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DEVELOPMENT OF COMPOSITE LIFESPAN PREDICTION MODEL FOR EXPANSION JOINT USING FIELD DATA

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ABSTRACT

In this study, vibration durability test was executed by applying the expansion length of expansion joint at the time of occurrence of water hammer as the operational data of hydraulic actuator on expansion joint, which is vulnerable to water hammer, among the components of plant facility. It was presumed that internal pressure and temperature condition inside the expansion as the factors that accelerate the durability at the time of vibration durability test, which was executed by accelerating the pressure and temperature condition. Hypothesis was made that the lifespan data for each pressure condition comply with inverse power model and it was verified. In addition, in the case of temperature condition, hypothesis was made that lifespan data comply with the Arrhenius model and it was verified by inducing the coefficient value of each model formula. On the basis of the each of the induced lifespan prediction formula, Eyring model-based lifetime prediction model formula was induced by reflecting the temperature and pressure condition simultaneously, and it was verified. It is planned to develop lifespan prediction model that reflect even the deterioration condition, which is one of the factors that accelerate the vibration durability lifespan in the future.

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INTRODUCTION

With the advent of the 4th industrial revolution, smart plant capable of making decision on the time of replacement of components and predicting the symptoms of failure in advance, transcending the existing simple system of regular inspection of the equipment and materials, and ensuing replacement of components, is being demanded in relation to safety diagnosis technology for plant industry (Jeong, 2016). Trends in the improvement of ICT technology are promoting the improvement of diagnostic technologies capable of detecting the abnormalities in facilities by enabling not only real-time monitoring but also generation of big data on the safety status of plant industry by utilizing sensors. However, with regard to the evaluation of prediction of occurrence of failure and remaining useful lifetime (RUL), accurate lifetime prediction is difficult until now due to the lack of algorithm for prediction of failure to handle enormous quantity of data appropriately. Meanwhile, there is inducing of lifespan prediction model formula through accelerated lifetime test (ALT) as a technique of predicting failure lifespan. Although, ALT originally was a type of reliability test designed for the purpose of shortening the test time by artificially elevating the level of stress to the level higher than the actual conditions of the use, it can be applied to the lifespan in prediction of failure by applying the test results to lifespan – stress model formula (LIM, 2017, YU, 2015, KIM 2017, KIM 2007). Accordingly, this study aims to deduce failure lifespan prediction model by applying the on-site operational conditions of equipment and materials of actual plant to ALT.

Diagnosis of lifetime prediction: Fig. 1 illustrates Single type expansion Joint for 150A used as specimen in this study. Single type expansion joint (hereinafter, referred to as expansion joint) is being applied to plant facility systems to absorb abnormal impacts such as vibration and water hammering as well as thermal deformation through expansion and contraction due to the changes in the temperature of operational fluids. Expansion joint used as specimen in this study has designed water pressure of 10 kg_f/cm^2,operating temperature of less than 220°C and operational fluids including steam, cold and hot water, and gas, etc. It has maximum expansion length of 35 mm with the flange section made of

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SS400, while bellows section is made of STS 304 and composed of dual bellows membrane with capacity of 0.6t and structure of external cover for protection against external impact wrapping the bellows section. Key failure modes of the expansion joint include leakage due to crack in the surface of bellows, deformation of internal and external parts due to impact, and destruction of connecting and supporting sections of the piping due to impact, etc.

Fig. 1. Specimen: Bellows type expansion joint

Deduction of lifespan through application of field data

Field data for vibration durability test: Fig. 2 illustrated the changes of length in the expansion joint induced and measured at the time of occurrence of waterhammer after the trip of the pump operation in pipeline and the maximum P-P value (Peak to Peak) of expansion joint length is 9 mm approximately. (Oh, 2018). In this study, expansion length for vibration duration test will be used repetitively as the operational data for displacement-control data of hydraulic exciter

