

Postulated Tendon Failure of Offshore Triceratops

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Abstract

Offshore triceratops is one of the successful manifestations of the form-dominant design approaches deployable in ultra-deepwater oil and gas exploration. The deck's geometric shape and partial isolation from the legs counteract lateral loads. Legs are position-restrained to the sea bed by taut-moored tendons, while ball joints partially isolate the deck from the buoyant legs. However, compliance in the horizontal plane imposes large displacements, intuiting the necessity to examine tendon failure. Numerical analysis of triceratops under wave and wind combined action is carried out under the postulated conditions of a tendon failure. 10-yr, 100-yr, and 1 000-yr post-Katrina hurricane conditions are assumed as loading to the platform. Results confirm a marginal increase in the natural periods of stiff degrees of freedom even under postulated failure conditions, ensuring good adaptability to ultra-deep water. Under postulated failure, the tension of adjacent tendons varies significantly, causing a shift to the mean position of the platform. Fatigue life is significantly reduced under the postulated failure of tendons, making the platform free-floating without affecting its stability. Results also show that the pitch response of the deck is a clear manifestation of the postulated failure, which is otherwise absent due to the presence of ball joints. The attempted study deliberates on the fatigue life of tendons, assessing the platform's suitability to ultra-deep waters and identifying the vulnerable legs for the chosen load combinations.

Keywords Ball joints; Tendons; Buoyant legs; Fatigue life; Irregular waves; Postulated failure

1 Introduction

Due to the increase in the severity of the environmental loads acting on offshore platforms commissioned in greater water depths, their geometric form attracts special attention (Halkyard et al., 1991; Perryman et al., 1995; Shaver et al., 2001; Liu et al., 2022; Zou et al., 2023). Offshore triceratops has better motion characteristics to sustain loads from harsh environments (White et al., 2005; Chandrasekaran et al., 2013). Ball joints between the deck and legs make the platform novel, addressing the scarcity in the literature studies (Chandrasekaran and Seeram, 2015;

Chandrasekaran and Nannaware, 2014). The Leg's translational displacements are transferred to the deck through ball joints. In contrast, their rotational displacements are isolated, indicating a rigid body motion in the vertical plane (Chandrasekaran and Nagavinothini, 2019). Triceratops resembles spar platform and TLP for their deep-draft and positively-buoyant characteristics (Chandrasekaran and Nagavinothini, 2018; 2020; Nagavinothini and Chandrasekaran, 2019; 2020). Excess buoyancy is counteracted by imposing pretension to tendons. Experimental investigations also confirmed a higher degree of compliance in the horizontal plane (Chandrasekaran and Madhuri, 2015). Motion stability and installation issues are addressed by providing additional stiffeners in the legs (Chandrasekaran et al., 2015). A postulated failure is defined as an intended failure caused on the platform. The postulated failure cases help examine the efficiency of the system without any physical damage to the model. The fundamental assumption is that the failure alone occurs in the platform; the other failures have no cumulative effect on the system. Under postulated failure of tendons, fatigue assessment becomes important to classify the service life of taut moored compliant platforms (Chandrasekaran and Rao, 2019; Chandrasekaran et al., 2021; Cheng et al., 2021; Kim and Zhang, 2009; Tabeshpour et al., 2018; Qi et al., 2019; Ren et al., 2022; Yu et al., 2019; Chen et al., 2022). The ANSYS AQWA com-

Article Highlights

- Offshore triceratops under the combined action of wind, wave and currents are studied for ultra-deep-waters with different heading angles.
- Postulated failure conditions of tendons are examined.
- Under intact and postulated failure conditions, the equilibrium positions of the platform are studied. Further the dynamic response of the deck and legs are examined.
- Also included the fatigue life of the tendons under the each leg.

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mercial software is well established and widely used software package specifically designed for the analysis of offshore structures, including floating platforms (Zhu et al., 2021; Li et al., 2021; Chen et al., 2022; Liu et al., 2022; Zou et al., 2023) is used for the numerical simulations in the present study. The major objective of the current study is to examine its performance under the postulated failure condition of the tendons through time history responses and phase plots in the active degrees of freedom. Additionally the fatigue life of the tendons is calculated using S-N curve approach in both intact and postulated failure conditions.

2 Numerical model of the offshore triceratops

The geometric details of the platform proposed by Chandrasekaran and Nagavinothini (2018) are considered for the present study. The legs are modelled as tubular elements (Morison elements, $D/L < 0.2$) and their self-weight is computed by program control. The ballast load is applied as a point mass to lower the vertical CG of the legs by -112.74 m, and the forces acting on the legs are calculated by using the Morison equation:

$$q_n = \frac{1}{2} \rho C_d dA (v_n - \dot{x}_n) |v_n - \dot{x}_n| + \rho dV a_n + (C_m - 1) \rho dV (a_n - \ddot{x}_n) \quad (1)$$

where C_d , C_m represents the drag and inertia coefficients; v_n and a_n are water particle velocity and acceleration; $\ddot{x}_n$, $\dot{x}_n$ are structure's acceleration and velocity; ρ is the density of seawater; dA and dV are exposed area and displaced volume per unit length, respectively. The deck weight and payload are applied as a point mass at CG. Tubular tendons are connected to the legs for position-restraining. The convolution integration technique solves the following equation of motion in ANSYS AQWA to obtain the response history in all degrees of freedom.

$$[M + M_a] \ddot{x}(t) + C \dot{x}(t) + Kx(t) = F(t) \quad (2)$$

where $\ddot{x}(t)$, $\dot{x}(t)$, $x(t)$ and $F(t)$ are acceleration, velocity, displacement, and force vectors; M and M_a are the structural mass and added mass matrices; C is the damping matrix; and K is the stiffness matrix. The geometric details of the platform and tubular tendons are shown in Table 1 and Table 2, respectively. Figure 1 and Figure 2 show the plan view and numerical model of the platform. Steel tubes are used as tendons as the inner core is useful for a fluid flow conduit (American Petroleum Institute, 2010). The arrangement of tendons to the legs is shown in Figure 3, amongst which (T_9 , T_{11}) of leg-3 are considered for postulated failure conditions.

Table 1 Geometric details

Geometric details	Value
C/C distance of legs (m)	61.77
Diameter of leg (m)	15.0
Freeboard (m)	20.24
Draft (m)	154.0
Tendon length (m)	2 246.0
Water depth (m)	2 400.0
Self-weight+payload (MN)	562
Buoyancy force (MN)	821
Total pretension (MN)	259

Table 2 Tendon details

Description	Quantity
Total number of tendons	12
Leg-1, leg-2, and leg-3	Tendons 1-2-3-4, tendons 5-6-7-8 and tendons 9-10-11-12
Outer diameter of tendon (m)	1.29
Thickness of tendon (m)	0.043
Total elements	250
Stiffness of tendon (MN/m)	15.8
Length of each element (m)	8.89
Grade of steel	X65
Yield strength (MPa)	450
Tensile strength (MPa)	535
Postulated failure tendons	Tendon 9, 11 under leg-3

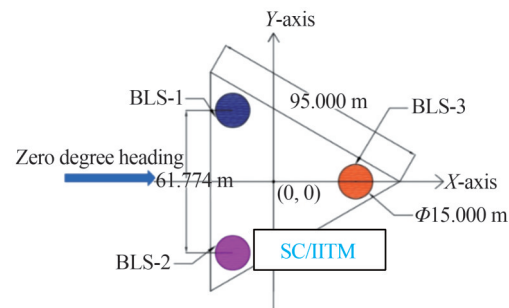


Figure 1 Plan view of the platform

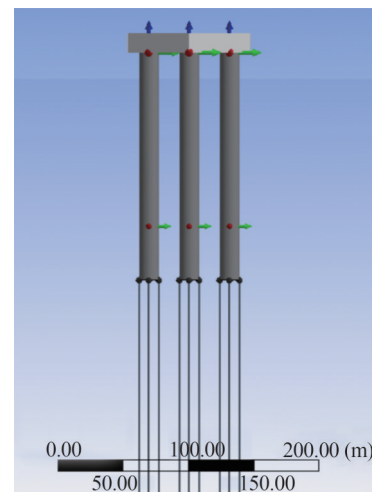


Figure 2 Numerical model

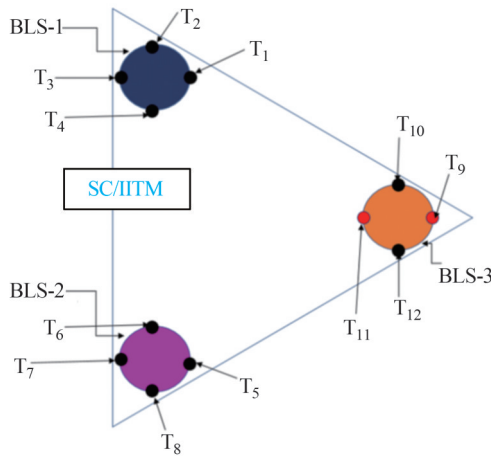


Figure 3 Tendon connections to each leg

3 Environmental loads

A 10-year, 100-year, and 1 000-year return period of hurricanes in the region of the Gulf of Mexico is considered in the present study (Yang and Kim, 2010). The critical sea state conditions lead to the dynamic tension variation in the tendons and are defined as load cases-A, B and C, as shown in Table 3. The present study assumes the wind, wave, and current are colinear and concurrent.

