Reliability analysis of Tension-Leg Platform Tendon with Respect to Fatigue Failure under Environmental Condition of Caspian Sea

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ABSTRACT

The primary objective of this paper is probabilistic quantification of the fatigue life of tension-leg platforms (TLP) using reliability methods. The need for such methods stems from the significant uncertainty in the loads exerted on offshore structures. The scope of this paper is limited to the study of fatigue in TLP tendons. For this purpose, nonlinear time-history of force response of the TLP tendon under random-wave load is computed via MOSES software and the damage due to fatigue is estimated in accordance with the Palmgren-Miners rule. Assuming a Rayleigh distribution for stress variation and eight different sea states, the ultimate fatigue damage is computed by accumulating the damage over all individual sea states. This cumulative damage enters the limit-state function that is based on the Palmgren-Miners rule. Prevailing sources of uncertainty in this problem are those in the estimation of fatigue stresses, fatigue strength, and the Palmgren-Miners rule. Finally, reliability analysis is carried out for four different service lives using the first- and second-order reliability methods (FORM and SORM) and Monte Carlo sampling. The results indicate that FORM computes the probability of failure sufficiently accurate. It is concluded that the probability of failure increases drastically with the service life. The importance vector from the sensitivity analysis in FORM reveals that the model error is the most influential source of uncertainty on the probability of failure.

1. Introduction

TLP’s are floating structures anchored to the sea bottom through vertical tensioned tendons. The tendons hold the platform in place and they remain tensioned due to the excess of buoyancy caused by the floating hull. The tendon system is a critical component for the TLPs, since its failure may lead to the collapse of the whole structure involving human lives, economic losses and damages to the environment. Thus, the tendon system has to be designed to withstand the possible occurrence of different limit states like fatigue. Since offshore structures are subjected to random wave loading, which may contribute to fatigue failure, analyzing and making realistic predictions of failure probability is necessary.

Chatterjee et al. [1] developed a computational tool to handle hydrodynamic and structural aspects of TLP together. They also generated relevant information for a nonlinear static local stress analysis of TLP components from a dynamic hydro-structural global analysis. Lotsberg [2], Banon and Harding [3], Amanullah et al. [4], Khan and Siddiqui [5] studied reliability of TLP tendons under conventional environmental forces. The reliability assessment of TLP tendons under less probable small duration impulsive forces such as that arising due to collision of ships, icebergs, big marine or sea creatures, etc. Siddiqui and Ahmad [6] studied fatigue and fracture reliability of TLP tendons under random loading of sea waves. In this study, fatigue reliability of TLP tendons are evaluated using two common methods, i.e., first order reliability method (FORM) and Mont Carlo simulation. A more detailed application of reliability methods in fatigue assessment of existing offshore structures can be found in Gerhard [7]. Tabeshpour and Malayjerdi [8] stated the effect of pitch degree of freedom on the dynamic response of tendons that can affect the stress in tendons. Such fatigue can lead to tendon failure [9]. In this research, reliability analysis is performed using an approximate method, which models the structure directly as a system rather than modeling of the structural system as a system of components.
2. Limit state function

Fatigue failure has been defined through the limit state function \( g(z) \) which is negative or zero at failure. \( z \) is vector of basic variables describing load, material properties, geometry variables, statistical estimates and model uncertainties. The probability of failure or probability of limit state violation is defined as

\[
P_f = P[g(z) < 0] = \int g(z) < 0 \, f_z(z) \, dz \quad (1)
\]

where \( f_z(z) \) is the joint probability density function of vector \( z \) which is the product of individual probability density function of uncorrelated random variables. For fatigue of offshore platforms the major uncertainties involved are due to:

- Estimation of environmental parameters.
- Calculation of hydrodynamic and wind loads.
- Calculation of structural response.
- Calculation of local stresses (stress concentration factors) and stress intensity factors.

In the present study on fatigue reliability the following model has been employed for the formulation of limit state function.

2.1 Miner-Palmgren damage model

Equations in this approach, the fatigue strength is expressed in terms of S-N relation, which gives the number of stress cycles \( N \) with stress range \( S \) to cause failure. The S-N model generally used for high-cycle fatigue is given as

\[
NS^m = A \quad (2)
\]

where \( S \) is the stress range; \( m, A \) are empirical constants; and \( N \) is the number of cycles causing failure. The TLP is subjected to environmental loadings, which are random in nature. Consequently, the tendon stresses are random in nature. The estimation of fatigue damage under stochastic loading is commonly done by the Miner-Palmgren model. In this model it is assumed that the damage on the structure, per load cycle, \( D_j \) is constant at a given stress range \( S_j \) and is equal to

\[
D = \frac{1}{N(S_j)} \quad (3)
\]

Where \( N(S_j) \) is the total number of cycles to failure at stress range \( S_j \). The total damage accumulated in time \( T_s \) is thus given by

\[
D = \sum_{j=1}^{N(T_s)} \frac{1}{N(S_j)} \quad (4)
\]

Where \( N(T_s) \) is the total number of stress cycles in time \( T_s \). In this formulation, it is assumed that the accumulated damage \( D \) is independent of sequence in which stress cycles occur.