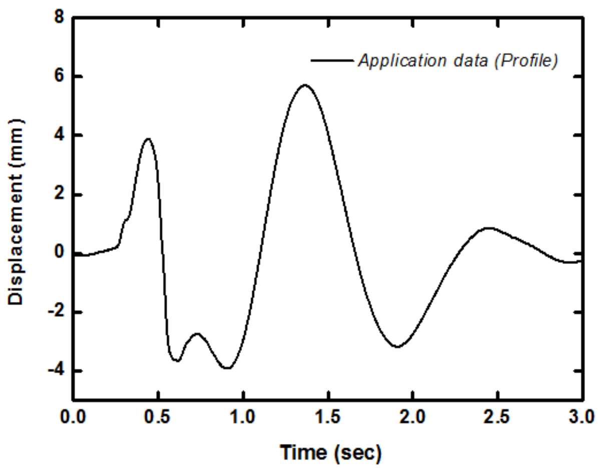


Fig. 2. Operating data applied to hydraulic exciter for vibration reproducing

Test Set-up: Set-up for application of the expansion change profile of vibration durability test on expansion joint was composed as illustrated in Fig.3. Test set-up is composed largely of hydraulic exciter(Max. 100 kN), exciter control and monitoring software. After having installed the expansion joint at the bottom of actuator, water pressure tester for controlling of supply and pressure of water was placed at the external aspect of the expansion joint.

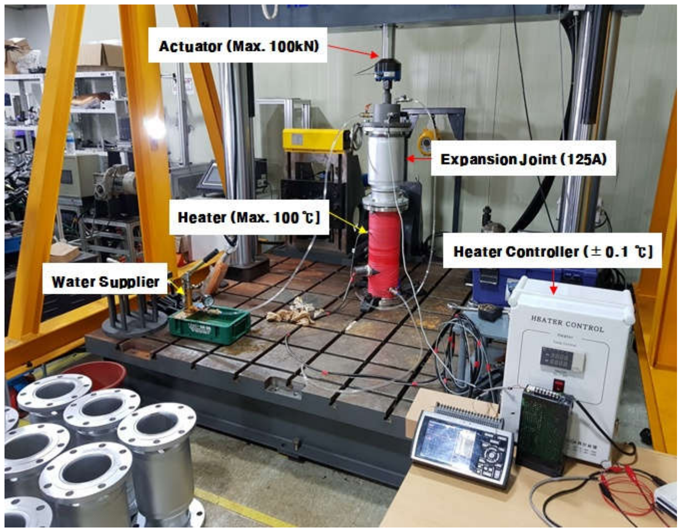


Fig. 3. Set-up for durability test of expansion joint using field data

Moreover, pressure transmitter (Max.50kg$_f$/cm^2) to confirm the changes in the internal pressure of expansion joint according to the status of water pressure and operation of actuator at the time of supply of water pressure. Meanwhile, heater was installed at the bottom of the expansion joint for vibration durability test on the expansion joint in accordance with the temperature changes and the temperature control was set at within ± 0.1^{o}C.

Test Plan: Pressure and temperature conditions inside the expansion joint were considered as factors that accelerate the vibration durability and lifespan characteristics in this study. The test conditions and quantities in accordance with the pressure and temperature conditions are given in Tables 1 and 2. Test was stopped in the event of occurrence of leakage, which is a key failure mode of expansion joint during the vibration durability test.

Table 1. Test condition according to inner pressure status

Case	Pressure (kg$_f$/cm^2)	Q'ty of Specimen
I	10	3
II	11	3
III	13	3

Table 2. Test condition according to inner temperature status

Case	Temperature (^{o}C)	Q'ty ofSpecimen
I	30	3
II	50	3
III	65	3

Test Results: Table 3 is the summary of the test results for each internal pressure when the temperature inside the expansion joint is 20^{o}C. Examination of the results illustrate that the average failure life is approximately 2,700 until the occurrence of failure when the internal water pressure of expansion joint is 10kg$_f$/cm^{2,} while they decrease to approximately 1,800 and 1,000 cycles when the internal water pressure is increased to 11kg$_f$/cm^2 and 13kg$_f$/cm^2, respectively.
Table 4 illustrates the test results for each internal temperature condition when the pressure inside the expansion joint is set at 14 kg$_f$/cm^2. Results illustrate that the average failure life is approximately 900 until the occurrence of failure when the internal temperature of the expansion joint is 30^{o}C, while they decrease to approximately 600 and 420 cycles when the internal temperature is increased to 50^{o}Cand 60^{o}C respectively,

thereby showing the trend of the lifecycle decreasing with the increase in the internal temperature in the expansion joint.

