The 2018 Structures Congress (Structures18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Fatigue life evaluation of offshore wind turbine support structure considering load uncertainty

*Dong Hyawn Kim[1)] and Gee Nam Lee[2)]

[1)] School of Architecture and Coastal Construction Engineering, Kunsan Nat'l Univ., Gunsan 54150, Korea
[2)] Department of Ocean Science and Engineering, Kunsan Nat'l Univ., Gunsan 54150, Korea
[1)] welcomed@naver.com
[2)] southweather@naver.com

ABSTRACT

Since offshore structures are exposed to different environmental loads each year, estimated fatigue life is also different year to year. However, if an observed period of environmental load is short, this short term data cannot represent load variation during design life of structure. It is a limitation that can cause under-estimate or over-estimate design life time. Therefore, in this study, annual maximum load of each observation data is selected and fatigue analysis of an offshore wind turbine support structure is performed using it. Rain-flow counting method and Miner's rule were used to estimate fatigue life of support structure. From the results of the fatigue analysis, it was concluded that design lifetime of offshore support structure should be estimated by considering annual variability of ocena environmental load.

1. INTRODUCTION

Unlike onshore wind turbines, offshore wind generators are affected by the ocean environment. Not only wind load, but other environmental load such as current, wave, are applied to wind turbines at the same time. Support structures of offshore wind turbines are responsible for most of these complex loads. Since maritime composite loads are strongly influenced by the characteristics of the installation site, the prediction and evaluation of the load is an essential process before the design. Also, the support structure takes up a considerable cost of the entire system, and the installation cost is too high. Therefore, environmental impact assessment at ocean is an important process for economical design. In addition, since offshore wind turbines are exposed to the marine environment during their design lifetime, the constantly acting loads have a significant impact on the lifetime of the structure. Extreme loads such as typhoons can

---

[1)] Professor
[2)] Graduate Student

cause loss of function or structural collapse. However, even if a relatively small composite load is continuously applied, cracks may be generated in the fragile member, leading to collapse. The damage caused by such a low but continuous load acting on the structure is the so called fatigue.

Design methods for fatigue damage of offshore wind turbine support structures are presented in various design criteria (AISC 2005, API 2007, DNV 2011). In addition, studies on fatigue damage have been performed variously by many researchers (Agarwal et al. 2011, Dong et al. 2011, Dong et al. 2012, Yeter et al. 2015). Those are evaluation of fatigue damage in the time domain and frequency domain and fatigue reliability evaluation. These studies estimate the probability distribution of loads from the observed data during relatively short period of time compared with design life and assume the observed data will be repeated for the future. In another study, fatigue damage was calculated by defining the stress transfer function in the frequency domain. However, the distribution of loads has a different shape every year. For example, the wind speed in the next year may be higher or lower than the observed year. But the assumption that the same wind speed will be repeated in the future is not reasonable and might give bad estimation of fatigue life of the structure. The purpose of this study is to investigate how the variability in ocean environment affects the lifetime of support structure. Simulation was performed by varying the accumulation period of the data used to estimate the probability distribution of loads. Through numerical analysis, the transfer function between load and response (stress) was constructed. The stress history was calculated by inputting the simulation results into transfer function. Cumulative fatigue damage was calculated using rain-flow counting method, Goodman Equation, and Miner's rule. Finally, the fatigue life of the offshore wind turbine support structures for the cumulative period of the load data was estimated.

2. PROBABILISTIC MODEL

Environmental loads acting on an offshore wind turbine include wind, wave, current and so on. In the past, these environmental loads were assumed to be independent variables and used for analysis. However, these variables are correlated, and IEC 61400-3 (2009) suggests the use of joint probability models in fatigue analysis. Johannessen (2001) proposed a joint probability model of mean wind speed, significant wave height and peak period in the Northern North Sea. In this study, a probabilistic model proposed for fatigue analysis and observed data around an offshore wind turbine were used. However, since there is no long-term observed data in Korea, hind-cast simulation data was used for 25 years (KORDI 2005). The hind-cast wind speed used in the study is calculated at 10 m above sea level. Since the wind velocity at the hub position is used for analysis, the following power law should be used.

$$V(z) = V_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} \tag{1}$$

1 hour mean wind speed (with power law) and significant wave height, and the frequency distribution over the entire period of the significant wave period are shown in Fig. 1.