Table 3 Characteristics of sea state

Load case (LC)	Return period	H_s (m)	T_p (s)	γ	Wind (m/s)	Depth (m)	Current (m/s)
A	10-year	10	13	2.2	33	0	1.32
						-34.99	0.99
						-69.31	0
						-2 400	0
B	100-year	15.1	15.1	2.2	48	0	1.8
						-49.98	1.35
						-100.79	0
						-2 400	0
C	1 000-year	18.81	16.95	2.2	60	0	2.25
						-63.00	1.69
						-126.00	0
						-2 400	0

The API wind spectrum is useful for defining offshore structures' wind loads (Chandrasekaran et al., 2022) due to higher energy availability under low frequencies. Figure 4 shows the spectral plot.

$$S(f) = \frac{\sigma(Z)^2}{f} S(\tilde{f}) \quad (3)$$

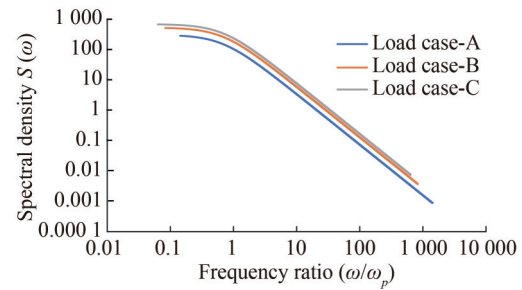


Figure 4 Wind spectral plots for different load cases

$$S(\tilde{f}) = \frac{(\tilde{f})}{(1 + 1.5\tilde{f})^{\frac{5}{3}}} \quad (4)$$

$$(\tilde{f}) = \frac{f}{f_p} \quad (5)$$

$$f_p = 0.025 \frac{\bar{V}_Z}{Z} \quad (6)$$

where $\bar{V}_Z$ is the mean speed duration 1 hour at the height Z (m); f and f_p are in Hz. Wind force coefficients are assigned as follows:

$$F_w = \frac{1}{2} \rho_{\text{air}} C_D v^2 A \cos(\theta) \quad (7)$$

where ρ_{air} is density of air ($=1.25 \text{ kg/m}^3$), C_D is drag coefficient $=1.2$, A is projected area ($=95 \times 15 \text{ m}^2$ for deck and $15 \times 20.24 \text{ m}^2$ for legs). The total aerodynamic load on the deck and the legs is calculated with respect to mean sea level and summarized in Table 4.

JONSWAP spectrum (Figure 5) depending on the fetch and wind speed is used for wave load and given below:

$$S(\omega) = \frac{\alpha g^2 \gamma^a}{\omega^5} e^{-\left(\frac{5\omega_p^4}{4\omega^4}\right)} \quad (8)$$

ω_p is the peak frequency in rad/s, γ is the peak enhancement factor and α is a constant that relates to the wind speed and the peak frequency of the wave spectrum

$$a = \exp \left\{ -\frac{(\omega - \omega_p)^2}{2\sigma^2 \omega_p^2} \right\} \quad (9)$$

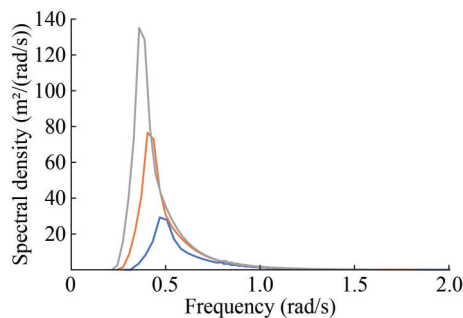
$$\sigma = \begin{cases} 0.07 & \text{for } \omega \leq \omega_p \\ 0.09 & \text{for } \omega > \omega_p \end{cases} \quad (10)$$

Because α is a constant, the integration of this spectrum can be expressed as below:

$$M_0 = \int_0^\infty S(\omega) d\omega = \alpha \int_0^\infty \frac{\alpha g^2 \gamma^a}{\omega^5} e^{-\left(\frac{5\omega_p^4}{4\omega^4}\right)} d\omega = \left\{ \frac{H_s}{4} \right\}^2 \quad (11)$$

Table 4 Wind force coefficients

Direction	Structure	Surge (N/(m/s) ²)	Sway (N/(m/s) ²)	Roll (N·m/(m/s) ²)	Pitch (N·m/(m/s) ²)
0°	Deck	1 029.42	0	0	1 822.07
	Legs	219.32	0	0	388.19
30°	Deck	891.5	514.7	-911	1 577.95
	Legs	189.93	109.66	-194	336.17
60°	Deck	514.71	891.5	-1 577.95	911.03
	Legs	109.66	189.93	-336.17	194.09
90°	Deck	0	1 029.42	-1 822.07	0
	Legs	0	219.32	-388.19	0
120°	Deck	-514.71	891.5	-1 577.95	-911.03
	Legs	-109.66	189.93	-336.17	-194.09
150°	Deck	-891.5	514.71	-911.03	-1 577.95
	Legs	-189.93	109.66	-194.09	-336.17

**Figure 5** Wave Spectral plots for different load cases

In the present study, current is considered a three-point profile, i.e., surface speed, the speed at the midpoint, and zero speed at a depth of 40% to 80% of the draft for all three load cases. Free oscillation tests are conducted to estimate damping using the logarithmic decrement method. The natural periods and damping ratios of the platform under intact tendon condition is compared with Chandrasekaran and Nagavinothini (2018) for validation and summarized in Table 5.

4 Results and discussions of the deck and legs under intact and postulated failure conditions

Table 6 indicates the tendon tension variation for different heading angles under load case-C. For a heading angle of 0°, the maximum tendon tension variation is approximately 39.5 MN for tendons T_9 and T_{11} under leg-3. Regarding heading angles 120° and 150°, the maximum tension variation occurs for tendons T_1 and T_3 under leg-1, measuring about 38.9 MN and 39.4 MN, respectively. Based on these findings, it can be concluded that the tendons under leg-3 are more critical for a heading angle of 0° than other heading angles.

The numerical analysis is carried out for intact and postulated failure of tendons under the combined wind, wave, and current. In the present study, the tendons (9, 11) in leg-3

are selected as postulated failure tendons due to subjecting of more tendon tension force by their geometric location. The AQWA-LIBRIUM is used to assess the equilibrium position of the platform under intact and postulated failure conditions. The static stability is assessed through an eigenvalue analysis of the global stiffness matrix at equilibrium. The global stiffness matrix is non-linear and comprises of terms arising from the hydrostatic pressure, tendon tension and stiffness due to the heading variation in wind, current and wave drifting forces and moments. In each step of the iterative solver, $\mathbf{K}$, $\mathbf{F}$ are updated to determine the static equilibrium position:

$$\mathbf{X}_{j+1} = \mathbf{X}_j + \mathbf{K}^{-1}(\mathbf{X}_j)\mathbf{F}(\mathbf{X}_j) \quad (12)$$

$\mathbf{X}_j$ is the position of the body in each degree of freedom (DOF), $\mathbf{K}$ is the stiffness matrix of the system, and $\mathbf{F}$ is the force matrix. The above equation is under program control to get precise equilibrium positions of the bodies and extracts the eigenvalues of the linearized stiffness matrix at equilibrium by the standard Jacobi successive rotation method.

$$\mathbf{K}\mathbf{X} - \lambda\mathbf{X} = 0 \quad (13)$$

While the positive eigenvalues (λ) imply stable equilibrium, negative and zero eigenvalues imply unstable and neutral stability. Table 7 shows the equilibrium positions of the legs and deck for intact and postulated failure conditions. Due to the postulated failure of tendons (9, 11) in leg-3, the equilibrium position of deck and L-3 are shifted from 27.74 m to 28.45 m and -112.74 m to -111.17 m in heave degree, respectively. The differential heave motion in legs leads to the deck's pitch mean position from 0° to -1.4°. The corresponding hydrostatic parameters computed from the diffraction analysis are summarized in Table 8.

Table 9 shows the natural periods of the deck under intact and postulated failure of tendons. It is observed that the natural surge periods in both conditions are marginally different. The heave and pitch periods increase under postulated failure due to a decrease in the tendon stiffness.

Table 5 Natural periods

Active-degrees-of-freedom	Intact condition (Present study)		Chandrasekaran and Nagavinothini (2018)	
	Natural periods (s)	Damping ratio (%)	Natural periods (s)	Damping ratio (%)
Surge	221.4	5.38	215	5.14
Sway	222.3	5.16	215.4	5.03
Heave	3.45	0.58	4.3	0.51
Roll	4.1	6.4	6.2	6.23
Pitch	4.3	6.28	6.1	6.08
Yaw	219.7	5.9	215.9	5.68

Table 6 Tendons tension variation for different heading angles under LC-C

Heading angle	Statistics	Tether tension under each leg (MN)											
		Leg-1				Leg-2				Leg-3			
		T ₁	T ₂	T ₃	T ₄	T ₅	T ₆	T ₇	T ₈	T ₉	T ₁₀	T ₁₁	T ₁₂
0°	Max	38.8	38.7	38.8	38.7	38.8	38.7	38.8	38.7	39.5	39.3	39.5	39.3
	Min	12.6	12.5	12.6	12.5	12.6	12.5	12.6	12.5	14.8	13.7	14.6	13.8
30°	Max	37.5	37.4	37.5	37.4	37.5	37.4	37.5	37.4	38.6	38.4	38.6	38.4
	Min	12.1	11.9	12.1	11.9	12.1	11.9	12.1	11.9	12.2	11.8	12.2	11.8
60°	Max	37.9	37.8	37.9	37.8	37.9	37.8	37.9	37.8	38.7	38.3	38.7	38.3
	Min	13.5	12.9	13.6	12.9	13.5	12.9	13.6	12.9	10.6	11.9	10.4	11.4
90°	Max	37.4	37.3	37.4	37.3	38.2	38.1	38.2	38.1	38.3	38.1	38.3	38.1
	Min	10.2	9.9	10.2	9.9	9.4	8.7	9.4	8.7	8.3	8.9	8.3	8.9
120°	Max	38.9	38.8	38.9	38.8	38.7	38.6	38.7	38.6	38.8	38.7	38.8	38.7
	Min	13.4	12.7	13.4	12.7	12.9	12.8	12.9	12.8	13.4	13.1	13.4	13.1
150°	Max	39.4	39.3	39.4	39.3	39.1	39.0	39.1	39.0	39.3	39.2	39.3	39.2
	Min	13.1	12.8	13.1	12.8	12.2	12.4	12.2	12.4	13.7	12.9	13.4	12.9

Table 7 Equilibrium position under intact and postulated failure condition of tendons

DOF	Deck		Buoyant leg, L-1		Buoyant leg, L-2		Buoyant leg, L-3 (Tendons postulated failure leg)	
	Intact	Postulated failure	Intact	Postulated failure	Intact	Postulated failure	Intact	Postulated failure
Surge (m)	0	−0.18	−17.83	−17.83	−17.831	−17.829	35.66	35.66
Sway (m)	0	0	30.88	30.88	−30.88	−30.88	0	0
Heave (m)	27.74	28.45	−112.74	−112.74	−112.74	−112.74	−112.74	−111.17
Roll (°)	0	0	0	0	0	0	0	0
Pitch (°)	0	−1.4	0	0	0	0	0	0
Yaw (°)	0	0	0	0	0	0	0	0

