ASSESSMENT OF DRILLING & WORKOVER RIG STORM SEA FASTENINGS ON OFFSHORE FLOATING PLATFORMS DURING HURRICANE IVAN

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PHASE 1: Analysis Report

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PHASE 1: Analysis Report

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Executive Summary

Drilling and workover rigs on Floating Production Systems (FPS's) are fastened to the decks of offshore structures sea fastenings to prevent movement during hurricanes. Tie-down systems include bolted clamps, weldments, or other mechanical means. During Hurricane Ivan, a number of drilling or workover rigs shifted. These movements were studied and assessed relative to current design philosophy and installation practices, and onboard storm operational practices to ready FPS's for a hurricane. Results will provide information that can be used to assess any needs to revise tie-down criteria or practices to avoid future damage.

Information was gathered for the FPS's with rig movement during Ivan. Information was obtained for Horn Mountain (BP), Medusa (Murphy), and Ram Powell (Shell). No information was obtained for Devils Tower (Dominion). An interim report to MMS and an OTC paper summarized the observations and learnings from these rig movements. We were also able to work with the API's Hurricane Evaluation & Assessment Team (HEAT) and provide input to API Bulletin 2TD, Guidelines for Tie-Downs on Offshore Production Facilities for Hurricane Season, First Edition that was issued in June 2006.

This report describes the analyses for a hypothetical TLP and Spar to further study the loads and failure modes for rig tie-down clamps for drilling rigs during hurricanes. Results tended to confirm the observation from hurricane Ivan, and illustrate that tie-down clamps should be purpose-designed for the functional requirements and motion characteristics the specific FPS.

Introduction

The initial goal for the analysis was to gather sufficient information and data regarding one of the sea fastening failures that occurred during hurricane Ivan and analyze that case to better understand the likely cause of the failure. As discussed in references 1 and 2, there were three cases in which sea fastenings failed to prevent a drilling rig from moving during hurricane Ivan. However, we were not able to gather sufficient data for the specific facilities to allow a detailed forensic study of any of these cases.

Instead, we chose to study two hypothetical structures, a TLP and a Truss Spar during several hurricane environmental conditions. The analyses were used as the basis for studying the loads and failure modes for rig tie-down clamps. The study used a typical clamp design and did not attempt to design a clamp for the specific location or FPS type.

The TLP, Spar, and the drilling rig analyzed were not actual designs, but represented realistic examples of FPS's and a drilling rig. The global loads and deck motions of the FPS's and the wind loads and motions of the drilling rig and its substructure were simulated for hurricane wind, wave, and current environments that represented 10-year and 100-year return period and maximum conditions near the eye during hurricane Ivan. These motions and loads were used to estimate the maximum forces and moments at the locations where tie-down clamps secure (1) the derrick and drill floor to the substructure, and (2) the substructure to the deck. See Figure 1.

A set of tie-down clamps were selected to investigate failure of simple bolted clamps. Three failure modes were considered: (1) slip, (2) bolt failure in tension, and (3) bolt failure in shear. The capacities of the clamps to resist the hurricane forces and loads were computed for several coefficients of friction and bolt pre-tensions, and were compared to the simulated hurricane loads. The same clamps were used for the TLP and the Spar, and at both elevations on each FPS. Results provided a basis for examining and comparing the loads and different failure modes of the clamps. The clamps selected were based on typical designs observed during our visits to four offshore facilities and discussions with operators.

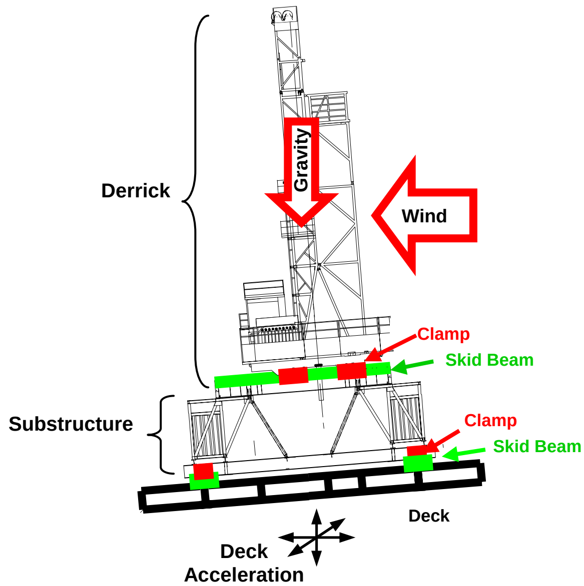

Figure 1. Drilling Rig, Substructure, and Tie-Down Clamps

Appendices A and B contain details of the analyses.

Appendix A (Assessment of the Performance of Tie-Down Clamps for a Drilling Rig on a Spar in Severe Hurricane Environments by J. Gebara and N. Ghoneim of Technip Offshore Inc. focuses on the motions of the spar, wind loads on the derrick, and provides details regarding the clamp design, failure modes, and performance.

Appendix B (Assessment of the Performance of Tie-Down Clamps for a Drilling Rig on a TLP in Severe Hurricane Environments by M.H. Kim and C.K. Yang of Texas A&M University, Civil Engineering Department focuses on the analysis of the TLP motions, wind loads on the derrick, and performance of the clamps.

Hurricane Environment

The table below summarizes the environmental conditions used in this study. Winds, waves and currents representing 10-year and 100-year hurricane conditions and maximum conditions near the eye of hurricane Ivan are shown in Table 1 below. The JONSWAP spectrum was used to simulate long crested irregular wave generation with the given stiffness parameter. Time varying wind speeds were simulated using the API spectrum. The wind and the current speeds are those associated with and colinear with maximum wave condition.

Table 1. Hurricane Environmental Conditions

Return Period	10 year		100 year		Ivan	
Hs (ft)	24.9		40.0		51.1	
Tp (sec)	11.9		14.0		15.6	
γ *	2.4		2.4		3.0	
Wind Speed**(kts)	50.9		81.3		87.9	
Current Profile	Depth (ft)	Speed (ft/s)	Depth (ft)	Speed (ft/s)	Depth (ft)	Speed (ft/s)
	0	2.59	0.0	4.9	0	8.2
	98	1.97	98	3.8	16	8.2
	197	0.95	197	1.8	82	3.9
	295	0.33	2957	0.3	164	3.7
	3000	0.33	3000	0.3	264	2.4
					328	1.0
					492	1.0
					984	0.9
					3000	0.0

* JONSWAP spectrum is used for the irregular wave generation with the given γ.

** The wind speed is 1 hour averaged at 10m above MWL, and API wind spectrum is used for the time varying wind speed generation.

Wind Forces on the Drilling Rig & Substructure

The derrick and the substructure are schematically shown in Figure 2 and 3 below.

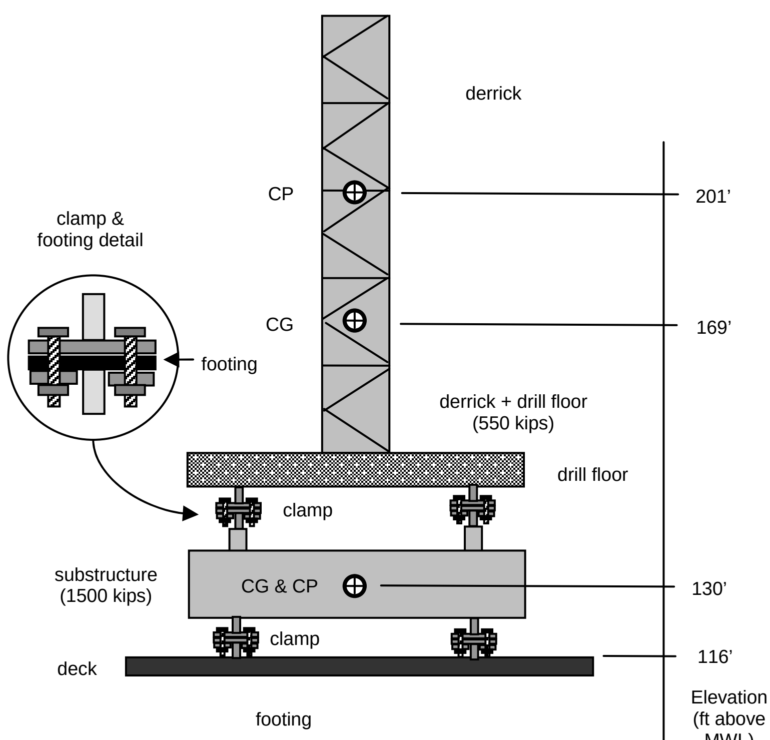

Figure 2. Drilling Rig and Substructure

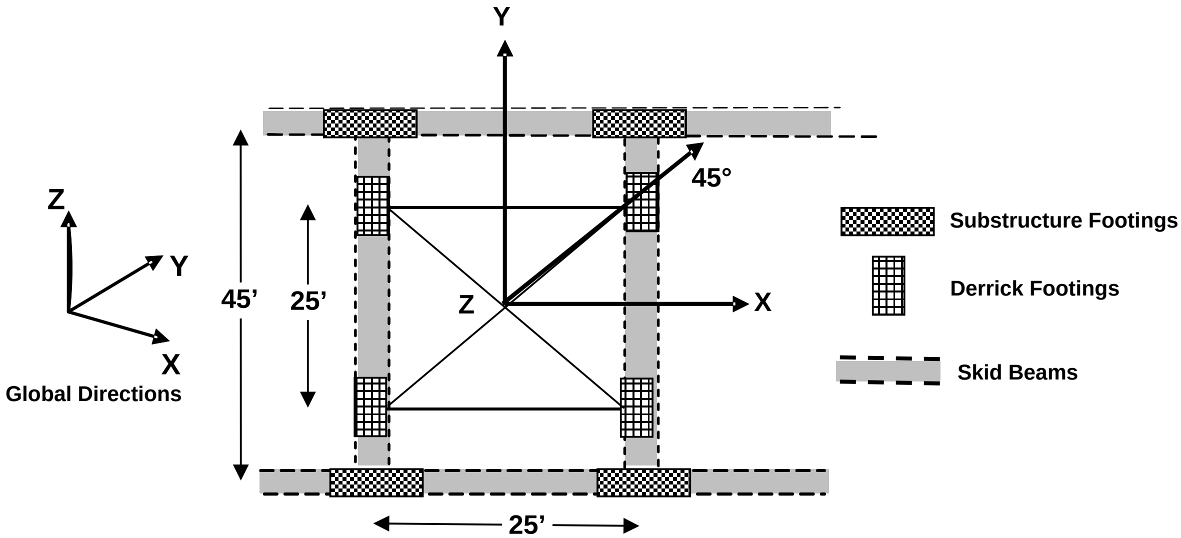

Figure 3. Upper Derrick & Substructure Footings (Plan View)

Select parameters involved used in calculating the wind forces are shown in Table 2.

Table 2. Wind Force Parameters

Parameter	Derrick	Substructure	Total
Weight (kips)	550	1500	2050
Projected Area (ft^2)	2940	500	3440
Center of Pressure from MWL (ft)	201	130	190
Center of Gravity from MWL (ft)	169	130	140.5
Height Coefficient(C_h)*	1.37	1.19	1.24
Shape Coefficient(C_s)*	1.25	1.25	1.25

Wind forces on the derrick were computed following the recommendations in API 4F. The derrick was assumed to be rigid. The projected area was based on the exposed areas of the two opposite sides of the derrick. Forces at the center of pressure were computed for wind velocities corresponding to 10-year, 100-year, and Ivan conditions. Forces were computed for the winds aligned with the X axis, the Y axis, and at an angle of 45 degrees. The area used for the force in the 45 degree direction was the square root of the sum of the squares of the areas projected areas in the X and Y directions.

The resulting wind loads on the derrick are shown in Table 3.

Table 3. Wind Forces on Derrick

Environment	Velocity (kts)	X & Y Wind Force (kips)	45 Degree Wind Force (kips)
10-year	51	44	62
100-year	81	112	158
Ivan	88	131	185
API 4F	107	195	276

Wind speed measurements near the eye during Ivan are not available, but hindcasts values were 89 knots (1hour average, 10 m elevation). The API 4F wind force of 107 knots is shown for illustrative purposes only, and was not used in our final assessment of the performance of tie-down clamps in this study. Note that the 107 kt wind speed resulted in a wind force on the derrick that was 50 percent greater that the maximum wind speed in Ivan.

Hull Accelerations

The TLP and the Spar were analyzed to describe the global motions for each environmental condition (see Appendices A and B for details). Due to the symmetry of the TLP and Spar, the motions in the X and Y directions were equal. The hull accelerations were used to determine the inertial loads of the derrick and substructure.

The maximum accelerations at the hull center-of-gravity (CG) in the X and Y directions are shown in Table 4 below.

Table 4. Maximum Hull Accelerations

Environment	Motion	Accelerations @ Hull CG (accel/g)	
		TLP	Spar
10-year	Horizontal	0.109	0.083
	Rotational	0.004	0.007
	Heel (static)	0.001	0.056
100-year	Horizontal	0.173	0.124
	Rotational	0.005	0.010
	Heel (static)	0.002	0.146
Ivan	Horizontal	0.220	0.154
	Rotational	0.006	0.013
	Heel (static)	0.003	0.187

Note the differences in the accelerations for the TLP and the Spar hull CGs. The TLP has larger horizontal accelerations, whereas the Spar has larger rotational and heel accelerations.

Derrick and Substructure Accelerations

The accelerations at the CGs of the derrick and substructure are needed to compute the inertial loads of the derrick and substructure on their footings so that the forces on the clamps can be determined. The accelerations at the derrick and substructure CGs were calculated from the hull CG accelerations and the vertical distances from the hull CG to the derrick and substructure CGs (see Figure x above) as shown in the Table 5 below.

Table 5. Vertical Locations of Centers of Gravity

FPS	CG relative to MWL	CG relative to Hull CG	
	Hull	Derrick	Substructure
TLP	28	141	102
Spar	-177	346	307

The maximum total acceleration at the CGs of the derrick and substructure are shown in Table 6 below. Again note the differences in the accelerations for the TLP and the Spar.

Table 6. Max. Total Accelerations at the Derrick and Substructure CGs

Environment	Max. Total Accelerations @ Derrick CG (accel/g)		Max. Total Accelerations @ Substructure CG (accel/g)	
	TLP	Spar	TLP	Spar
10-year	0.130	0.223	0.125	0.207
100-year	0.200	0.417	0.194	0.378
Ivan	0.253	0.503	0.246	0.490

These differences in accelerations need to be recognized in designing or evaluating tie-down systems for drilling rigs and other equipment placed on the decks.

Loads on the Footings for the Derrick and Substructure Clamps

The maximum loads on the footings were determined by combining the gravity, inertial, wind, and static loads for the derrick and substructure.

The derrick and substructure were modeled as rigid structures. The maximum inertial loads for the derrick and substructures were determined a bit differently for the TLP and the Spar. For the TLP, the inertial loads of the derrick and substructure were simulated in a random time series analysis that included all the acceleration components at their respective phases, and the maximum inertial forces were determined directly. For the Spar, instantaneous values (‘snapshots”) were determined for the (1) maximum lateral and associated vertical acceleration, (2) maximum positive vertical and the associated lateral acceleration, and (3) maximum negative vertical and the associated lateral acceleration. The method used for the TLP is a more direct approach to determine the maximum forces, but the differences were checked and determined not to be important for this study.

Loads and moments on the footings were computed using the inertial loads in the X and Y directions and wind loads on the derrick and substructure from the X, Y, and 45 degree directions (see Figure 3). Forces at the footings were analyzed assuming both pinned and fixed connections. There was a small difference which was judged to be unimportant given the assumptions in this study. However for detailed design studies, the difference between pinned and fixed footings should be assessed on a case by case basis.

The maximum uplift loads and global moments (acceleration and wind components and the total) on the footings are shown in Tables 7 – 10 below.

Table 7. TLP Derrick Footing Loads & Moments

Environment	Max UPLIFT Load per Clamp Footing (kips)			Global Moments At Derrick Footings Level (kip-ft)								
	Load Direction											
	X	Y	45°	X			Y			45°		
	F_Z			M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
Calm	-138 (dead load)			0								
10-Year	-48	-48	38	1898	1212	3110	1898	1212	3110	2683	1715	4398
100-Year	42	42	216	2530	3093	5623	2530	3093	5623	3578	4374	7952
Ivan	79	79	290	3289	3616	6905	3289	3616	6905	4651	5114	9765

Table 8. TLP Substructure Footing Loads & Moments

Environment	Max UPLIFT Load per Clamp Footing (kips)			Global Moments At Derrick Footings Level (kip-ft)								
	Load Direction											
	X	Y	45°	X			Y			45°		
	F_Z			M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
Calm	-513 (dead load)			0								
10-Year	-274	-380	-147	7523	1966	9488	7523	1966	9488	10638	2780	13418
100-Year	-92	-270	131	10030	5015	15045	10030	5015	15045	14185	7092	21277
Ivan	7	-210	282	13039	5862	18901	13039	5862	18901	18440	8291	26730

Table 9. Spar Derrick Footing Loads & Moments

Environment	Max UPLIFT Load per Clamp Footing (kips)			Global Moments At Derrick Footings Level (kip-ft)								
	Load Direction											
	X	Y	45°	X			Y			45°		
	F_Z			M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
Calm	-138 (dead load)			0								
10-Year	-34	-34	69	2732	1212	3945	2732	1212	3945	3864	1715	5579
100-Year	86	86	308	4971	3093	8065	4971	3093	8065	7031	4374	11405
Ivan	137	137	410	6426	3616	10042	6426	3616	10042	9088	5114	14202

Table 10. Spar Substructure Footing Load & Moments

Environment	Max UPLIFT Load per Clamp Footing (kips)			Global Moments At Derrick Footings Level (kip-ft)								
	Load Direction											
	X	Y	45°	X			Y			45°		
	F_Z			M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
Calm	-513 (dead load)			0								
10-Year	-220	-349	-58	10643	1966	12609	10643	1966	12609	15052	2780	17832
100-Year	76	-184	403	19394	5015	24408	19394	5015	24408	27427	7092	34519
Ivan	230	-133	639	25098	5862	30960	25098	5862	30960	35494	8291	43785

The maximum uplift forces F_Z and total moments M_T are also shown graphically in Figures 4 – 7 in terms of increasing loads and moments, values are shown for calm, 10-year, 100-year, and Ivan hurricane conditions.

The forces FZ for the "calm" cases are the dead load due only to the weight of the derrick or the derrick plus the substructure, and the corresponding moments are zero. The forces and moments increase with increasingly severe environment as indicated by the increasing total moment M_T, and the derrick would begin to tip (if not restrained by the clamp) when the maximum uplift force becomes positive.

The maximum uplift forces F_Z and total moment M_T for the derrick footings are the same in the X and Y directions since the derrick footings are in a square pattern. The uplift forces F_Z for the derrick and substructure are larger for the Y direction because of the larger spacing between footings in the Y direction than the X direction for the substructure footings.

The uplift force F_Z and total moment M_T in the 45 degree directions is larger than in either X or Y directions in a given environments because of the larger wind force in the 45 degree direction.