Using the S-N curve, the accumulated damage, \( D \), is given as

\[
D = \sum_{j=1}^{N(T_s)} \frac{S_j^m}{A} \quad (5)
\]

Since each stress range is a random variable \( \sum_{j=1}^{N(T_s)} S_j^m \) is also a random variable. If \( N(T_s) \) is sufficiently large, the uncertainty in the sum is very small and the sum can be replaced by its expected value. Therefore

\[
E\left[\sum_{j=1}^{N(T_s)} \frac{S_j^m}{A}\right] = E[N(T_s)]E[S_j^m] \quad (6)
\]

For a narrow-band Gaussian process, stress ranges are Rayleigh distributed. The mean value of the stress range follows directly as

\[
E[S_j^m] = \int_0^\infty (2x)^m \frac{x}{\sigma_x} \exp \left(-\frac{1}{2} \frac{x^2}{\sigma_x^2}\right) dx = (2\sqrt{2})^m \sigma_x^m \Gamma(1 + \frac{m}{2}) \quad (7)
\]

Hence, the accumulated damage is given as

\[
D = \frac{1}{A} E[N(T_s)]E[S_j^m] \quad (8)
\]

If we consider the environmental condition being described as a set of stationary short-term sea states, the total damage can be obtained by summing the accumulated damage over all sea states. Thus, the total damage \( D \) yields:

\[
D = \frac{T_s}{A} \Omega \quad (9)
\]

Where \( \Omega \) is stress parameter given as

\[
\Omega = (2\sqrt{2})^m \Gamma(1 + \frac{m}{2}) \sum_{q=1}^{m_q} f_q \nu_{q0} \sigma_q^m \quad (10)
\]

\[
\sigma_q = \sqrt{m_0} \quad (11)
\]

Failure occurs if \( D > \Delta_F \) where \( \Delta_F \) is the value of the Miner-Palmgren damage index at failure. Often \( \Delta_F \) is taken as 1.

Letting \( D = \Delta \), the time for fatigue failure \( T \) of a joint is obtained as

\[
T = \frac{\Delta_F A}{\Omega} \quad (12)
\]

In order to take into account the uncertainties associated with the above expression, the factors involved in the expression shall be modeled as random variables. The time to failure \( T_i \) of joint I may be given as

\[
T = \frac{\Delta_F A}{B_i^m \Omega} \quad (13)
\]

Where, \( \Delta_F, A_i, B_i \) are random variable.

In the above Eq.(13), \( B_i \) describe the inaccuracies in estimating the fatigue stresses. The actual stress range is assumed equal to the product of \( B_i \) and the estimated stress range \( S \). The uncertainties in fatigue strength, as evidenced by scatter in S-N data, are accounted by
considering $A_i$ to be a random variable. The random variable $\Delta g$ quantifies modeling error associated with Miner-Palmgren rule.

Uncertainty in fatigue stress estimates is assumed to stem from five sources. Attempts are made as follows to quantify the uncertainty contributed by each. A suggested model for $B_i$ is [10]:

$$B = B_m B_a B_r B_q B_h$$

(14)

In which, each $B_i$ is a random variable describing uncertainty as follows: $B_m$ is fabrication and assembly operations; $B_s$ is sea state description; $B_F$ is wave load predictions; $B_N$ is nominal member loads; $B_H$ is the estimation of hot spot stress concentration factors. As the model error depends on various parameters it is found hard and time taking to determine it. Thus, according to the rules, a lognormal probability distribution function with specified mean and standard deviation is assumed for modeling error parameter [10]. The fatigue failure occurs when the random variable $T_i$ is smaller than $T_s$ where the $T_s$ is the lifetime of the structure. Thus, the limit state function is

$$G(z) = \frac{\Delta g A}{B_m f} - T_s$$

(15)

where

$$z = (\Delta g, A, B)$$

(16)

The surface $g(z)$ is the limit state surface, and $z$ is the vector of basic random variables in the problem. The failure probability is computed using First order reliability method and Monte Carlo simulation technique. If

$$z_1 = \Delta g$$

$$z_2 = A$$

$$z_3 = B$$

Then the limit state function is

$$G(Z) = \frac{z_1 z_2}{z_3} - T_s$$

(17)

And the probability of failure $P_f$ is

$$P_f = P(T_i < T_s) = P[G(z) \leq 0]$$

(18)

The reliability or safety index is thus obtained by

$$\beta = \Phi^{-1}(P_f)$$

(19)

Where $\Phi^{-1}$ is the inverse of the standardized normal distribution function.