Table 8 Hydrostatic parameters of buoyant legs

Description	Value
Hydrostatic heave stiffness (MN/m)	1.8
Hydrostatic roll stiffness (MN·m/(°))	171
Hydrostatic pitch stiffness (MN·m/(°))	171
Cut water plane area (m ²)	176.7
I_x, I_y (m ⁴)	2 485.1, 2 485.0
Distance from CoG to CoB (m)	−35.74
Metacentric height GM _x , GM _y (m)	35.83, 35.83
Distance from CoB to Metacentre BM _x , BM _y (m)	0.09, 0.09

Table 9 Natural periods in intact and postulated failure condition of tendons

DOF	Intact condition			Postulated failure condition		
	Natural periods (s)	Natural frequency (rad/s)	Damping ratio (%)	Natural Periods (s)	Natural frequency (rad/s)	Damping ratio (%)
Surge	221.4	0.028 3	5.38	228.6	0.027 48	5.14
Sway	222.3	0.028 2	5.16	229.0	0.027 4	5.03
Heave	3.45	1.821 2	0.58	3.7	1.698 1	0.51
Roll	4.1	1.532 4	6.4	4.89	1.284 9	6.23
Pitch	4.3	1.402 4	6.28	5.51	1.140 3	6.08
Yaw	219.7	0.028 5	5.9	227.4	0.027 63	5.68

The heave damping ratio is significantly low compared to other degrees of freedom by its geometric configuration. It is important to note that triceratops is stiff in heave degree by its geometry, and hence damping provided by geometry is lower. The time response analysis is carried out under all three load cases (wind+wave+current) with a heading angle of 0° , 30° , 60° , 90° , 120° , and 150° for a water depth of 2400 m with a freeboard of 20.24 m. The simulation time taken for the analysis is 2000 s with a time step of 0.1 s.

In the present study, the response plots of the deck are drawn for load case-C under 0° and 60° heading angles. The legs and deck responses for all load cases of 0° , 30° , 60° , 90° , 120° , and 150° are tabulated in Table 13 to Table 20, respectively. Time history and the phase plots of the platform deck are plotted for a heading angle of 0° and 60° under loading condition C. Figure 6 shows deck phase plots for the 60° under the intact and postulated failure of tendons. It is seen that the surge and sway mean shifted from 41.54 m to 44.8 m and 64.2 m to 68.9 m, respectively; the mean heave displacement is increased to 0.55 m. A significant shift in the pitch mean (-4.5°) is also noticed under the postulated failure of tendons. A mean shift in the yaw response from negative to positive under the intact and postulated failure conditions (-6.9° to 10.2°) is also observed.

Figure 7 demonstrates the time response of the deck for 0° heading under the intact and postulate failure of chosen tendons. The maximum offset of the deck is 79.4 m and 84.5 m, which is about 3.3% and 3.5% of the water depth, and the set down is 3.04 m to 4.12 m, respectively. Due to the platform surge and coupled heave motion, tether tension variation is caused. Under the imbalanced tension in each leg, differential heave sets-in, resulting in pitch motion. The maximum pitch response is about 1.8° under the postulated failure condition of tendons. The power spectral density (PSD) plots for 0° heading under load case-C in intact and postulated failure conditions are shown in Figure 8. The maximum surge PSD in intact and postulated failure conditions are $4800 \text{ m}^2/\text{s}$ and $5400 \text{ m}^2/\text{s}$. The maximum heave PSD peaks are noticed at the frequencies of 1.9 rad/s and 1.78 rad/s, respectively, under intact and postulated failure conditions of tendons due to the heave natural frequencies of 1.82 rad/s and 1.7 rad/s. The maximum heave amplitudes are about $5 \text{ m}^2/\text{s}$ and $5.9 \text{ m}^2/\text{s}$ for intact and postulated failure conditions. The first maximum heave peaks are observed within the frequency band of 0.02 to 0.03 rad/s, closely aligned with the surge natural frequency. This observation suggests a high coupling between surge and heave. Under the intact condition, the maximum pitch peak amplitude is about $0.9 (\text{m}^2/\text{s})$, and the corresponding frequency is about 1.42 rad/s. Also noticed a significant increase in pitch peak amplitude of $6 (\text{m}^2/\text{s})$ at the frequency of 1.16 rad/s under postulated failure condition. In both conditions, the maximum pitch peaks are observed nearer to the pitch natural frequencies. Smaller peaks are noticed

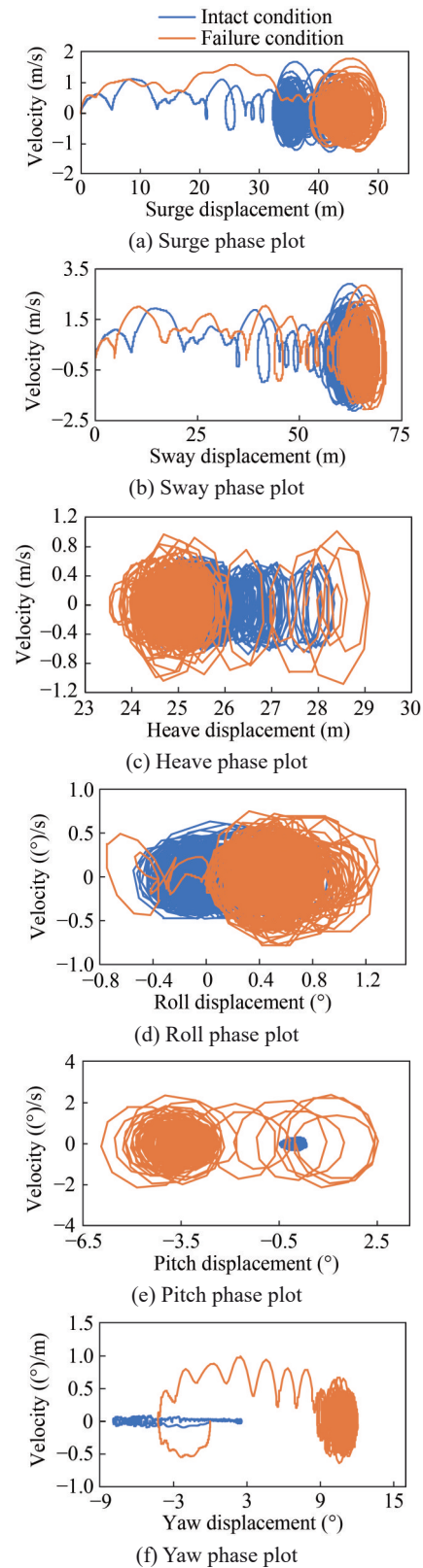


Figure 6 Phase plots for 60° heading under intact and postulated failure condition of tendons for LC-C

for surge, heave and pitch PSDs around the frequency of 0.4 rad/s, close to the forcing frequency of 0.37 rad/s. The

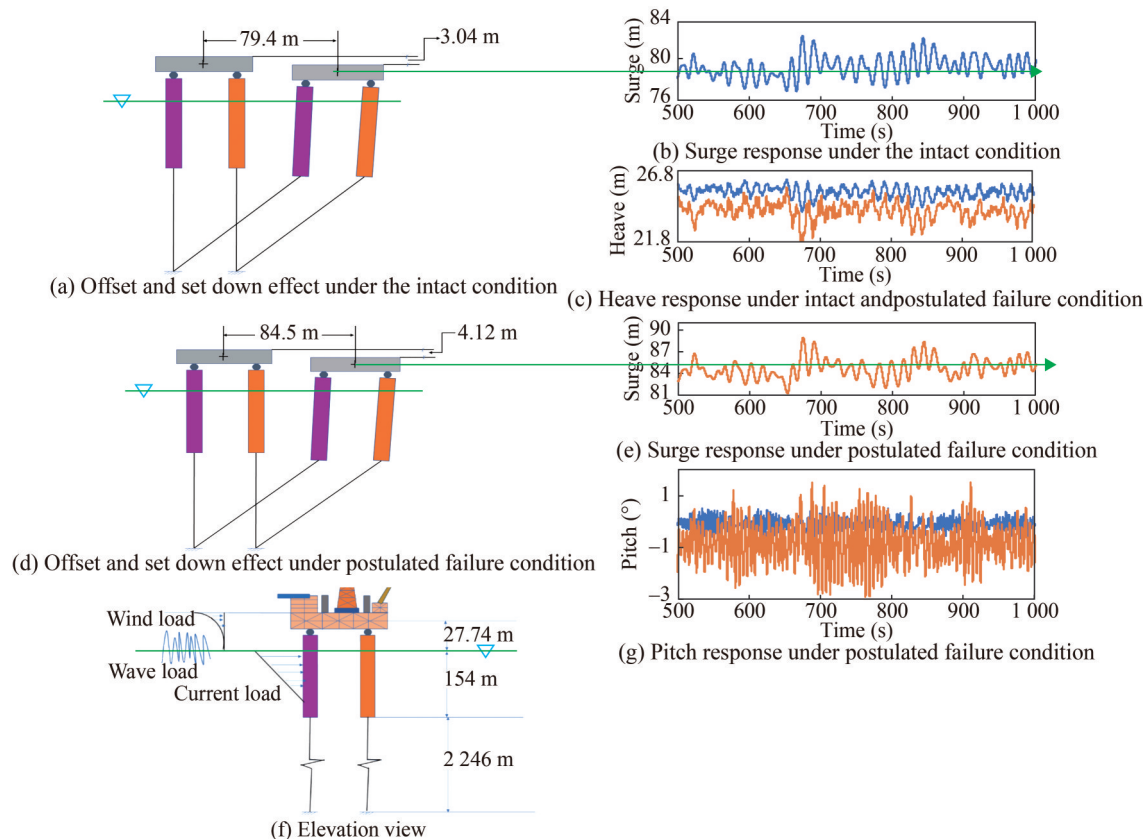


Figure 7 Deck responses for 0° heading under the intact and postulated failure condition of tendons for LC-C

smaller peaks are also noticed for postulated failure conditions in both heave and pitch PSDs due to the sudden change in the tendon tension.