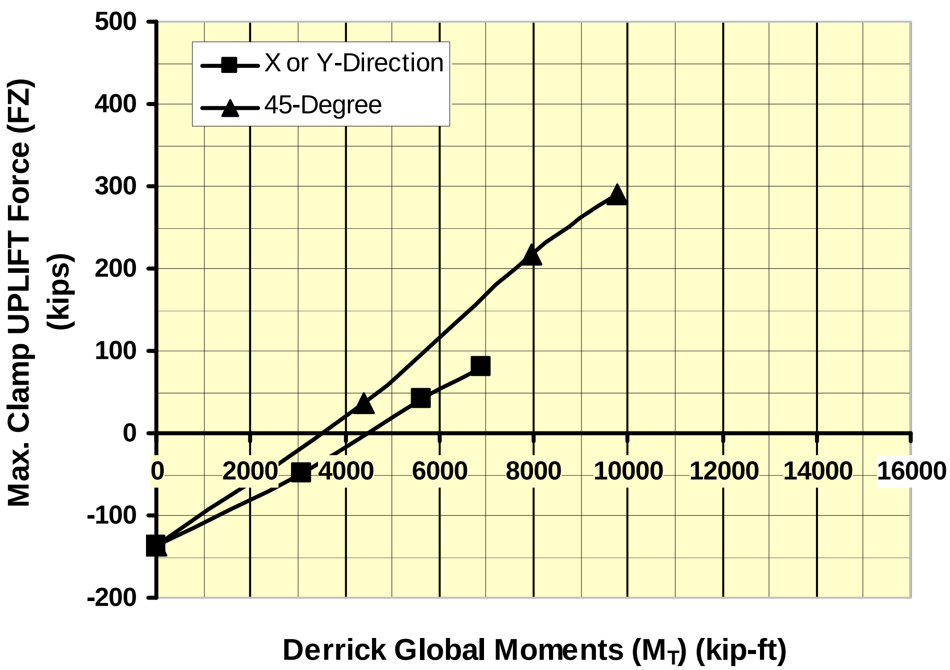

Figure 4. TLP Derrick Global Moments vs. Max Uplift Force at Footing for Derrick Clamp (Calm, 10 yr, 100 yr, Ivan)

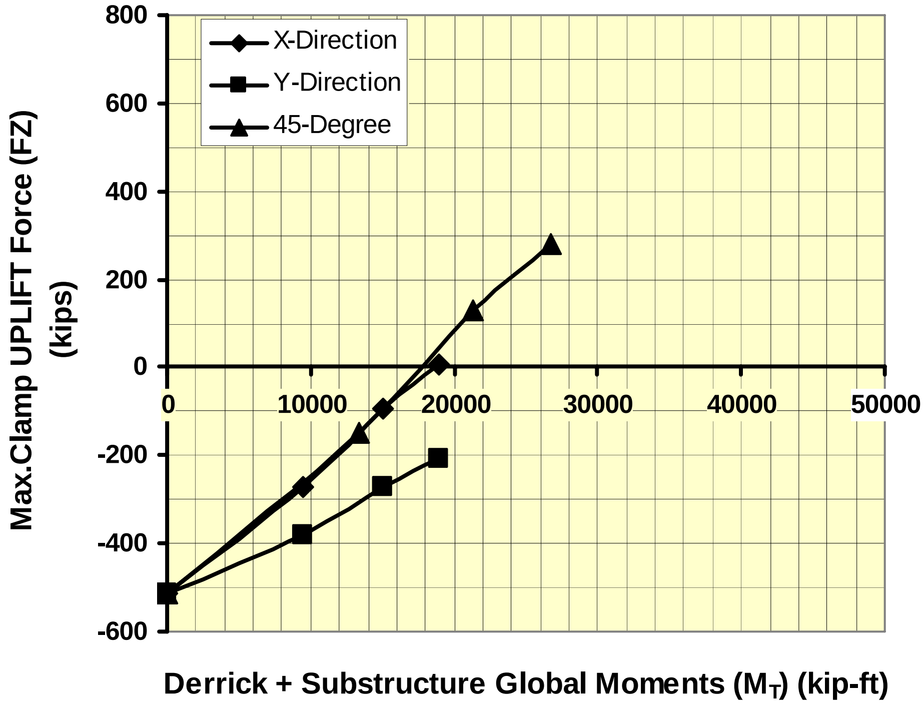

Figure 5. TLP Derrick + Substructure Global Moments vs. Max Uplift Force at Footing for Substructure Clamp (Calm, 10 yr, 100 yr, Ivan)

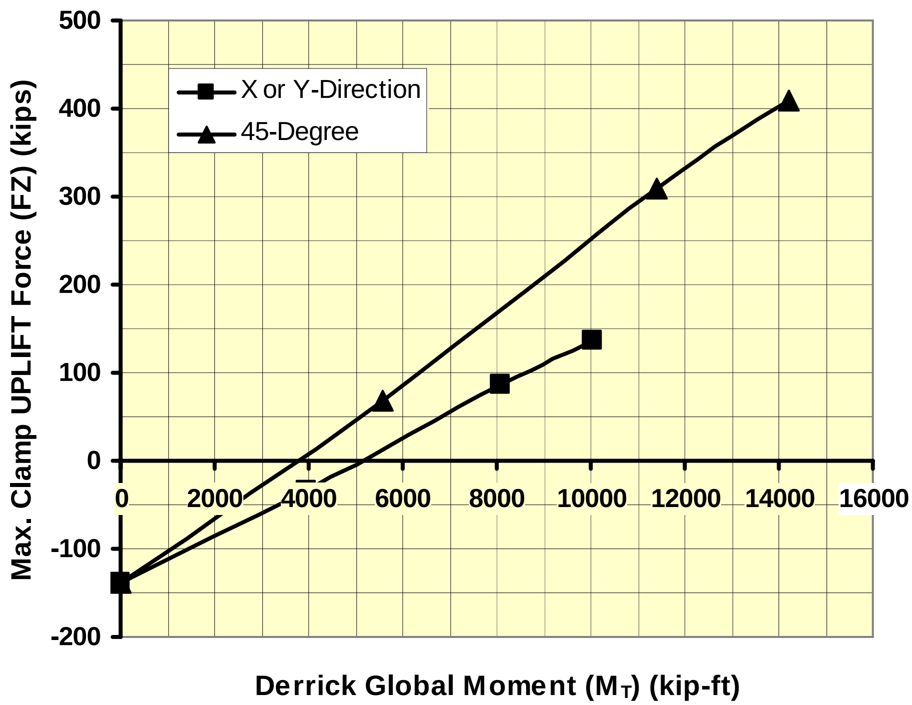

Figure 6. Spar Derrick Global Moments vs. Max Uplift Force at Footing for Derrick Clamp (Calm, 10 yr, 100 yr, Ivan)

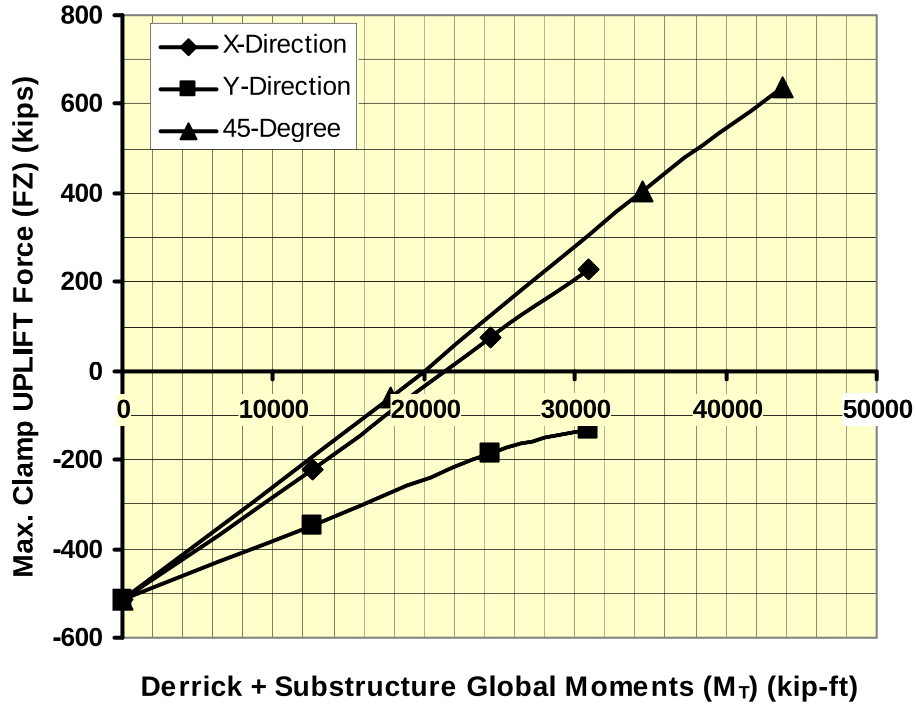

Figure 7. Spar Derrick + Substructure Global Moments vs. Max Uplift Force at Footing for Substructure Clamp (Calm, 10 yr, 100 yr, Ivan)

Clamps

A simple tie-down clamp was "configured" to investigate failure of clamps. There was no intent to do a detailed design or optimize the clamp for motions of either the TLP or the Spar. The same clamps were used for the TLP and the Spar, and at both elevations, i.e. the derrick-substructure interface and at the substructure-deck interface. The clamp configuration is shown in Figure 8 below.

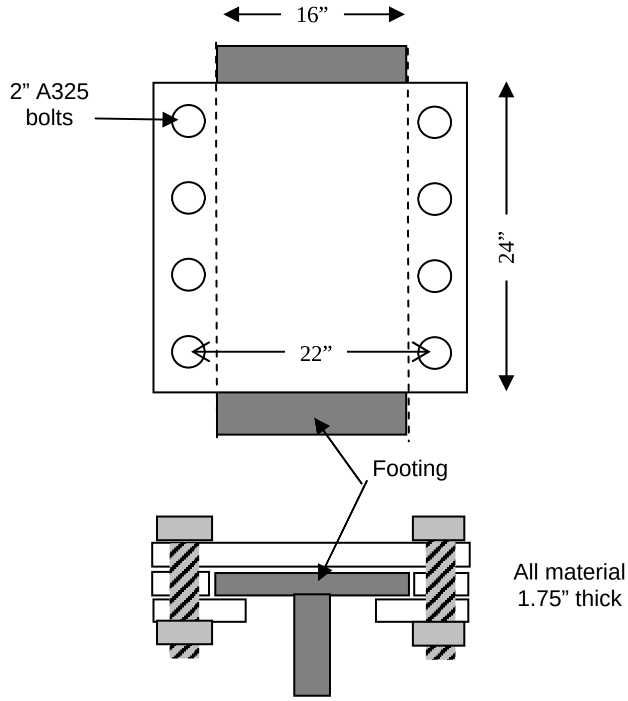

Figure 8. Bolted clamp configuration

Clamp Capacity vs. Environmental Loads

Three failure modes were considered: (1) slip, (2) bolt failure in tension, and (3) bolt failure in shear. The capacities of the clamps were computed for three coefficients of friction (0.1, 0.3, and 0.5) and four bolt pre-tensions (75, 137.5, 150, and 225 kips). These capacities were compared to the maximum loads and moments for each hurricane environment and load direction. A Clamp Capacity / Max Load ratio of less than 1 indicates that the configured clamp capacity is exceded for that failure mode. Note there were no instances where the clamp capacity was exceeded due to bolt shear. This does not imply that this failure mode is not possible, but it is only an indication that the capacity was not exceeded for the particular clamp used.

Values for the ratios of Clamp Capacity / Max Loads for all three failure modes are shown in Table 11 for the TLP and Table 12 for the Spar for 10-year, 100-year, and hurricane Ivan conditions.

Figures 9 and 10 show plots of the ratios of Clamp Capacity / Max Load for the Slip and Tensile Bolt Failure modes for the TLP derrick and substructure clamps in 100-year, and hurricane Ivan conditions. Figures 11 and 12 show similar plots for the Spar. The Clamp Capacity / Max Load ratio value of 1 is emphasized in the figures.

Table 11. TLP Results - Clamp Capacity/Max Load for Failure Mode, Environment, and Location

Environment		Derrick									Substructure								
		Failure Modes									Failure Modes								
		Slip				Bolt Shear	Bolt Tension				Slip				Bolt Shear	Bolt Tension			
	Bolt Pre-Tension (kips)	75	137	150	225		75	137	150	225	75	137	150	225		75	137	150	225
	Coeff of Friction																		
Ivan	0.1	**1.0**	1.6	1.8	2.6						**0.7**	1.1	1.1	1.5					
	0.3	2.9	4.9	5.3	7.7	10.9	4.6	2.9	2.6	0.6	2.2	3.2	3.4	4.6	5.5	4.9	3.1	2.7	**0.6**
	0.5	4.9	8.2	8.9	12.9						3.7	5.4	5.7	7.7					
100 yr	0.1	1.2	1.9	2.1	3.0						**0.9**	1.2	1.3	1.8					
	0.3	3.5	5.9	6.4	9.2	13.0	7.4	4.7	4.2	1.0	2.5	3.7	3.9	5.3	6.3	10.4	6.7	5.9	1.4
	0.5	5.8	9.8	10.6	15.3						4.2	6.2	6.5	8.8					
10 yr	0.1	2.1	3.5	3.8	5.5						1.6	2.3	2.4	3.3					
	0.3	6.3	10.6	11.4	16.6	23.2	100.0	100.0	100.0	100.0	4.7	6.9	7.3	9.9	11.2	100.0	100.0	100.0	100.0
	0.5	10.5	17.6	19.1	27.7						7.9	11.5	12.2	16.4					

Table 12. Spar Results - Clamp Capacity/Max Load for Failure Mode, Environment, and Location

Environment		Upper Derrick									Substructure								
		Failure Mode									Failure Mode								
		Slip				Bolt Shear	Bolt Tension				Slip				Bolt Shear	Bolt Tension			
	Bolt Pre-Tension (kips)	75	137	150	225		75	137	150	225	75	137	150	225		75	137	150	225
	Coeff of Friction																		
	0.1	**0.7**	1.2	1.3	1.9						**0.4**	**0.5**	**0.6**	**0.8**					
Ivan	0.3	2.1	3.6	3.9	5.6	7.9	3.2	2.0	1.8	**0.4**	1.1	1.6	1.7	2.3	2.6	1.9	1.2	1.1	**0.2**
	0.5	3.5	5.9	6.4	9.3						1.8	2.6	2.8	3.8					
	0.1	**0.9**	1.5	1.6	2.2						**0.5**	**0.7**	**0.7**	**1.0**					
100 yr	0.3	2.7	4.5	4.8	7.0	9.8	4.2	2.7	2.4	**0.6**	1.4	2.0	2.1	2.9	3.3	2.9	1.8	1.6	**0.4**
	0.5	4.4	7.4	8.0	11.6						2.3	3.4	3.6	4.8					
	0.1	1.8	3.0	3.2	4.6						**0.9**	1.3	1.3	1.8					
10 yr	0.3	5.3	8.9	9.6	13.9	19.6	18.7	12.0	10.6	2.4	2.6	3.8	4.0	5.4	6.0	11.9	7.6	6.7	1.5
	0.5	8.8	15.0	16.0	23.2						4.3	6.3	6.7	9.0					

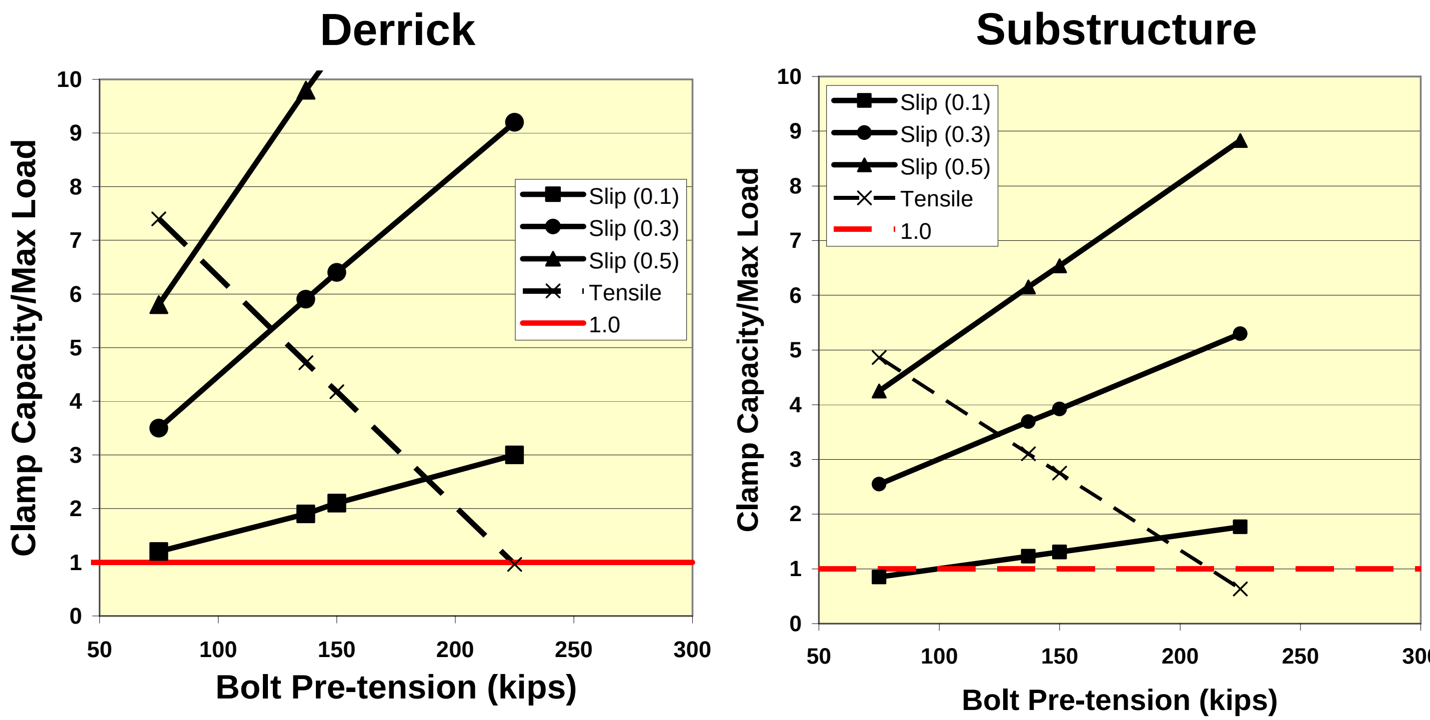

Figure 9. TLP in 100-year Hurricane Conditions: Clamp Capacity vs. Max Load for Tie-Down Clamps for Derrick and Substructure

