반 잠수식 시추선의 스펙트랄 피로해석에 관한 연구

A Study on the Spectral Fatigue Analysis Method for Semi-submersible Rig Structure

조 규 남*
Cho, Kyu-Nam

요 약

해양구조물의 피로파괴 형태는 매우 다양하며 설계단계에서 구조요소의 피로수명 예측은 중요하다. 각가지 피로해석 방법에 대해서 연구가 활발히 진행되었으며 접근방법에 대한 논의도 활발한 연구와 함께 진행되었다.

본 논문에서는 피로해석 방법중 스펙트랄 방법과 그 구성요소에 대해서 연구되었으며 간략화된 피로해석 방법이 제시되었고 그 특성이 비교 검토되었다. 두가지 피로해석 방법의 장단점이 조사되었고 관련된 인자인 응력집중계수, 응력폭-수명 관계 곡선 또한 연구되었다.

전형적인 반 잠수식시추선의 브레이싱 부재의 피로수명 예측을 위하여 간략화된 피로해석 방법과 스펙트랄 피로해석 방법이 작용되었으며 이를 통하여 두 방법의 유용성이 확인되었다. 또한 간략화된 피로해석 방법을 이용한 민감도 해석이 수행되었다. 본 논문에서 수행된 피로해석 결과는 스펙트랄 피로해석 방법이 보다 현실적인 피로수명 예측을 할 수 있는 방법이라는 사실을 보여주었다.

1. INTRODUCTION

Ocean waves encountering a mobile offshore unit cause the cyclic stresses in the structural elements, and some elements may experience a metal fatigue problem, which can cause them to fail.

This paper outlines the analysis premises and computational steps required to estimate the fatigue lives of the semi-submersible type platform structural elements when subjected to ocean waves.

The simplified fatigue analysis approach based on design wave is outlined. Design waves are assumed to be uniformly crested and propagate across a hypothetical ocean surface with constant shape and speed.

The character of the forces generated by these waves depend on the relative size and shape of the structure. The practical simplified fatigue analysis procedure is studied.[1, 2)]

For most offshore structures, a spectral fatigue analysis approach, where in the entire long term distribution of fatigue stresses is determined in each specific case, considering the

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* 홍익대학교 조선해양공학과

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characteristics, such as significant wave height, representative wave period, of each sea state and the time spent in it, may be performed without any difficulties.

The spectral method applies the theory of stochastic process for calculation of the response to enviromental loading especially wave loading. For a particular sea state, the spectrum of a response variable is found by combining the wave spectrum with the integrating the response spectrum, the variance of the response and the spectral moments can be calculated. Once the stress is known, predictions of the stresses experienced at that location can be made. All statistical stress predictions are related to the monents of the relevant stress spectrum about the origin.[2, 3]

In the followings, the components of the simplified and spectral fatigue analysis are reviewed and the feasibility of the method is explored. Also the theory and the methods are applied to typical semi-submersible rig structure's fatigue life estimation.

2. THEORY AND ANALYSIS PREMISES

2.1 General

Fatigue design may be carried out by methods based on fatigue tests (S-N curves) and/or methods based on fracture mechanics. For design purpose, fatigue analysis based on fatigue tests is normally the most suitable method, evaluating the actual detail against a set of standard details. For assessment of in-service cracks with respect to maximum inspection intervals or time before repair, the crack propagation must be evaluated by means of fracture mechanics.[2]

The fatigue life consists of three stages; crack initiation, crack propagation and final fracture. A fatigue analysis based on fatigue tests may be considered to include the first two stage. A fracture mechanics analysis may be used to calculate the number of load cycle in the crack propagation stage of the actual structure. The extent to which a fracture mechanics calculation can provide comparable information on fatigue life with that derived from S-N curves, will depend on the number of load cycles in the initiation stage. Frequently, however, the initiation stage for welded joints is almost negligible, because a fatigue crack will develope from existing defects, which may often be situated in areas with stress concentration. Dependent on definitions of failure criteria the crack growth period until unstable fracture may also to some extent be different for the two calculation methods.