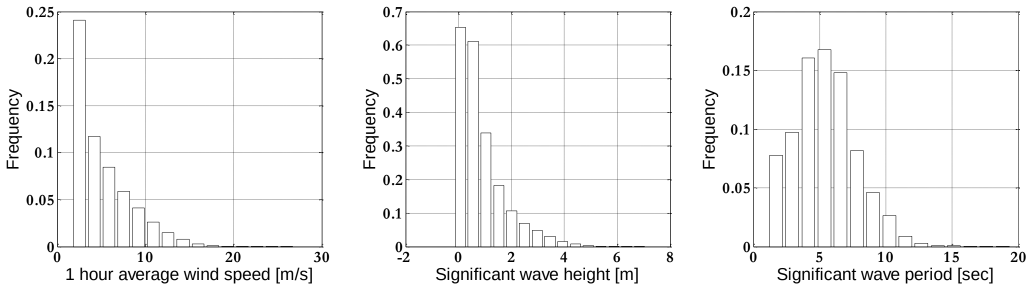

Fig. 1 Frequency distribution of hind-cast data

In the Johannessen (2001) probabilistic model mentioned above, the probability distribution of wind speed is presented as a 2-parameter Weibull function. However, the probability distributions for the hind-cast wind speeds used in the study were found to be more suitable for the Generalized Pareto (GP) distribution. Fig. 2 shows fit and PDF with hind-cast wind speed using several distributions often used in various studies.

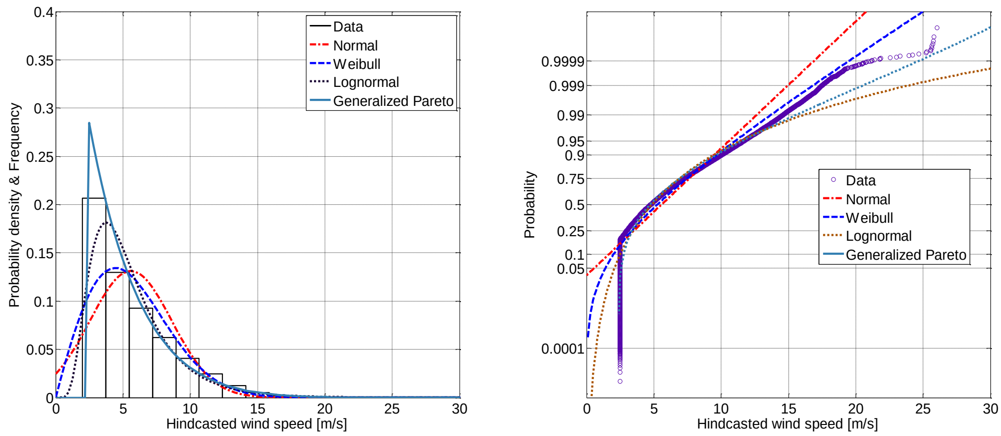

Fig. 2 Probability density and goodness of fit of hind-cast wind speed

Conditional probability distributions for significant wave height when wind speeds are given are based on the 2-parameter Weibull distribution proposed by Johannessen (2001). The Shape parameter k_h and the scale parameter σ_h are calculated as in Eq (2). The coefficients a_k, b_k, c_k, a_σ, and b_σ used here are estimated to match the hind-cast significant wave height. The calculated coefficients are shown in Table 1.

$$k_h = a_k + b_k * U^{c_k}$$
$$\sigma_h = a_\sigma + b_\sigma * U \qquad (2)$$

The conditional probability distribution for the wave period when the wind speed and wave height were determined was log-normal distribution. The mean μ_{T_p} and the standard deviation σ_{T_p}, which are the parameters of the normal distribution, can be calculated from Eq (3). And the parameter of normal distribution and the parameter of log-normal distribution are defined by the relation of Eq (4).