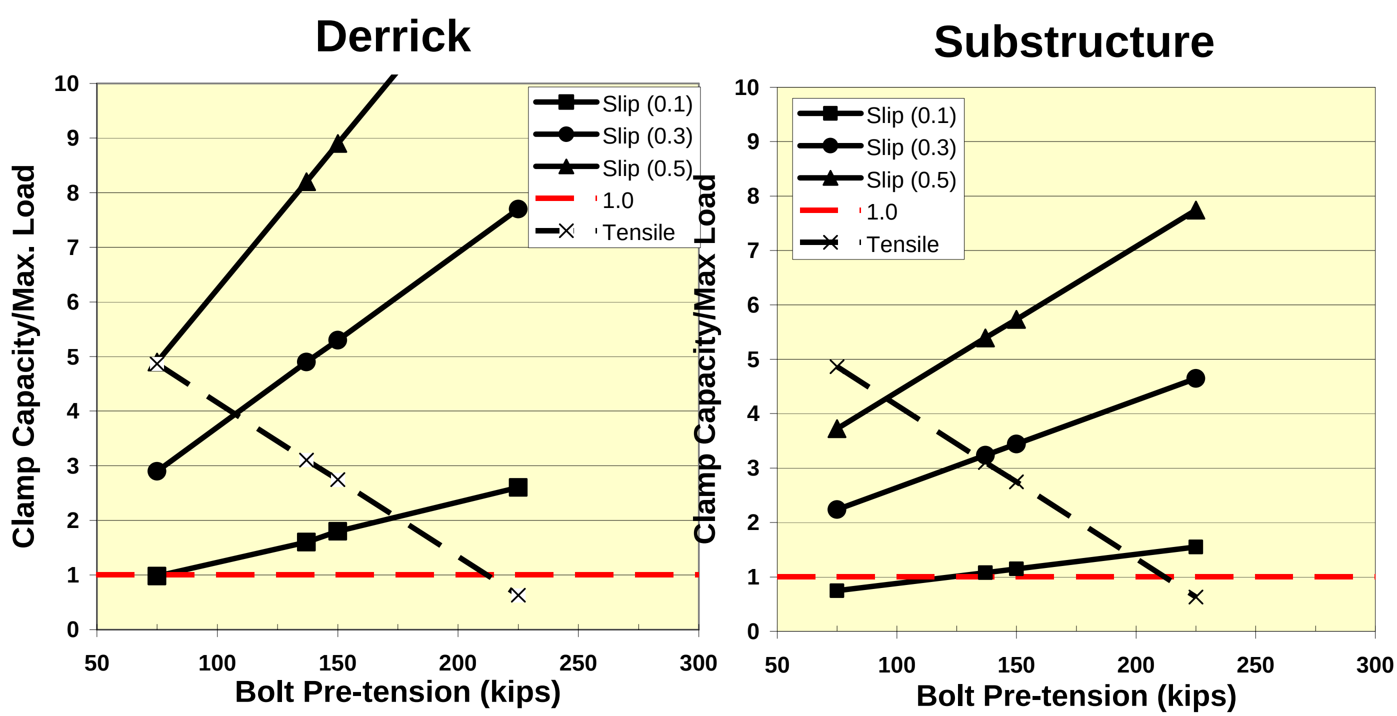

Figure 10. TLP in Hurricane Ivan Conditions: Clamp Capacity vs. Max Load for Tie-Down Clamps for Derrick and Substructure

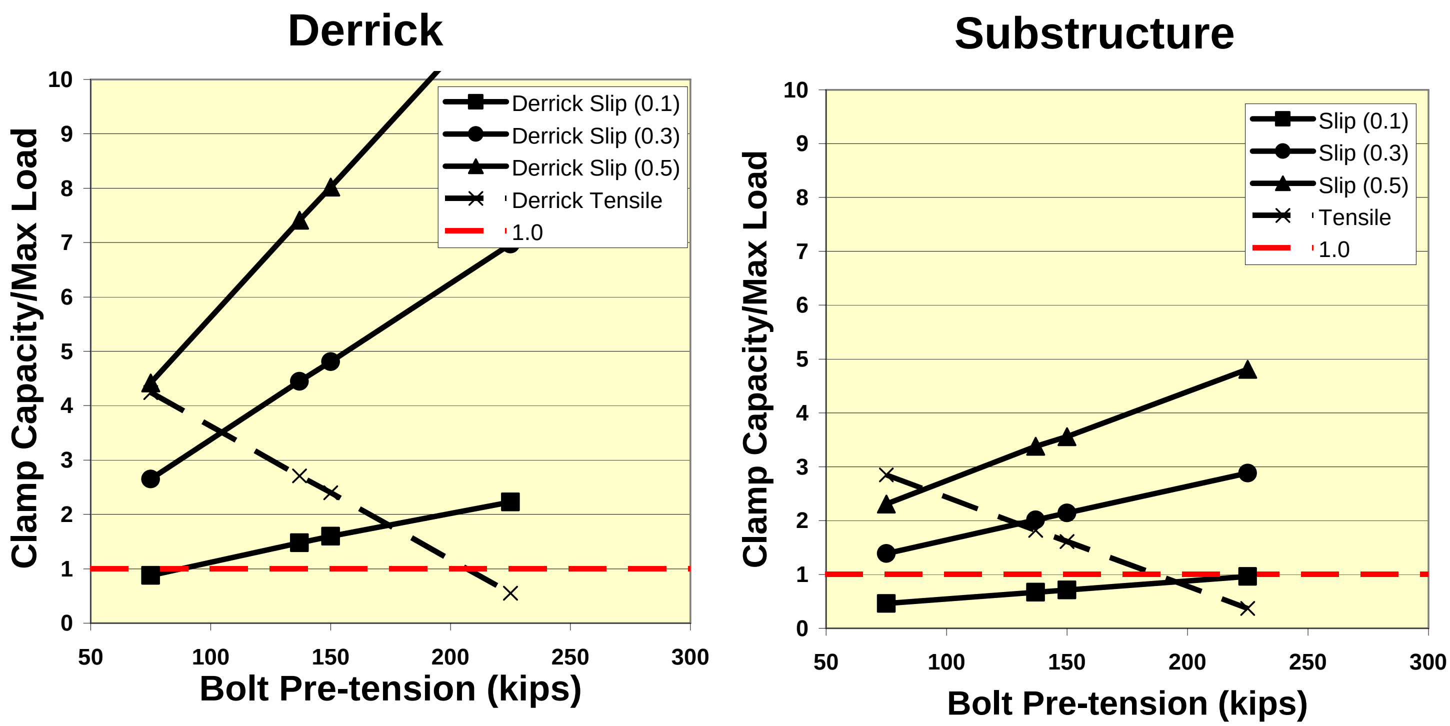

Figure 11. Spar in 100-year Hurricane Conditions: Clamp Capacity vs. Max Load for Tie-Down Clamps for Derrick and Substructure

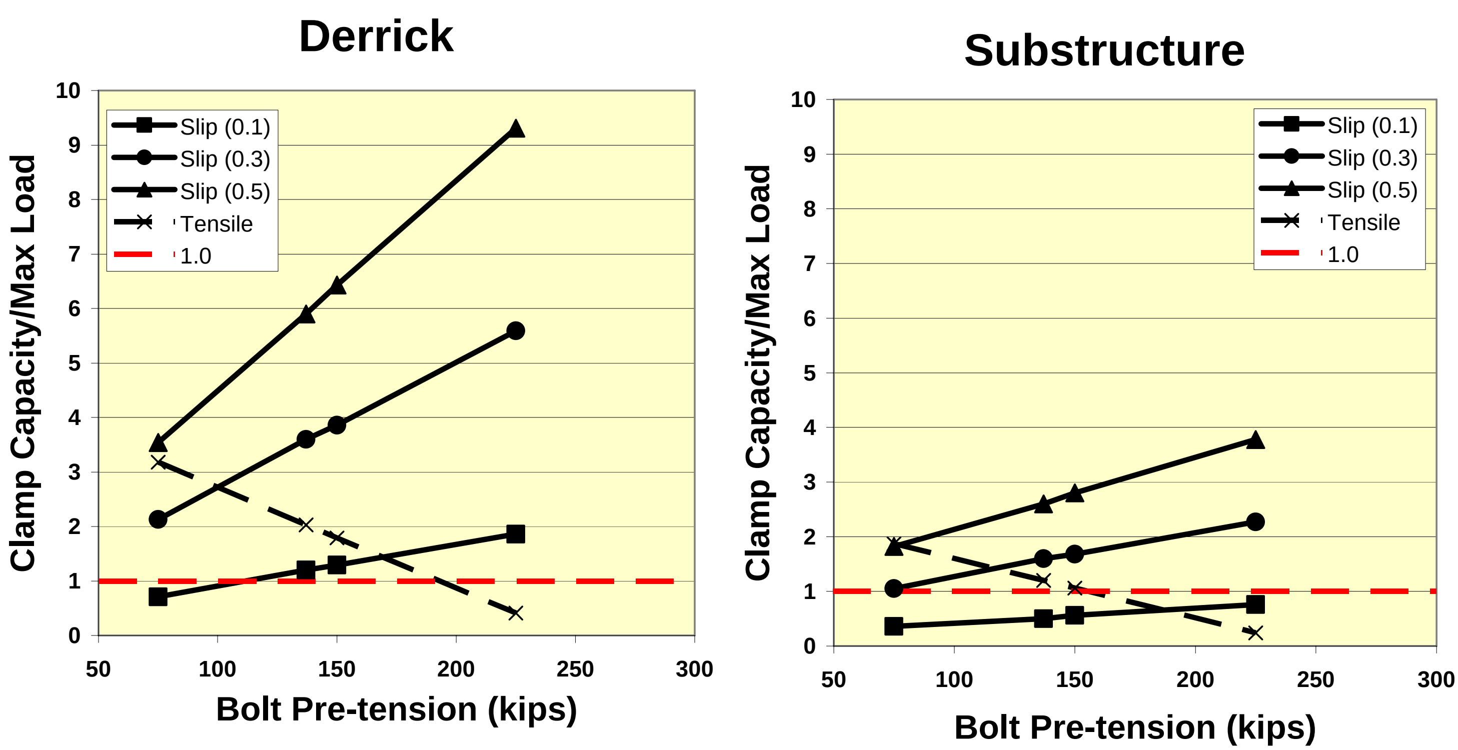

Figure 12. Spar in Hurricane Ivan Conditions: Clamp Capacity vs. Max Load for Tie-Down Clamps for Derrick and Substructure

Some basic characteristics of the relationship between the failure modes are apparent in all the Figures 9 - 12. The clamp's capacity to resist sliding increases with the coefficient of friction. As the bolt pre-tension increases the clamp's capacity to resist sliding also increases. But as the bolt pre-tensions increase, tensile failures of bolts can cause the clamp capacity to be exceeded due to uplift forces before sliding would occur. Thus there needs to be a balance between consideration of sliding failures and tensile bolt failures when designing or securing a clamp.

Recall that the same clamp was used in this study for both the TLP and the Spar, and for both the derrick and the substructure. It is instructive to examine the implications of this.

For both the TLP and the Spar, the Clamp Capacity / Max Load ratios were smaller for the substructure clamps than for the derrick clamps for both sliding and bolt tension failures. This is principally due to larger inertial loads on the substructure clamps due to the combined masses of the substructure plus the deck.

The Clamp Capacity / Max Load ratio for the TLP were always higher than corresponding cases for the Spar. This was due to the higher inertial loads on the clamps due to the larger accelerations of the Spar.

Approximate Estimates of Acceleration (API 4F)

Table 13 below compares acceleration computed from the time series simulations of the structure motions with those estimated from the approximations given in API 4F.

Table 13. Comparison of Max. Total Accelerations at the Derrick and Substructure CGs as Calculated from the Time Series Analyses and API 4F Methodology

Environment	Max. Total Accelerations @ Derrick CG (accel/g)				Max. Total Accelerations @ Substructure CG (accel/g)			
	Time Series		API 4F		Time Series		API 4F	
	TLP	Spar	TLP	Spar	TLP	Spar	TLP	Spar
10-year	0.130	.216	.096	0.223	0.125	.207	.095	0.220
100-year	0.200	.393	.197	0.417	0.194	.378	.197	0.405
Ivan	0.253	.508	.237	0.503	0.246	.490	.236	0.516

The API 4F approximations for accelerations are within about 5 percent of those predicted by the time series analysis. For the TLP, the API 4F underestimates the accelerations by a factor of approximately 25 percent.

Discussion

As mentioned in the Introduction, there were three cases in which sea fastenings failed to prevent a drilling rig from moving during hurricane Ivan (reference 1,2). We were able to gather some information on the rig movements on Shell's Ram Powell TLP and Murphy's Medusa Spar. Because we were not able to gather sufficient data to allow a detailed study of any of these cases, we conducted the study of a hypothetical TLP and Spar with a drilling rig to study the performance of a simple bolted clamp tie down system.

While the TLP and Spar studied here were different than Ram Powell and Medusa, it is still interesting to compare the hypothetical TLP with Ram Powell's performance, and the hypothetical Spar with Medusa's performance.

The derrick and drill floor on the Ram Powell TLP were moved during hurricane Ivan, but it was not toppled and remained onboard partially due to the rig impacting process equipment on the deck (reference 4). Ram Powell was located just east of Ivan's track, and the eye of the storm likely passed over Ram Powell. Hindcast values for the maximum hindcast significant wave was 52 ft and the maximum windspeed was 88 kts (30 min average at 10 m elevation). Shell reported that the derrick and drill floor skidded 60 ft along the skid beams until it became wedged against a field gas compressor. Shell concluded that the bolts for the clamps were not properly torqued. Figure x for the TLP and derrick studied here suggests that a combination of low torque and low coefficient of friction could lead to a sliding failure during Ivan conditions.

The Medusa derrick and substructure on Medusa were toppled during Hurricane Ivan. Murphy reported that the measured maximum wave height on Medusa was 72 ft (significant wave height of 41 ft) and the maximum wind speed was73 knots. Their studies indicated that the skid base slid relative to the deck and the rig slid off its skid beams into the sea 1 to 2 hours earlier when the wave heights and winds were lower. Platform motions were well within design limits throughout the storm. Murphy and Nabors concluded that while the clamp was able to prevent the rig from being blown over, it was not able to prevent sliding. Their findings are not inconsistent with the results of the Spar and drilling rig studied here in that Figure x for the Spar derrick and substructure studied here indicate that sliding of both the derrick and substructure cold occur in 100-year conditions.

Conclusions & Recommendations

Inertial Loads on Tie-Down Clamps

The performance of tie-down clamps for a drilling rig on a TLP and Spar subjected to a in a range of hurricane environments was analyzed. The same tie-down clamps were used to secure the drilling rig to the substructure, and the substructure to the deck for both structures. The loads on the tie-down clamps are due to weight, wind loads and inertial loads due to the motions of the FPS.

The results of this study show that the loads that tie-down clamps must resist can be significantly different for

- the TLP and a Spar
- the derrick and the substructure

The differences in clamp tie-down loads for the TLP and Spar are due to the differences in the inertial loads that result from the different motion characteristics of the two FPSs.

The differences between the clamp tie-down loads for the derrick and the substructure are due to the differences in acceleration of their CGs (due to location, i.e., elevation) and the masses of the derrick and the derrick plus the substructure. The total loads on the clamps for the substructure will always be greater that those for the derrick alone.

These results illustrate that clamps should be purpose-designed for the specific FPS’s motions and function. In the case of a different drilling rig being transferred to another structure, the clamps should be assessed to ensure that they can resist the loads imposed by the new combination of different wind and inertial (masses and accelerations) loads.

Bolted Tie-Down Clamps

Sliding and bolt tensile failures are the most important failure modes for bolted tie-down clamps.

Sliding – Clamp failure in slip is resisted by friction, which is dependent upon the coefficient of friction, weight of the derrick and the substructure, and the bolt clamping forces. There is uncertainty in the static and dynamic coefficients of friction that would be effective during hurricane conditions because of the condition of surfaces of the clamp faces and skid beam surfaces, e.g.,

- surface rust and oxidation
- the presence of lubricants used during rig skidding operations
- general cleanliness (presence of drilling mud, lubricants, dirt
- wetness due to rain and spray during a hurricane

This uncertainty in the coefficient of friction should be accounted for in the design of the clamps. Additional clamping forces may be generated by more pre-tension on the bolts (but see discussion below).

Positive stops along the skid beams that could arrest sliding in shear (e.g., shear pins in predrilled regularly spaced holes in the skid beams) might also be considered as a means to arrest movement in the event of clamp slippage.

Tensile Bolt Failure – Tensile bolt failures occur when the sum of the bolt's pre-tension and the tension caused by uplift forces on the clamp exceed the bolt's tensile capacity. Tensile bolt failure can lead to the loss of clamp's capacity to prevent slipping or uplift. It is expected that the tensile failure of the first bolt in a clamp would lead to the progressive failure of the remaining bolts in the clamp.

Bolt pre-tension is also the means for increasing the clamp's resistance to sliding. The design of a clamp must balance the bolt pre-tension to provide the necessary amount of friction to prevent sliding and yet leave sufficient tensile capacity to resist the expected uplift forces. This design bolt pre-tension must be carefully and accurately applied when preparing for a hurricane and should not be exceeded. It is important to note that a change in the drilling rig live loads prior to a hurricane can also significantly change the bolt pre-tensions. For example, a reduction in drilling fluids or pipe in the setback can increase the bolt pre-tension and affect the capacity of the clamps.

Hull Accelerations

API Specification 4F presents an approximate method for estimating accelerations for use in computing the inertia loads for tie-down clamp design. The results of this study indicate that the accelerations may not provide accurate estimates of accelerations for all FPSs or motion components. Vessel motions and acceleration used in the design should be the preferred basis for tie-down clamp design.

Acknowledgements

We would like to acknowledge the support of the Minerals Management Service. In addition to MMS funding the project, Mr. Tommy Laurendine arranged for us to visit a number of FPS's to examine rig tie-down systems and discuss operational issues with platform staff, which added great value to this study.

A number of industry personnel also provided valuable advice and information. We would like particularly to thank the following: George Rodenbusch, Randy Abadie and Bill Pritchett (Shell), Paul Fourchy (Murphy); George King (Nabors); Tom VonAschwege and Pierre Beynet (BP); and Lynn LeJune (Technip)**,**

References

1. Assessment of Drilling & Workover Rig Storm Sea Fastenings on Offshore Floating Platforms during Hurricane Ivan Phase 1: Data Collection Report, by E.G. Ward and J.M. Gebara, August 1, 2006

2. Assessment of Storm Sea Fastenings for Drilling and Workover Rigs on Floating Production Systems during Hurricane Ivan: Phase 1, E. G. Ward (OTRC) and J. M. Gebara, Technip Offshore Inc. (USA), 2006 Offshore Technology Conference, Paper 18324

3. American Petroleum Institute, "Specification for Drilling and Well Servicing Structures", API Specification 4F, Second Edition, June, 1995.

4. Shell's Experience with Hurricane Ivan, George E. Sgouros, Ph. D., P.E., William M. Pritchett, P.E., Dennis R. Schafer, Douglas L. Jones – Shell Exploration and Production Company, EP – Americas, 2005 Offshore Technology Conference, Paper17733

Appendix A

Assessment of the Performance of Tie-Down Clamps for a Drilling Rig on a Spar in Severe Hurricane Environments

J. Gebara
N. Ghoneim

Technip USA Inc.

January 2007

TECHNIP OFFSHORE, INC.

INTERNAL MEMORANDUM

Dept.

Our Ref.

303859-IM-0001

Date : 15/01/2007

To : Joe Gebara

From : Nadia Ghoneim, Michael Szczglowski

Subject : MMS Rig Tie Down Study: Structural Analysis of Clamped Connections for Spar drilling and workover rigs, and a comparison of Spar and TLP rig tie-downs.

TECHNIP OFFSHORE, INC.

INTERNAL MEMORANDUM

Dept.

Our Ref.

303859-IM-0001

Date : 15/01/2007

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1. INTRODUCTION AND SCOPE OF WORK

This document pertains to the MMS Study of Rig Tie-Down with particular focus on Spar drilling and workover rigs and on comparing spar and TLP rig tie-downs. It presents a comparative analysis for acceleration calculations based on 2 different approaches and the structural analysis of the capacity of upper derrick and substructure clamped connections.

