaluate the life of a fender by visual inspection is published by Coastal Development Institute of Technology [2]. The National Oil Storage Base (NOSB) assumed that the impact of aging on fender performance is 105% of initial reaction force of the Circular Shaped Buckling fender (hereafter CSB) [3]. Figure 1 shows the photo of CSB fender with frontal panel and weight supporting chains. The authors focused on the CSB fender for the survey of old fenders and studied how to predict the performance change over time. The non-destructive inspection is the most practical method to evaluate the impact of aging but issues remain to be resolved.

Fig.1 - Photo of Circular Shaped Buckling fender

2. Performance tests of used fenders

The average life span of the CSB fender is 20 to 30 years. Although it is uncommon for the old fender to be sent to the manufacturer for a compression test, the authors took this opportunity to collect the records. Figs.2, 3 & 4 show the profile of the performance where the Y-axis is the non-dimensional reaction force (=Measured reaction force / Catalogue value of reaction force at 25% deflection). Fig.2 illustrates fenders smaller than 1000mm in height (<1000H), Fig.3 illustrates fenders between 1000 and 2000mm and Fig.4 illustrates fenders over 2000mm. The fenders are old and most of the initial test data before delivery has been lost therefore the catalogue values were used. Note that standard production tolerance is ±10% so each plot has ±0.1 variance in Y-axis. It is evident that the data spreads further in the smaller fender. 1000H after 32 years and 40 years both displayed severe cracks on their bodies when they were compressed. 800H after 25 years showed uneven buckling and the fender top had slid sideways with the reaction force dropping after 20% compression. The reasons for differences of aging impact by size are considered to be as follows:

- smaller size fenders have more aging of oxidation from the surface;
- smaller size fenders have more effect from surface damage such as cracks to the performance relative to larger sizes; and
- larger fenders tend to be used by larger vessels and more tugboat assist, therefore the control of berthing manoeuvre is improved.