$$\mu_{T_p} = (a_\mu + b_\mu \cdot {H_s}^{c_\mu}) \cdot \left\{ d_\mu - e_\mu \cdot \left[\left. U_w - \left(f_\mu + g_\mu \cdot {H_s}^{h_\mu} \right) \middle/ f_\mu + g_\mu \cdot {H_s}^{h_\mu} \right. \right] \right\} \quad (3)$$

$$\sigma_{T_p} = \mu_{T_p}\left[a_{\sigma_T} + b_{\sigma_T} \cdot \exp\left(c_{\sigma_T} \cdot H_s\right)\right]$$

$$\mu_{\ln(T_p)} = \ln\left[\left. \mu_{T_p} \middle/ \sqrt{1 + \left(\sigma_{T_p}/\mu_{T_p}\right)^2} \right. \right] \quad (4)$$

$$\sigma_{\ln(T_p)} = \ln\left[\left(\sigma_{T_p}/\mu_{T_p}\right)^2 + 1\right]$$

Table 1 The coefficients used in the probabilistic model

Coefficient	Value	Coefficient	Value
a_k	1.9189	d_μ	1.0457
b_k	7.9896	e_μ	1.1540
c_k	2.1071	f_μ	0.1465
a_σ	-0.4525	g_μ	0.1424
b_σ	0.2729	h_μ	0.5811
a_μ	-0.1384	a_{σ_T}	33.1610
b_μ	-0.0698	b_{σ_T}	-32.9710
c_μ	0.5893	c_{σ_T}	0.0011

3. TARGET STRUCTURE

In this study, the structure used for numerical analysis is 3MW offshore wind turbine. The shape and basic specifications are shown in Fig. 3, Table 2. The support structure type is Tripod and the foundation is suction bucket. The effects of the ground were considered by using the coefficient of subgrade reaction estimated from the numerical analysis.

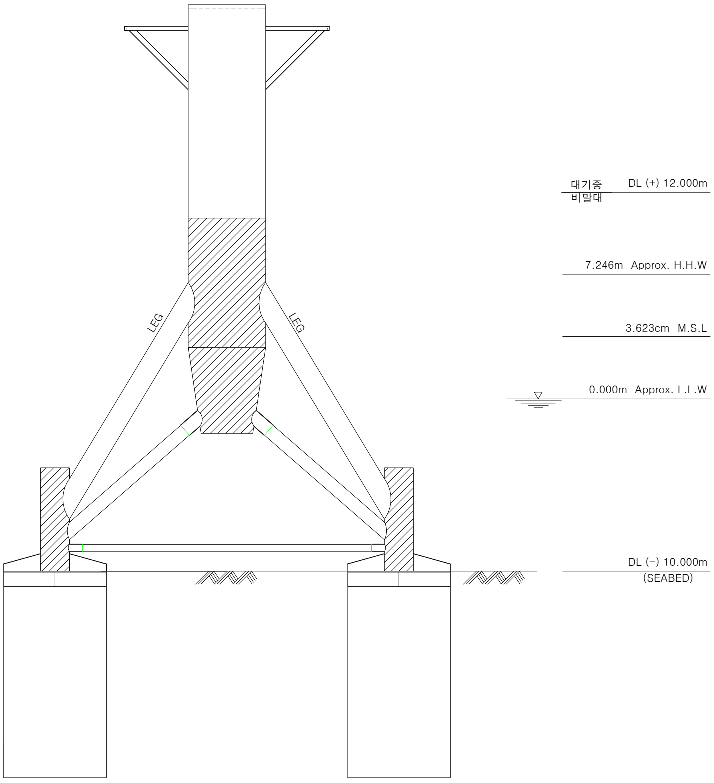

Fig. 3 Offshore wind turbine of suction bucket foundation & tripod type

Table 2 Specification and environmental condition of offshore wind turbine

Item	Value		Item	Value	
Rating	3	MW	Tower mass	358	ton
Hub height	80.0259	m	Mean sea level	13.623	m
Cut-in, Rated, Cut-out wind speed	3, 10, 25	m/s	Aerodynamic drag coefficient	0.7	-
Design life	25	years	Hydrodynamic drag coefficient	1.0	-
Rotor mass	58	ton	Hydrodynamic inertia coefficient	2.0	-
Nacelle mass	128	ton	Wind gradient	0.105	-

4. TRANSFER FUNCTION

It is practically impossible to perform the dynamic analysis in the time domain with respect to the design life of an offshore wind turbine. Generally, numerical analysis is performed in the frequency domain, or a transfer function is used. In this study, the ocean environment factor and the transfer function of response are defined through static analysis and the fatigue life is estimated by using the transfer function.