2.2 S-N Curves and Stress Concentration Factor

2.2.1 Basic S-N Curves

The fatigue strength of a structural component is normally given in terms of stress range (S) versus number of cycle (N). Fatigue results for different welded joints are devided into several classes depending on weld geometry, quality and how the load is acting. Curves for mean life mimus 1 and 2 standard deviations have been computed for each class. With constant stress range the basic S-N curves are given by:

$$N=\alpha \times s^{-d} \times S^{-m} \quad \text{or}$$

$$\mathrm{Log}(\alpha)-d\times \mathrm{Log}(s)-m\times \mathrm{Log}(S)$$

where

N=Number of stress cycles to failure

α, m=Material constants

s=Standard deviation

d=Number of standard deviations the actual curve lies below the mean value

S=Range of stress (double amplitude)

The parameters in the basic S-N curve are derived from laboratory test in air of small specimens subjected to a uniform stress. There is a considerable scatter in the results, and the value of standard deviation gives a good estimate of scatter.

In terms of probability of failure, the mean curves correspond to the expected fatigue life.

The mean curves minus 1 standard deviation correspond to the 84.1% survival limit, while the mean minus 2 standard deviations correspond to the 97.7% survival limit.

2.2.2 S-N Curves for Practical Design

The S-N curves for practical engineering fatigue calculation are based on the basic mean S-N curves minus 2 standard deviation.

S-N data from laboratory tests are usually available for N up to 2.0E6 cycles which may be associated with fatigue limit due to constant stress amplitudes in air. To take into account variable stress amplitude in air, the S-N curves are linearly extrapolated in a Log(N) −Log(S) diagram until N=1.0E7 cycles, and for N>1.0E7 cycles the curves are given a change in slope.[1, 2, 3] For structural elements exposed to seawater, but with cathodic protection, the S-N curves are linearly extrapolated to N=2.0E8 cycles where the curves are given a cut-off level(fatigue limit). When the elements are exposed to seawater without any protection, the linearly extrapolated S-N curves should be reduced by a factor of 2 on lifetime and'a cut-off level equal to zero.

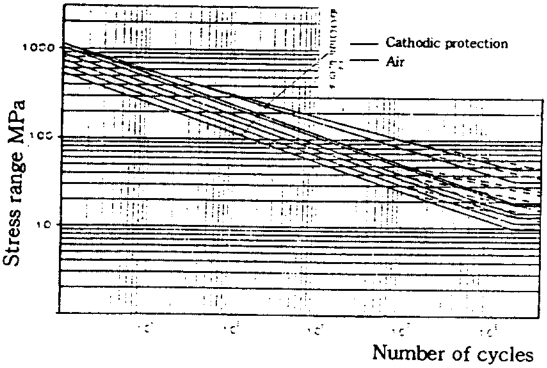

Fig. 1 S-N design curves for non-tubular members and connections

Table 1. Details of basic S-N curves - sea water and cathodic protection

Class	Log a	Log s	Log a	m	So[1)] (MPa)
B	15.3697	0.1821	15.01	4.0	48
C	14.0342	0.2041	13.63	3.5	33
D	12.6007	0.2095	12.18	3.0	20
E	12.5169	0.2509	12.02	3.0	18
F	12.2370	0.2183	11.80	3.0	15
F2	12.0900	0.2279	11.63	3.0	13
G	11.7525	0.1793	11.39	3.0	11
W	11.5662	0.1846	11.20	3.0	10
T	12.6606	0.2484	12.16	3.0	19

1)S_0 is cut-off level at $N=2 \cdot 10^8$ cycles

When performing a simplified fatigue analysis, the cut-off level is neglected.

Fig. 1 and Table 1 show the S-N curves used in the case study here.

2.2.3 Stress Concentration Factor

Stress concentration can be defined as a condition in which a stress distribution has high localized stresses: usually induced by an abrupt change in the shape of a member; in the vicinity of notches, holes, changes in diameter of shaft, and so on. Maximum stress is several times greater than where there is no geometrical discontinuity. The stress concentration facton(SCF) is the ratio of the greatest stress in the region of stress concrentration to the corresponding norminal stress. The location of the stress concentrations are called hot spot. In the fatigue analysis of offshore structures, the SCF is considered to play a most important role.[9, 10, 13)]

The SCF may be calculated from theory of elasticity by various methods. Analytical methods tend to become mathematically complicated, and are applicable to simple geometries only. Finite element methods are more versatile. For 3-dimensional case, the finite element method is still practical, but is very expensive in many cases.