The scope of the analysis includes:

1- Calculating accelerations based on API-4F (Ref. 1) specifications at CG. of upper derrick and CG. of substructure for 10-year, 100-year and Ivan environmental criteria and comparing results with accelerations derived from Time Domain analysis (Ref.2).
2- Developing rigid models comprising the upper derrick and substructure masses and extracting the 6 DOF reactions resulting from API-4F loading as well as loading based on Time Domain accelerations for the above load cases.
3- Calculating ultimate capacities of clamped connections with respect to lateral loads (taking into account 3 different coefficients of friction) and vertical (tension) loads.
4- Comparing connections actual loading to corresponding ultimate capacities and determining factors of safety for all load cases.
5- Summarizing the results to provide an overview of the status of the clamped connection with respect to various bolts modes of failure.

The analysis is performed with the aid of STRUCAD*3D Version 4.3 finite element software One model representing the derrick mass of 550 kips and a second model combining the derrick mass and substructure mass of 1500 kips were developed. The boundary conditions for all the support joints are fixed. The models include wind loading on the structure as well as dynamic loading.

Forces due to wind and dynamics are applied in three directions, Pitch (X) direction; Roll (Y) direction and at 45^{o} angle where Pitch & Roll are combined The importance of the latter case is to determine the maximum tensile forces to which the connection bolts may be subjected.

Two cases of wind loading are investigated:

1- API-4F recommended 107 knots minimum wind loading, applied to all load cases.
2- According to Time Domain analysis: 87.9 knots wind loading for Ivan hurricane, 81.3 knots wind loading for 100-year hurricane and 50.9 knots wind loading for 10-year hurricane.

In addition, this document includes results of a similar analysis performed using Inertia loads derived for TLP rigs. Comparative results of Spar & TLP rig tie-down clamp connections draw attention to the specific sea fastening requirements of rigs on different offshore floating systems.

An overview of the structure geometry and dimensions employed in the analysis is shown in Figure 1. Details of the analysis performed are provided and a summary of the analysis findings is also included at the end of this document.

The analysis demonstrates the conservatism of the API-4F approach for dynamic loading calculations for Spar rigs and the vulnerability of the Spar drilling and workover rig clamps to slip and tensile failures compared to the TLP rig tie down.

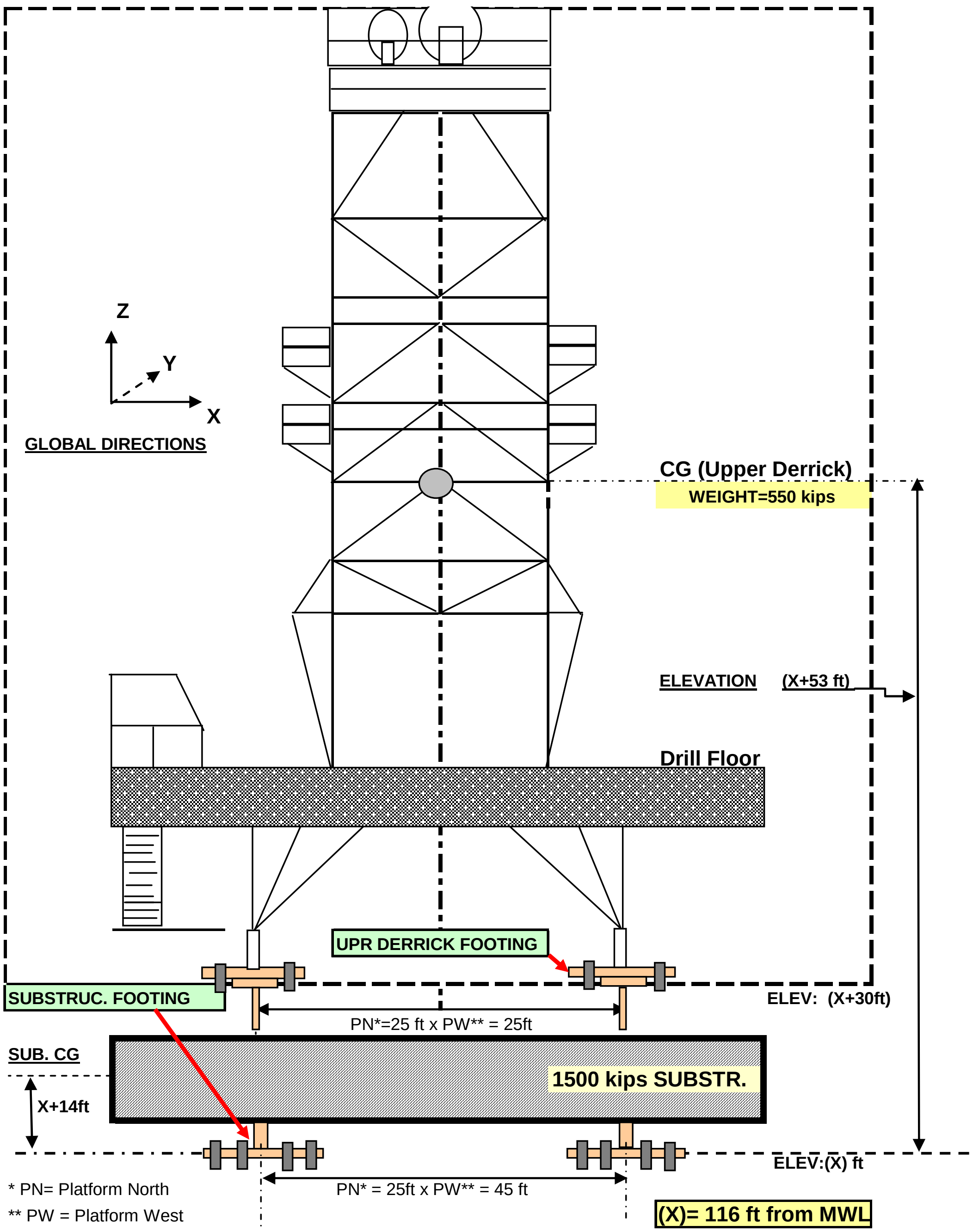

Figure 1 Structure General Arrangement

2. API-4F ACCELERATION CALCULATIONS

Information pertaining to accelerations details required to determine dynamic loading on the structure for three different load cases are obtained from the Spar Motion Analysis Memo (303859-IM-0001, Rev A) and summarised in the following Tables.

Table 1 Motion Details

LOAD CASE	MOTION	AMPLITUDE	PERIOD	HEAVE		LIST
		Φ* (degree)	T (sec)	H** (ft)	T (sec)	α (degree)
10 yh	ROLL	1.2	11.25	1.7	17.82	3.2
	PITCH	1.2	11.25			
100 hwv	ROLL	2.2	12.26	5.8	18.66	8.4
	PITCH	2.2	12.26			
Ivan	ROLL	3.1	13.02	9.1	18.74	10.8
	PITCH	3.1	13.02			

* Single Amplitude

** Double Amplitude

Table 2 Translational (Lateral) Accelerations at Spar CG.

	SURGE & SWAY	
CASE STUDY	SURGE (X) (g)	SWAY (Y) (g)
10yh	0.0830	0.0830
100hwv	0.1240	0.1240
Ivan	0.1540	0.1540

g= 32.2 ft/sec2

Table 3 Distance from centre of Masses to Spar CG.

DISTANCE FROM SPAR CG TO	
UPPER DERRICK* CG. (ft)	SUBSTRUCTURE** CG. (ft)
346	307

*** Distance=177ft+116ft+53ft=346ft**
****Distance=177ft+116ft+14ft=307ft**

The above motion details are employed to calculate the translational (lateral) and rotational accelerations at the CG. of the upper derrick and CG. of the substructure in accordance with API-4F specifications.

ROTATIONAL ACCELERATION DUE TO ROLL OR PITCH:

$$\text{ACCEL.} = \frac{4\Pi^2 x \Pi \Phi}{T^2 x 180} \qquad \Pi = 3.14 \qquad \boxed{\text{ACCEL} = 0.6880\ \frac{\Phi}{T^2}}\ \text{rad/sec}^2 \qquad \text{.....Eq (1)}$$

Table 4 API-4F Calculated Rotational Accelerations

ROTATIONAL ACCEL		rad/sec^2
10yh	ROLL	0.0065
	PITCH	0.0065
100hwv	ROLL	0.0101
	PITCH	0.0101
Ivan	ROLL	0.0126
	PITCH	0.0126

ACCELERATIONS DUE TO LIST (HEEL):

α^o= **LIST ANGLE** $\boxed{\text{ACCEL} = \sin\alpha^o}$ **(g)** **.....Eq (2)**

Table 5 Accelerations Due to Heel (List)

LOAD CASE	ACCELER.=sinα		ACCEL. (g)	
10yh	α^o=	3.2	sinα=	0.056
100hwv	α^o=	8.4	sinα=	0.146
Ivan	α^o=	10.8	sinα=	0.187

In the following Tables (Tables 6 & 7), the "Total Translational" (lateral) accelerations are calculated as follows at derrick and substructure CG. for Pitch & Roll directions respectively,

Pitch direction (X):
Total Acceleration= List accel. (Table 5) + (accel. due to weight+ accel. due to Surge+ accel. due to Pitch (Tables 6&7))

Roll direction (Y):
Total Acceleration= List accel. (Table 5) + (accel. due to weight+ accel. due to Sway+ accel. due to Roll (Tables 6&7))

TOTAL TRANSLATIONAL ACCELERATIONS
UPPER DERRICK

g= 32.2 ft/sec2

Center of Derrick at: L1= 346 ft from Center of Rotation

Table 6 API-4F Total Translational Accelerations at Upper Derrick CG.

LOAD CASE	a_w= WGHT. COMP. ACCEL=			sinΦ	(g)	SWAY= a_Y (g)	SURGE= a_X (g)	AT C.G of DERRICK* a_R (g)	a_P (g)	LIST= a_L (g)	TOTAL** (g)
10yh	ROLL (Y)	Φ=	1.2	sinΦ=	0.021	0.0830		0.0701		0.056	0.230
	PITCH (X)	Φ=	1.2	sinΦ=	0.021		0.0830		0.0701	0.056	0.230
100hwv	ROLL (Y)	Φ=	2.2	sinΦ=	0.038	0.1240		0.1082		0.146	0.417
	PITCH (X)	Φ=	2.2	sinΦ=	0.038		0.1240		0.1082	0.146	0.417
Ivan	ROLL (Y)	Φ=	3.1	sinΦ=	0.054	0.1540		0.1352		0.187	0.531
	PITCH (X)	Φ=	3.1	sinΦ=	0.054		0.1540		0.1352	0.187	0.531

* Translational Accel. At CG of Upper Derrick (g)= Rotational Accel (rad/sec^2)xL1(ft) / g(ft/sec^2)

** Total Accel. (X)= Σ (a_W + a_X+ a_P + a_L) Total Accel. (Y)= Σ (a_W + a_Y + a_R + a_L)

SUBSTRUCTURE

Center of Substruc. at: L= 307 ft from Center of Rotation

Table 7 API-4F Total Translational Accelerations at Substructure CG.

LOAD CASE	a_w= WGHT. COMP. ACCEL=			sinΦ	(g)	SWAY= a_y (g)	SURGE= a_x (g)	AT C.G of SUBSTR.* a_R (g)	a_P (g)	LIST= a_L (g)	TOTAL** (g)
10yh	ROLL (Y)	Φ=	1.2	sinΦ=	0.021	0.0830		0.0622		0.056	0.222
	PITCH (X)	Φ=	1.2	sinΦ=	0.021		0.0830		0.0622	0.056	0.222
100hwv	ROLL (Y)	Φ=	2.2	sinΦ=	0.038	0.1240		0.0960		0.146	0.404
	PITCH (X)	Φ=	2.2	sinΦ=	0.038		0.1240		0.0960	0.146	0.404
Ivan	ROLL (Y)	Φ=	3.1	sinΦ=	0.054	0.1540		0.1199		0.187	0.515
	PITCH (X)	Φ=	3.1	sinΦ=	0.054		0.1540		0.1199	0.187	0.515

* Translational Accel. At CG of Sub. (g)= Rotational Accel (rad/sec^2)xL(ft) / g(ft/sec^2)

** Total Accel. (X)= Σ (a_W + a_X+ a_P + a_L) Total Accel. (Y)= Σ (a_W + a_Y + a_R + a_L)

ACCELERATIONS DUE TO HEAVE

g= 32.2 ft/sec^2

ACCEL= $\frac{2\Pi^2 H}{gT^2}$

$$\boxed{\text{ACCEL}= 0.6124\ \frac{H}{T^2}}\ \text{(g)} \qquad \text{.....Eq (3)}$$

Table 8 API-4F Calculated Heave Accelerations

LOAD CASE	ACCELERATION
10yh	0.0033 g
100hwv	0.0102 g
Ivan	0.0159 g

ACCELERATIONS COMPARISON

Tables 9 & 10 summarise the final results for accelerations at the CG. Of upper derrick and at the CG. of substructure derived from two approaches: API-4F specifications and Time Domain analysis.

Table 9 Summary of API-4F Accelerations

API-4F ACCELERATIONS						
LOAD CASE	ROTATIONAL		LATERAL			HEAVE (g)
	DIRECTION	API-4F rad/sec2	DIRECTION	AT CG. DERRICK (g)	AT CG. SUBS. (g)	
10yh	ROLL (Y)	0.0065	(Y)	0.230	0.222	0.0033
	PITCH (X)	0.0065	(X)	0.230	0.222	
100hwv	ROLL (Y)	0.0101	(Y)	0.417	0.404	0.0102
	PITCH (X)	0.0101	(X)	0.417	0.404	
Ivan	ROLL (Y)	0.0126	(Y)	0.531	0.515	0.0159
	PITCH (X)	0.0126	(X)	0.531	0.515	

Table 10 Time Domain Accelerations

TIME DOMAIN ANALYSIS					
	MAX. LATERAL ACCEL.			HEAVE AT TIME MAX. LAT. ACCEL.	
LOAD CASE	DIRECTION	AT CG. DERRICK (g)	AT CG. SUBS. (g)	AT CG. DERRICK (g)	AT CG. SUBS. (g)
10yh	(Y)	0.2160	0.2070	0.003	0.003
	(X)	0.2160	0.2070		
100hwv	(Y)	0.3930	0.3780	0.003	0.003
	(X)	0.3930	0.3780		
Ivan	(Y)	0.5080	0.4900	0.015	0.015
	(X)	0.5080	0.4900		

The above results indicate that the accelerations calculated based on API-4F specifications are consistently more conservative when compared with those from Time Domain Analysis.

The API-4F lateral accelerations exceed those from Time Domain Analysis by 4.5% to 6.5%. In the case of vertical acceleration, the API-4F 100 YR heave value exceeds that from Time Domain Analysis by nearly 2.5 times when compared to the acceleration associated with the maximum lateral accelerations.

3. SAMPLE CALCULATIONS OF WIND AND DYNAMIC LOADING

As described previously, reactions at the footings of the upper derrick & substructure are derived from a combination of wind and dynamic loading on the structure. Loading applied at a 45^{o} angle incorporates all dynamic components & the highest wind surface exposure.

In this section a sample calculation is provided to demonstrate the applicability of the API-4F procedure. This calculation is based on Ivan dynamic loading on the upper derrick and a wind velocity of 107 knots. The derrick supports are assumed to be pinned (rotations allowed) to simplify hand calculations.

Other information pertaining to force and reactions calculations is the wind projected area. The projected area of upper derrick is 1470 ft^2 and CP at 201 ft from MWL.

The analysis in the following sections is based on an estimated wind area for substructure of 500 ft^2 and the centre of pressure is assumed to coincide with the centre of gravity.

A summary of wind Area and CP for API-4F force calculations for upper derrick is provided in the following Table:

Table 11 Upper Derrick Wind Projected Area

A	PROJECTED AREA	(API-4F)[a] PROJECTED AREA	CP[b]	DIRECTION
		UPPER DERRICK		
A_{1X}	1470.0 ft2	2940.0 ft2	201 ft	**X**
A_{1Y}	1470.0 ft2	2940.0 ft2	201 ft	**Y**
$A^{c}_{1\text{-}45^{o}}$		4157.8 ft2	201 ft	**45^{o} ANGLE**

a: Exposed Areas of two opposite sides (API-4F Section 7.2.1)
b: Distance from MWL to center of wind Area
c: A_1-45^{o}= Square Root of Sum of Squares of Areas in (X) & (Y) Directions

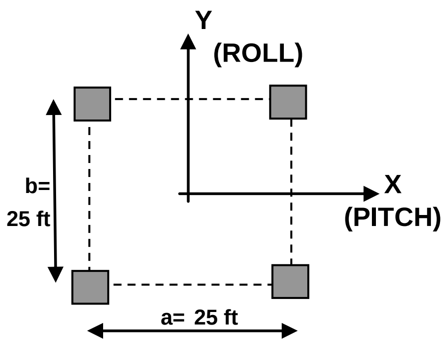

Figure 2 Upper Derrick Footings Projection

Derrick Reaction Forces Due to Weight

Total Derrick weight=	550	kips
Total No of Clamped Connections =N=	4	
Reaction Force per Con. (due to weight)=	**137.5**	**kips**

Derrick Reaction Forces due to Wind Loading

API-4F Min. Design Wind Velocity= 107 knots

Y-DIRECTION

Wind Velocity= V =	107 knots		
Height* Co.=	C_h=	1.37	(for Height= 201 ft)
Shape Co.=	C_s=	1.25	

** Vertical distance from water surface to the center of area*

P= .00338xV^2xC_hxC_s= 66.27 lb/ft^2

Derrick Projected Wind Area= A_{1Y} = 2940.0 ft^2

F_{1Y} = Wind Loading= ((PxA_{1Y})/1000)= 194.83 kips

X-DIRECTION

F_{1X} = Wind Loading= ((PxA_{1X})/1000)= 194.83 kips

45° ANGLE-DIRECTION

Wind Loading= F_{45}= 275.5 kips

Elevation of Centre of pressure of wind area is at 201 ft from MWL
Elevation of upper derrick footings from MWL is at (116 ft +30 ft) = 146 ft

Moment Arm for Wind Force= 201ft-146 ft=h=		55.00 ft
a=	25.00 ft	
b=	25.00 ft	
$d=(a^2+b^2)^{1/2}=$	35.36 ft	

SHEAR FORCES

X-Shear Force/ Connection= $F_{1X}/N=$	48.71 kips
Y-Shear Force/ Connection=$F_{1Y}/N=$	48.71 kips
Shear Force per Connection Due to 45^o-Wind= F_{45} =	**68.88 kips**

TENSION FORCES

Tension Force per Connection Due to X-Wind= $F_{1X} \times h/(2a)=$	214.32 kips
Tension Force per Connection Due to Y-Wind= $F_{1Y} \times h/(2b)=$	214.32 kips
Tension Force per Connection Due to 45^o-Wind= $F_{45} \times h/(d)=$	**428.63 kips**

(IVAN) Dynamic Loading on Derrick

L= distance from pitch/roll axis to the center of gravity of the upper derrick
W= derrick weight= 550 kips

X-DIRECTION (PITCH)

FP= (WL/g)x(Rotational Accel)+ Wx Transl. Accel(g)= W x (Total Translational Acceleration (g))

FP= 291.83 kips X-Direction

Y-DIRECTION (ROLL)

FR= (WL/g)x(Rotational Accel)+ Wx Transl. Accel(g)= W x (Total Translational Acceleration (g))

FR= 291.83 kips Y-Direction

F at 45^o direction=$(FP^2+FR^2)^{1/2}$= 412.7 kips

Derrick Reactions Due to Dynamics

N= number of Derrick support connections=	4	
a=	25.00 ft	
b=	25.00 ft	
$d=(a^2+b^2)^{1/2}=$	35.36 ft	
Moment Arm for Dynamic Forces=H=53'-30'=		23.00 ft

SHEAR FORCES

X-Shear Force/ Clamp connection= FP/N=	72.96 kips
Y-Shear Force/ Clamp connection= FR/N=	72.96 kips
Shear Force per Clamp connec. Due to 45^o Loading=	103.18 kips

TENSION FORCES

Tension Force per Clamp connection Due to X-Loading= FPx 23/(2a)=	134.24 kips
Tension Force per Clamp connection Due to Y-Loading= FRx 23/(2b)=	134.24 kips
Tens. Force per Clamp connec. Due to 45^o-Ldng.=$((FR^2+FP^2)^{1/2})$x23/d=	268.48 kips

HEAVE LOADING

Max. Uplift due to Heave/ Clamp Connection= WxHeave Accel/N= 2.19 kips

The final reactions at the connection are obtained by adding the various loading components. These components are summarised in the following Table.