4.1 Selection of sample points

The input variables of the transfer function are wind speed, wave height, and period, and the relationship between input variables and stress is defined using the response surface method. First, determine the range in which the input variable can be generated, and select sample points within the range. Sample points can be selected as bucher-bourgund design (BBD), saturated design (SD) and central composite design (CCD) (Bucher and Bourgund 1987, Haldar and Mahadevan 2000, Box and Wilson 1951). In this study, the SD method, which is used efficiently in consideration of ductile term, was used. However, if there is a correlation between input variables, sample points should be selected considering this. Therefore, the sampling points were selected by specifying the range of input variables.

4.2 Thrust force calculation

The wind loads used to estimate the structure response can be taken into account by estimating the thrust for a given average wind speed. The calculation was performed using Gh-bladed, a program for wind turbine design (Bossanyi 2009).

4.3 Peak wave period

In IEC 61400-3 (2009), it is proposed to use the combined probability model of wind velocity, wave height and period. The wave period is suggested to use the peak wave period. However, the hind-cast wave period is a significant wave period T_s. Therefore, the peak wave period T_p was estimated using Goda's (2000) proposed equation. Here, γ means a peak enhancement factor.

$$\begin{gathered} T_p \cong T_s \cdot [1 - 0.132 \cdot (\gamma + 0.2)^{-0.559}] \\ \gamma = 1 \sim 7 \; (mean\ of\ 3.3) \end{gathered} \tag{5}$$

4.4 Static wave load calculation

The wave theory used in the design of the offshore structure is determined from Fig. 4 from the environmental information (water depth, wave height, wave period) of the design area. The velocity and acceleration of the water particles are calculated according to the determined wave theory, and the static wave load acting on the vertical pile can be calculated using the Morison equation (Morison et al. 1950).

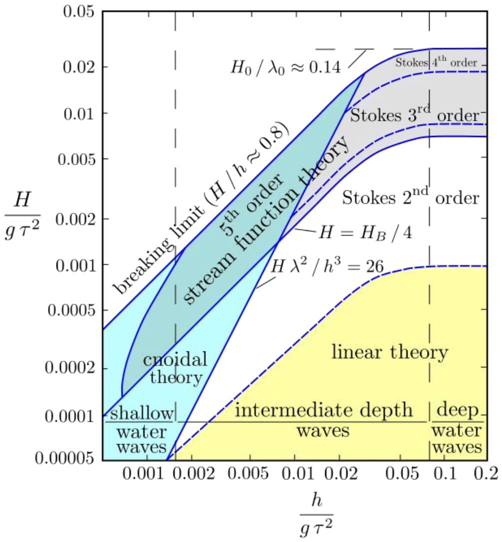

Fig. 4 Regular wave theory selection diagram (Le Méhauté 1969)

$$F = C_D \frac{1}{2} \rho_w D |u| u + C_I \rho_w \frac{\pi}{4} D^2 \frac{\partial u}{\partial t} \tag{6}$$

Where C_D, C_I, ρ_w, u, and $\partial u / \partial t$ denote the drag coefficient, inertia coefficient, density of water, water particle velocity and water particle acceleration, respectively.

4.5 Response surface method

The transfer function should be expressed in the form of a positive function. However, the response obtained through the structural analysis shows an implicit form. In this case, it can be approximated as a explicit form using a response surface method, which is a kind of regression analysis (Scheuller et al., 1989, Raymond et al., 2002). Static numerical analysis was performed by applying the wind and wave loads calculated for the sample points to the structures. ANSYS (2000), a universal finite element analysis program, was used for numerical analysis. The target structure modeled using the finite element analysis program is shown in Fig. 5.

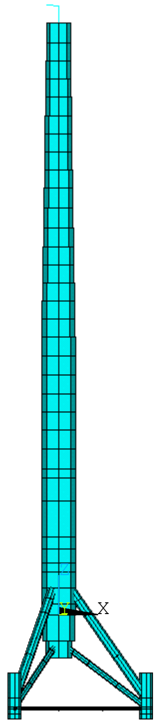

Fig. 5 FE Model of offshore wind turbine

The selected sample points and the stresses calculated by numerical analysis are expressed in the form of positive functions by inputting them into the response surface method of Eq (7).

$$R(X_1, X_2, X_3) = b_0 + \sum_i^n b_i X_i + \sum_i^n b_{ii} X_i^2 + \sum_i^{n-1} \sum_{j>1}^n b_{ij} X_i X_j \qquad (7)$$

Here, X_1, X_2, and X_3 denote wind speed, wave height, and period in the selected sampling points, and b denotes coefficient values constituting the transfer function.