Figure 9 illustrates the shifting of the deck heave mean position under load case-C for different heading angles with respect to the heave equilibrium position under intact and postulated failure conditions. The maximum and minimum difference in heave mean shift for intact and postulated failure conditions is about 0.85 m and 0.3 m under a heading angle of 150° and 0°, respectively. Table 13 shows the deck responses for all the load cases for 0°, 30°, 60°, 90°, 120°, and 150° under intact and postulated failure. For 30°, the maximum surge response for load case-1, 2, 3 is 26 m, 46 m, 66 m, 28.8 m, 51.2 m, and 72.8 m, respectively. In terms of water depth, it is about 1.08%, 1.91%, 2.75%; 1.2%, 2.13%, 3.03%, respectively. For 120° heading, the minimum surge response is -16.04 m, -29.96 m, -44.0 m, and -18.75 m, -34.9 m, -49.02 m. In terms of water depth, it is about 0.66%, 1.24%, 1.8% and 0.78%, 1.45%, 2.04% of water depth, respectively.

The dynamic responses of the legs are measured from their static equilibrium positions in all six degrees of freedom. The surge response of the legs-1, 2, 3 is measured from -17.831 4 m, -17.831 4 m, and 35.663 m along the surge axis, as shown in Table 7. Tables 15–20 show the legs' responses under all three load cases with a heading angle of 0°, 30°, 60°, 90°, 120°, and 150° for intact and

postulated failure condition of tendons. It's noticed that the max surge response of L-3 under 0° heading for a load case-C is about 114.8 m and 124.8 m, respectively, in intact and failure conditions of tendons. It shows that the deck and legs are monolithic in the translational degree of freedom. The maximum pitch response of the legs under 0° heading for a load case-C in the intact and postulated failure condition of tendons is 4.18° and 5.96°, respectively; therefore, the deck and the legs undergo different rotations due to the presence of ball joints. The sway response is activated for other than 0° heading angles. The maximum sway responses are about 79.8 m and 81.4 m, respectively, from its static equilibrium position for a load case-C with 90° heading under intact and postulated failure condition of tendons. The maximum yaw response of L-3 is about 8.2° for a heading angle of 60° under load case-C in the postulated failure condition of tendons.

5 Dynamic tension variation in tendons

The tension variation of tendons under load case-C with 0° heading is shown in Figure 10. Under the intact condition, the mean tension of tendon-3 and tendon-7 of leg-2 and leg-3 are 22.7 MN. While the mean tension of tendon-3 remains the same, tension of tendon-10 under leg-3 is in-

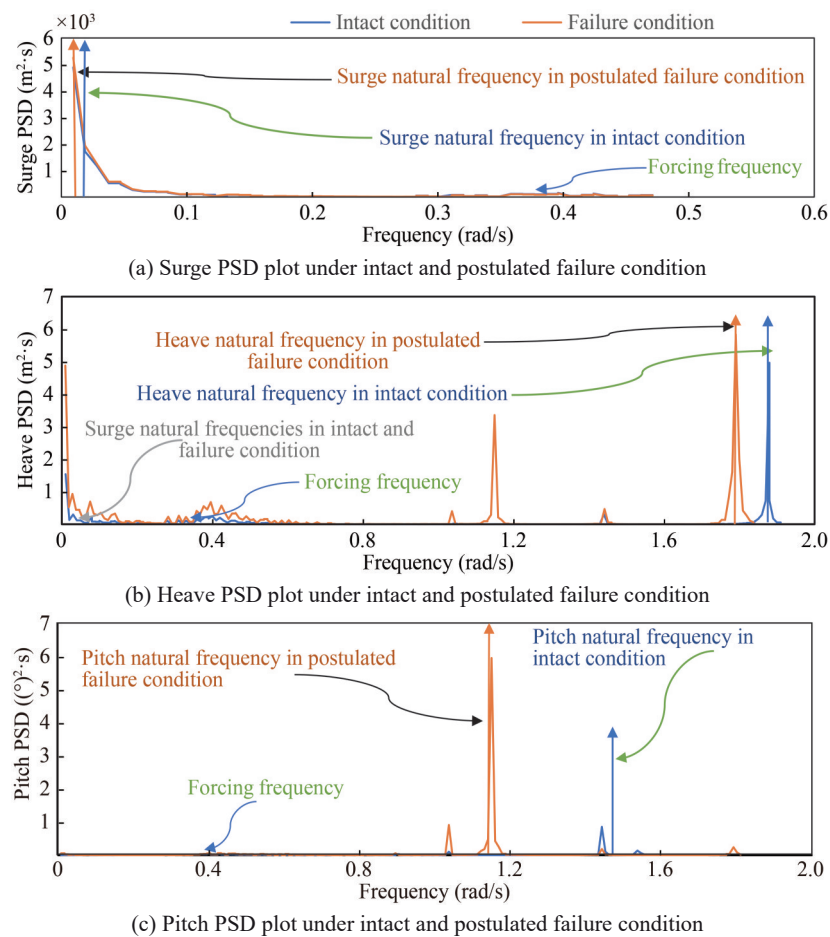


Figure 8 PSD plots for 0° heading under intact and postulated failure condition for LC-C

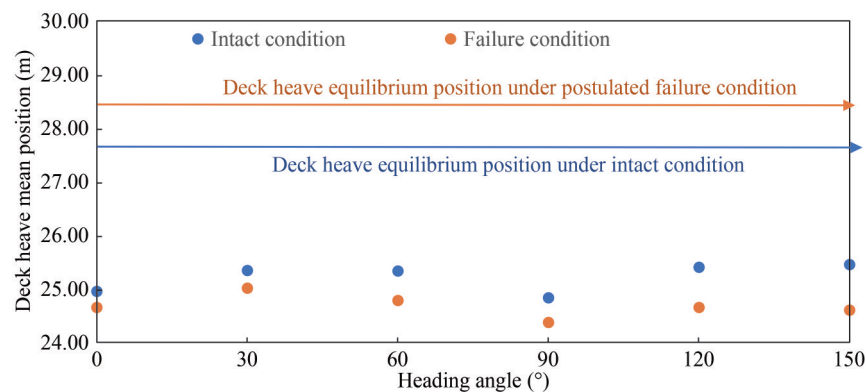


Figure 9 Deck heave mean position under different heading angles for load case-C in intact and postulated failure conditions

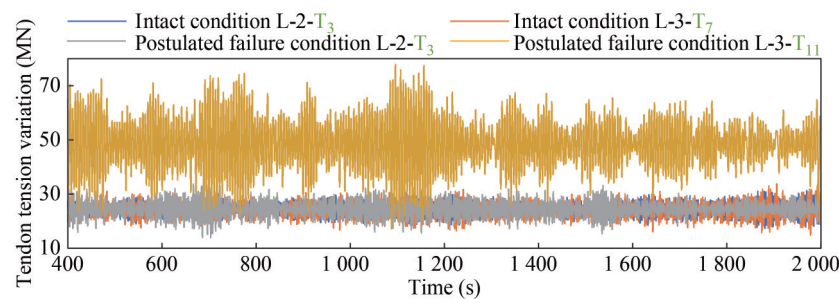


Figure 10 Tendon tension variation under the intact and postulated failed conditions of tendons

creased to 46 MN when tendons postulated failure resulting in a significant shift of mean tension variation. Table 10 shows the stress range variation under intact and postulated failure conditions of tendons for all load cases with 0°, 30°, 60°, 90°, 120°, and 150°. It is noticed that the maximum stress is observed under the 0° heading for all load cases in both intact and postulated failure conditions of tendons. Table 11 represents the percentage increase in stress for adjacent tendons under L-3 for postulated failure conditions in all heading angles. It is seen that for 0° and 120° heading angles, the maximum percentage increase in stress of about 95.7% and 73.3%, respectively.

Table 10 Tendons stress variation under Leg-3

Heading angle	Load case	Stress (N/mm ²)			
		Intact		Postulated failure	
		Max	Min	Max	Min
0°	LC-A	170.43	84.48	385.5	75.61
	LC-B	224.4	57.93	442.6	83.65
	LC-C	234.6	87.88	459.2	95.0
30°	LC-A	151.63	56.42	370.25	70.89
	LC-B	118.28	48.29	411.7	77.2
	LC-C	227.9	72.6	425.3	67.1
60°	LC-A	155.77	41.12	362.8	45.14
	LC-B	220.3	54.9	401.7	79.46
	LC-C	229.7	63.01	407.8	45.8
90°	LC-A	151.38	46.31	358.4	42.8
	LC-B	119.7	62.9	379.4	50.8
	LC-C	227.5	49.6	394.6	69.3
120°	LC-A	151.32	51.55	362.4	49.8
	LC-B	120.8	71.2	383.6	60.8
	LC-C	230.4	79.5	399.3	78.42
150°	LC-A	151.38	72.24	373.4	52.7
	LC-B	122.9	59.4	401.7	70.34
	LC-C	234.32	81.6	411.5	81.9

Table 11 The maximum increase in stress for adjacent tendons closer to the postulated failure tendons under L-3

Heading angle	Max increase in stress in adjacent tendons (%)
0°	95.7
30°	86.6
60°	77.53
90°	73.4
120°	73.3
150°	75.6

6 Fatigue life of tendons

Tendons, as they are under high initial pretension (taut-

moored), they are more susceptible to fatigue failure due to 1) platform drift under the action of wind, waves, and current, 2) variable submergence effect, and 3) vibration induced by vortex shedding. Tendons' fatigue life under the intact and damaged condition (tendons 9, 11 of leg-3) are investigated. The dynamic variation of pretension in the tendons makes the stress response a non-zero mean process that could not be used directly in S-N curves. Therefore, after obtaining the cycle ranges and averages, each cycle is converted into an equivalent stress range of zero-mean using the Goodman Diagram. The rain flow counting method suggested is used to find the stress ranges corresponding to the simulation time. The parameters for the S-N curve are chosen according to DNV-GL (2005). The corresponding number of cycles required to cause fatigue failure is computed using the S-N curve approach. For the slope of the bilinear curve, $m=3$, $\lg a=12.081$, and the horizontal axis ($\log N$ axis) intercept is valid up to a stress range of 103 MPa, after which slope changes to $m=5$, $\lg a=16.081$. The endurance limit is taken as 41.45 N/mm² at 10⁸ cycles. Palmgren-Miner's rule is applied as a correction factor to account for environmental loading conditions, and fatigue damage is estimated:

$$FD = \sum_{i=1}^m \frac{n_i}{N_i} \quad (14)$$

where n_i is the number of cycles per year for a given tension range interval and N_i is the cycles to failure under tension range ' i ' according to the S-N curve. In the present study, the fatigue life of tendons is calculated for 0° heading under all load cases in both intact and postulated failure tendons due to maximum stress variation compared to other heading angles is shown in Table 12. The fatigue life of tendons in leg-3 is lesser than legs-1, 2 under intact conditions by their geometry. The minimum fatigue life of 0.006 1 years and 4.28 years are observed under load case-C in the intact and postulated failure condition of tendons in leg-3; if the load case-C occurs for 0.006 1 years, the tendons in leg-3 fail catastrophically. A significant percentage reduction in fatigue life is noticed for tendons in leg-3 due to postulated failure of tendons (9, 11) in leg-3.