Table 3. Test results according to inner pressure status at 20 °C

Pressure (kg_f/cm^2)	Specimen	Failure life (cycle)	Average Failure Life (cycle)
	#1	2,403	
10	#2	2,589	2,733
	#3	3,208	
	#1	2,025	
11	#2	1,890	1,814
	#3	1,528	
	#1	1,138	
13	#2	1,257	1,073
	#3	824	

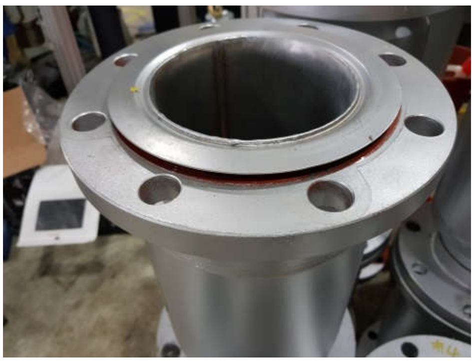
Table 4. Test results according to inner temperature status at 14kgf/cm²

Temp. (°C)	Specimen	Failure life (cycle)	Average Failure Life (cycle)
30	#1	521	904
	#2	937	
	#3	1254	
50	#1	494	605
	#2	846	
	#3	612	
65	#1	507	502
	#2	524	
	#3	475	

According to the test results, there is a tendency of increased deviation in the test with decrease in the internal water pressure of the expansion joint. It is presumed to be the result of relatively slow generation of changes in the internal pressure of expansion joint and ensuring deformation and expansion of bellows section in the low temperature and pressure domains at the time of the vibration durability test on expansion joint

Fig.4 illustrates the failure mode of expansion joint detected during and after the test.

(a) Inner deformation



(b) Separation from flange part (breakage)

(c) Leakage under durability test

Fig.4. Failure modes

Development of lifetime prediction model for expansion joint

Lifespan prediction model according to pressure condition: Firstly, under the presumption that the distribution of durability lifespan of expansion joint comply with the inverse power law model, which is appropriate for the distribution of lifespan of mechanical components, durability lifetime model formula (1) is illustrated as follows

$$L_1 = A\left(\frac{1}{P_1}\right)^{N_1} \tag{1}$$

Here,
L_1 = Anticipated lifespan (cycle)
A= Constant in inverse power model
P_1 = Pressure statusin inverse power model
N_1 = Stress indexin inverse power model

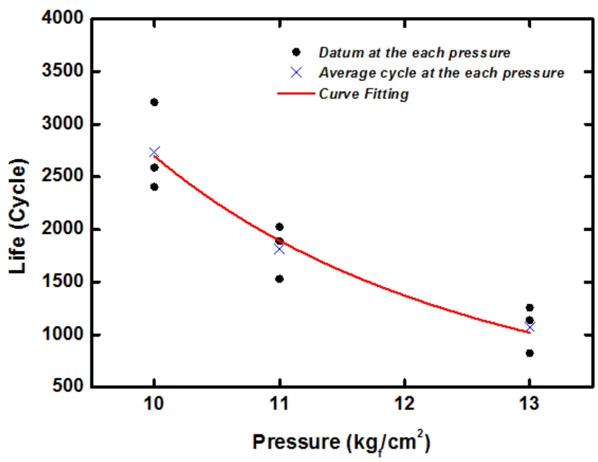


Fig. 5. Curve fitting for datum at each pressure

After having illustrated the test results as in Fig. 5 to extract each coefficient of model formula, curve that passes through the test results in accordance with each water pressure setting were fitted. As the result, the mathematical equation that follows the trend of this curve is a typical inverse power model with the coefficient,A was confirmed to be approximately 1.38×10^7 and the stress indexN_1 to be approximately 3.71. Meanwhile, vibration durability test was executed at the water pressure setting of 7kgf/cm² in order to verify the model formula induced in Section III. As the results of the test illustrated in Table 5, the average lifespan of vibration durability of expansion joint is approximately 12,400 cycles, which is the result that is well within the deviation of the test relatively in consideration of approximately 10,106 cycles for the predicted lifespan through the prediction model formula and the test results in relatively low pressure domains.