Number of Bolts per Connection=n=	8.00 bolts
Bolt Diameter= D=	2.00 in
Bolt Area= $\pi D^2/4$=	3.14 in^2

Table 12 Reactions per Single Clamp Connection at Upper Derrick Footings Level

DIRECT.	TYPE	WIND (kips)	DYNAM. (kips)	WEIGHT (kips)	HEAVE (UP) (kips)	TOT. LOAD kips	BOLT FORCE (kips)	BOLT STRESS (ksi)
X LOADING	SHEAR	48.71	72.96			121.67	15.21	4.84
	TENSION	214.32	134.24	-137.50	2.19	213.24	26.66	8.49
Y LOADING	SHEAR	48.71	72.96			121.67	15.21	4.84
	TENSION	214.32	134.24	-137.50	2.19	213.24	26.66	8.49
45^o LOADING	SHEAR	68.88	103.18			172.06	21.51	6.85
	TENSION	428.63	268.48	-137.50	2.19	561.80	70.23	22.36

From Table 12, the maximum tension force per connection for this case is 561.8 kips and the shear force amounts to 121.67 kips for each direction, X-direction & Y-direction.
In addition to demonstrating the applicability of the API-4F specifications and methodology, these numbers validate the results of the STRUCAD analysis (see section 5, Table 18).

4. CLAMPED CONNECTION CAPACITY

A schematic representation for the clamped connections under study is shown in Figure 3.

This section determines the ultimate capacity of the clamped connection with respect to 3 modes of failure for the bolts, namely slip resistance, shear and tension.

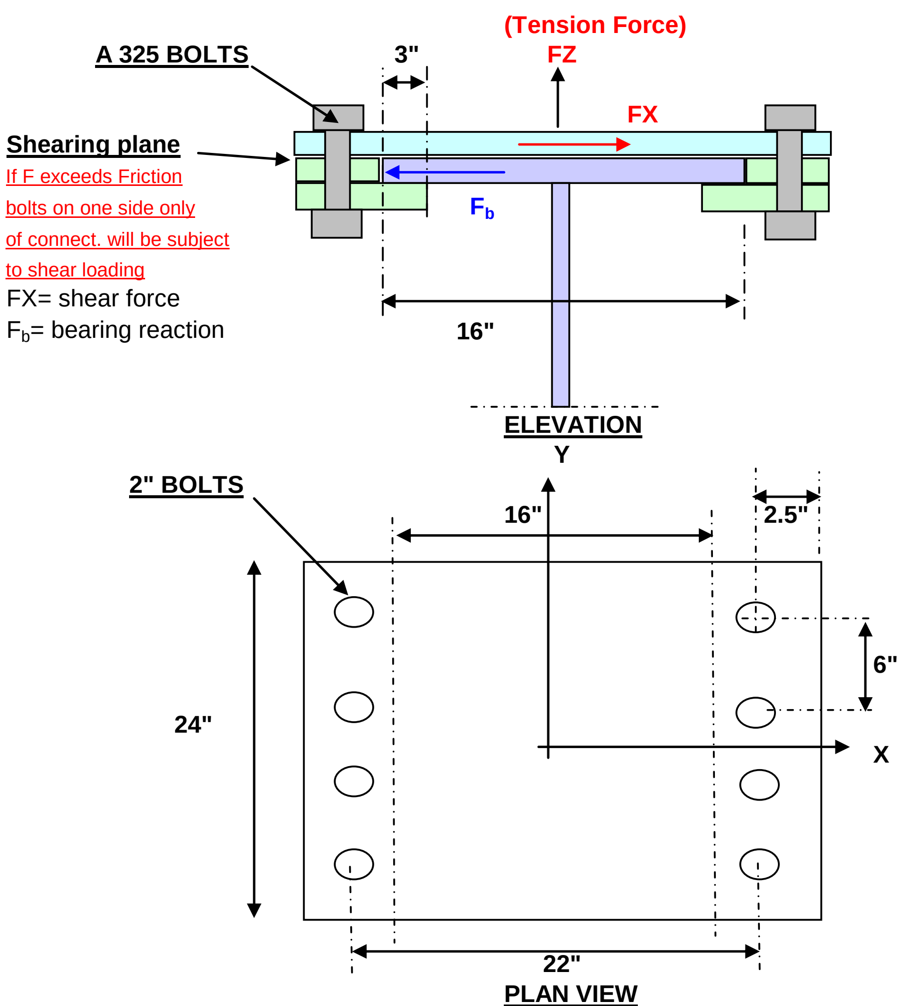

Figure 3 Clamped Connection Detail

4.1 Connection Slip Capacity

Coefficient of Friction for the Analysis (μ)	0.1	0.3	0.5

<u>BOLT PRETENSION CALCULATIONS AS FUNCTION OF TORQUE</u>

MT=0.2 D T **Then:** $\boxed{\text{T=MT/ (0.2 D)}}$ (Ref. 3)

MT= initial Bolt Torque (Lb-in)

D= nominal Bolt Diameter= 2 in

T= individal Bolt Load (Pretension) (Lb)

Table 13 Torque Value & Corresponding Bolt Pretension Load

TORQUE (MT) (lb-ft)	TORQUE (MT) (lb-in)	PRETENSION (T) (kips)
2500	30000	75
5000	60000	150
7500	90000	225

Bolt pretension creates a slip resistance force P between connected plates as shown below:

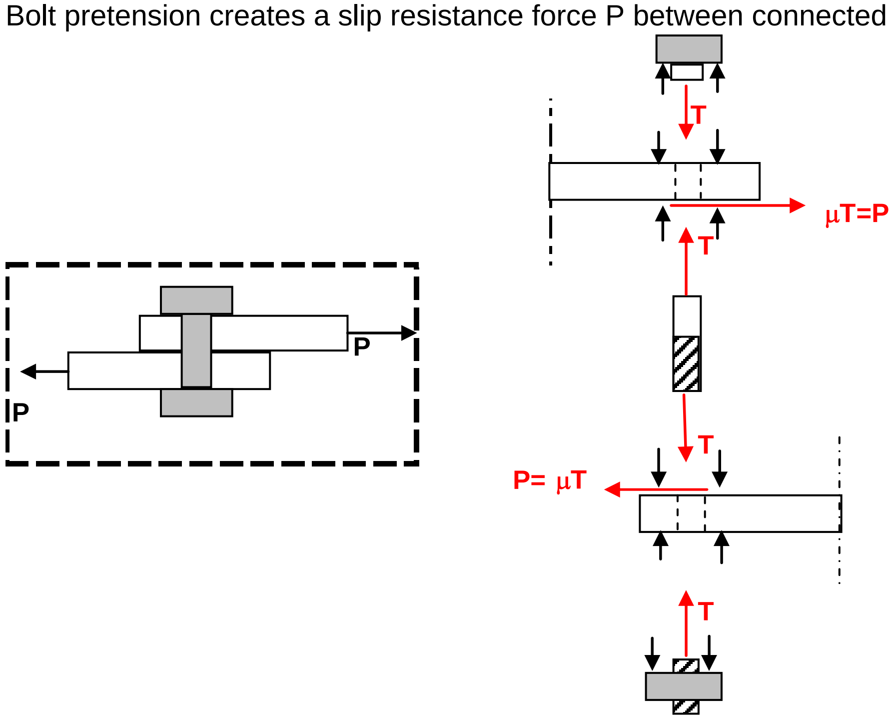

Figure 4 Typical Transfer of Load in Pretensioned High Strength Bolted Connection
Based on (Ref. 4, Chapter 4).

The Frictional resistance can be calculated from the following equation.

Frictional Resistance= Slip Capacity=	**$P=\mu T$**	………………………	**Eq. 5**
	T=	Tensile Force	
	μ=	Coefficient of Friction	

n=number of bolts per conc.=	8 bolts		
Upper Derrick weight=W1=	550 kips		
Substructure weight=W2=	1500 kips		
Total Structure weight carried by substr. footings=		W=550+1500=	2050 kips
Structure weight carried per upper derrick clamp connection=		w1=	137.5 kips
Structure weight carried per substructure clamp connection=		w2=	512.5 kips
Frictional resistance per connection due to weight=		**$\mu\ w_i=P_i$**	

Consequently, the total slip capacity of a single clamp connection is calculated for various pretension bolt load and summarised in Table 14.

Table 14 Connection Slip Capacity VS Bolt Pretension Loading

BOLT PRETENS. (T) (kips))	BOLT (TORQUE) (MT) (Lbft	COEFF. OF FRICTION μ	BOLT PRET. SLIP CAP. $\mu T=P$ (kips)	TOT. PRET. SLIP CAP. $nxP=P_T$ (kips)	SLIP CAPACITY DUE TO WEIGHT (kips) P_D DERRICK	P_S SUBSTR.	TOTAL* SLIP CAPACITY PER CLAMP CONNEC. (kips) DERRICK	SUBSTR.
75	**2500**	**0.1**	7.5	**60.0**	13.8	51.3	**73.8**	**111.3**
		0.3	22.5	**180.0**	41.3	153.8	**221.3**	**333.8**
		0.5	37.5	**300.0**	68.8	256.3	**368.8**	**556.3**
150	**5000**	**0.1**	15.0	**120.0**	13.8	51.3	**133.8**	**171.3**
		0.3	45.0	**360.0**	41.3	153.8	**401.3**	**513.8**
		0.5	75.0	**600.0**	68.8	256.3	**668.8**	**856.3**
225	**7500**	**0.1**	22.5	**180.0**	13.8	51.3	**193.8**	**231.3**
		0.3	67.5	**540.0**	41.3	153.8	**581.3**	**693.8**
		0.5	112.5	**900.0**	68.8	256.3	**968.8**	**1156.3**
137.3	**4576.7**	**0.1**	13.7	**109.8**	13.8	51.3	**123.6**	**161.1**
		0.3	41.2	**329.5**	41.3	153.8	**370.8**	**483.3**
		0.5	68.7	**549.2**	68.8	256.3	**618.0**	**805.5**

*** TOTAL SLIP CAPACITY FOR: DERRICK= P_T+P_D SUBSTRUCTURE= P_T+P_S**

NOTE: 137.3 KIPS IS THE RECOMMENDED AISC PRETENSIONFOR 2" BOLTS
CALCULATED AS A LINEAR FUNCTION BASED ON 1-1/2" BOLTS
(AISC Table J3.4).

The bolt pretension, the coefficients of friction and the resulting slip resistance capacity of the connection are interrelated and can be represented in several ways. This is demonstrated in the following.

Table 15 Pretension, Coefficient of Friction & Connection Capacity

COEF. OF FRICTION (μ)		0.1	0.3	0.5
T (kips)	MT (Lbs-ft)	CONNECT. SLIP CAPACITY P_T (kips)		
75	**2500**	60	180	300
150	**5000**	120	360	600
225	**7500**	180	540	900

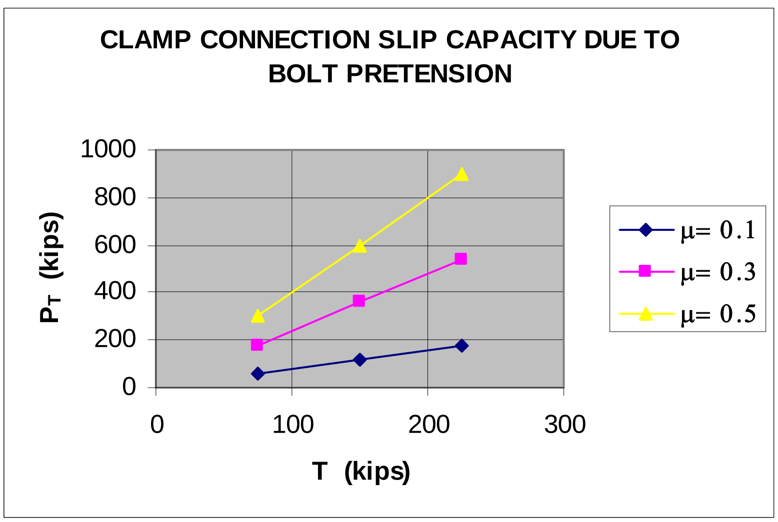

Figure 5 Bolt Pretension, Coefficient of Friction & Slip Capacity Chart

The same results can be represented as follows.

Table 16 Bolt Torque, Coefficient of Friction, Pretension and Slip Capacity

μ	MT Lb-ft **2500**	MT Lb-ft **5000**	MT Lb-ft **7500**
	T kips **75**	T kips **150**	T kips **225**
0.1	60	120	180
0.3	180	360	540
0.5	300	600	900

A graphical representation of Table 16 is shown in Figure 6.

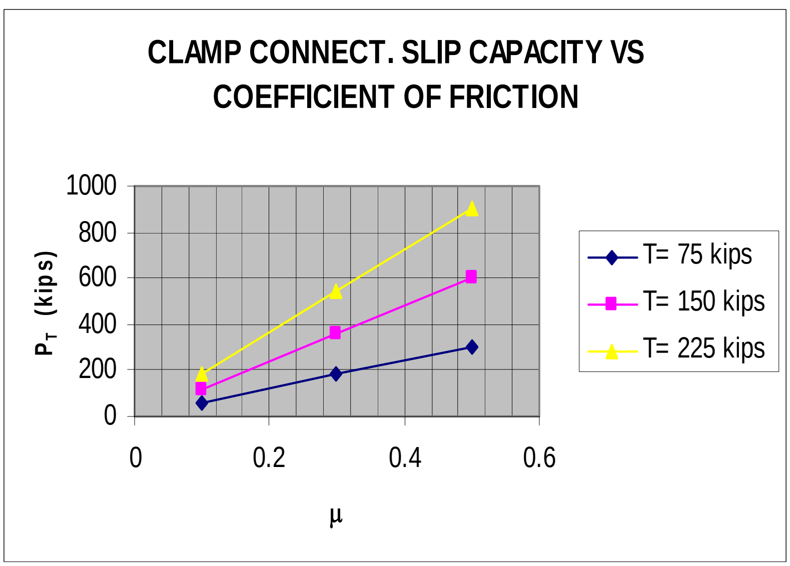

Figure 6 Connection Slip Capacity VS Coefficient of Friction Chart

Given that the structural weight adds to the slip resistance capacity of the connection, the slip resistance capacity of an upper derrick connection and that of a substructure connection are different. These capacities are graphically represented below.

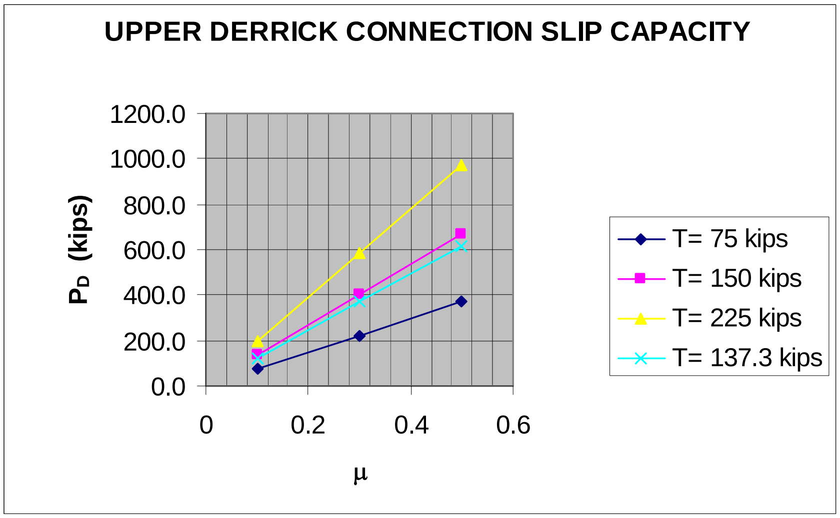

Figure 7 Upper Derrick Connection Slip Capacity Chart

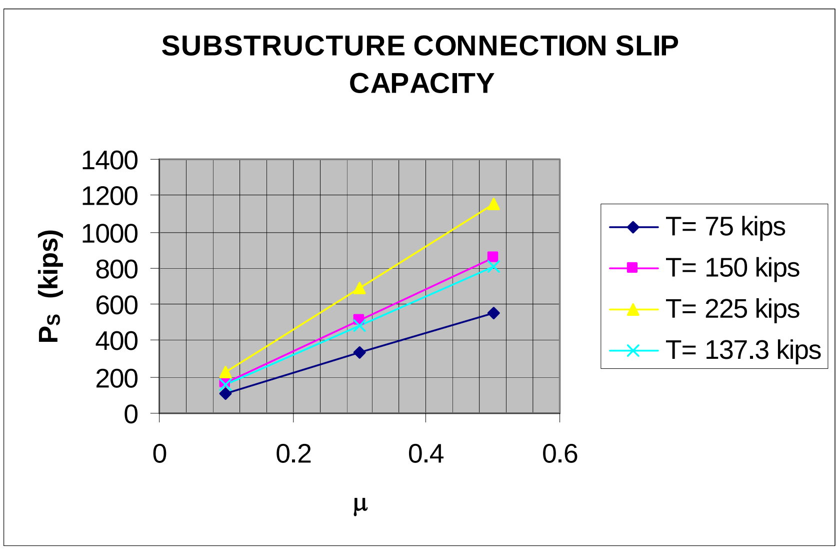

Figure 8 Substructure Connection Slip Capacity Chart

4.2 Connection Tensile Capacity

Tensile Strength of Bolt:

$R_n = F_u^b \times A_n$ (Ref. 4, Chapter 4)

$R_n =$ Nominal Strength for one bolt

$F_u^b =$ Tensile strength of bolt material

$A_{n=}$ Area through the threaded portion of bolt= tensile stress area

$A_{n=}$ .75 A_b

$A_{b=}$ bolt gross area

$\boxed{R_n = F_u^b \times .75\, A_b}$

D=	2	in	(bolt Diameter)
A_b=	3.14	in^2	
$A_{n=}$	2.355	in^2	
F_u^b =	120	ksi	(AISC, Part 4, Table I-C for 1" A325 bolts)
F_u^b =	105	ksi	(AISC, Part 4, Table I-C for 1-1/2" A325 bolts)
Take F_u^b =	**105**	**ksi**	**for 2" Bolts**

TENSILE CAPACITY WITHOUT PRETENTION:

Bolt Tensile Capacity=	**R_n=**	**247.3**	**kips**
Connection Tensile Capacity=	**nxR_n=**	**1978.2**	**kips**

TENSILE CAPACITY WITH PRETENTION:

Capacity (kips)= Capacity without Pretension (kips)- Bolt Pretension (kips)

n= 8 bolts

Table 17 Bolts Tensile Capacity per Clamp Connection

R_n kips	**T** kips	**T_B*** kips	**T_C**** kips	
247.3	75.0	**172.3**	**1378.2**	
247.3	**137.3**	**109.9**	**879.6**	(Recom. Pretension, based on AISC Table J 3.7 for 1-1/2" bolts)
247.3	150.0	**97.3**	**778.2**	(2x103/1.5=137.3 kips)
247.3	225.0	**22.3**	**178.2**	

*$T_B = R_n - T$ & **$T_C = nT_B$

In fixed type bolted connections where reactions include moments in three directions, the distribution of tensile forces over the connection bolts vary. One bolt will be subject to higher tension force than the rest of the connection bolts.
Therefore, the integrity of the bolted connection relies on the single bolt that carries the highest tensile load.