1.1. System Reliability

TLP tendons are made of welded elements that form a series system. If any of its joints fails, the system fails. If the failure of any joint of any member in a series system were mutually independent, the system probability of failure $P_{sys}$ can be formulated in terms of welded joints failure probabilities $P_{ij}$ form basic probability considerations:

$$P_{sys} = 1 - \prod_{i=1}^{n} (1 - P_{ij})$$

(20)

And reliability index as is:

$$\beta_{sys} = -\Phi^{-1}(P_{sys})$$

(21)

where $n$ is the number of joints.

2.2 Wide Band Correction

Fatigue stresses are assumed narrow band random process. However, if they are wide band random process then the stress parameter $\Omega$ has to be modified accordingly through a correction factor. In the present study, Wirsching’s wide band correction factor ($\lambda$) has been applied to modify the expression of $\Omega$. Therefore, the corrected expression for stress parameter ($\Omega$) is:

$$\Omega = (2\sqrt{z})^{m'} \left(1 + \frac{m}{2}\right) \sum_{q=1}^{n} f_q v_{aq} \sigma_{mq}^m \lambda_q$$

(22)

Where $\lambda$ is Wirsching’s wide band correction factor for $q^{th}$ sea state [10]. Estimates of $\lambda_q$ is obtained by the following empirical expressions given by:

$$\lambda_q = a(m) + [1 - a(m)] (1 - \varepsilon_q)^{b(m)}$$

(23)

$$a(m) = 0.926 - 0.033m$$

$$b(m) = 1.587 - 2.323$$

And $\varepsilon_q$ is the spectral width parameter for $q^{th}$ sea state. For a typical ocean structure problem if $\varepsilon_q > 0.5$, then $\lambda_q \approx 0.79$ for $m = 4.38$ and $\lambda_q \approx 0.86$ for $m = 3$.

3 Environment

In this study, environmental condition is limited to random waves only. According to data from Iranian Institute of Oceanography and Atmospheric Science, time series of significant wave-height for Caspian Sea is extracted. Thus, eight sea states are obtained based on the probability distribution function that is fitted over mentioned data [12] (Table 1).

$$\sum f(H_s) \Delta H_s \approx 1$$

(24)

And zero up crossing period $T_z$ is estimated as [13]

$$T = 3.21 (H_s)^{0.5}$$

Table 1. Caspian Sea Seastates

| Seastate | Significant Wave height | $T_z$ | Occurrence Probability |
|----------|-------------------------|-------|------------------------|
| 1        | 1.18                    | 3.46  | 0.314329               |
| 2        | 2.15                    | 4.67  | 0.270879               |
| 3        | 3.65                    | 6.09  | 0.251491               |
| 4        | 5.15                    | 7.23  | 0.102182               |
| 5        | 6.65                    | 8.22  | 0.033753               |
| 6        | 8.15                    | 9.10  | 0.009534               |
| 7        | 9.69                    | 9.93  | 0.002394               |
| 8        | 11.15                   | 10.65 | 0.000499               |

4 Numerical Study

ISSC TLP as described in Table 2 was chosen for reliability study for eight simulated sea states [14]. Dynamic analysis was performed with MOSES software for long-crested random wave idealizing the platform hull as rigid body anchored to the seabed acting like springs. The analysis was carried out using three-dimensional diffraction theory. This non-linear dynamic analysis considers hydrodynamic loading due to random sea represented by JONSWAP spectrum.
The effects of wind and current was ignored in this study. The stress time-series of the tendons were carried out for 500 seconds with the time step of 0.5 sec. The response was assumed to follow a zero mean Gaussian process. This assumption would be violated particularly if springing and ringing, a higher order wave effects, were considered in the analysis. These major non-linearity causing effects were not being considered in the present study. Figure 2 shows schematic arrangement of tendons under each column. The stress time-series were statistically analyzed and statistical parameters of stress response were obtained (Table 3). Reliability analysis was carried out using Miner-Palmgren damage model. A brief description of statistics of the random variables are summarized in Table 4.