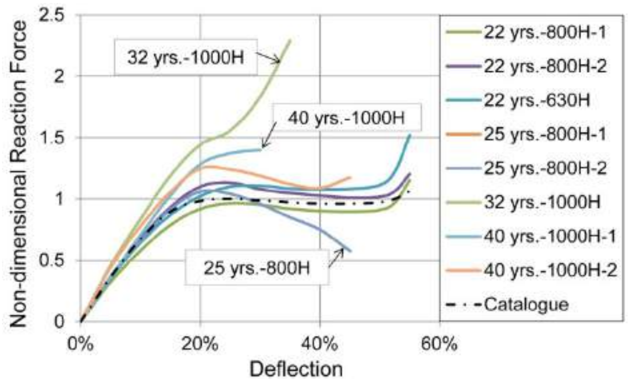

Fig.2 - Performance of used fenders: H≦1000mm fender

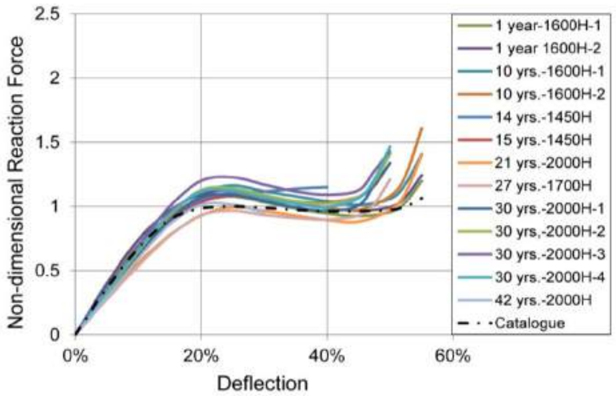

Fig.3 - Performance of used fenders: 1000mm<H≦2000mm

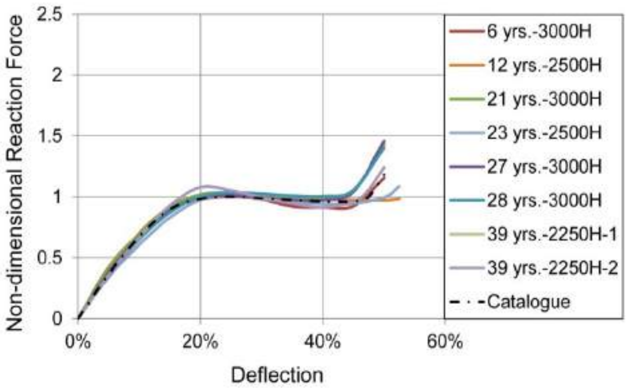

Fig.4 - Performance of used fenders: H>2000mm

Rubber material for fenders is a mixture of natural rubber (NR) and styrene-butadiene rubber (SBR) which increase its modulus over time. So, the reaction force is expected to increase by years in service. Fig.5 shows the reaction force rate (= Measured reaction force at 25% deflection / Catalogue reaction force at 25% deflection). The standard value of performance is the average value of 2nd and 3rd compression which has been a custom for a long time and the 1st compression has normally been ignored [4]. In Fig.5, the red circled plots are the case, 3rd compression were cancelled for safety reasons. The same reaction force rate of the 1st compression is shown in Fig.6. This increase may affect the design of structure because this is not an initial performance but the recovery after the long interval without being compressed. The data in Fig.5 and Fig.6 appear to be spreading to the right with a small increase annually. Table 1 shows the statistical data of reaction force rates.

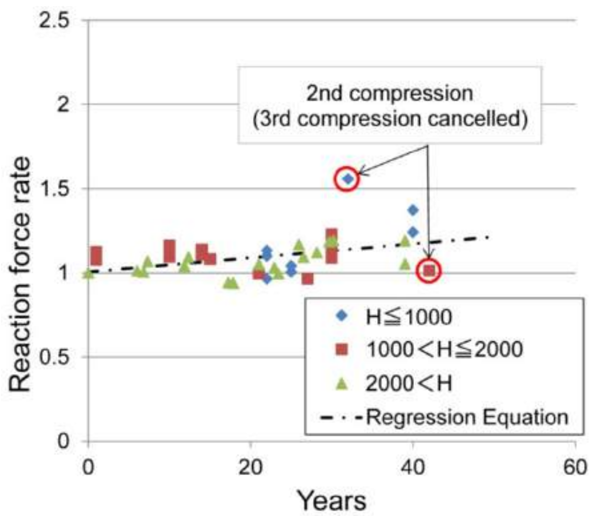

Fig.5 - Reaction force rate (Average of 2-3 compression cycles)

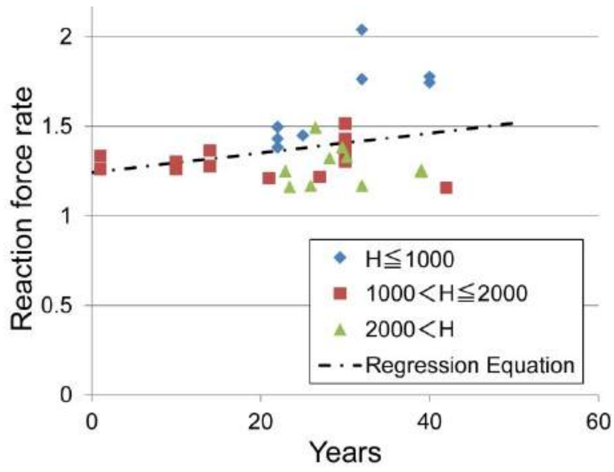

Fig.6 - Reaction force rate (1st compression cycles)

Table 1 - Statistical data of reaction force rate

H: Fender height (mm)

Compress-ion cycle	Data	Total	H≦1000	1000＜H≦2000	2000＜H
2-3 Average	Number of data	48	8	14	26
	Standard deviation	0.0993	0.1605	0.0705	0.0560
	Slope of regression	0.0042	0.0176	-0.0010	0.0037
1st compress-ion	Number of data	31	8	13	10
	Standard deviation	0.2014	0.1669	0.1006	0.1124
	Slope of regression	0.0055	0.0219	0.0003	-0.0005

In Table 1, the slope of regression equation of 2-3 average of total fenders is 0.4% annually but standard deviations are bigger in small fenders.