5. TIME HISTORY ANALYSIS

5.1 Turbulence intensity

The turbulence intensity is an important factor because it has a great influence on the wind load calculated by the wind field analysis. In IEC 61400-1 (2005), the following turbulence intensity equation is given for the normal turbulence model (NTM) condition.

$$I_1 = I_{ref}(0.75\, V_{hub} + 5.6)/V_{hub} \qquad (8)$$

Where, I_{ref} is the expected value of the turbulence intensity at 15 m/s. In Table 3, parameters for wind turbine classes are selected and used. In this study, we selected A class with the highest turbulence characteristics.

Table 3 Basic parameters for wind turbine classes

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42.5	37.5	Values specified by the designer
A	I_{ref} (-)	0.16			
B	I_{ref} (-)	0.14			
C	I_{ref} (-)	0.12			

5.2 Analysis of wind field

Fatigue is a phenomenon in which fracture occurs due to cyclic loading. Fatigue damage calculations use stress amplitude and average stress, and cycle times. In order for fatigue failure to occur, the stress cycle must be sufficiently applied. To accurately estimate the above factors, a stress time history of sufficiently small time intervals is required. However, the hind-cast wind speed is the average wind speed per hour. Therefore, the wind field analysis was performed for the given 1 hour average wind speed. The wind speed range used for wind field analysis is from 2 m/s to 28 m/s and the wind speed interval is 0.1 m/s. The analysis program used Gh-bladed.

6. Fatigue analysis

The wind speeds used in the fatigue analysis are generated from simulation from the estimated probability distributions. The data used to estimate the probability distribution have a large impact on the result. In this study, the probability distribution is estimated by varying the accumulation period of data. One hour average wind speed, which occurs for one year from each different probability distribution according to the cumulative period, is simulated. Then, the time history corresponding to the simulated one hour average wind speed is found from the wind field analysis results. For example, if the simulated wind speed is 3 m / s, the wind field analysis results (time history) for 3 m / s are used for the next step. The wind speed time history is input to the probability model to calculate the significant wave height and period. Here, the significant wave period is converted into a peak wave period by the equation proposed by Goda (2000). The calculated wind speed, wave height, and period are input to the transfer function to calculate the one - year stress time history.

6.1 Rain-flow counting

The cycle counting method reduces the variable stress time history to a constant size load and processes it so that the linear damage rule can be used. The cycle counting algorithm is derived from various information related to the fatigue behavior of the member. Three important features are the stress amplitude, the mean stress, and the corresponding number of load cycles. The matrix consisting of these three factors is called the markov matrix. The markov matrix can be estimated by applying the rain-flow counting method to the previously calculated stress time history (Matsuishi et al. 1968, Rychlik 1987).

6.2 Goodman equation

The average stress occurring in reality is often not zero. However, when calculating fatigue damage, it is most likely to be performed under fully reversed conditions with an average stress of zero. The complete reversal condition refers to the case where the stress ratio ($R = \sigma_{min}/\sigma_{max}$) is -1. As the average stress increases, the stress ratio increases in the positive direction and the fatigue limit increases accordingly. If the average stresses in the various cycles are different, the threshold value of the stress range may be different even if they have the same amplitude. Therefore, efficient computation is possible by making the threshold of the stress range universal. Goodman (2000) devised the Goodman equation for this problem as follows.

$$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_u} = 1 \tag{9}$$

Where σ_a, σ_e, σ_m and σ_u mean stress amplitude, equivalent stress amplitude, mean stress, and tensile strength, respectively.

6.3 Cumulative damage law

Quantification of fatigue was first attempted by Miner and is still used by many researchers. Fatigue failure of a structure occurs when members reach the limit by various composite loads. The damage at this time is assumed to occur only when the maximum stress exceeds the fatigue limit. There is a problem that stress lower than fatigue limit can affect damage. Various damage laws have been proposed to improve these defects, but they have not been able to overcome many of the effects of complicated loads. Despite the above defects, Miner's linear damage rule is still used. It is as follows.

$$D = \sum_{i=1}^{n_{total}} \frac{n_i}{N_i} \tag{10}$$

Where, n_{total}, n_i and N_i denote the total number of stress cycles, the number of cycles generated for the i-th stress range, and the lifetime at the S-N curve for the i-th stress range.