SCF employed in the case study is based on the reference.[3, 9]

2.3 Simplified Fatigue Analysis

2.3.1 General

A simplified fatigue analysis can be based on a design wave method. Extreme wave heights are expressed in terms of wave heights having a low probability of occurrence. The probability Pn that a design wave with a return period of N years will be exceeded in a given duration is given by:

$$Pn=1-(1-1/N)^n$$

Design waves are assumed to be uniformly crested, propagate across a hypothetical ocean surface with constant shape and speed. The character of the forces generated by these waves depend on the relative size and shape of the structure.

2.3.2 Calculation Procedure

The practical simplified fatigue analysis procedure is based on the main headings and wave heights used in the reference.[4, 7]

From this analysis extreme stresses(100 year stresses) are taken directly and transferred to fatigue stresses(20 year stresses) by the following formula:

$$\sigma_{20}=\left[\frac{\mathrm{Log}(N_{20})}{\mathrm{Log}(N_{100})}\right]^{(1/h)} \qquad \sigma_{100}=0.92^{1/h}\,\sigma_{100}$$

where

N_{20}=Number of waves in 20 years ($N_{20}\sim10^8$)

N_{100}=Number of waves in 100 years ($N_{100}\sim10^{8.7}$)

Fatigue lives are calculated by means of the following equation

$$T=\frac{20}{D}=\frac{2s^2(t/22)^{m/4}18.42^{m/h}}{10^7\Delta\sigma_0^m\Gamma(m/h+\tau)}$$

where

$\Delta\sigma_0$=Max. stress range in the period under consideration 20years

a, m=Material parameter

h=Weibull paramters

$\Gamma(\cdot)$=The gamma function

Logs=The standard deviation of Log N

t=Thickness through which the potential crack fatigue will grow.

2.4 Spectral Fatigue Analysis

2.4.1 General

The spectral method applies the theory of stochastic process for calculation of the response to hydrodynamic loading. For a particular seastate, the spectrum of a response variable is found by combining the wave spectrum with transfer function relating the wave amplitude to the amplitude of response. By intergrating the response spectrum, calculation normally be performed numerically. Particular care must be taken in these numerical calculation to ensure that the frequency grid used for the integration of the response spectrum is appropriate.

Furthermore, attention should be given to the selection of integration points in the vicinity of any irregularities in the response spectrum, to ensure that an accurate integration is achievced.

2.4.2 Calculation Procedure

The analysis steps are briefly discussed in the followings.[11]

1) Selection of environmental conditions, i.e., various kinds of corresponding sea states. Sea states may be expressed in terms of wave energy spectrum.

2) For a wave component of an assumed direction, amplitude and period, the amplitudes

of the stress response at all points of interest within the structure are determined in order to obtainthe ratio of the stress amplitude to the wave amplitude at each point. This process is repeated for a sufficient number of wave periods to define the ratio throughout the range of realistic wave frequencies for particular direction of wave approach. The results yield the required stress transfer function.

3) Stress concentration factor (SCF) is incorporated with in order to obtain the stress transfer function of hot spots.

4) The stress spectrum is obtained by multiplying the wave spectrum by the square of the transfer function as shown below.

$$S\sigma(\omega, \alpha) = H\,\sigma^2 \cdot S(\omega)$$

where

$S\sigma(\omega, \alpha)$ stress spectrum as a function of the wave frequency and the wave direction with respect to the structure.

$H\sigma(\omega, \alpha)$ response amplitude function or transfer function

$S(\omega)$ wave spectrum

5) Statistical stress distributions during one particular stationary sea state, i.e., short-term stress statistics are obtained.

6) Statistical stress distributions during an extended period of time in which many different states occur, i.e, long-term stress statistics are obtained.

7) The fatigue life is caculated based on the assumption of linear cumulative damage(Palmgren-Miner rule). Application of this assumption implies that the long-term distribution of stress range is replaced by a stress histogram consisting of a convenient number of constant amplitude stress range blocks, σi, each with a number of stress repetitions. The fatigue criteria then reads as equation above. In calculation of fatigue life, proper S-N curve as discussed in chapter 2.2 is incorporated.