3. Performance estimation of aged fenders

In this section, two approaches to estimate the aged fender performance are introduced; by miniature models and by Finite Element Analysis (FEM). In both approaches, the thermal accelerated oxidation of rubber material was conducted to obtain the activation energy.

3.1 Accelerated thermal oxidation of rubber

The thermal acceleration of the rubber sheet was conducted in order to obtain the activation energy which is known as the Arrhenius method. The result of rubber sheet is shown in Fig.7 which is called the Arrhenius plot. The rubber sheets were 2mm thick and the tests were based on the "Japan Industrial Standards: JIS K-6250 and K-6251" at 3 different temperatures. The increasing rate of stress at 100% strain was chosen as an aging factor because this relates mostly to the elasticity of rubber and consequently to the reaction force of the fender. In Fig.7, T is the absolute temperature, and t is the time of aging. The aging time is estimated by extrapolation of lines in Fig.7 which may contain errors. In order to minimize errors, the test conditions were based on the recommendation of IEC publication [5]. The activation energy is

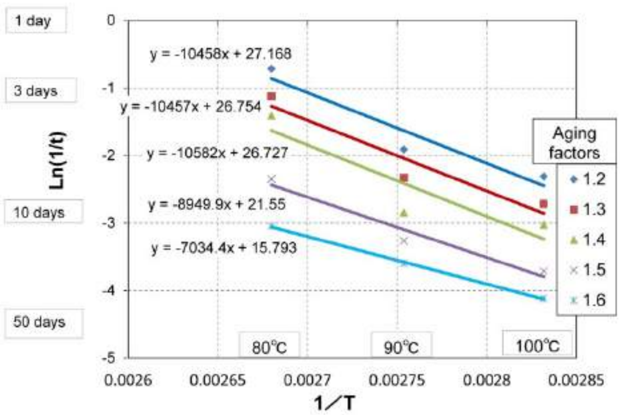

Fig.7 - Arrhenius plot of rubber sheet (Stress at 100% strain)

derived from the average gradient of four lines in Fig.7 and divided by the gas constant (=0.008315 kj/mol/K) resulting in 78.96 kj/mol/K.

3.2 Accelerated aging of miniature models

Miniature models were aged in a heat chamber at 80℃ for 35, 70, 140 and 210 days which are equivalent to 17, 34, 68 and 102 years in normal temperature (23℃). Fig.8 shows the compression tester with heat chamber. The size of model was 100mm and compressed 3 times with the speed: 1mm/sec. The non-dimensional reaction forces of 2-3 cycle average are shown in Fig.9 and that of 1st compression is in Fig.10, respectively. The retracting curves with hysteresis loss of each performance are also shown. The model fender of 102 years aging was destroyed by the 1st compression, therefore 68 years is meant to be the maximum number of years during which this fender keeps flexibility to absorb berthing energy. Considering that the Arrhenius's method may have some error/s, the rate of reaction force (2.319 for the 1st and 1.325 for 2-3 average) is a more reliable index than number of years at which this fender has lost its function.

Fig.8 - Compression tester for miniature model

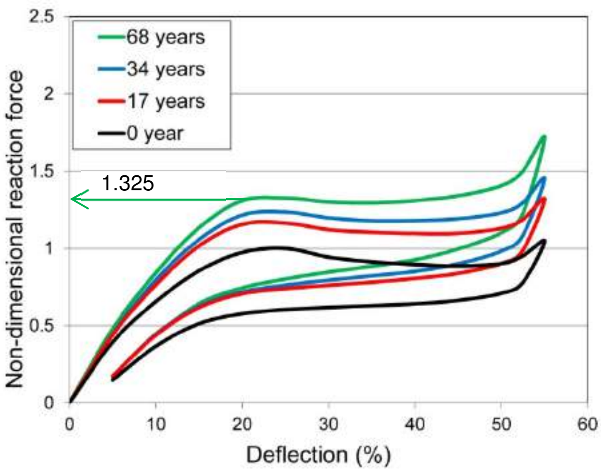

Fig.9 - Performance of miniature fender: 100H (Average of 2-3 compression cycles)