6.4 Verification of method

The following fatigue analysis was carried out to verify the feasibility of the method using the transfer function. This fatigue analysis is performed based on time history analysis for accuracy. The load was used hind-cast data for 6 days. Gh-bladed was used for wind field analysis and thrust calculations. ANSYS was used for the irregular wave generation and calculation of stress time history. The given 1 hour average wind speed is calculated by the wind field analysis and the thrust force is calculated by inputting the wind speed time history into the structure. The calculated thrust force is input to ANSYS as a wind load. The significant wave height and peak wave period of the same occurrence time are used as parameters of the JONSWAP spectrum, and ANSYS considers the random wave generated by the parameter as the wave load. The stress time history is calculated from numerical analysis using ANSYS. The fatigue life was estimated using the rain-flow counting method and the Miner's rule for the stress time history. In this paper, case 1 is method based on time history analysis, and case 2 is method based on transfer function.

Case 2 uses the simulation of the probability model, so the calculated fatigue life differs each time. Therefore, the fatigue life is repeated about 500 times to find a suitable probability distribution, and the parameters are calculated. The probability distribution of fatigue life is shown to fit the Normal, Lognormal, and Generalized Extreme Value (GEV) distributions as shown in the following figure.

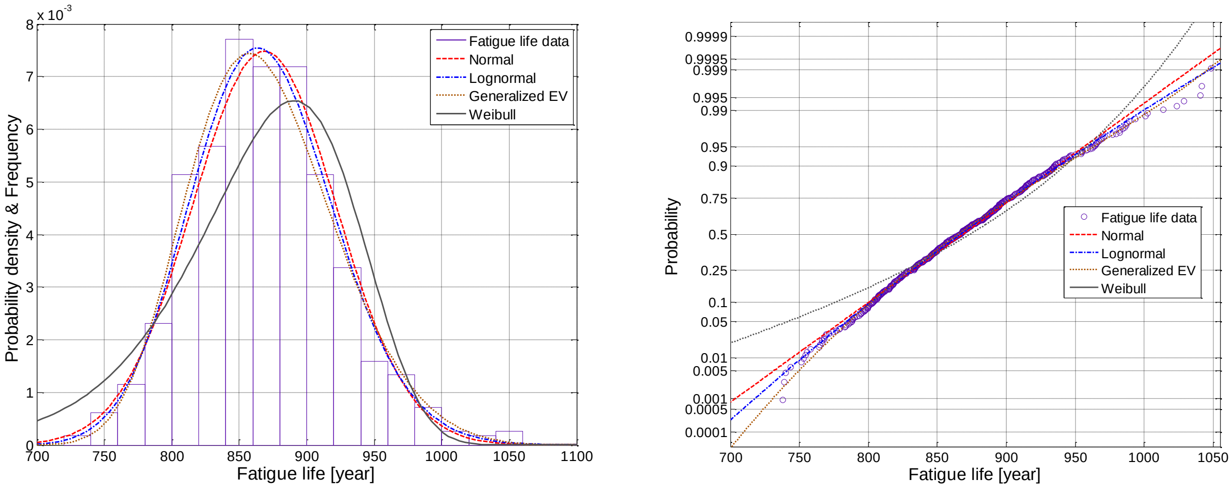

Fig. 6 Probability density and goodness of fit of fatigue life (Case 2)

Goodness of fit tests were performed on the three distributions to select the most suitable distributions. In this paper, the K-S (Kolmogorov-Smirnov) method using cumulative probability is used for the goodness of fit test. The results are shown in the following table.

Table 4 Goodness of fit test (K-S)

Distribution	Critical value (D_n^{α})	Maximum difference (D_n)	P-value
Normal	0.0569	0.0283	0.7469
Lognormal		0.0171	0.9958
GEV		0.0204	0.9699
Weibull		0.0785	0.0018

From the fitness test results, the lognormal distribution with the highest p-value was found to be a suitable distribution for fatigue life. The average fatigue life for Case 2 is 869 years, with a volatility of about 6%. The fatigue life and errors of the two cases are shown in the following table.