Table 12 Fatigue life of tendons under legs

Load case	Tendons under legs	Fatigue life under intact condition (Year)	Fatigue life under postulated failure condition (Year)	Reduction in fatigue life (%)
LC-A	L-1, 2	9.68	9.37	3.202
	L-3	8.93	0.529	94.076
LC-B	L-1, 2	6.71	6.28	6.408
	L-3	6.01	0.039	99.351
LC-C	L-1, 2	4.95	4.53	8.484
	L-3	4.28	0.0061	99.857

Table 13 Deck response under the intact conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	33.40	58.00	82.71	0.02	0.00	0.00	28.29	28.35	28.35	0.00	0.00	0.00	0.13	0.20	0.67	0.00	0.03	0.00
	Min	-0.16	0.00	0.00	-0.01	-0.23	0.00	25.60	25.40	23.80	0.00	-0.01	0.00	-0.11	0.31	-0.57	-0.04	-0.24	0.00
	Mean	29.84	52.00	79.10	0.00	-0.03	0.00	26.71	26.20	24.80	0.00	0.00	0.00	0.01	-0.01	0.09	-0.01	-0.03	0.00
	St. deviation	5.04	9.33	13.60	0.00	0.05	0.00	0.31	0.86	1.69	0.00	0.00	0.00	0.03	0.17	0.04	0.01	0.05	0.00
30°	Max	26.00	46.00	66.00	16.48	28.69	40.02	28.30	28.34	28.34	0.23	0.32	0.27	0.14	0.31	0.50	0.74	0.17	0.15
	Min	-0.22	0.00	0.00	-0.13	0.00	0.00	26.34	25.94	25.14	-0.24	-0.34	-0.41	-0.13	-0.21	-0.30	-1.70	-4.30	-4.36
	Mean	25.88	45.60	65.20	14.68	25.67	35.80	26.90	27.10	25.34	0.00	-0.02	-0.05	0.01	0.02	0.02	-0.46	-1.14	-1.87
	St. deviation	4.40	8.21	12.08	2.49	4.54	6.33	0.30	0.87	1.69	0.06	0.08	0.11	0.04	0.11	0.11	0.42	0.77	0.66
60°	Max	16.40	31.88	46.80	27.50	47.75	68.23	28.45	28.34	28.34	0.10	0.52	0.80	0.05	0.16	0.30	0.00	0.00	3.20
	Min	-0.19	0.00	0.00	-0.32	0.00	0.00	26.37	25.94	25.12	-0.08	-0.51	-0.56	-0.10	-0.34	-0.51	-2.24	-5.89	-8.26
	Mean	14.64	28.48	41.54	24.57	42.48	64.20	27.18	26.87	25.33	0.00	-0.06	-0.13	-0.02	-0.08	0.12	-1.89	-4.88	-6.93
	St. deviation	2.51	5.35	8.05	4.14	7.25	10.30	0.23	0.81	1.58	0.02	0.13	0.09	0.02	0.09	0.07	0.37	1.21	1.62
90°	Max	0.00	0.00	0.00	31.58	57.51	81.35	28.34	28.34	28.34	0.07	0.12	0.24	0.13	0.35	0.50	3.06	7.06	7.95
	Min	-0.64	-4.44	-7.00	0.00	0.00	0.00	25.62	25.50	23.84	-0.10	-0.60	-0.41	-0.11	-0.19	-0.13	-0.16	-0.11	-0.04
	Mean	-0.46	-3.18	-5.76	28.61	51.34	72.75	26.75	26.31	24.83	-0.02	-0.06	-0.08	0.01	0.06	0.17	1.66	4.07	6.33
	St. deviation	0.12	1.02	1.81	4.74	9.12	13.23	0.27	0.83	1.63	0.03	0.12	0.10	0.04	0.09	0.11	0.43	1.02	1.30
120°	Max	16.04	29.96	44.00	23.69	46.70	66.80	28.35	28.34	28.43	0.06	0.50	0.84	0.04	0.29	0.19	0.05	0.97	2.40
	Min	0.70	0.20	0.94	0.00	0.00	-0.58	26.33	25.89	25.20	-0.08	-0.60	-0.43	-0.04	-0.35	-0.12	-0.05	-0.34	-8.40
	Mean	14.56	26.64	42.50	25.12	45.28	63.20	26.91	26.10	25.40	-0.01	-0.04	0.12	-0.01	-0.02	-0.02	0.00	0.18	0.08
	St. deviation	2.41	4.78	7.10	4.16	8.11	12.47	0.28	0.87	1.85	0.02	0.13	0.31	0.01	0.07	0.05	0.02	0.29	0.05
150°	Max	0.00	0.00	0.61	16.08	29.41	44.18	28.30	28.30	28.31	0.11	0.32	0.40	0.08	0.49	0.40	0.58	0.17	0.68
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mean	-27.48	-47.20	-70.00	0.00	0.00	-0.35	26.35	26.03	25.30	-0.12	-0.35	-0.42	-0.10	-0.55	-0.48	-1.88	-5.07	-4.20
	St. deviation	-24.80	-42.40	-61.20	14.56	26.34	38.80	27.01	26.75	25.45	0.00	-0.01	0.01	0.00	-0.04	-0.08	-0.37	-1.46	-2.13