Based on the bolt size (2") and the recommended AISC Pretension load for fully tightened bolts (Table J3.7):

The Tensile Capacity of the Clamped Connection is:

R_n-137.3 kips=	**109.9 kips per bolt**

4.3 Connection Shear Capacity

Shear Strength of Bolt:

$\boxed{R_n = m \times \tau_u \times A_b}$ ……………………………………………………**Eq.7**

(Ref. 4, Chapter 4)

R_n= Nominal Strength for one bolt

τ_u=.62 F_u^b = Ultimate shear stress across the gross area A_b of Bolt

m= Number of shear planes

F_u^b = **105 ksi**

m= 1

Shear Capacity per Bolt= $\boxed{R_n = 204.4 \text{ kips}}$

If Shear occurs: one side (1/2 the number of bolts in the connection) will carry the shear load, as shown in Figure 3.

Total Clamp Connection Shear Capacity =V_C = $\boxed{(n/2) \times R_n = 817.7 \text{ kips}}$

5. RIGID MODELS ANALYSIS AND RESULTS

The STRUCAD*3D finite element software is employed to develop rigid models representing the upper derrick mass only and a combined upper derrick and substructure masses for the purpose of applying wind and dynamic loading to the structure and extracting 6 DOF reactions at the footings of the upper derrick and substructure. Those models are shown below.

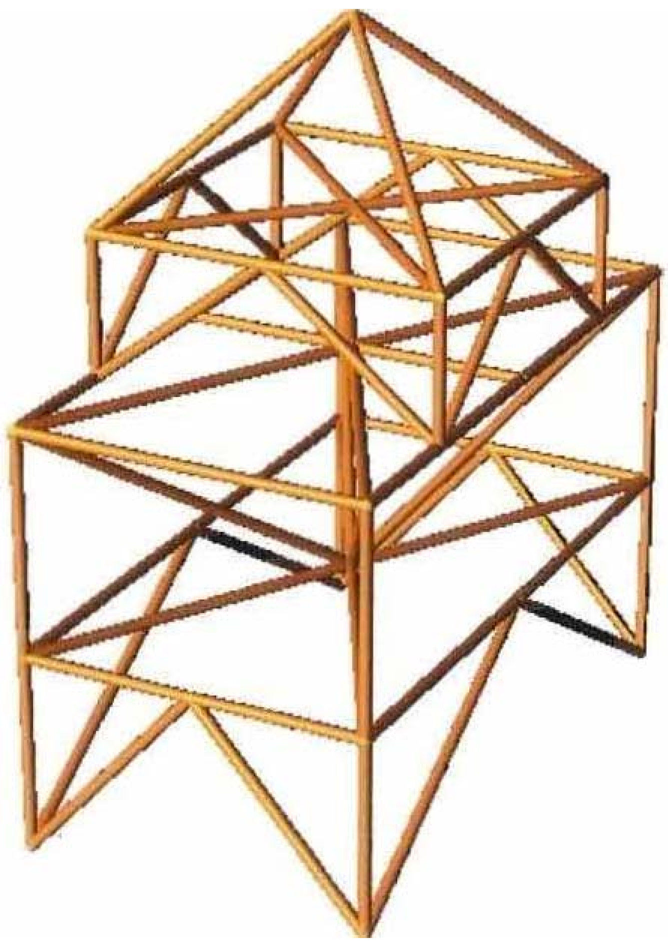

Figure 9 Combined Upper Derrick & Substructure Rigid Model

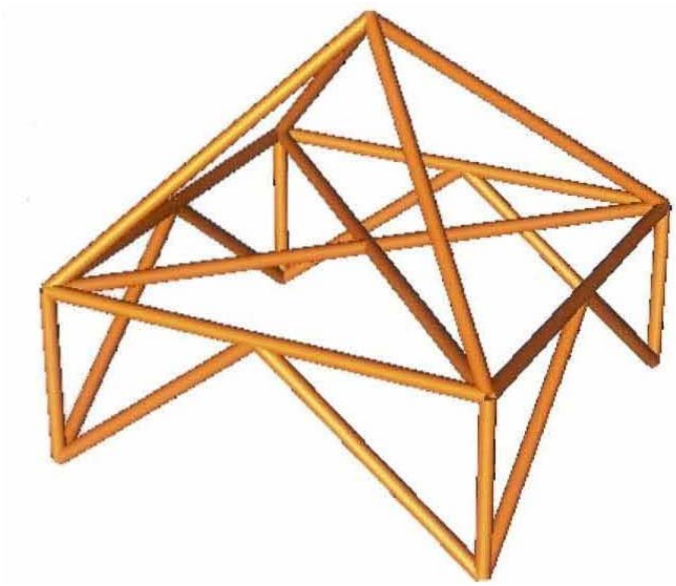

Figure 10 Upper Derrick Rigid Model

Three Load Cases are included in the Analysis:
1- IVAN environmental criteria,
2- 100 year hurricane environmental criteria,
3- 10 year hurricane environmental criteria.

For each load case, three combinations of accelerations and wind loading on the structure are analysed:
1- API-4F recommended 107 knots wind velocity and accelerations derived based on API-4F specifications,
2- Wind velocities matching those in the Time Domain analysis and accelerations derived based on API-4F specifications,
3- Wind velocities and accelerations from the Time Domain analysis.

In addition, for every wind and acceleration combination from the above, wind and accelerations are considered in three directions:
1- Pitch direction (X),
2- Roll direction (Y),
3- 45^o angle direction, which combines 100% of wind and dynamic loading on the structure in (X) & (Y) directions simultaneously and provides the highest wind area exposure for the structure.

The reaction forces and moments obtained from the STRUCAD models for all the above cases are summarised below.

Figure 9 shows the nodes location and reference number, for upper derrick and substructure, associated with the reactions.

The reactions included in the Tables are shown as absolute values. The numbers highlighted in the FZ columns represent tension loading on the clamp connection bolts.

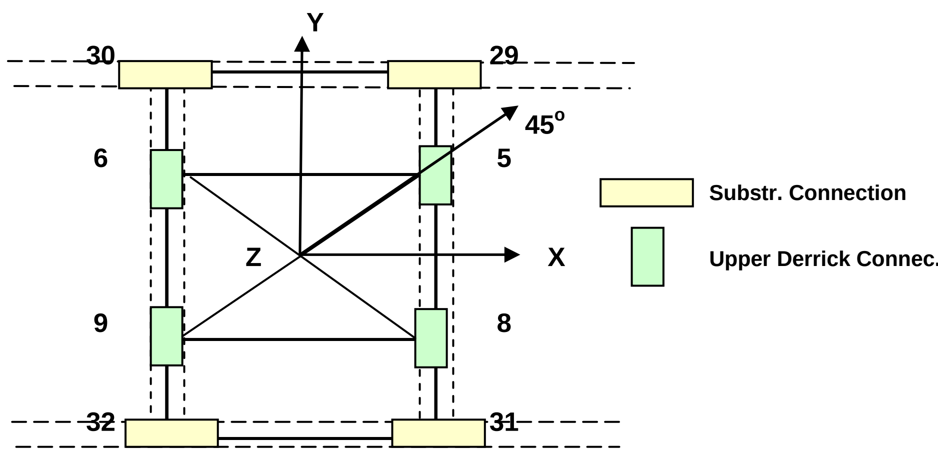

Figure 11 Reference Node Numbers and Wind & Accelerations Loading Directions for Upper Derrick & substructure Footings

A- WIND & DYNAMIC LOADING AT 45° ANGLE

Table 18 Reaction Forces & Moments (IVAN)

UPPER DERRICK REACTIONS (IVAN)

API-4F 107 KNOTS WIND			(45 Degree Direction)			
REFERENCE NODE No	FX kips	FY kips	FZ kips	MX kip-in	MY kip-in	MZ kip-in
6	120.28	121.98	135.31	101.28	38.32	29.14
5	123.04	123.04	831.14	151.90	151.90	0.00
8	121.98	120.28	135.31	38.32	101.28	29.14
9	121.34	121.34	**560.51**	88.94	88.94	0.00
API-4F 87.9 KNOTS WIND			(45 Degree Direction)			
6	104.45	106.14	135.31	100.61	37.65	29.14
5	107.20	107.20	691.78	151.23	151.23	0.00
8	106.14	104.45	135.31	37.65	100.61	29.14
9	105.51	105.51	**421.15**	88.27	88.27	0.00
TIME DOMAIN ANALYSIS: 87.9 KNOTS WIND					(45 Degree Direction)	
6	101.37	103.06	135.44	97.76	34.74	27.91
5	104.08	104.06	680.54	146.23	146.23	0.00
8	103.06	101.37	135.44	34.74	97.76	27.91
9	102.38	102.38	**409.67**	83.21	83.21	0.00

SUBSTRUCTURE REACTIONS (IVAN)

API-4F 107 KNOTS WIND			(45 Degree Direction)			
REFERENCE NODE No	FX kips	FY kips	FZ kips	MX kip-in	MY kip-in	MZ kip-in
30	324.06	324.53	122.98	172.22	198.27	77.14
29	334.74	312.71	1865.41	364.77	399.47	155.14
31	330.34	346.09	895.97	577.40	265.46	176.61
32	328.47	334.27	**846.45**	384.86	332.27	55.67
API-4F 87.9 KNOTS WIND			(45 Degree Direction)			
30	303.51	303.98	173.19	172.56	197.18	77.14
29	314.19	292.15	1689.67	365.10	398.38	155.14
31	309.78	325.54	845.76	577.07	264.38	176.61
32	307.91	313.71	**670.72**	384.52	331.19	55.67
TIME DOMAIN ANALYSIS: 87.9 KNOTS WIND					(45 Degree Direction)	
30	291.05	291.25	179.02	178.17	186.72	71.70
29	301.48	279.91	1648.14	364.27	381.30	150.06
31	297.26	312.62	830.60	564.60	253.30	170.26
32	295.26	301.27	**638.52**	378.50	314.72	51.50

Table 19 Reaction Forces & Moments (100 YR)

DERRICK REACTIONS (100 YR)

NODE No	FX kips	FY kips	FZ kips	MX kip-in	MY kip-in	MZ kip-in
API-4F 107 KNOTS WIND (45 Degree Direction)						
6	104.72	106.44	137.47	87.24	23.27	22.89
5	107.28	107.28	775.93	126.99	126.99	0.00
8	106.44	104.72	137.47	23.27	87.24	22.89
9	105.56	105.56	**500.99**	63.03	63.03	0.00
API-4F 81.3 KNOTS WIND (45 Degree Direction)						
6	84.14	85.86	137.47	86.37	22.40	22.89
5	86.69	86.69	594.77	126.12	126.12	0.00
8	85.86	84.14	137.47	22.40	86.37	22.89
9	84.97	84.97	**319.83**	62.16	62.16	0.00
TIME DOMAIN ANALYSIS: 81.3 KNOTS WIND (45 Degree Direction)						
6	80.91	82.62	137.09	83.26	19.47	21.59
5	83.41	83.41	582.47	120.75	120.75	0.00
8	82.62	80.91	137.09	19.47	83.26	21.59
9	81.69	81.69	**308.29**	56.97	56.97	0.00

SUBSTRUCTURE REACTIONS (100 YR)

CONNECT. No	FX kips	FY kips	FZ kips	MX kip-in	MY kip-in	MZ kip-in
API-4F 107 KNOTS WIND (45 Degree Direction)						
30	267.28	265.97	175.77	217.68	148.94	49.58
29	277.05	256.68	1693.11	369.02	321.73	132.79
31	273.59	287.65	849.02	536.25	216.52	149.62
32	270.74	278.36	**668.32**	384.91	254.15	32.75
API-4F 81.3 KNOTS WIND (45 Degree Direction)						
30	240.56	239.25	241.04	218.11	147.53	49.58
29	250.33	229.96	1464.66	369.45	320.32	132.79
31	246.87	260.93	783.75	535.81	215.11	149.62
32	244.02	251.64	**439.86**	384.47	252.74	32.75
TIME DOMAIN ANALYSIS: 81.3 KNOTS WIND (45 Degree Direction)						
30	227.51	225.86	250.59	226.53	136.35	43.56
29	237.06	217.08	1424.62	371.05	302.67	127.80
31	133.80	247.49	771.33	525.29	203.74	143.32
32	130.77	238.71	**402.70**	380.76	235.28	28.04

Table 20 Reaction Forces & Moments (10YR)

UPPER DERRICK REACTIONS (10YR)

REFERENCE NODE No	FX kips	FY kips	FZ kips	MX kip-in	MY kip-in	MZ kip-in
API-4F 107 KNOTS WIND			**(45 Degree Direction)**			
6	79.24	80.95	137.05	63.30	0.47	12.63
5	81.41	81.41	681.46	85.24	85.24	0.00
8	80.95	79.24	137.05	0.47	63.30	12.63
9	79.70	79.70	**407.37**	21.47	21.47	0.00
API-4F 50.9 KNOTS WIND			**(45 Degree Direction)**			
6	41.55	43.27	137.05	61.71	2.06	12.63
5	43.72	43.72	349.84	83.64	83.64	0.00
8	43.27	41.55	137.05	2.06	61.71	12.63
9	42.01	42.01	**75.75**	19.88	19.88	0.00
TIME DOMAIN ANALYSIS: 50.9 KNOTS WIND				**(45 Degree Direction)**		
6	39.65	41.36	137.09	59.94	3.85	11.87
5	41.80	41.80	342.87	80.55	80.55	0.00
8	41.36	39.65	137.09	3.85	59.94	11.87
9	40.08	40.08	**68.69**	16.76	16.76	0.00

SUBSTRUCTURE REACTIONS (10 YR)

REFERENCE NODE No	FX kips	FY kips	FZ kips	MX kip-in	MY kip-in	MZ kip-in
API-4F 107 KNOTS WIND			**(45 Degree Direction)**			
30	174.00	169.86	256.05	287.59	68.29	4.93
29	182.20	164.73	1403.87	371.69	193.63	95.49
31	180.29	191.48	765.56	464.00	135.66	104.66
32	175.91	186.35	**382.25**	379.90	126.25	4.24
API-4F 50.9 KNOTS WIND			**(45 Degree Direction)**			
30	125.09	120.95	375.52	288.39	65.71	4.93
29	133.29	115.82	985.69	372.48	191.04	95.49
31	131.38	142.56	646.09	463.20	133.08	104.66
32	127.00	137.43	35.93	379.11	123.67	4.24
TIME DOMAIN ANALYSIS: 50.9 KNOTS WIND				**(45 Degree Direction)**		
30	117.59	113.24	382.05	294.00	59.23	1.36
29	125.67	108.40	963.45	373.83	180.92	92.67
31	123.88	134.86	639.87	457.81	126.62	101.12
32	119.38	130.03	58.48	377.98	113.53	7.09

B- WIND & DYNAMIC LOADING IN (X) DIRECTION

The upper derrick and substructure reaction forces and moments pertaining to tension loading on the clamped connections are summarised in the following tables.

Table 21 Reaction Forces & Moments (IVAN), X-Direction Loading

UPPER DERRICK REACTIONS (IVAN)				SUBSTRUCTURE REACTIONS (IVAN)			
API-4F 107 KNOTS WIND				(0 Degree Direction)			
REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in	REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in
6	212.60	6.17	63.63	30	361.73	278.54	265.26
5	483.23	56.79	126.59	29	1380.69	471.09	332.46
8	483.23	56.79	126.59	31	1380.68	471.08	332.46
9	212.60	6.17	63.63	32	361.73	278.54	265.27
API-4F 87.9 KNOTS WIND				(0 Degree Direction)			
6	142.92	62.96	62.96	30	248.76	278.54	264.20
5	413.54	125.92	125.92	29	1267.70	471.08	331.38
8	413.55	125.92	125.92	31	1267.70	471.08	331.37
9	142.92	62.96	62.96	32	248.76	278.54	264.18
TIME DOMAIN ANALYSIS: 87.9 KNOTS WIND				(0 Degree Direction)			
6	137.12	7.28	58.97	30	229.75	278.33	250.72
5	407.99	55.74	121.99	29	1239.37	464.40	317.30
8	407.99	55.74	121.99	31	1239.37	464.40	317.30
9	137.12	7.28	58.97	32	229.74	278.33	250.70

Table 22 Reaction Forces & Moments (100-YR), X-Direction Loading

UPPER DERRICK REACTIONS (100 YR)				SUBSTRUCTURE REACTIONS (100 YR)			
API-4F 107 KNOTS WIND				(0 Degree Direction)			
REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in	REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in
6	181.75	12.10	43.15	30	246.27	301.29	201.54
5	456.70	51.86	107.12	29	1271.06	452.63	269.13
8	456.70	51.86	107.12	31	1271.06	452.63	269.13
9	181.76	12.11	43.15	32	246.27	301.29	201.54
API-4F 81.3 KNOTS WIND				(0 Degree Direction)			
6	91.18	12.11	42.28	30	99.40	301.29	200.13
5	366.12	51.86	106.25	29	1124.20	452.60	267.71
8	366.12	51.86	106.25	31	1124.20	452.60	267.71
9	91.18	12.11	42.28	32	99.40	301.29	200.13
TIME DOMAIN ANALYSIS: 81.3 KNOTS WIND				(0 Degree Direction)			
6	85.60	13.15	38.22	30	76.05	303.64	185.82
5	359.78	50.64	102.01	29	1097.98	448.18	253.21
8	359.78	50.64	102.01	31	1097.98	448.18	253.21
9	85.60	13.15	38.22	32	76.05	303.64	185.82