The probability of failure and reliability indices for four different service lives obtained for long crested random waves using Miner-Palmgren damage model are shown in Table 5. The reliability computations were performed utilizing RT software [16]. Three methods were applied for reliability analysis: First and second order reliability method and Monte Carlo simulation. Two of the most commonly used reliability methods are first and second order reliability. The basic idea of these methods is to ease the computational difficulties through simplifying the calculations and approximating the limit-state function. The name of First Order Reliability Method (FORM) comes from the fact that the limit state function is approximated by the first order Taylor expansion and the Second Order Reliability Method (SORM) uses the second order Taylor expansion. In Monte Carlo simulation, probability of failure is calculated by generating random numbers according to the probability distribution function of the random variables. Therefore, the outcome of the Monte Carlo simulation is considered as the accurate solution for the comparison. In RT, the maximum iterations and coefficient of variation were set ten million and 2% respectively for convergence criteria. Also for system reliability analysis, it was assumed that each tendon was made of 40 welded elements forming a series system. Stress time-history should be calculated for each joint to obtain system reliability but for simplicity, it was logical to assume that the statistic variables of stress at joints were equal.

3 Discussion of results

Figure 3 and 4 show that the FORM results have close proximity with Monte Carlo simulation results. Although SORM uses accurate approximations in comparison with FORM, its computations are often more complicated and time taking. Therefore, FORM is equally sufficient for such problems as Monte Carlo simulation method. Thus, it can be recommended for economical and efficient computation of reliability or probability of failure.

Service life directly affects the probability of failure or reliability of a system. It is seen that as the service life increases, the corresponding probability of failure increases drastically. This is an expected trend.

![Figure 1: ISSC TLP](image)

| Table 2. Platform and tendon characteristics [14] |
| Characteristic | Value |
| --- | --- |
| Column spacing | 86.25 [m] |
| Column diameter | 8.44 [m] |
| Pontoon height | 10.5 [m] |
| Pontoon width | 7.5 [m] |
| Vertical center of gravity | 38 [m] |
| Draft | 35 [m] |
| Mass of platform | 40.5*10[^6] [kg] |
| Depth | 800 [m] |
| Number of tendons | 12 |
| Total pretension | 137.2*10[^6] [N] |
| Length of tendon | 765 [m] |
| Tendon outer diameter | 600 [mm] |
| Tendon wall thickness | 88 [mm] |
| Tendon young modulus | 2.1*10[^11] [N/m^2] |

![Table 3. Statistic for random response](image)

| Seastate | Probability | RMS stress [MPa] | \( T_s \) |
| --- | --- | --- | --- |
| 1 | 0.31432 | 2.28114 | 2.61E-01 |
| 2 | 0.27087 | 3.73885 | 5.93E-01 |
| 3 | 0.25149 | 3.74159 | 3.24E-01 |
| 4 | 0.10218 | 3.77027 | 3.49E-01 |
| 5 | 0.03375 | 4.74215 | 3.51E-01 |
| 6 | 0.00953 | 5.81377 | 2.08E-01 |
| 7 | 0.00239 | 7.48678 | 4.15E-01 |
| 8 | 0.00049 | 7.4988 | 1.24E-01 |

![Table 4. Random variables statistics [6]](image)

| Variable | Distribution | Median / Mean | COV |
| --- | --- | --- | --- |
| Fatigue strength coefficient, \( A \) | lognormal | \( \overline{A} = 5.27 \times 10^{-12} \) | 0.63 |
| Stress modeling error, \( B \) | lognormal | \( \overline{B} = 1 \) | 0.2 |
| Miner-Palmgren damage index error | lognormal | \( \overline{\Delta} = 1 \) | 0.3 |
| Fatigue exponent, \( m \) | constant | 3 | - |
The system reliability analysis of TLP tendon is done assuming that it is consisted of 40 elements. The results are shown in Table 6. Acceptable range of reliability index as based on rules is from $3.09$ to $4.75$ and of probability of failure from $10^{-6}$ to $10^{-3}$. Therefore, the calculated values of probability of failure and reliability indices for joint and system are in accepted range [17].