2.5 Standard Simplified and Spectral Fatigue Analysis Assumptions Proposed

For the typical semi-submersible rig structure's fatigue analysis the standard analysis assumptions are proposed as follows. The basis for this is derived from the several case studies performed previously.[4,7,8,9,10]

Previous fatigue analysis were carried out based on the assumptions which were not consistent with each other. Sometimes 'long and /or short crested sea condition' were used and nonunique Weibull parameter was used, wave heights which were different from those used in main strength analysis were used, the thickness effect was ignored.[2,4,11] In this paper the simplified fatigue analysis with proper assumptions which were obtained from several application examples[4,7] is proposed.

The simplified fatigue analysis with the following assumptions is proposed.

- Long crested sea
- Maximum wave heights which are used in main strength analysis
- Weibull parameter equal to 1.0
- Uni-direction wave heights, i.e., all waves are assumed to propagate in the same direction in 20 years.
- Allowable S-N curves with the thickness effect included but the "cut off" is neglected.

For the spectral fatigue analysis, there is no unified and unique analysis procedure. For example, transfer functions were built up by use of more than 20 wave periods, the wave spectra were discretized to 4, the thickness effects were not considered in the analysis.[2,4,11] The spectral fatigue analysis with proper assumptions based on the several analysis results[4,7] is proposed.

The spectral fatigue analysis with the following assumptions is proposed.

- Short crested sea
- Transfer functions built up by use of 14 single wave periods (4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 8.0, 9.0, 10.0, 12.0, 15.0, 18.0, 25.0)
- Pierson-Moskowitz spectrum used(Optional)
- The wave spectra are discretized to 8 main directions with equal probability.

These are 0, 45, 90, 135, 225, 270, and 315 degrees.

- The fatigue damages are calculated from 2.5 year of wave from each main directions, i.e., damages from totally 20 years of waves.
- Allowable S-N curves include the thickness effect and the "cut off".

3. NUMERICAL ANALYSIS OF TYPICAL SEMI-SUB. RIG

3.1 Ojbect Structure and Elements to be Analysed[12)]

In general, all areas which are subjected to the cyclic stresses must be investigated. On a mobile offshore unit of typical type it is obvious that some areas are more sensible to fatigue than others, such areas are:

- Attachments, holes and stiffeners on trusses(especially where global stress concentrations are occurred near the weldments)
- Areas where plate thickness on trusses are changing.
- Intersections between trusses and columns.
- Intersections between trusses.

For semi-submersibles, the vertical trusses are highly compressed in the static load conditions. This leads that dynamic forces will pulsate in the compressive stress range of the members. Therefore the fatigue strength check of the vertical trusses are omited in this analysis. The investigated sections in the horizontal trusses are seen in the Fig. 2. In this analysis, the wave scatter diagram of North Sea is taken and consequently wave loadings are based on North Sea environmetns.[5)]

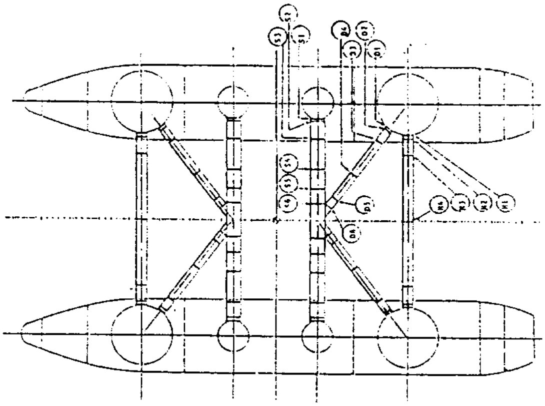

Fig. 2 The analysis sections of the rig structure

3.2 Analysis Results

Results by the two methods of these points are as follows

Section Type	Point No.	Weld Class	SCF used	Simplified method	Specttal method
H1	12	F	1.5	30.4 years	47.6 years
H2	3	F2	1.2	27.3 years	52.6 years
H3	7	F	1.1	20.2 years	26.3 years
H4	5	F	1.0	25.0 years	28.6 years
S1	12	F	1.5	15.3 years	37.0 years
S2	7	F2	1.2	16.6 years	40.0 years
S3	7	F	1.1	17.5 years	41.7 years
S4	6	f	1.0	45.2 years	122.0 years
S5	6	F	1.1	49.0 years	131.2 years
S6	5	F	1.5	34.4 years	71.4 years
D1	10	F	1.5	33.4 years	62.5 years
D2	3	F	1.2	27.2 years	45.5 years
D3	3	F	1.1	15.5 years	22.2 years
D4	6	F	1.0	21.4 years	35.7 years
D5	6	F	1.1	14.4 years	24.4 years
D6	6	F	1.5	21.4 years	38.5 years

It is shown from the analysis that the vessel has sufficient strength in the horizontal trusses to withstand 20 years of operation.