Table 5. Test results at 7kg$_f$/cm^2

Pressure (kg$_f$/cm^2)	Specimen	Failure life (cycle)	Average FailureLife (cycle)
7	#1	15,128	12,420
	#2	11,229	
	#3	10,904	

Lifespan prediction model in accordance with temperature condition: Secondly, under the presumption that the distribution of durability lifetime of expansion joint in accordance with the temperature changes complies with the Arrhenius model, durability lifespan model formula (2) is illustrated as follows

$$L_2 = Be^{\left(\frac{E_a}{kT}\right)} \quad (2)$$

Here,
L_2 = Anticipated lifetime (cycle)
B= Arrhenius model constant
E_a=Activation energy (eV)
k=Boltzmann constant$(8.167 \times 10^{-5}\ eV/K)$
T= Absolute temperature (K)

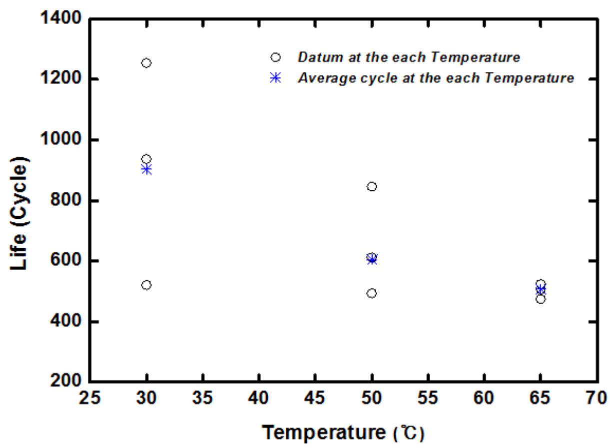


Fig.6. Distribution of life datum at the each temperature

Meanwhile, Arrhenius model formula can be converted into linear expression as follows (3)

$$\ln(L_2) = \ln(B) + \frac{E_a}{kT} \quad (3)$$

When the results of the test in Fig.6 is regressed into linear equation that comply with the data after having converted it into linear expression as illustrated in Fig. 7. In order to extract the coefficient of $\frac{E_a}{k}$, which corresponds to the gradient of the linear equation, is approximately 1,714.9 and it is possible to induce approximately 1.135 forln (B)that corresponds to the intercept. Through this, activation energy, E_a was0.148 and constant value, B, 3.112 could be obtained respectively. In order to verify model formula induced above, vibration durability test was executed at the internal expansion joint temperature of80^{o}Cas illustrated in Table 6. As the results of the test, the average vibration durability of the expansion joint is approximately 420 cycles and it was possible to confirm that the test results are in concordance with the anticipated lifespan of approximately 403 cycles obtained through lifespan prediction model formula.

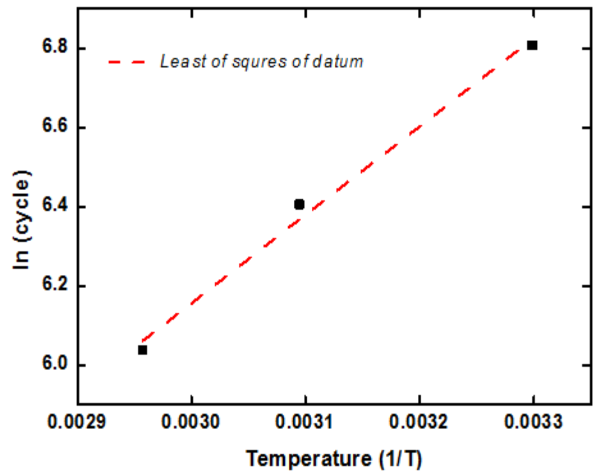


Fig.7. Linear transformation of law datum

Table 6. Test results at 80℃

Temp. (^{o}C)	Specimen	Failure life (cycle)	Average Failure Life (cycle)
80	#1	477	419
	#2	452	
	#3	328	