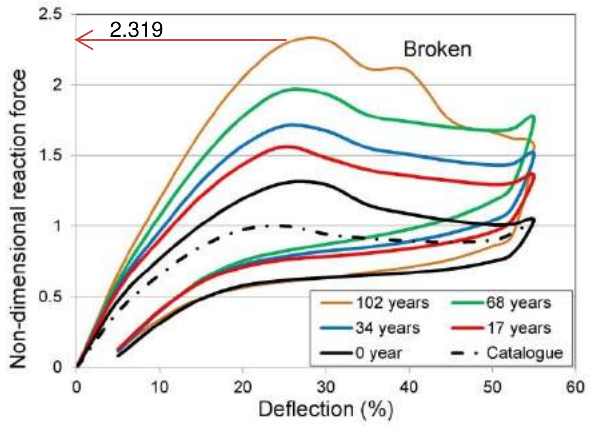

Fig.10 - Performance of miniature fender: 100H (1st compression cycle)

The reaction force rate of 100H models are added to Fig.5 and Fig.6 then shown in Fig.11 and Fig.12 respectively. Considering the fact that the miniature models don't have any damage other than thermal aging, a little higher reaction force than actual fenders from the site is a reasonable result.

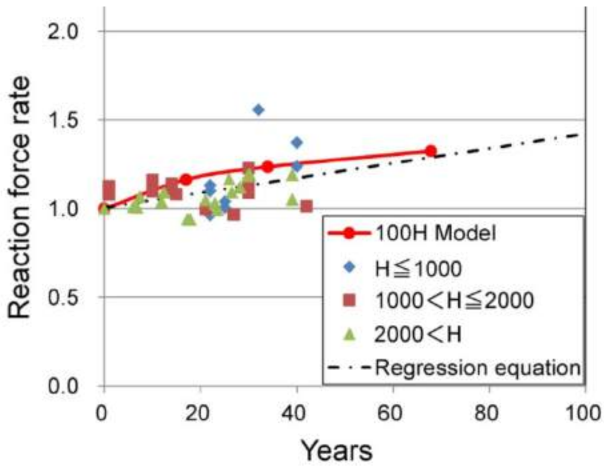

Fig.11 - Reaction force rate: 100H Model (Average of 2-3 compression cycles)

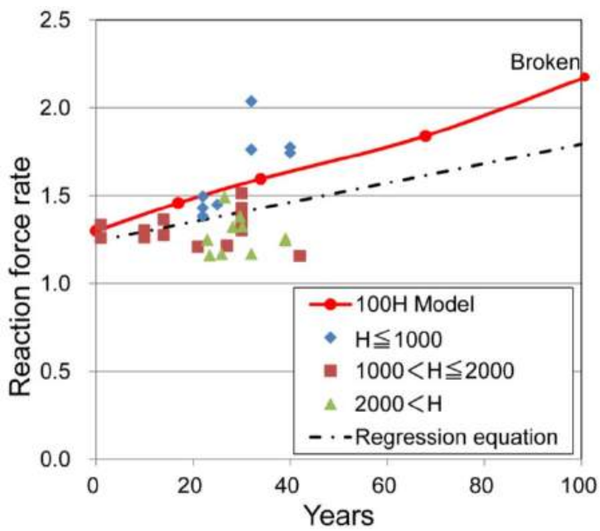

Fig.12 - Reaction force rate (1st compression cycle)

3.2 Estimation by FEM

It would be helpful if the performance after aging could be calculated with laboratory testing of material. The estimation by FEM was completed by using the following steps:

- a block of rubber had been exposed under sunlight and under the sunshade then the temperature history at each depth from surface was recorded for one year;
- the material properties with the equivalent aging to the said rubber block were chosen to the element property of FEM. Fig.13 illustrates; when the primary strain of elements reaches to the elongation at the breaking point, the layer of element was eliminated to simulate the crack and the calculation continued;
- the rate of reaction forces at each aging are compared to the performance at 0 year which was calculated by the initial property; and
- the estimated performances at each aging interval (10 to 60 years) are obtained by multiplying the rate to the standard performance.