Table 14 Deck response under postulated failure conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	34.24	63.20	88.80	0.10	2.24	0.02	29.11	29.10	29.19	0.01	0.01	0.05	0.83	1.98	1.76	0.09	0.09	2.96
	Min	0.00	0.00	-0.72	-0.12	0.00	-0.11	23.59	23.46	22.89	0.00	0.00	-0.04	-1.90	-2.40	-2.98	-0.03	-0.06	0.00
	Mean	31.04	56.40	83.90	0.00	1.81	-0.01	26.80	26.40	24.65	0.00	0.12	0.00	-1.60	-1.69	-1.86	0.00	0.00	2.44
	St. deviation	5.10	10.03	14.27	0.04	0.49	0.03	0.39	1.05	1.87	0.00	0.16	0.02	0.59	1.08	0.83	0.02	0.02	0.41
	Max	28.88	51.20	72.80	20.20	39.17	55.19	29.12	29.08	29.04	0.54	1.96	1.73	0.89	2.58	2.78	9.46	11.60	11.21
30°	Min	-0.08	0.00	-0.64	0.00	0.00	-0.35	26.80	25.84	25.06	-0.12	-0.89	-0.42	-2.03	-3.13	-3.09	-0.19	-0.31	0.00
	Mean	23.52	40.80	57.60	18.28	35.08	49.13	26.89	26.30	25.01	277.00	0.58	0.75	-1.67	-1.72	-1.92	7.94	9.17	9.00
	St. deviation	3.56	6.57	9.80	3.26	6.78	9.34	0.36	0.95	1.71	0.10	0.35	0.35	0.59	1.13	0.84	1.62	1.66	1.37
	Max	19.40	35.80	50.12	29.48	55.76	72.50	29.24	29.11	29.12	0.28	1.89	1.12	1.23	2.23	2.57	6.37	10.37	12.08
	Min	-0.03	0.00	-0.02	0.00	0.00	-0.64	25.43	25.12	24.12	-0.15	-0.98	-0.77	-2.40	-3.32	-6.03	-0.32	-0.29	-4.80
60°	Mean	16.80	31.04	44.80	26.76	50.12	68.90	26.70	26.40	24.78	0.04	0.10	0.56	-1.61	-2.30	-3.20	2.97	7.80	10.20
	St. deviation	3.33	4.19	6.32	4.43	4.94	5.61	0.35	0.90	1.67	0.06	0.33	0.28	0.54	0.95	0.75	0.96	2.81	4.14
	Max	4.32	5.88	0.00	32.10	60.90	84.60	29.12	29.13	29.08	0.19	1.56	1.67	0.68	1.36	1.63	4.69	13.20	14.01
	Min	-0.38	-0.03	-3.67	0.00	0.00	0.00	23.61	23.50	22.92	-0.26	-1.17	-0.69	-3.42	-3.70	-3.28	-0.18	-0.39	-1.20
	Mean	3.40	2.76	-3.08	22.24	50.90	64.20	26.94	26.30	24.37	-0.05	-0.04	0.27	-1.49	-1.65	-2.03	3.10	9.40	10.80
90°	St. deviation	1.22	1.07	0.67	3.10	8.39	3.74	0.27	0.71	0.47	0.06	0.36	0.37	0.61	0.92	0.45	4.20	3.40	3.64
	Max	18.75	34.90	49.02	27.76	50.78	72.40	29.11	29.06	29.06	0.39	1.20	1.32	1.23	1.33	2.70	3.15	8.70	11.80
	Min	0.00	0.00	0.00	0.00	0.00	0.00	25.41	25.23	24.04	-0.24	-1.41	-0.70	-3.13	-4.35	-6.28	-1.23	-2.70	-4.17
	Mean	14.89	27.90	40.80	21.28	34.48	60.87	26.80	26.32	24.65	0.14	0.18	0.62	-1.80	-2.13	-3.70	2.80	7.40	11.38
	St. deviation	3.90	6.94	10.07	3.10	5.08	8.35	26.80	0.48	0.98	0.09	0.54	1.03	0.69	1.15	2.79	1.80	4.28	6.78
120°	Max	0.00	0.00	0.00	14.33	25.25	32.51	29.12	29.09	29.07	0.35	1.57	1.65	1.61	2.06	2.67	2.02	2.08	2.26
	Min	-21.92	-36.44	-45.60	0.00	0.00	0.00	25.23	25.04	24.19	-0.26	-1.21	-0.82	-3.40	-3.30	-3.73	-6.20	-7.46	-8.39
	Mean	-19.32	-29.60	-40.40	12.91	21.15	28.08	26.79	26.20	24.60	0.13	0.58	1.18	-1.80	-2.06	-2.80	-5.78	-6.61	-6.89
	St. deviation	2.63	4.24	5.25	1.93	3.22	4.14	0.29	0.46	0.62	0.09	0.40	0.39	0.82	0.73	0.67	1.92	3.16	3.15
	Max	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 15 Leg-1 responses under intact conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	21.7	43.8	114.8	-30.8	-30.9	-30.8	-112.1	-112.1	-112.1	0.0	0.0	0.0	2.2	3.6	4.5	0.1	0.0	0.0
	Min	-17.8	-17.8	35.7	-30.9	-31.3	-30.8	-114.2	-114.0	-116.0	0.0	0.0	0.0	-0.1	0.0	0.0	-0.1	-0.1	0.0
	Mean	18.9	38.6	109.8	-30.8	-30.9	-30.8	-113.2	-113.8	-115.4	0.0	0.0	0.0	1.6	2.7	3.4	0.0	0.0	0.0
	St. deviation	4.6	8.8	13.2	0.0	0.1	0.0	0.3	0.7	1.6	0.0	0.0	0.0	0.2	0.3	0.4	0.0	0.0	0.0
30°	Max	17.8	37.8	79.0	-13.2	0.7	11.2	-112.1	-112.1	-112.1	0.1	0.0	0.0	2.0	3.2	3.9	0.4	0.2	1.4
	Min	-17.8	-17.8	35.7	-30.8	-30.8	-30.8	-113.0	-114.2	-115.0	-1.1	-1.8	-2.3	-0.2	0.0	0.0	-0.6	1.2	-1.4
	Mean	15.4	33.1	72.4	-12.5	-2.4	8.9	-113.2	-113.5	-114.9	-0.8	-1.3	-1.6	1.4	2.3	3.0	0.0	-0.8	-0.3
	St. deviation	4.0	7.8	11.7	5.7	10.7	15.4	0.3	0.8	1.6	0.1	0.2	0.2	0.2	0.3	0.4	0.2	-0.1	0.5
60°	Max	2.30	14.075	52.080	-4.30	16.450	36.280	-112.0	-112.0	-112.0	0.27	0.00	0.00	1.18	1.75	2.20	0.64	0.12	0.00
	Min	-18.0	-17.80	35.660	-31.0	-30.90	-30.80	-113.0	-116.0	-117.74	-2.00	-3.16	-4.0	-0.16	0.00	0.00	-0.57	-2.28	-2.72
	Mean	-8.70	11.900	48.750	-3.40	12.800	32.890	-113.0	-113.5	-115.0	-1.40	-2.24	-2.83	0.82	1.24	1.54	0.04	-1.20	-1.76
	St. deviation	5.51	8.900	17.640	9.50	9.890	20.450	0.248	0.72	1.460	0.24	0.31	0.38	0.13	0.17	0.20	0.14	0.48	0.51
90°	Max	-17.4	-17.30	35.66	2.60	26.70	51.00	-112.0	-112.0	-112.00	0.00	0.00	0.00	0.06	0.17	0.23	0.31	1.96	2.33
	Min	-18.0	-25.50	19.16	30.80	-30.80	-30.40	-113.7	-114.0	-115.52	-2.04	-3.52	-4.44	-0.08	-0.11	-0.10	-0.24	-0.36	-0.24
	Mean	-18.0	-23.00	22.10	1.20	24.80	47.30	-113.0	-113.8	-114.69	-1.48	-2.51	-3.18	0.00	0.04	0.06	0.02	1.14	1.54
	St. deviation	0.22	2.08	4.33	10.80	21.40	24.50	0.22	0.715	1.490	0.21	0.34	0.42	0.02	0.04	0.06	0.08	0.47	0.56
120°	Max	-18.8	-17.80	35.80	-2.80	20.900	44.800	-112.0	-112.0	-112.00	0.00	0.00	0.26	0.00	0.00	0.15	0.54	1.28	1.59
	Min	-33.0	-47.9	-9.7	-30.8	-30.8	-31.2	-113	-114.6	-115.30	-1.76	-3.08	-4.40	-1.00	-1.68	-2.64	-0.52	-0.56	-0.84
	Mean	-29.8	-37.3	17.8	-18.6	15.96	37.5	-113.0	-114.0	-114.9	-1.32	-2.24	-2.96	-0.76	-1.28	-1.68	0.02	0.23	0.20
	St. deviation	5.5	11.25	17.15	9.6	19.13	30.15	0.23	0.76	1.720	0.17	0.28	0.41	0.10	0.17	0.24	0.13	0.28	0.45
150°	Max	-17.8	-17.8	35.7	-14.3	0.7	16.8	-112.0	-112.0	-112.00	0.00	0.00	0.10	0.00	0.00	0.19	0.37	0.03	0.03
	Min	-45.3	-64.9	-34.8	-30.9	-30.8	-31.3	-113.3	-113.5	-115.20	-0.98	-1.56	-2.37	-1.72	-2.94	-4.32	-0.59	-2.09	-3.20
	Mean	-32.8	-56.7	3.8	20.4	-6.7	5.47	-113.0	-113.2	-114.2	-0.78	-1.22	-1.58	-1.35	-2.23	-2.96	-0.16	-1.02	-1.32
	St. deviation	9.42	8.47	26.8	5.55	11.0	17.55	0.22	0.66	1.53	0.10	0.14	0.20	0.17	0.27	0.40	0.14	0.36	0.52

Table 16 Leg-1 responses under postulated failure conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	24.80	49.70	71.30	30.98	30.89	30.89	-112.0	-112.0	-112.0	0.01	0.14	0.04	2.24	3.90	5.36	0.05	0.42	0.9
	Min	-17.80	-17.8	-17.80	30.86	30.61	30.89	-114.0	-113.0	-115.6	-0.02	-0.04	-0.08	0.00	0.00	-0.28	-0.08	-0.20	-0.12
	Mean	19.40	45.20	62.80	30.88	30.82	30.88	-114.3	-114.7	-116.8	0.00	0.05	0.00	1.76	2.92	3.68	0.00	0.12	0.00
	St. deviation	11.94	7.80	32.93	0.01	0.12	0.00	0.31	0.85	1.73	0.00	0.02	0.01	0.21	0.34	0.49	0.03	0.04	0.05
30°	Max	8.90	28.40	47.80	50.90	69.80	86.75	-111.8	-112.0	-112.0	0.00	0.00	0.12	1.68	3.20	4.40	0.45	0.68	0.81
	Min	-18.20	-17.8	-17.80	30.70	30.89	30.89	-113.4	-116.0	-117.0	-0.96	-1.36	-1.91	0.00	0.00	-0.20	-0.41	-0.24	-0.17
	Mean	-4.80	10.80	34.80	43.70	57.30	77.10	-114.0	-114.6	-116.4	-0.76	-1.04	-1.36	1.28	2.32	3.00	0.42	0.62	0.71
	St. deviation	10.56	19.97	19.84	5.78	11.70	15.67	0.28	0.72	1.50	0.08	0.11	0.16	0.16	0.30	0.43	0.32	0.87	1.10
60°	Max	-7.20	1.30	25.40	61.40	86.20	109.80	-111.7	-111.8	-111.9	0.00	0.00	0.08	0.96	2.24	3.60	1.02	1.24	1.54
	Min	-18.10	-17.8	-17.80	30.25	30.88	30.88	-113.8	-116.3	-117.0	-1.64	-2.54	-3.64	0.00	0.00	-0.04	-0.36	-0.92	-1.39
	Mean	-1.40	-9.70	12.40	56.20	73.50	94.10	-113.3	-114.3	-115.8	-1.36	-2.08	-2.76	0.72	1.56	1.92	0.73	0.84	1.06
	St. deviation	6.02	13.96	20.86	9.95	17.35	25.90	0.30	0.75	1.64	0.15	0.21	0.31	0.08	0.27	0.35	0.41	0.90	0.47
90°	Max	-17.80	-17.8	-17.50	62.80	91.40	110.40	-111.8	-111.7	-111.8	0.00	0.00	4.16	0.36	0.40	0.24	0.30	0.97	1.70
	Min	-21.20	-30.3	-37.30	30.88	30.88	30.89	-113.7	-115.5	-114.4	-1.92	-3.02	-3.02	-0.16	-0.20	-3.80	-1.01	-1.50	-1.62
	Mean	-19.60	-27.0	-33.80	54.90	84.10	101.47	-114.2	-114.6	-115.8	-1.52	-2.26	3.03	0.08	-0.04	-0.06	-0.70	-1.10	-1.24
	St. deviation	0.42	2.71	4.68	10.84	21.30	32.23	0.26	0.62	0.23	0.17	0.33	0.92	0.08	0.07	0.49	0.64	0.88	1.20
120°	Max	-17.80	-17.8	-15.60	53.70	71.08	90.80	-111.0	-111.0	-111.0	0.00	0.00	7.42	0.09	0.06	1.63	1.03	1.26	1.60
	Min	-29.40	-38.5	-54.80	30.88	30.88	31.27	-112.7	-115.0	-117.8	-3.71	-6.04	-9.62	-2.24	-7.83	-8.87	-0.74	-1.62	-1.98
	Mean	-18.70	-77.20	-35.40	46.20	62.40	80.70	-113.2	-113.9	-115.4	-2.97	-4.27	-4.06	-1.41	-5.06	-3.52	0.55	-1.20	-1.64
	St. deviation	6.02	12.60	17.98	10.20	8.57	7.40	0.19	0.36	1.14	0.32	0.78	3.28	0.23	1.75	1.58	1.30	1.60	1.21
150°	Max	-17.80	-17.8	-16.6	46.80	58.30	64.2	-111.0	-111.0	-111.0	0.00	0.00	0.0	0.07	0.03	0.01	2.37	0.51	0.34
	Min	-42.80	-55.7	-69.4	30.88	30.88	30.62	-113.5	-115.	-115.0	-2.08	-3.47	-4.67	-3.46	-6.17	-8.78	-12.30	-14.50	-17.2
	Mean	-71.59	-40.1	-58.41	41.70	49.74	57.9	-112.9	-113.7	-115.6	-1.64	-2.20	-2.51	-2.60	-4.04	-4.79	-8.23	-10.40	-14.2
	St. deviation	9.47	18.24	27.5	5.56	12.94	18.93	0.23	0.34	0.4	0.18	0.34	0.43	0.31	0.61	0.89	4.60	3.22	3.4