3.3 Sensitivity Study

As is well known, there can be significant variability in the fatigue life according to the different fatigue paramters.[6] In order to study the effect of SCF, weld class, and Weibull parameter, a sensitivity analysis of these three fatigue parameters has been performed using the simplified method. The results show that the SCF plays an important role in fatigue life significantly and nextly weld classes does. The Weibull parameter may not significantly influence in fatigue life. Table 2 shows the results of the sensitivity study.

Table 2. Sensitivity study - SCF, Weld Class, Weibull parameter

stress point	100-year strs AMP (MPA)	20 year strs (MPA)	20yr(THK) strs AMP (MPA)	SCF	weld class	Weibull parameter	allowable strs AMP (MPA)	fatigue life year
6	92.05	84.69	95.11	0.90	F	1.0	83.39	26.2
6	92.05	84.69	95.11	0.95	F	1.0	[illegible]	22.3
6	92.05	84.69	95.11	1.00	F	1.0	83.39	19.1
6	92.05	84.69	95.11	1.05	F	1.0	83.39	16.5
6	92.05	84.69	95.11	1.10	F	1.0	83.39	14.4
6	92.05	84.69	95.11	1.15	F	1.0	83.39	12.6
6	92.05	84.69	95.11	1.20	F	1.0	83.39	11.1
6	92.05	84.69	95.11	1.25	F	1.0	83.39	9.8
6	92.05	84.69	95.11	1.30	F	1.0	83.39	8.7
6	92.05	84.69	95.11	1.40	F	1.0	83.39	7.0
6	92.05	84.69	95.11	1.50	F	1.0	83.39	5.7
6	92.05	84.69	95.11	1.10	B	1.0	209.55	512.1
6	92.05	84.69	95.11	1.10	C	1.0	165.18	148.5
6	92.05	84.69	95.11	1.10	D	1.0	111.63	34.4
6	92.05	84.69	95.11	1.10	E	1.0	98.73	23.8
6	92.05	84.69	95.11	1.10	F	1.0	83.39	14.4
6	92.05	84.69	95.11	1.10	F2	1.0	73.19	9.7
6	92.05	84.69	95.11	1.10	G	1.0	60.88	5.6
6	92.05	84.69	95.11	1.10	W	1.0	52.62	3.6
6	92.05	84.69	95.11	1.10	T	1.0	120.73	43.5
6	92.05	83.91	94.33	1.10	F	0.9	99.67	25.2
6	92.05	84.69	95.11	1.10	F	1.0	83.39	14.4
6	92.05	85.33	95.83	1.10	F	1.1	71.43	8.8

4. CONCLUSIONS

Characteristcs of the simplified method and spectral analysis for semi-submersible rig structure's fatigue life estimation are comprehensively studied and the guideline for the analysis is presented.

Also, the fatigue strength of the horizontal trusses of typical semi-submersible rig is numerically investigated.

According to the results obtained in this analysis, the following conclusion may be drawn.

(1) The proposed simplified and spectral fatigue analysis procedures and relevant assumtions are useful for the semi-submersible type fatigue structural analysis.

(2) The details investigated are calculated by use of a S-N curve approach which is conservative for the detail.

(3) The results from the simplified method is conservative due to the assumptions taken for this method.

(4) The simplified fatigue analysis can be used satisfactorily in the early design stage of the details. And the Weibull parameter in the stress range distribution is approximatly 1.0 for this type structure in the North Sea region.

(5) The results from the spectral analysis give a more realistic picture of the fatigue life especially because of taking into account the wave headings distributed over a region of 360 degrees.

(6) The vessel has sufficient strength in the horizontal trusses to withstand 20 year of operation.

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