The commercially available FEM software called ABAQUS was used and Yeoh's theory [6] was adopted for the constitutive equation. The viscosity of rubber was ignored and only elasticity was considered. The example of estimated performance for the 3000H fender is shown in Fig.14. The cracks began after 20 years and the calculation became unstable at 60 years due to the fracture of the main body when the maximum principal strain exceeded the elongation breaking

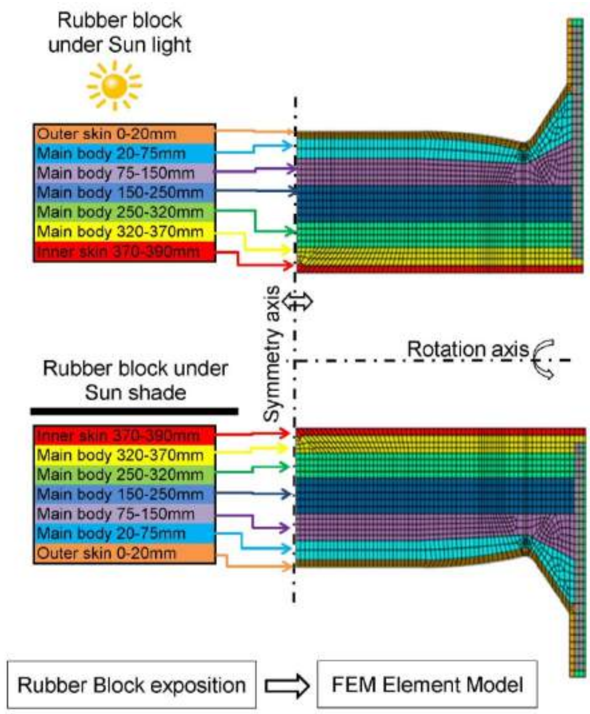

Fig.13 - Exposition test of rubber for FEM elements

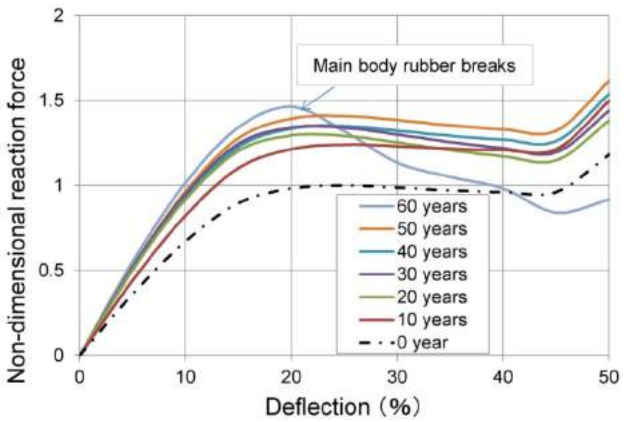

Fig.14 - Estimated aged performance by FEM

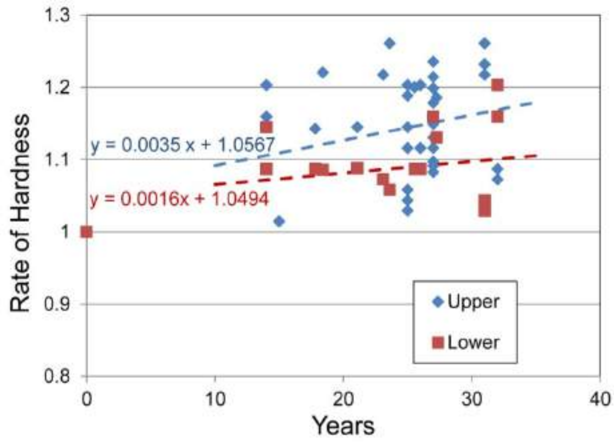

Fig.16 - Rate of hardness by year

point of the material. This implies the aging limit (before major failure) of this fender relates to the time it takes a crack to spread from the surface to the main body of the fender. The reaction force rate is added to the additional data in Fig.11 and illustrated in Fig.15. The accelerated thermal aging of 100H model showed a higher reaction force rate when compared to the FEM test results. A major reason for this is due to the thermal oxidation of the rubber, FEM was conducted using 2mm thick rubber sheets, but the 100H fender model has a rubber thickness of 16mm, therefore the percentage and degree of oxidation is less.