Table 17 Leg-2 responses under intact conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	21.7	43.8	114.8	-30.8	-30.9	-30.8	-112.	-112.1	-112.1	0.0	0.0	0.0	2.2	3.6	4.5	0.1	0.0	0.0
	Min	-17.8	-17.8	35.7	-30.9	-31.3	-30.8	-114	-114.0	-116.0	0.0	0.0	0.0	-0.1	0.0	0.0	-0.1	-0.1	0.0
	Mean	18.9	38.6	109.8	-30.8	-30.9	-30.8	-113.	-113.8	-115.4	0.0	0.0	0.0	1.6	2.7	3.4	0.0	0.0	0.0
	St. deviation	4.6	8.8	13.2	0.0	0.1	0.0	0.3	0.7	1.6	0.0	0.0	0.0	0.2	0.3	0.4	0.0	0.0	0.0
30°	Max	17.8	37.8	79.0	-13.2	0.7	11.2	-112.	-112.1	-112.1	0.1	0.0	0.0	2.0	3.2	3.9	0.4	0.2	1.4
	Min	-17.8	-17.8	35.7	-30.8	-30.8	-30.8	-113.	-114.2	-115.0	-1.1	-1.8	-2.3	-0.2	0.0	0.0	-0.6	1.2	-1.4
	Mean	15.4	33.1	72.4	-12.5	-2.4	8.9	-113.	-113.5	-114.9	-0.8	-1.3	-1.6	1.4	2.3	3.0	0.0	-0.8	-0.3
	St. deviation	4.0	7.8	11.7	5.7	10.7	15.4	0.3	0.8	1.6	0.1	0.2	0.2	0.2	0.3	0.4	0.2	-0.1	0.5
60°	Max	2.30	14.075	52.080	-4.30	16.450	36.280	-112.	-112.0	-112.0	0.27	0.00	0.00	1.18	1.75	2.20	0.64	0.12	0.00
	Min	-18.0	-17.80	35.660	-31.0	-30.90	-30.80	-113.0	-116.0	-117.74	-2.00	-3.16	-4.0	-0.16	0.00	0.00	-0.57	-2.28	-2.72
	Mean	-8.70	11.900	48.750	-3.40	12.800	32.890	-113.0	-113.5	-115.0	-1.40	-2.24	-2.83	0.82	1.24	1.54	0.04	-1.20	-1.76
	St. deviation	5.51	8.900	17.640	9.50	9.890	20.450	0.248	0.72	1.460	0.24	0.31	0.38	0.13	0.17	0.20	0.14	0.48	0.51
90°	Max	-17.4	-17.30	35.66	2.60	26.70	51.00	-112.0	-112.0	-112.00	0.00	0.00	0.00	0.06	0.17	0.23	0.31	1.96	2.33
	Min	-18.0	-25.50	19.16	30.80	-30.80	-30.40	-113.7	-114.0	-115.52	-2.04	-3.52	-4.44	-0.08	-0.11	-0.10	-0.24	-0.36	-0.24
	Mean	-18.0	-23.00	22.10	1.20	24.80	47.30	-113.0	-113.8	-114.69	-1.48	-2.51	-3.18	0.00	0.04	0.06	0.02	1.14	1.54
	St. deviation	0.22	2.08	4.33	10.80	21.40	24.50	0.22	0.715	1.490	0.21	0.34	0.42	0.02	0.04	0.06	0.08	0.47	0.56
120°	Max	-17.8	-17.80	35.80	-2.80	20.900	44.800	-112.	-112.0	-112.00	0.00	0.00	0.26	0.00	0.00	0.15	0.54	1.28	1.59
	Min	-33.0	-47.9	-9.7	-30.8	-30.8	-31.2	-113	-114.6	-115.30	-1.76	-3.08	-4.40	-1.00	-1.68	-2.64	-0.52	-0.56	-0.84
	Mean	-29.8	-37.3	17.8	-18.6	15.96	37.5	-113.	-114.0	-114.9	-1.32	-2.24	-2.96	-0.76	-1.28	-1.68	0.02	0.23	0.20
	St. deviation	5.5	11.25	17.15	9.6	19.13	30.15	0.23	0.76	1.720	0.17	0.28	0.41	0.10	0.17	0.24	0.13	0.28	0.45
150°	Max	-17.8	-17.8	35.7	-14.3	0.7	16.8	-112.0	-112.0	-112.00	0.00	0.00	0.10	0.00	0.00	0.19	0.37	0.03	0.03
	Min	-45.3	-64.9	-34.8	-30.9	-30.8	-31.3	-113.3	-113.5	-115.20	-0.98	-1.56	-2.37	-1.72	-2.94	-4.32	-0.59	-2.09	-3.20
	Mean	-32.8	-56.7	3.8	20.4	-6.7	5.47	-113.0	-113.2	-114.2	-0.78	-1.22	-1.58	-1.35	-2.23	-2.96	-0.16	-1.02	-1.32
	St. deviation	9.42	8.47	26.8	5.55	11.0	17.55	0.22	0.66	1.53	0.10	0.14	0.20	0.17	0.27	0.40	0.14	0.36	0.52

Table 18 Leg-2 responses under postulated failure conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	24.80	49.70	71.30	30.98	30.89	30.89	-112.0	-112.0	-112.0	0.01	0.14	0.04	2.24	3.90	5.36	0.05	0.42	0.9
	Min	-17.80	-17.8	-17.80	30.86	30.61	30.89	-114.0	-113.0	-115.6	-0.02	-0.04	-0.08	0.00	0.00	-0.28	-0.08	-0.20	-0.12
	Mean	19.40	45.20	62.80	30.88	30.82	30.88	-114.3	-114.7	-116.8	0.00	0.05	0.00	1.76	2.92	3.68	0.00	0.12	0.00
	St. deviation	11.94	7.80	32.93	0.01	0.12	0.00	0.31	0.85	1.73	0.00	0.02	0.01	0.21	0.34	0.49	0.03	0.04	0.05
	Max	8.90	28.40	47.80	50.90	69.80	86.75	-111.8	-112.0	-112.0	0.00	0.00	0.12	2.00	3.56	4.80	0.45	0.68	0.81
30°	Min	-18.20	-17.8	-17.80	30.70	30.89	30.89	-113.4	-116.0	-117.0	-0.96	-1.36	-1.91	0.00	0.00	-0.36	-0.41	-0.24	-0.17
	Mean	-4.80	10.80	34.80	43.70	57.30	77.10	-114.0	-114.6	-116.4	-0.76	-1.04	-1.36	1.48	2.56	3.20	0.42	0.62	0.71
	St. deviation	10.56	19.97	19.84	5.78	11.70	15.67	0.28	0.72	1.50	0.08	0.11	0.16	0.18	0.33	0.50	0.32	0.87	1.10
	Max	-7.20	1.30	25.40	61.40	86.20	109.80	-111.7	-111.8	-111.9	0.00	0.00	0.08	0.96	2.24	3.60	1.02	1.24	1.54
	Min	-18.10	-17.8	-17.80	30.25	30.88	30.88	-113.8	-116.3	-117.0	-1.64	-2.54	-3.64	0.00	0.00	-0.04	-0.36	-0.92	-1.39
60°	Mean	-1.40	-9.70	12.40	56.20	73.50	94.10	-113.3	-114.3	-115.8	-1.36	-2.08	-2.76	0.72	1.56	1.92	0.73	0.84	1.06
	St. deviation	6.02	13.96	20.86	9.95	17.35	25.90	0.30	0.75	1.64	0.15	0.21	0.31	0.08	0.27	0.35	0.41	0.90	0.47
	Max	-17.80	-17.8	-17.50	62.80	91.40	110.40	-111.8	-111.7	-111.8	0.00	0.00	4.16	0.36	0.40	0.24	0.30	0.97	1.70
	Min	-21.20	-30.3	-37.30	30.88	30.88	30.89	-113.7	-115.5	-114.4	-1.92	-3.02	-3.02	-0.16	-0.20	-3.80	-1.01	-1.50	-1.62
	Mean	-19.60	-27.0	-33.80	54.90	84.10	101.47	-114.2	-114.6	-115.8	-1.52	-2.26	3.03	0.08	-0.04	-0.06	-0.70	-1.10	-1.24
120°	St. deviation	0.42	2.71	4.68	10.84	21.30	32.23	0.26	0.62	0.23	0.17	0.33	0.92	0.08	0.07	0.49	0.64	0.88	1.20
	Max	-17.80	-17.8	-15.60	53.70	71.08	90.80	-111.0	-111.0	-111.0	0.00	0.00	7.42	0.08	0.06	0.04	1.03	1.26	1.60
	Min	-29.40	-38.5	-54.80	30.88	30.88	31.27	-112.7	-115.0	-117.8	-3.71	-6.04	-9.62	-2.18	-3.94	-10.7	-0.74	-1.62	-1.98
	Mean	-18.70	-77.2	-35.40	46.20	62.40	80.70	-113.2	-113.9	-115.4	-2.97	-4.27	-4.06	-1.67	-2.62	-3.92	0.55	-1.20	-1.64
	St. deviation	6.02	12.60	17.98	10.20	8.57	7.40	0.19	0.36	1.14	0.32	0.78	3.28	0.21	0.38	1.33	1.30	1.60	1.21
150°	Max	-17.80	-17.8	-16.6	46.80	58.30	64.2	-111.0	-111.0	-111.0	0.00	0.00	0.0	0.07	0.04	0.01	2.37	0.51	0.34
	Min	-42.80	-55.7	-69.4	30.88	30.88	30.62	-113.5	-115.	-115.0	-2.08	-3.47	-4.67	-3.46	-5.84	-8.78	-12.30	-14.5	-17.2
	Mean	-71.59	-40.1	-58.41	41.70	49.74	57.9	-112.9	-113.7	-115.6	-1.64	-2.20	-2.51	-2.60	-4.36	-4.79	-8.23	-10.4	-14.2
	St. deviation	9.47	18.24	27.5	5.56	12.94	18.93	0.23	0.34	0.4	0.18	0.34	0.43	0.31	0.55	0.89	4.60	3.22	3.4