Composite life time prediction model

Lastly, under the presumption that the distribution of durability lifespan of expansion joint with more than 2 acceleration factors including temperature and pressure, etc. comply with the Eyring model, durability lifespan model formula is illustrated as follows (4)

$$L_3 = Ce^{\left(\frac{E_a}{kT}\right)}\left(\frac{1}{P_2}\right)^{N_2} \quad (4)$$

Here,
L_3 = Anticipated lifetime (cycle)
C= Eyring model constant
P_2 = Pressure status in Eyring model
N_2 = Stress index in Eyring model

Eyring model formula also can be converted into linear equation as follows (5)

$$\ln(L_3) = \ln(C) + \frac{E_a}{kT} + N_2 \ln\left(\frac{1}{P_2}\right) \quad (5)$$

In addition, When the activation energy value of the lifespan prediction model according to the temperature condition and failure lifespan datum according to the pressure condition in the previous section are illustrated as in Fig. 8 below, it can be expressed as a more simplified linear equation. Pressure stress index, N_2 that corresponds to the gradient of the linear equation is3.516 and $\ln(C) + \frac{E_a}{kT}$ that corresponds to the interceptis 15.979 approximately. Moreover, regarding the pressure condition applied to Equation (5), it is possible to induce the Eyring model constant, C to be approximately 17,943 by utilizing the internal temperature of expansion joint, 20^{o}C (293.15 K), and activation energy and Boltzmann constant induced in the previous section. Vibration durability test was executed by setting the internal pressure and temperature of the expansion joint at 15kg$_f$/cm^2 and70^{o}C, respectively, as illustrated in the Table 7 for verification of model formula.

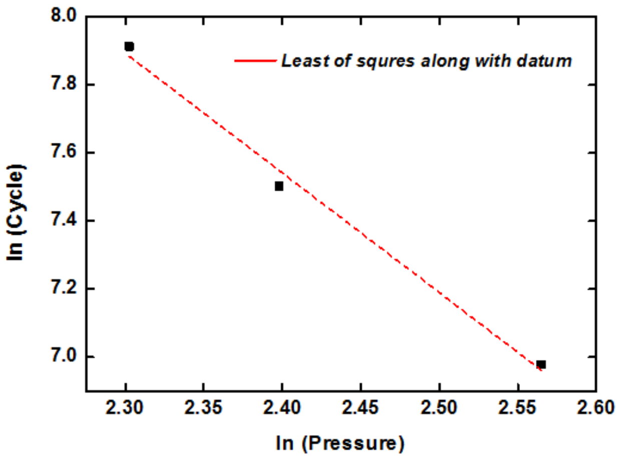


Fig. 8. Conversion into linear transformation of failure lifetime in accordance at 20°C and pressure condition

As the results of test, the average vibration durability of expansion joint is approximately 210 cycles and it was possible to confirm that this is in concordance with the anticipated lifespan of 256 cycles through composite lifespan prediction model relatively well.

Table 7. Test results at 15kg$_f$/cm^2

Temp. (°C)	Specimen	Failure life (cycle)	Average Failure Life (cycle)
70	#1	192	210
	#2	205	
	#3	233	

Conclusion

In this study, vibration durability test that used expansion length that is conveyed when water hammer occurs in expansion joint joints in plants that are actually being operated and vibration reproducing was executed. At the time of vibration durability test, internal pressure and temperature conditions of the expansion joint were set as the accelerating factors of durability lifespan, and lifespan prediction model was induced and verified by using the test results in accordance with the variations in pressure and temperature conditions.

However, the lifespan prediction model induced in this study has the limitation of being applicable to plant equipment and materials used under particular subject and environmental conditions of operation. It is planned to develop composite lifespan prediction model formula that considers the deterioration conditions according to temperature for expansion joint in the future.

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