4. Feasibility study on Non-destructive inspection

The most convenient way to evaluate aging of a fender is to inspect the rubber surface at site. The following two methods were used in this study:

4.1 Rubber hardness

The durometer is a small handy device by which rubber hardness can be measured. Fig.16 is showing the measured rate of hardness of the used fenders and then divided by the initial (standard) value. In Fig.16, the upper side (blue broken line) becomes harder than the lower side (red broken line). The upper side was exposed to more sunlight so it is understandable that it aged quicker than the lower side. However, the deviation is too great to estimate a value and requires some improvement to the accuracy before this method can be used as a conventional tool to judge the service life.

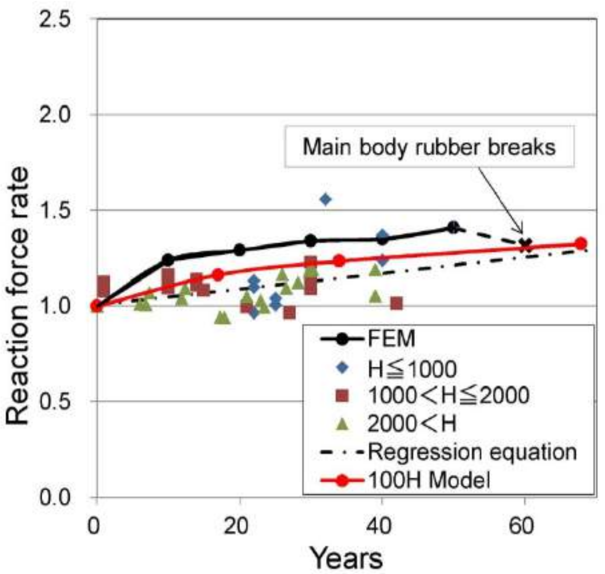

Fig.15 - Reaction force rate: FEM estimation

4.2 Elastic wave measurement

Another possibility of non-destructive inspection is to use the elastic wave measurement to obtain the elasticity of rubber inside fender body.

- Hammering

In order to inspect the aging, the wave speed has to be measured to determine the rubber elasticity. As shown in Fig.17, two AE (Acoustic Emission) sensors (CH1 and CH2) were glued to the surface of rubber block of a 22 year old fender and the side was then struck by steel spheres of 6 to 19mm in diameter. Fig.18 illustrates the signal intensities by the impact of 6mm sphere at CH1 and CH2 in the time domain. Fig.19 illustrates the power spectrum of those signals in the frequency domain. The signal patterns of CH1 and CH2 are similar and the peaks have a time lag, but they appear like surface waves rather than the signal echoed at the other end of rubber body. This method needs to be developed to separate the echoed signals so that the elasticity could be calculated by the wave

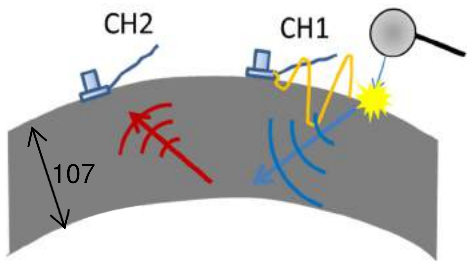

Fig.17 - Hammering

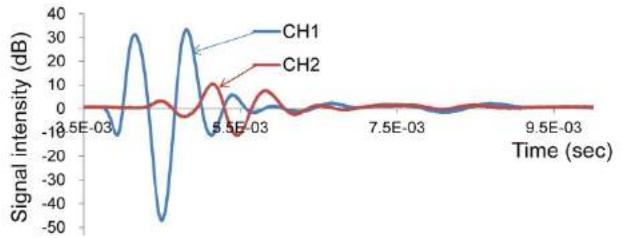

Fig.18 - Time history of hammering: ϕ 6mm

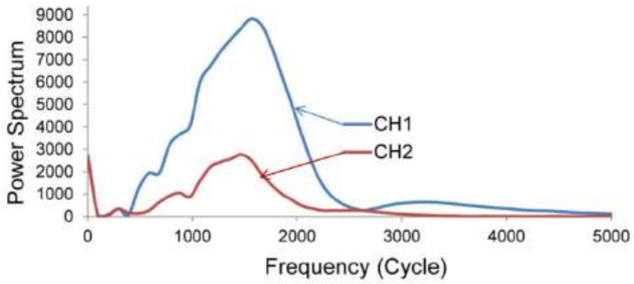

Fig.19 - Power spectrum of hammering: ϕ 6mm

speed through the fender body.