Table 5 Fatigue life and relative error

Case No.	Fatigue life [year]	Relative error [%]
1	818	-
2	869	5.87

6.5 Fatigue life by cumulative period

The probability distribution of the wind speeds used in the probability model is estimated based on the observed wind speed. In this study, the distribution was estimated by varying the cumulative duration of wind speed. The interval is one year. The period of occurrence of the wind speeds simulated from the estimated probability distributions is all one year. The simulated wind speeds were used in the fatigue analysis process to calculate the lifetime. The fatigue life according to the accumulation period of load is shown in the following figure.

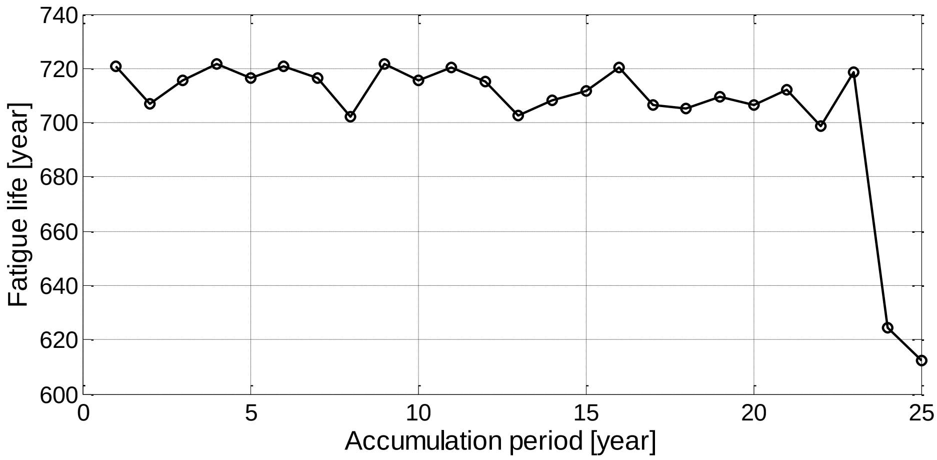

Fig. 7 Fatigue life according to accumulative period

From the above graph, it can be seen that the calculated fatigue life differs according to the variation of the accumulation period of load factors. Very low fatigue life was calculated especially in the cumulative period of 24, 25 years. It differs by more than 10% compared to the average fatigue life in the 1-23 year cumulative period.

7. Conclusions

This paper deals with the fatigue life of offshore wind turbine support structures. The core of the paper is to analyze how fatigue life varies depending on the accumulation period of load factors. The probabilistic model used here is composed of ocean environmental data in the North Sea region, but is different from the turbine installation area used in the study. Therefore, the coefficient values constituting the probability model are calculated from the ocean environment data of the target area and used for the analysis.

The probability distributions of the wind speed over the accumulative period were different, and the fatigue life was also different. The difference in lifes was more than 100 years, and the effect of accumulative period was considered to be very high. From this it can be seen that the assumption that a particular load is repeatedly applied during the design life of the structure can lead to considerable error. Finally, it is confirmed that the uncertainty of the period used for the distribution estimation has a direct effect on the fatigue life. On the other hand, in the design of the actual work, the irregular load of short period is repeatedly used, or the size and period are set by the target site and applied as a regular load. Such a design method excludes in the dynamic characteristics of the load or uncertainties of load period. These cases are usually conservatively designed using various safety factors, but they involve cost problems due to over-design. In addition, changes in the ocean environment such as anomalous high waves caused by various causes are threatening the stability of ocean structures. Therefore, accurate measurement of environmental loads and analysis of design loads are the most important processes.

As a limitation of this study, the transfer function is constructed based on the static analysis due to the time required. It is necessary to consider the dynamic effects of loads and structures and to develop a simple method that solves time problems. In addition to the wind turbines, the analysis method of this study is expected to improve the safety evaluation technology of various ocean structures.

ACKNOWLEDGMENTS

This research was supported by the Basic Science Research Program (Grant No. NRF-2016R1D1A3B03933885) of the National Research Foundation of Korea(NRF) grant funded by the Ministry of Education, and the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (Grant No. 20174030201670).