Sensitivity analysis performed for random variables appearing in limit state function based on Miner-Palmgren damage model (Table 7). The sensitivity factors for Miner-Palmgren damage index $\alpha_{\Delta}$ and fatigue strength coefficient $\alpha_A$ are negative hence, they are resistance variables and contribute to the resistance part of the limit state function. Sensitivity factor for stress modeling error or response uncertainty factor $\alpha_B$ is positive thus, it will contribute to load part of the limit state function. Therefore, an increase in Miner-Palmgren damage index and fatigue-strength coefficient will enhance the reliability of tendon. On the contrary, an increase in stress modeling error will reduce the reliability of TLP tendon. Furthermore, out of the two resistance variables, reliability is more sensitive to fatigue strength than Miner-Palmgren damage index.

| Service life (years) | Monte Carlo $\beta$ | $P_f$ | FORM $\beta$ | $P_f$ | SORM $\beta$ | $P_f$ |
|---------------------|---------------------|-------|--------------|-------|---------------|-------|
| 20                  | 4.26489             | 1.00E-05 | 4.62554 | 1.87E-06 | 4.65572 | 1.61E-06 |
| 25                  | 4.10748             | 2.00E-05 | 4.38029 | 5.93E-06 | 4.40615 | 5.26E-06 |
| 30                  | 4.01281             | 3.00E-05 | 4.17645 | 1.48E-05 | 4.1987 | 1.34E-05 |
| 35                  | 3.84613             | 6.00E-05 | 4.00267 | 3.13E-05 | 4.02188 | 2.89E-05 |

| Table 6. Values of $\beta$ and $P_f$ for different service lives |
|---------------------|-----------------|
| Joint               | System          |
| $\beta$             | $P_f$           |
| 4.62554             | 1.87E-06        |
| 3.79                | 7.48E-05        |

Figure 4: Effect of service life on Probability of failure

| Table 7. Sensitivity factors |
|-----------------------------|
| Sensitivity factor | $\alpha_{\Delta}$ | $\alpha_B$ | $\alpha_A$ |

4 References
[1] Chatterjee PC, Das PK, Faulkner D. (1997). A hydrostructural analysis program for TLPs. Ocean Engineering; 24(4):313–34.
[2] Lotsberg I. (1991). Probabilistic design of the tethers of a tension leg platform. J Offshore Mech Arctic Eng.; 113:162–9.
[3] Banon H, Harding SJ. A methodology for assessing the reliability of TLP tethers under maximum and minimum lifetime load. Proceedings of the fifth international conference [4] Amanullah M, Siddiqui NA, Umar A, Abbas H. (2002). Fatigue reliability analysis of welded joints of a TLP tether system. International Journal of Steel and Composite Structure. 2(5):331–54.
[5] Khan RA, Siddiqui, N.A., Ahmad, Suhail, (2006), Reliability Analysis of TLP tether under Impulsive Loading, Reliability Engineering and System Safety 91 73-83.
[6] Siddiqui, N.A., Ahmad, Suhail, (2001). Fatigue and fracture reliability of TLP tethers under random loading. Marine Structure. 14, 331–352.
[7] Gerhard E., 2005. Assessment of existing offshore structures for life extension, Doctoral Thesis, University of Stavanger.
[8] Golafshani, A.A., Gholizad, A., (2009). Friction damper for vibration control in offshore steel jacket platforms. J. Constr. Steel Res. 65 (1). January, Elsevier.
[9] Tabeshpour MR, Ahmadi A, Malayjerdi E., (2018). Investigation of TLP behavior under tendon damage. Ocean Engineering 156, 580-595
[10] Wirsching PH. 1984. Fatigue reliability for offshore structures. J. Struct Div ASCE; 110(10): 2340-56.
[11] Siddiqui, N.A., and Ahmad, S., (2000). Reliability analysis against progressive failure of TLP tethers in extreme tension, Reliability Engineering and System Safety, Vol. 16, pp. 195–205.
[12] Mazaheri, S., Haji Valiei, F., (2012). Wave Atlas Preparation for Persian Gulf, Oman Sea and Caspian Sea, Iranian Institute of Oceanography and Atmospheric Science.
[13] Golshani, A.A., Chegini, V., Taebi, S., (2005), Analysis of extreme wave and wind with different directions for Caspian Sea, Persian Gulf and Oman, Technical report, Tehran, Iran.
[14] Tan S., and Gie, (1981). The wave induced motion of a tension leg platform in deep water, 13th annual OTC Houston, USA.
[15] Mahmoodi, M.R. (2017) Stability and dynamic response of tension leg platform in damaged condition (tendon removed) (experimental and numerical). Master thesis, Sharif University of Technology. Iran.
[16] Mahsuli, M., (2012). Probabilistic models, methods, and software for evaluating risk to civil infrastructure. Doctoral thesis, University of British Columbia.
[17] DNV Classification Notes 30.6, (1992), Structural Reliability Analysis of Marine Structures.