Table 19 Leg-3 responses under intact conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	70.9	97.8	114.8	0	0	0	-112.1	-112.1	-112	0	0.1	0	2.3	3.4	4.2	0.1	0.6	0.84
	Min	34	35.7	35.7	0	-0.7	0	-113.9	-114	-116	0	-0.1	0	0	0	0	0	-0.8	0-0.65
	Mean	67.9	89.7	109.8	0	-0.1	0	-113.5	-113.8	-116	0	0	0	1.7	2.6	3.3	0	0.4	0.65
	St. deviation	4.6	8.8	109.8	0	0.2	0	0.3	0.8	1.6	0	0	0	0.2	0.3	0.4	0	0.2	0.32
30°	Max	39.1	59.2	79	16.5	28.9	41	-112.1	-112.1	-112	0	0	0	1.9	3	3.8	0.4	0.7	1.1
	Min	34.9	35.7	35.7	-0.4	0	0	-113.9	-114.2	-115	-1.1	-1.7	-2.4	0	0	0	-0.7	-0.91	-1.2
	Mean	36.7	54.4	72.4	15.9	20.5	36.8	-113.4	-113.5	-115	-0.8	-1.4	-1.7	1.5	2.4	3	-0.2	-0.3	-0.7
	St. deviation	4.1	7.8	11.7	5.8	10.7	15.2	0.3	0.8	1.6	0.1	0.2	0.2	0.2	0.3	0.3	0.2	0.3	0.5
60°	Max	51	67.9	52	28	47.7	66.9	-111.9	-112.1	-112	0	0	0	1.04	1.51	1.87	0	0	0
	Min	35.2	35.6	35.6	-0.65	0	0	-113.7	-115.9	-118	-1.83	-2.9	-3.9	-0.1	0	0	-0.47	-0.86	-1.2
	Mean	49.2	59.8	48.7	23.8	41.2	62.8	-113.3	-113.5	-115	-1.3	-2.2	-2.9	0.78	1.2	1.5	-0.47	-0.56	-0.8
	St. deviation	5.7	19.7	17.6	9.3	16.4	22.8	0.25	0.67	1.38	0.18	0.27	0.32	0.1	0.12	0.14	0.19	0.73	0.78
90°	Max	35.6	35.6	35.6	32	81.42	79.8	-112.1	-112	-112	0	0	0	0.02	0.22	0.4	0.5	0.8	1.05
	Min	34.2	25.38	19.1	0	0	0	-113.7	-114	-116	-1.96	-3.4	-4	-0.02	-0.02	-0.03	0	0	-0.01
	Mean	34.6	28.2	22.1	28.54	75.4	73.8	-113.3	-113.8	-115	-1.5	-2.6	-3.3	0	0.08	0.12	0.33	0.8	1.2
	St. deviation	0.28	2.42	4.23	11	21.8	22.8	0.23	0.74	1.58	0.19	0.32	0.36	0.006	0.04	0.07	0.09	0.54	0.65
120°	Max	35.6	35.6	35.8	27.9	50.9	75.8	-112	-112	-112	0	0	0.26	0	0	0.14	0.54	0.47	0.95
	Min	19.4	5.7	-9.7	0	0	-0.3	-113.6	-114.6	-115	-1.76	-3.08	-4.4	-1	-1.6	-2.6	-0.42	-0.56	-0.84
	Mean	26.78	14.9	17.8	24.8	43.5	64.9	-113	-114	-115	-1.32	-2.24	-2.8	-0.76	-1.2	-1.68	0.02	0.22	0.2
	St. deviation	5.5	11.2	17.1	9.6	19.1	30.1	0.23	0.76	1.7	0.15	0.28	0.4	0.1	0.16	0.24	0.12	0.27	0.45
150°	Max	35.6	35.6	35.7	16.1	29.4	44.3	-112	-112	-112	0	0	0.18	0	0	0.42	0.01	0.14	0.04
	Min	8.53	-12.5	-34.8	0	0	-0.06	-113.2	-113.5	-115	-1	-1.7	-2.4	-1.79	-3.01	-4.4	-0.43	-1.08	-1.6
	Mean	28.6	27.9	3.8	13.8	23.7	36.9	-113	-113.2	-114	-0.7	-1.2	-1.5	-1.3	-2.21	-2.8	-0.05	-0.74	-1
	St. deviation	9.4	8.9	26.8	5.5	11	17.1	0.22	0.6	1.5	0.1	0.16	0.23	0.18	0.29	0.44	0.12	0.34	0.46

Table 20 Leg-3 responses under postulated failure conditions

Heading angle	Statistics	Surge (Offset)			Sway (Offset)			Heave (Set down)			Roll			Pitch			Yaw		
		LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C	LC-A	LC-B	LC-C
0°	Max	72.8	99.7	124.8	0.019	0.001	0	-110	-110	-110	0.00	1.03	0.03	3.29	4.84	7.96	0.06	0.47	0.91
	Min	34.8	35.66	35.64	-0.033	-0.67	-0.002	-113	-113.7	-115	0.00	-0.80	-0.02	0.00	0.00	-0.04	-0.08	-0.20	-0.12
	Mean	64.8	66.7	115.4	-0.01	-0.09	0	-114	-114	-115	0.00	0.04	0.00	7.02	3.98	4.56	0.00	0.12	0.00
	St. deviation	11.92	8.4	33.01	0.009 5	0.16	4E-04	0.52	1.2	1.75	0.00	0.38	0.00	0.37	0.49	0.52	0.02	0.05	0.03
	Max	60.5	81.9	102.6	20.6	39.2	55.2	-110	-110	-110	0.09	1.52	1.59	3.34	5.00	6.24	0.61	0.85	0.94
30°	Min	34.99	35.66	35.66	-0.41	0	0	-112	-112.9	-115	-0.61	-1.94	-2.28	0.00	0.00	-0.02	-0.48	-0.24	-0.19
	Mean	52.4	72.4	95.7	14.89	32.07	48.1	-112	-113.9	-114	-0.26	-0.32	-0.52	2.85	4.20	4.88	0.42	0.62	0.71
	St. deviation	10.23	19.54	20.4	5.89	11.64	15.98	0.5	1.17	1.63	0.11	0.54	0.67	0.40	0.50	0.54	0.32	0.87	1.10
	Max	46.87	54.6	79.2	29.8	55.8	78.9	-109	-109.6	-110	0.00	1.68	1.96	3.27	4.96	6.16	1.10	1.37	1.64
	Min	35.6	35.6	35.6	-0.65	0	0	-113	-116.2	-117	-1.00	-2.96	-4.00	0.00	0.00	-0.02	-0.36	-0.92	-1.39
60°	Mean	38.9	49.2	70.4	24.6	46.9	69.4	-112	-113.6	-115	-0.56	-0.84	-1.32	2.79	4.04	4.40	0.73	0.84	1.06
	St. deviation	5.89	12.36	19.9	9.44	16.46	24.2	0.47	1.02	1.43	0.16	0.76	1.08	0.40	0.52	0.65	0.41	0.90	0.47
	Max	35.2	35.6	35.8	32.1	61.7	81.4	-110	-109.4	-110	0.00	0.00	0.82	0.03	3.56	0.03	0.30	0.97	1.70
	Min	36.2	25	19.84	0	0	0	-113	-115	-114	-1.12	-2.80	-2.48	-2.83	0.00	-4.88	-1.23	-1.70	-1.92
	Mean	34.6	28.2	22.1	24.6	52.7	68.4	-112	-113.4	-114	-0.48	-1.72	0.49	-1.90	2.27	-3.64	-0.80	-1.20	-1.34
120°	St. deviation	0.28	2.425	4.69	11.03	21.85	33.01	0.49	0.91	0.37	0.15	0.40	0.31	0.44	0.48	0.58	0.64	0.88	1.20
	Max	35.69	35.67	37.51	23.7	40.97	-56.49	-109	-109	-110	0.40	1.90	3.90	0.10	0.00	1.90	1.03	1.26	1.60
	Min	23.7	14.2	-4.5	0	0	-1.34	-113	-114	-119	-2.00	-3.40	-5.60	-7.80	-11.5	-12.8	-0.74	-1.62	-1.98
	Mean	14.8	4.68	19.5	18.4	32.8	48.07	-112	-112.9	-114	-0.40	-0.70	-1.30	-6.10	-7.10	-2.90	0.55	-1.20	-1.64
	St. deviation	6.31	12.7	17.87	10.32	9.7	6.7	0.58	0.79	1.6	0.20	1.10	1.60	0.80	1.90	1.30	1.30	1.60	1.21
150°	Max	35.7	35.6	35.4	15	27.4	30.9	-109	-109	-109	0.80	2.30	1.40	0.00	0.00	0.00	0.20	0.00	0.00
	Min	11.9	-4.8	-15.7	0	0	-1.1	-113	-114	-115	-1.00	-1.50	-1.60	-8.20	-12.5	-15.9	-0.49	-0.96	-1.30
	Mean	-18.6	17.4	5.8	11.4	23.4	24.7	-112	-112.3	-114	-0.10	0.30	0.90	-6.70	-9.50	-11.8	-0.21	-0.69	-0.98
	St. deviation	9.5	18.8	27.7	5.6	13	19.1	0.7	0.6	0.6	0.40	0.40	0.30	0.90	1.20	1.40	0.23	0.25	0.64
	Max	35.7	35.6	35.4	15	27.4	30.9	-109	-109	-109	0.80	2.30	1.40	0.00	0.00	0.00	0.20	0.00	0.00

7 Conclusions

Based on the numerical analysis carried out on triceratops under intact and postulated failure of tendons under 10-yr, 100-yr, and 1 000-yr post-Katrina hurricane conditions, the following conclusions are drawn:

1) The natural periods of stiff degrees of freedom are marginally increased due to the decrease in stiffness in postulated failure tendons and the static equilibrium position of the deck in pitch degree is shifted from 0° to -1.4° under the postulated failure condition due to the differential heave motion of the legs.

2) The deck is subjected to maximum surge response under 0° heading angle compared to other headings. The response is about 8.5% and 9.1% of the water depth, respectively, under intact and postulated failure.

3) The maximum heave and pitch PSD peaks are observed nearer to the natural frequencies of respective DOF for intact and postulated failure conditions.

4) The neighboring tendon tension variation significantly increases in the postulated failure condition of tendons under leg-3 for load cases-3. The shift of mean tension is about 46 MN for 0° heading. Further the fatigue life is significantly reduced under the postulated failure of tendons which is about 0.006 1 years for tendons in leg-3.

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