REFERENCES

Agarwal, P. and Manuel, L. (2011), “Incorporating irregular nonlinear waves in coupled simulation and reliability studies of offshore wind turbines”, *Applied Ocean Research*, **33**(3), 215-227.

AISC (2005), *Specification for structural steel buildings*, AISC 360-05.

ANSYS Inc. (2009), *ANSYS 12.0 user’s Guide*, Canonsburg, PA, USA.

API, RP 2A-WSD (2007), *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms–Load and Resistance Factor Design*, Washington DC, USA: First Edition, American Petroleum Institute.

Bossanyi, E.A. (2009), *GH Bladed user manual*, *Garrad Hassan Bladed*.

Box, J. and Wilson, W. (1951), “Central composites design”. *JR Stat Soc*, **1**, 1-35.

Bucher, C.G. and Bourgund, U. (1987), *Efficient use of response surface methods*, Universität Innsbruck, Institut für Mechanik.

DNV (2011), *Fatigue design of offshore steel structures*, Recommended Practice DNV-RP-C203.

Dong, W., Moan, T. and Gao, Z. (2011), “Long-term fatigue analysis of multi-planar tubular joints for jacket-type offshore wind turbine in time domain”, *Engineering Structures*, **33**(6), 2002-2014.

Dong, W., Moan, T. and Gao, Z. (2012), “Fatigue reliability analysis of the jacket support structure for offshore wind turbine considering the effect of corrosion and inspection”, *Reliability Engineering & System Safety*, **106**, 11-27.

Goda, Y. and Takagi, H. (2000), “A reliability design method of caisson breakwaters with optimal wave heights”, *Coastal Engineering Journal*, **42**(4), 357-387.

I.E.C. (2005), *IEC 61400-1: Wind turbines–part 1: Design requirements*. International Electro-technical Commission, Geneva.

I.E.C. (2009), *IEC 61400-3: Wind turbines part 3: Design requirements for offshore wind turbines*. International Electro-technical Commission, Geneva.

Johannessen, K., Meling, T.S. and Hayer, S. (2001), "Joint distribution for wind and waves in the northern north sea", *In the Eleventh International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

KORDI (2005), *Estimation report of deep-sea design wave in the whole sea area (II)*, Ministry of Land Infrastructure and Transport, Ansan-si, Republic of Korea: Korea Ocean Research & Development Institute.

Le Méhauté, B. (1969), *An Introduction to Hydrodynamics and Water Waves Volume II: Water Wave Theories*. TR ERL 118-POL-3-2, U.S. Department of Commerce, ESSA, Washington, D.C.

Matsuishi, M. and Endo, T. (1968), "Fatigue of metals subjected to varying stress", *Japan Society of Mechanical Engineers*, **68**(2), 37-40.

Miner, M.A. (1945), "Cumulative fatigue damage", *Journal of applied mechanics*, **12**(3), A159-A164.

Morison, J.R., Johnson, J.W., and Schaaf, S.A. (1950), "The force exerted by surface waves on piles", *Journal of Petroleum Technology*, **2**(5), 149-154.

Raymond, H.M. and Douglas, C.M. (2002), *Response surface methodology: Process and product optimization using designed experiments*, John Wiley & Sons, New York.

Rychlik, I. (1987), "A new definition of the rainflow cycle counting method", *International journal of fatigue*, **9**(2), 119-121.

Schuëller, G.I., Bucher, C.G., Bourgund, U. and Ouypornprasert, W. (1989), "On efficient computational schemes to calculate structural failure probabilities", *Probabilistic Engineering Mechanics*, **4**(1), 10-18.

Taylor, M., Ralon, P. and Ilas, A. (2016), *The power to change: solar and wind cost reduction potential to 2025*. International Renewable Energy Agency (IRENA).

Vorpahl, F., Popko, W. and Kaufer, D. (2011), *Description of a basic model of the" UpWind reference jacket" for code comparison in the OC4 project under IEA Wind Annex 30*. Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Germany.

Yeter, B., Garbatov, Y. and Soares, C.G. (2015), "Fatigue damage assessment of fixed offshore wind turbine tripod support structures", *Engineering Structures*, **101**, 518-528.

Yeter, B., Garbatov, Y. and Soares, C.G. (2015), "Fatigue reliability assessment of an offshore supporting structure", *The Maritime Technology and Engineering, Taylor&Francis Group, UK*, 671-680.