Table 23 Reaction Forces & Moments (10-YR), X-Direction Loading

UPPER DERRICK REACTIONS (10-YR)				SUBSTRUCTURE REACTIONS (10-YR)			
API-4F 107 KNOTS WIND				(0 Degree Direction)			
REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in	REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in
6	135.16	20.92	10.49	30	63.10	333.75	97.27
5	409.25	42.85	74.27	29	1084.70	417.84	164.64
8	409.25	42.85	74.27	31	1084.70	417.84	164.64
9	135.16	20.92	10.49	32	63.10	333.75	97.27
API-4F 50.9 KNOTS WIND				(0 Degree Direction)			
6	30.65	20.92	8.90	30	205.73	333.74	94.69
5	243.45	42.85	72.67	29	815.89	417.84	162.06
8	243.45	42.85	72.67	31	815.89	417.84	162.06
9	30.65	20.92	8.90	32	205.73	333.74	94.69
TIME DOMAIN ANALYSIS: 50.9 KNOTS WIND				(0 Degree Direction)			
6	34.20	21.59	6.45	30	220.26	335.99	86.38
5	239.98	42.20	70.24	29	801.66	415.82	153.77
8	239.98	42.20	70.24	31	801.66	415.82	153.77
9	34.20	21.59	6.45	32	220.26	335.99	86.38

C- WIND & DYNAMIC LOADING IN (Y) DIRECTION

Table 24 Reaction Forces & Moments (IVAN), Y-Direction Loading

UPPER DERRICK REACTIONS (IVAN)				SUBSTRUCTURE REACTIONS (IVAN)			
API-4F 107 KNOTS WIND				(90 Degree Direction)			
REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in	REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in
6	483.23	126.59	56.79	30	994.20	268.50	100.60
5	483.23	126.59	56.79	29	994.20	268.50	100.60
8	212.60	63.63	6.17	31	24.76	481.13	33.41
9	212.60	63.63	6.17	32	24.76	481.13	33.41
API-4F 87.9 KNOTS WIND				(90 Degree Direction)			
6	413.55	125.92	56.79	30	931.43	268.83	100.60
5	413.55	125.92	56.79	29	931.43	268.83	100.60
8	142.92	62.96	6.17	31	87.52	480.80	33.41
9	142.92	62.96	6.17	32	87.52	480.80	33.41
TIME DOMAIN ANALYSIS: 87.9 KNOTS WIND				(90 Degree Direction)			
6	407.99	121.99	55.74	30	876.26	249.53	87.82
5	407.99	121.99	55.74	29	876.26	249.53	87.82
8	137.12	58.97	7.28	31	133.37	493.24	21.24
9	137.12	58.97	7.28	32	133.37	493.24	21.24

Table 25 Reaction Forces & Moments (100-YR), Y-Direction Loading

UPPER DERRICK REACTIONS (100 YR)				SUBSTRUCTURE REACTIONS (100 YR)			
API-4F 107 KNOTS WIND				(90 Degree Direction)			
REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in	REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in
6	456.70	107.12	51.86	**30**	934.44	293.35	86.40
5	456.70	107.12	51.86	**29**	934.44	293.35	86.40
8	**181.76**	43.15	12.11	**31**	90.35	460.58	18.82
9	**181.76**	43.15	12.10	**32**	90.35	460.58	18.82
API-4F 81.3 KNOTS WIND				(90 Degree Direction)			
6	366.12	106.25	51.86	**30**	852.85	293.78	86.40
5	366.12	106.25	51.86	**29**	852.85	293.78	86.40
8	**91.18**	42.28	12.10	**31**	171.95	460.14	18.82
9	**91.18**	42.28	12.10	**32**	171.95	460.14	18.82
TIME DOMAIN ANALYSIS: 81.3 KNOTS WIND				(90 Degree Direction)			
6	359.77	102.01	50.64	**30**	837.60	298.79	83.16
5	359.77	102.01	50.64	**29**	837.60	298.79	83.16
8	**85.60**	38.22	13.15	**31**	184.32	453.02	15.77
9	**85.60**	38.22	13.15	**32**	184.32	453.02	15.77

Table 26 Reaction Forces & Moments (10-YR), Y-Direction Loading

UPPER DERRICK REACTIONS (10-YR)				SUBSTRUCTURE REACTIONS (10-YR)			
API-4F 107 KNOTS WIND				(90 Degree Direction)			
REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in	REFERENCE NODE No	FZ kips	MX kip-in	MY kip-in
6	409.25	74.27	42.85	**30**	829.96	329.64	62.67
5	409.25	74.27	42.85	**29**	829.96	329.64	62.67
8	**135.16**	10.45	20.92	**31**	191.66	421.95	4.70
9	**135.16**	10.45	20.92	**32**	191.66	421.95	4.70
API-4F 50.9 KNOTS WIND				(90 Degree Direction)			
6	243.45	72.68	42.85	**30**	680.61	330.43	62.67
5	243.45	72.68	42.85	**29**	680.61	330.43	62.67
8	30.65	8.90	20.92	**31**	341.01	421.00	4.70
9	30.65	8.90	20.92	**32**	341.01	421.00	4.70
TIME DOMAIN ANALYSIS: 50.9 KNOTS WIND				(90 Degree Direction)			
6	239.98	70.24	42.20	**30**	672.75	333.92	60.85
5	239.98	70.24	42.20	**29**	672.75	333.92	60.85
8	34.20	6.46	21.59	**31**	349.18	417.89	6.54
9	34.20	6.46	21.59	**32**	349.18	417.89	6.54

6. CLAMP CONNECTIONS LOADS VS CAPACITY

Depending on the connection orientation, FX & FY forces will cause a shearing effect on the bolts (once slipping resistance is exceeded) or slipping effect only. The connections orientation for upper derrick and substructure are shown in Figure 12.The force FZ causes tension or compression loading on the bolts

The reaction moments will add to the above loading. MX & MY will affect the tension/compression loading while MZ adds to the bolts shear load. Due to the special configuration of the clamped connections, it is most likely that only the two outer bolts will be affected by the torsion moment MZ. This is depicted in Figure 12.

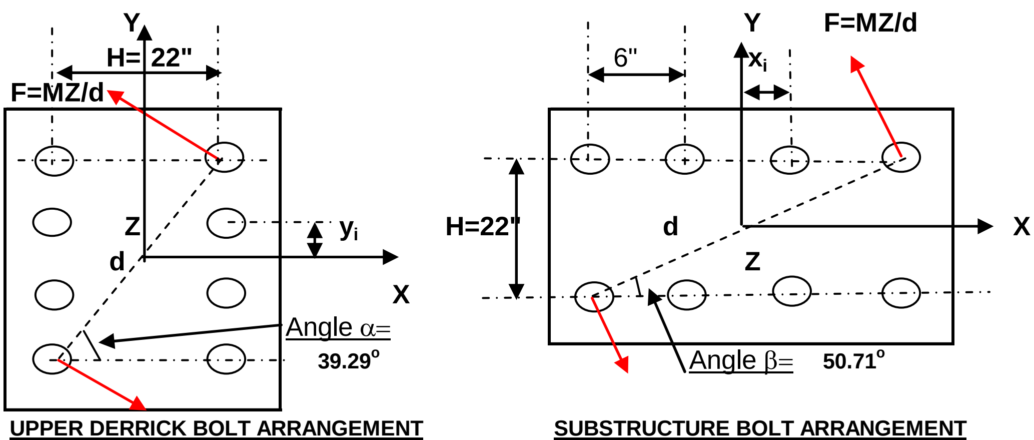

Figure 12 Bolt Arrangements for Derrick & Substructure Footings

(Note: The above sketches do not reflect dimensions to scale)

Details pertaining to bolt loading calculations are presented in Tables format for the different environmental criteria.

6.1 IVAN Load Case

6.1.1 Bolts Shear/Slip Loading

d=	28.4 in	(diagonal distance between outer bolts)			
p=	6 in	(bolt Spacing)			
α=	39.29	sinα=	0.633	cosα=	0.774
β=	50.71	sinβ=	0.774	cosβ=	0.633

Table 27 Total Lateral Forces per Connection (IVAN)

CONNECTION TOTAL LATERAL FORCES (IVAN)						TOTAL FORCE*	
UPPER DERRICK						ΣX-FORCES	ΣY-FORCES
NODE No	MZ kin	MZ/d=F kips	Fsinα= Fx kips	Fcosα= Fy kips	WIND & ACCELERATION COMBINATION	kips SHEAR	kips SLIP
6	29.14	1.03	0.65	0.79	(I)	120.93	122.77
5	0.00	0.00	0.00	0.00	API-4F ACCEL. &	**123.04**	**123.04**
8	29.14	1.03	0.65	0.79	107 KNOTS WIND	122.63	121.07
9	0.00	0.00	0.00	0.00		121.34	121.34
6	29.14	1.03	0.65	0.79	(II)	105.10	106.93
5	0.00	0.00	0.00	0.00	API-4F ACCEL. &	**107.20**	**107.20**
8	29.14	1.03	0.65	0.79	87.9 KNOTS WIND	106.79	105.24
9	0.00	0.00	0.00	0.00		105.51	105.51
6	27.91	0.98	0.62	0.76	(III)	101.99	103.82
5	0.00	0.00	0.00	0.00	TIME DOMAIN ACCEL.&	**104.08**	**104.06**
8	27.91	0.98	0.62	0.76	87.9 KNOTS WIND	103.68	102.13
9	0.00	0.00	0.00	0.00		102.38	102.38
SUBSTRUCTURE						ΣX-FORCES	ΣY-FORCES
NODE No	MZ kip-in	MZ/d=F kips	Fsinβ= Fx kips	Fcosβ=Fy kips	WIND & ACCELERATION COMBINATION	kips SLIP	kips SHEAR
30	77.14	2.71	2.10	1.72	(I)	326.16	326.25
29	155.14	5.46	4.22	3.46	API-4F ACCEL. &	**338.96**	316.17
31	176.61	6.21	4.81	3.93	107 KNOTS WIND	335.15	**350.02**
32	55.67	1.96	1.52	1.24		329.99	335.51
30	77.14	2.71	2.10	1.72	(II)	305.61	305.70
29	155.14	5.46	4.22	3.46	API-4F ACCEL. &	**318.41**	295.61
31	176.61	6.21	4.81	3.93	87.9 KNOTS WIND	314.59	**329.47**
32	55.67	1.96	1.52	1.24		309.43	314.95
30	71.70	2.52	1.95	1.60	(III)	293.00	292.85
29	150.06	5.28	4.09	3.34	TIME DOMAIN ACCEL.&	**305.57**	283.25
31	170.26	5.99	4.64	3.79	87.9 KNOTS WIND	301.90	**316.41**
32	51.50	1.81	1.40	1.15		296.66	302.42

*TOTAL FORCE (X) = FX (from Table 18) + Fx (from Table 27)
TOTAL FORCE (Y) = FY (from Table 18) + Fy (from Table 27)

The numbers highlighted in Table 27 are the maximum shear (V_{max}) and maximum slip (P_{max}) loads per clamp connection for this case.

6.1.2 Connection Shear/Slip Check (Ivan Loading)

From section 4.3, it was determined that the ultimate shear capacity per connection is 817.7 kips.
By dividing that number by the highest shear load per connection, the factors of safety are determined and included in Table 28 for Ivan load case.

Table 28 Bolts Shear Factor of Safety per Connection (IVAN)

(IVAN) REACTIONS FROM:	UPPER DERRICK (FS_{V1})	SUBSTRUCTURE (FS_{V2})
API-4F ACC. + 107 KNOTS WIND	6.65	2.34
API-4F ACC. + 87.9 KNOTS WIND	7.63	2.48
TIME DM. ACC. + 87.9 KNOTS WIND	7.86	2.58

Where FSv_i = Factor of Safety = V_C / V_{max}.

Similar to the above procedure, the highest force in slip direction per connection for upper derrick and substructure are compared with the various connection slip capacities resulting from varying the coefficient of friction & pretension (Section 4.1). The factors of safety are calculated. The connections having a factor of safety less than one (i.e. loading exceeds the capacity) indicate failure of the connection.

Table 29 Slip Check & Factor of Safety per Connection (IVAN)

	UPPER DERRICK			SUBSTRUCTURE		
AISC PRETENSION=137.3 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**123.6**	**370.8**	**618.0**	**161.1**	**483.3**	**805.5**
(IVAN) REACTIONS FROM:	FACTOR OF SAFETY (FS_{PD})			FACTOR OF SAFETY (FS_{PS})		
API-4F ACC.+ 107 KNOTS WIND	1.0	3.0	5.0	**0.5**	1.4	2.4
API-4F ACC.+ 87.9 KNOTS WIND	1.2	3.5	5.8	**0.5**	1.5	2.5
TIME DM Ac+ 87.9 KNOTS WIND	1.2	3.6	5.9	**0.5**	1.6	2.6
PRETENSION=75.0 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**73.8**	**221.3**	**368.8**	**111.3**	**333.8**	**556.3**
(IVAN) REACTIONS FROM:	FACTOR OF SAFETY (FS_{PD})			FACTOR OF SAFETY (FS_{PS})		
API-4F ACC.+ 107 KNOTS WIND	**0.60**	1.80	3.00	**0.33**	**0.98**	1.64
API-4F ACC.+ 87.9 KNOTS WIND	**0.69**	2.06	3.44	**0.35**	1.05	1.75
TIME DM Ac+ 87.9 KNOTS WIND	**0.71**	2.13	3.54	**0.36**	1.05	1.82
PRETENSION= 150 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**133.8**	**401.3**	**668.8**	**171.3**	**513.8**	**856.3**
(IVAN) REACTIONS FROM:	FACTOR OF SAFETY (FS_{PD})			FACTOR OF SAFETY (FS_{PS})		
API-4F ACC.+ 107 KNOTS WIND	1.09	3.26	5.44	**0.51**	1.52	2.53
API-4F ACC.+ 87.9 KNOTS WIND	1.25	3.74	6.24	**0.54**	1.61	2.69
TIME DM Ac+ 87.9 KNOTS WIND	1.29	3.86	6.43	**0.56**	1.68	2.80
PRETENSION= 225 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**193.8**	**581.3**	**968.8**	**231.3**	**693.8**	**1156.3**
(IVAN) REACTIONS FROM:	FACTOR OF SAFETY (FS_{PD})			FACTOR OF SAFETY (FS_{PS})		
API-4F ACC.+ 107 KNOTS WIND	1.57	4.72	7.87	**0.68**	2.05	3.41
API-4F ACC.+ 87.9 KNOTS WIND	1.81	5.42	9.04	**0.73**	2.18	3.63
TIME DM Ac+ 87.9 KNOTS WIND	1.86	5.59	9.31	**0.76**	2.27	3.78

Where: FS_{PD}= Slip Factor of Safety for Derrick connection = P_D / P_{max} ,
& FS_{PS}= Slip Factor of Safety for Substructure connection = P_S / P_{max}.

The same procedure is adopted to calculate the factors of safety for the cases of 100 year and 10 year hurricanes.

6.1.3 Bolts Tension Loading & Capacity Check

Maximum tension force per bolt= Sum of tension forces (T1+T2+T3)

Where:

T1= Tension force per bolt due to FZ

T2= Tension force per bolt due to MX

T3= Tension force per bolt due to MY

FOR UPPER DERRICK CONNECTION

T1= FZ/n= connection tension reaction/ number of bolts

T2= MX x y_{max}/ Σy_i^2

T3= MY / ((n/2)H)

Where: n= 8 bolts

y_{max}= 9 in

H= 22 in

y_i (in)	y_i^2 (in^2)
3	9
9	81

Σy_i^2= 4x(9+81)= 360 in^2 (for 8 bolts)

FOR SUBSTRUCTURE CONNECTION

T1= FZ/n= connection tension reaction/ number of bolts

T2= MY x x_{max}/ Σx_i^2

T3= MX / ((n/2)H)

Where: x_{max}= 9 in

H= 22 in

Σx_i^2= 4x(9+81)= 360 in^2 (for 8 bolts)

Connection total tensile forces are calculated as the sum of forces due to tension force and moments. Three directions for the wind and dynamic loading on the structures are considered. These directions include Pitch (0^o) direction, Roll (90^o) direction and 45^o direction which include a combination of Pitch and Roll. The later case is the most critical for tension loading on the clamps bolts

The results of those calculations are summarised in the following Tables of this Section. These Tables also include the factors of safety resulting from comparing actual tension forces on the bolts to the ultimate tensile capacities of the connection derived for the various bolt pretension cases discussed in section 4.2.

A- WIND & DYNAMIC LOADING AT 45^o ANGLE

Table 30 Bolt Tension Calculations & FS per Connection (IVAN) for 137.3 kips Pretension

BOLT TENSILE CAPACITY= 109.9 kips

LOAD COMBIN.	IVAN REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	560.51	88.94	88.94	70.06	2.22	1.01	**73.30**	**1.50**
API-4F ACCEL. & 87.9 KNOTS WIND	421.15	88.27	88.27	52.64	2.21	1.00	**55.85**	**1.97**
TIME-DM ACCEL. & 87.9 KNOTS WIND	409.67	83.21	83.21	51.21	2.08	0.95	**54.23**	**2.03**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	846.45	384.86	332.27	105.81	8.31	4.37	**118.49**	**0.93**
API-4F ACCEL. & 87.9 KNOTS WIND	670.72	384.52	331.19	83.84	8.28	4.37	**96.49**	**1.14**
TIME-DM ACCEL. & 87.9 KNOTS WIND	638.52	378.50	314.72	79.82	7.87	4.30	**91.98**	**1.20**

Table 31 Bolt Tension Calculations & FS per Connection (IVAN) for 75 kips Pretension

BOLT TENSILE CAPACITY= 172.3 kips

LOAD COMBIN.	IVAN REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	560.51	88.94	88.94	70.06	2.22	1.01	**73.30**	**2.35**
API-4F ACCEL. & 87.9 KNOTS WIND	421.15	88.27	88.27	52.64	2.21	1.00	**55.85**	**3.08**
TIME-DM ACCEL. & 87.9 KNOTS WIND	409.67	83.21	83.21	51.21	2.08	0.95	**54.23**	**3.18**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	846.45	384.86	332.27	105.81	8.31	4.37	**118.49**	**1.45**
API-4F ACCEL. & 87.9 KNOTS WIND	670.72	384.52	331.19	83.84	8.28	4.37	**96.49**	**1.79**
TIME-DM ACCEL. & 87.9 KNOTS WIND	638.52	378.50	314.72	79.82	7.87	4.30	**91.98**	**1.87**

Table 32 Bolt Tension Calculations & FS per Connection (IVAN) for 150 kips Pretension

BOLT TENSILE CAPACITY= 97.3 kips

LOAD COMBIN.	IVAN REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	560.51	88.94	88.94	70.06	2.22	1.01	**73.30**	**1.33**
API-4F ACCEL. & 87.9 KNOTS WIND	421.15	88.27	88.27	52.64	2.21	1.00	**55.85**	**1.74**
TIME-DM ACCEL. & 87.9 KNOTS WIND	409.67	83.21	83.21	51.21	2.08	0.95	**54.23**	**1.79**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	846.45	384.86	332.27	105.81	8.31	4.37	**118.49**	**0.82**
API-4F ACCEL. & 87.9 KNOTS WIND	670.72	384.52	331.19	83.84	8.28	4.37	**96.49**	**1.01**
TIME-DM ACCEL. & 87.9 KNOTS WIND	638.52	378.50	314.72	79.82	7.87	4.30	**91.98**	**1.06**

Table 33 Bolt Tension Calculations & FS per Connection (IVAN) for 225 kips Pretension

BOLT TENSILE CAPACITY= 22.3 kips

LOAD COMBIN.	IVAN REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	560.51	88.94	88.94	70.06	2.22	1.01	**73.30**	**0.30**
API-4F ACCEL. & 87.9 KNOTS WIND	421.15	88.27	88.27	52.64	2.21	1.00	**55.85**	**0.40**
TIME-DM ACCEL. & 87.9 KNOTS WIND	409.67	83.21	83.21	51.21	2.08	0.95	**54.23**	**0.41**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	846.45	384.86	332.27	105.81	8.31	4.37	**118.49**	**0.19**
API-4F ACCEL. & 87.9 KNOTS WIND	670.72	384.52	331.19	83.84	8.28	4.37	**96.49**	**0.23**
TIME-DM ACCEL. & 87.9 KNOTS WIND	638.52	378.50	314.72	79.82	7.87	4.30	**91.98**	**0.24**

Calculations for the tensile loading of upper derrick and substructure clamps bolts are performed in the same fashion as detailed above for the cases of wind and dynamic loading on the structure in the (X) and (Y) directions A summary of the resulting factors of safety for the three loading directions is given below.