- Ultrasonic wave

The ultrasonic wave attenuates in rubber and becomes very weak. The authors checked the transmission speed of ultrasonic wave through the rubber block, which was dissected from old fender, by two ultrasonic wave probes shown in Fig.20. The calculated wave speed was approximately 1600m/sec. Considering that the wave speed in water is approximately 1500m/sec, 3800-4200m/sec in concrete and 5000m/sec in steel, this value looks reasonable for rubber material. So, the possibility to measure the elasticity was suggested if two probes could be on the inner and outer surface but in order to measure only from the outer surface at the site, further study is required.

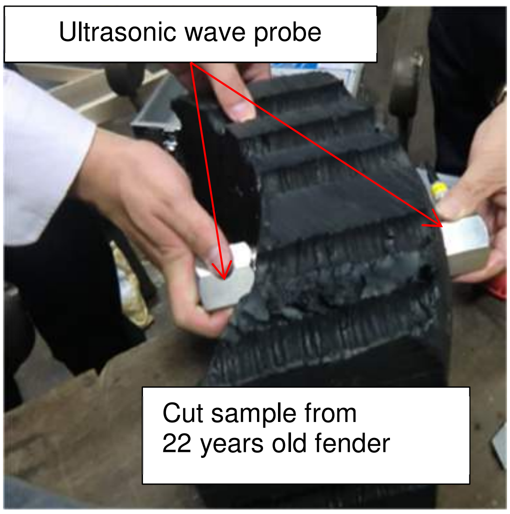

Fig.20 - Ultrasonic wave transmission through rubber

5. Conclusion

The three approaches to estimate the impact of aging on CSB type rubber marine fender were studied and the conclusions are as follows:

- The compression tests of used fenders suggested that the reaction force of aged fenders increases by years in service and the reaction force of the 1st compression can be significantly higher than the average of 2nd and 3rd compression. This issue requires further investigation.
- The performances of aged fenders were estimated by the accelerated thermal oxidation of miniature models and FEM analysis. Both methods showed good prediction of aging impact with a little higher reaction force than with the used fenders. It also indicated the ultimate aging limit is the time when the material of the main body breaks/fails because of reduced flexibility - approximately 60 to 68 years for this fender.
- The two non-destructive methods of inspection were studied. But the surface hardness had too large a deviation to estimate aging impact and we had issues separating the elastic wave (inside the rubber) from the surface wave.

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7. References

[1] Terauchi, K., Koizumi, T., Yamamoto, S., Hosokawa, K. (1997). The Deterioration actual state and the function evaluation on the rubber fender, Tech. note of the port and harbor research institute ministry of transport, Japan, 878, (Japanese)

[2] Maintenance guideline of rubber fenders, (2013) Coastal Development Institute of Technology,(Japanese)

[3] Omura, A.,Yamamoto, S., Okawa, T.,Mori, M.(2014), Kaijyo Choyu Sisetu ni okeru Keiryuyou Bougenzai no Torikaekijyun no Kentou, Journal of Coastal Development Institute of Technology, Vol.14, pp.55-58 (Japanese)

[4] Handbook for Execution of Port & Harbor Works, The Service Centre of Port Engineering（SCOPE）

[5] General Procedures for the Determination of Thermal Endurance Properties, Temperature Indices and Thermal Endurance Profiles,(1974), IEC Publication 216-1

[6] Yeoh, O.H., Fleming, P.D.(1997), A new attempt to reconcile the statistical and phenomenological theories of rubber elasticity, Journal of Polymer Science, B-35, pp.1919-1931