1- IVAN LOAD CASE

Table 34 Summary of Tensile Factors of Safety: IVAN Load Case

LOADING DIRECTION	45-DEGREE LOADING				0-DEGREE LOADING				90-DEGREE LOADING			
BOLT TENSILE CAPACITY	109.9 kips	172.3 kips	97.3 kips	22.3 kips	109.9 kips	172.3 kips	97.3 kips	22.3 kips	109.9 kips	172.3 kips	97.3 kips	22.3 kips
LOAD COMBINATION	FACTOR OF SAFETY UPPER DERRICK FOOTINGS				FACTOR OF SAFETY UPPER DERRICK FOOTINGS				FACTOR OF SAFETY UPPER DERRICK FOOTINGS			
API-4F 107 KNOTS ACCEL. & WIND	1.50	2.35	1.33	0.30	4.00	6.28	3.54	0.81	3.89	6.10	3.45	0.79
API-4F 87.9 KNOTS ACCEL. & WIND	1.97	3.08	1.74	0.40	5.87	9.20	5.19	1.19	5.64	8.83	4.99	1.14
TIME-DM 87.9 KNOTS ACCEL. & WIND	2.03	3.18	1.79	0.41	6.11	9.58	5.41	1.24	5.88	9.21	5.20	1.19
	SUBSTRUCTURE FOOTINGS				SUBSTRUCTURE FOOTINGS				SUBSTRUCTURE FOOTINGS			
API-4F 107 KNOTS ACCEL. & WIND	0.93	1.45	0.82	0.19	2.00	3.13	1.77	0.41	17.44	27.33	15.43	3.53
API-4F 87.9 KNOTS ACCEL. & WIND	1.14	1.79	1.01	0.23	2.69	4.22	2.38	0.55	17.46	27.35	15.44	3.54
TIME-DM 87.9 KNOTS ACCEL. & WIND	1.20	1.87	1.06	0.24	2.88	4.52	2.55	0.58	17.92	28.08	15.85	3.63

In Table 34 and similar Tables of the following Sections, the highlighted numbers with a numeric value less than one indicate bolt failure due to tension forces exceeding the ultimate tensile strength of the bolts.

6.2 100 Year Hurricane Load Case

In a similar fashion to that described in Section 6.1, the connections loadings and factor of safety calculations for the 100 Year hurricane load case are determined and included in this Section.

6.2.1 Bolts Shear/Slip Loading

Table 35 Total Shear/Slip Forces per Connection (100 YR)

CONNECTION TOTAL LATERAL FORCES (100 YR)							
UPPER DERRICK						ΣX-FORCES	ΣY-FORCES
NODE REF.	MZ	MZ/d=F	Fsinα= Fx	Fcosα= Fy	WIND & ACCELERATION	kips	kips
No	kin	kips	kips	kips	COMBINATION	SHEAR	SLIP
6	22.89	0.81	0.51	0.62	(I)	105.23	107.06
5	0.00	0.00	0.00	0.00	API-4F ACCEL. &	**107.28**	**107.28**
8	22.89	0.81	0.51	0.62	107 KNOTS WIND	106.95	105.34
9	0.00	0.00	0.00	0.00		105.56	105.56
6	22.89	0.81	0.51	0.62	(II)	84.65	86.48
5	0.00	0.00	0.00	0.00	API-4F ACCEL. &	**86.69**	**86.69**
8	22.89	0.81	0.51	0.62	81.3 KNOTS WIND	86.37	84.76
9	0.00	0.00	0.00	0.00		84.97	84.97
6	21.59	0.76	0.48	0.59	(III)	81.39	83.21
5	0.00	0.00	0.00	0.00	TIME DOMAIN ACCEL.&	**83.41**	**83.41**
8	21.59	0.76	0.48	0.59	81.3 KNOTS WIND	83.10	81.50
9	0.00	0.00	0.00	0.00		81.69	81.69
SUBSTRUCTURE						ΣX-FORCES	ΣY-FORCES
NODE REF.	MZ	MZ/d=F	Fsinβ= Fx	Fcosβ= Fy	WIND & ACCELERATION	kips	kips
No	kin	kips	kips	kips	COMBINATION	SLIP	SHEAR
30	49.58	1.74	1.35	1.10	(I)	268.63	267.07
29	132.79	4.67	3.62	2.96	API-4F ACCEL. &	**280.67**	259.64
31	149.62	5.26	4.07	3.33	107 KNOTS WIND	277.66	**290.98**
32	32.75	1.15	0.89	0.73		271.63	279.09
30	49.58	1.74	1.35	1.10	(II)	241.91	240.35
29	132.79	4.67	3.62	2.96	API-4F ACCEL. &	**253.95**	232.92
31	149.62	5.26	4.07	3.33	81.3 KNOTS WIND	250.94	**264.26**
32	32.75	1.15	0.89	0.73		244.91	252.37
30	43.56	1.53	1.19	0.97	(III)	228.70	226.83
29	127.80	4.50	3.48	2.85	TIME DOMAIN ACCEL.&	**240.54**	219.93
31	143.32	5.04	3.90	3.19	81.3 KNOTS WIND	137.70	**250.68**
32	28.04	0.99	0.76	0.62		131.53	239.33

6.2.2 Connection Shear/Slip Check

Table 36 Bolts Shear Factor of Safety per Connection (100 YR)

(100 YR) REACTIONS FROM:		UPPER DERRICK (FS_{V1})	SUBSTRUCTURE (FS_{V2})
API-4F ACCL. +	107 KNOTS WIND	7.62	2.81
API-4F ACCL. +	81.3 KNOTS WIND	9.43	3.09
TIME DOM. ACCL. +	81.3 KNOTS WIND	9.80	3.26

Table 37 Slip Factor of Safety per Connection (100 YR)

	UPPER DERRICK			SUBSTRUCTURE		
AISC PRETENSION=137.3 kips						
COEFFICIENT OF FRICTION	0.1	0.3	0.5	0.1	0.3	0.5
SLIP CAPACITY (kips)	123.6	370.8	618.0	161.1	483.3	805.5
(100 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACC+ 107 KNOTS WIND	1.15	3.46	5.76	**0.57**	1.72	2.87
API-4F ACC+ 81.3 KNOTS WIND	1.43	4.28	7.13	**0.63**	1.90	3.17
TIME DM.Ac + 81.3 KNOTS WIND	1.48	4.45	7.41	**0.67**	2.01	3.35
PRETENSION=75 kips						
COEFFICIENT OF FRICTION	0.1	0.3	0.5	0.1	0.3	0.5
SLIP CAPACITY (kips)	73.8	221.3	368.8	111.3	333.8	556.3
(100 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACC+ 107 KNOTS WIND	**0.69**	2.06	3.44	**0.40**	1.19	1.98
API-4F ACC+ 81.3 KNOTS WIND	**0.85**	2.55	4.25	**0.44**	1.31	2.19
TIME DM.Ac + 81.3 KNOTS WIND	**0.88**	2.65	4.42	**0.46**	1.39	2.31
PRETENSION=150 kips						
COEFFICIENT OF FRICTION	0.1	0.3	0.5	0.1	0.3	0.5
SLIP CAPACITY (kips)	133.8	401.3	668.8	171.3	513.8	856.3
(100 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACC+ 107 KNOTS WIND	1.25	3.74	6.23	**0.61**	1.83	3.05
API-4F ACC+ 81.3 KNOTS WIND	1.54	4.63	7.71	**0.67**	2.02	3.37
TIME DM.Ac + 81.3 KNOTS WIND	1.60	4.81	8.02	**0.71**	2.14	3.56
PRETENSION=225 kips						
COEFFICIENT OF FRICTION	0.1	0.3	0.5	0.1	0.3	0.5
SLIP CAPACITY (kips)	193.8	581.3	968.8	231.3	693.8	1156.3
(100 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACC+ 107 KNOTS WIND	1.81	5.42	9.03	**0.82**	2.47	4.12
API-4F ACC+ 81.3 KNOTS WIND	2.23	6.70	11.17	**0.91**	2.73	4.55
TIME DM.Ac + 81.3 KNOTS WIND	2.32	6.97	11.61	**0.96**	2.88	4.81

6.2.3 Bolts Tension Loading & Capacity Check

Table 38 Bolt Tension Calculations & FS per Connection (100 YR) for 137.3 kips Pretension

BOLT TENSILE CAPACITY: 109.9 kips

LOAD COMBIN.	(100 YR) REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	500.99	63.03	63.03	62.62	1.58	0.72	**64.92**	**1.69**
API-4F ACCEL. & 81.3 KNOTS WIND	319.83	62.16	62.16	39.98	1.55	0.71	**42.24**	**2.60**
TIME-DM ACCEL. & 81.3 KNOTS WIND	308.29	56.97	56.97	38.54	1.42	0.65	**40.61**	**2.71**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	668.32	384.91	254.15	83.54	6.35	4.37	**94.27**	**1.17**
API-4F ACCEL. & 81.3 KNOTS WIND	439.86	384.47	252.74	54.98	6.32	4.37	**65.67**	**1.67**
TIME-DM ACCEL. & 81.3 KNOTS WIND	402.70	380.76	235.28	50.34	5.88	4.33	**60.55**	**1.82**

Table 39 Tension Calculations & FS per Connection (100 YR) for 75 kips Pretension

BOLT TENSILE CAPACITY: 172.3 kips

LOAD COMBIN.	(100 YR) REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	500.99	63.03	63.03	62.62	1.58	0.72	**64.92**	**2.65**
API-4F ACCEL. & 81.3 KNOTS WIND	319.83	62.16	62.16	39.98	1.55	0.71	**42.24**	**4.08**
TIME-DM ACCEL. & 81.3 KNOTS WIND	308.29	56.97	56.97	38.54	1.42	0.65	**40.61**	**4.24**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	668.32	384.91	254.15	83.54	6.35	4.37	**94.27**	**1.83**
API-4F ACCEL. & 81.3 KNOTS WIND	439.86	384.47	252.74	54.98	6.32	4.37	**65.67**	**2.62**
TIME-DM ACCEL. & 81.3 KNOTS WIND	402.70	380.76	235.28	50.34	5.88	4.33	**60.55**	**2.85**

Table 40 Bolt Tension Calculations & FS per Connection (100 YR) for 150 kips Pretension

BOLT TENSILE CAPACITY: 97.3 kips

LOAD COMBIN.	(100 YR) REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	500.99	63.03	63.03	62.62	1.58	0.72	**64.92**	**1.50**
API-4F ACCEL. & 81.3 KNOTS WIND	319.83	62.16	62.16	39.98	1.55	0.71	**42.24**	**2.30**
TIME-DM ACCEL. & 81.3 KNOTS WIND	308.29	56.97	56.97	38.54	1.42	0.65	**40.61**	**2.40**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	668.32	384.91	254.15	83.54	6.35	4.37	**94.27**	**1.03**
API-4F ACCEL. & 81.3 KNOTS WIND	439.86	384.47	252.74	54.98	6.32	4.37	**65.67**	**1.48**
TIME-DM ACCEL. & 81.3 KNOTS WIND	402.70	380.76	235.28	50.34	5.88	4.33	**60.55**	**1.61**

Table 41 Bolt Tension Calculations & FS per Connection (100 YR) for 225 kips Pretension

BOLT TENSILE CAPACITY: 22.3 kips

LOAD COMBIN.	(100 YR) REACTIONS			TENSION FORCES				FACTOR OF SAFETY
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	500.99	63.03	63.03	62.62	1.58	0.72	**64.92**	**0.34**
API-4F ACCEL. & 81.3 KNOTS WIND	319.83	62.16	62.16	39.98	1.55	0.71	**42.24**	**0.53**
TIME-DM ACCEL. & 81.3 KNOTS WIND	308.29	56.97	56.97	38.54	1.42	0.65	**40.61**	**0.55**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	668.32	384.91	254.15	83.54	6.35	4.37	**94.27**	**0.24**
API-4F ACCEL. & 81.3 KNOTS WIND	439.86	384.47	252.74	54.98	6.32	4.37	**65.67**	**0.34**
TIME-DM ACCEL. & 81.3 KNOTS WIND	402.70	380.76	235.28	50.34	5.88	4.33	**60.55**	**0.37**

A summary of the factors of safety associated with the three wind and dynamic loading directions for the 100 Year hurricane case is given below.

Table 42 Summary of Tensile Factors of Safety: 100-Year Hurricane Load Case

LOADING DIRECTION	45-DEGREE LOADING				0-DEGREE LOADING				90-DEGREE LOADING			
BOLT TENSILE CAPACITY	109.9 kips	172.3 kips	97.3 kips	22.3 kips	109.9 kips	172.3 kips	97.3 kips	22.3 kips	109.9 kips	172.3 kips	97.3 kips	22.3 kips
LOAD COMBINATION	FACTOR OF SAFETY				FACTOR OF SAFETY				FACTOR OF SAFETY			
	UPPER DERRICK FOOTINGS				UPPER DERRICK FOOTINGS				UPPER DERRICK FOOTINGS			
API-4F ACCEL. & 107 KNOTS WIND	1.69	2.65	1.50	0.34	4.68	7.33	4.14	0.95	4.59	7.20	4.06	0.93
API-4F ACCEL. & 81.3 KNOTS WIND	2.60	4.08	2.30	0.53	9.03	14.14	7.99	1.83	8.73	13.68	7.73	1.77
TIME-DM ACCEL. & 81.3 KNOTS WIND	2.71	4.24	2.40	0.55	9.59	15.03	8.49	1.94	9.31	14.59	8.24	1.89
	SUBSTRUCTURE FOOTINGS				SUBSTRUCTURE FOOTINGS				SUBSTRUCTURE FOOTINGS			
API-4F ACCEL. & 107 KNOTS WIND	1.17	1.83	1.03	0.24	2.80	4.39	2.48	0.57	19.27	30.20	17.05	3.90
API-4F ACCEL. & 81.3 KNOTS WIND	1.67	2.62	1.48	0.34	5.27	8.26	4.66	1.07	19.29	30.23	17.07	3.91
TIME-DM ACCEL. & 81.3 KNOTS WIND	1.82	2.85	1.61	0.37	6.25	9.79	5.53	1.27	19.84	31.08	17.55	4.02

6.3 10 Year Hurricane Load Case

6.3.1 Bolts Shear/Slip Loading

Table 43 Total Shear/Slip Forces per Connection (10 YR)

CONNECTION TOTAL LATERAL FORCES (10YR)							
UPPER DERRICK						ΣX-FORCES	ΣY-FORCES
REFERENCE NODE No	MZ kip-in	MZ/d=F kips	Fsinα= Fx kips	Fcosα= Fy kips	LOAD COMBINATION	kips SHEAR	kips SLIP
6	12.63	0.44	0.28	0.34	(I)	79.52	81.29
5	0.00	0.00	0.00	0.00	API-4F ACCEL. &	**81.41**	**81.41**
8	12.63	0.44	0.28	0.34	107 KNOTS WIND	81.23	79.58
9	0.00	0.00	0.00	0.00		79.70	79.70
6	12.63	0.44	0.28	0.34	(II)	41.83	43.61
5	0.00	0.00	0.00	0.00	API-4F ACCEL. &	**43.72**	**43.72**
8	12.63	0.44	0.28	0.34	50.9 KNOTS WIND	43.55	41.89
9	0.00	0.00	0.00	0.00		42.01	42.01
6	11.87	0.42	0.26	0.32	(III)	39.91	41.68
5	0.00	0.00	0.00	0.00	TIME DOMAIN ACCEL.&	**41.80**	**41.80**
8	11.87	0.42	0.26	0.32	50.9 KNOTS WIND	41.62	39.97
9	0.00	0.00	0.00	0.00		40.08	40.08
SUBSTRUCTURE						ΣX-FORCES	ΣY-FORCES
REFERENCE NODE No	MZ kip-in	MZ/d=F kips	Fsinβ= Fx kips	Fcosβ= Fy kips	LOAD COMBINATION	kips SLIP	kips SHEAR
30	4.93	0.17	0.13	0.11	(I)	174.13	169.97
29	95.49	3.36	2.60	2.13	API-4F ACCEL. &	**184.80**	166.86
31	104.66	3.68	2.85	2.33	107 KNOTS WIND	183.14	**193.81**
32	4.24	0.15	0.12	0.09		176.03	186.44
30	4.93	0.17	0.13	0.11	(II)	125.22	121.06
29	95.49	3.36	2.60	2.13	API-4F ACCEL. &	**135.89**	117.95
31	104.66	3.68	2.85	2.33	50.9 KNOTS WIND	134.23	**144.89**
32	4.24	0.15	0.12	0.09		127.12	137.52
30	1.36	0.05	0.04	0.03	(III)	117.63	113.27
29	92.67	3.26	2.52	2.06	TIME DOMAIN ACCEL.&	**128.19**	110.46
31	101.12	3.56	2.75	2.25	50.9 KNOTS WIND	126.63	**137.11**
32	7.09	0.25	0.19	0.16		119.57	130.19

6.3.2 Connection Shear/Slip Check

Table 44 Bolts Shear Factor of Safety per Connection (10 YR)

(10 YR) REACTIONS FROM:	UPPER DERRICK (FS_{V1})	SUBSTRUCTURE (FS_{V2})
API-4F ACC. + 107 KNOTS WIND	10.04	4.22
API-4F ACC.+ 50.9 KNOTS WIND	18.70	5.64
TIME DM. ACC.+ 50.9 KNOTS WIND	19.56	5.96

Table 45 Slip Check & Factor of Safety per Connection (10 YR)

	UPPER DERRICK			SUBSTRUCTURE		
AISC PRETENSION=137.3 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**123.6**	**370.8**	**618.0**	**161.1**	**483.3**	**805.5**
(10 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACCL. + 107 KNOTS WIND	1.52	4.55	7.59	**0.87**	2.62	4.36
API-4F ACCL. + 50.9 KNOTS WIND	2.83	8.48	14.13	1.19	3.56	5.93
TIME DOM.ACC.+ 50.9.9 KNOTS WIND	2.96	8.87	14.78	1.26	3.77	6.28
PRETENSION= 75 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**73.8**	**221.3**	**368.8**	**111.3**	**333.8**	**556.3**
(10 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACCL. + 107 KNOTS WIND	**0.91**	2.72	4.53	**0.60**	1.81	3.01
API-4F ACCL. + 50.9 KNOTS WIND	1.69	5.06	8.43	**0.82**	2.46	4.09
TIME DOM.ACC.+ 50.9.9 KNOTS WIND	1.76	5.29	8.82	**0.87**	2.60	4.34
PRETENSION=150 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**133.8**	**401.3**	**668.8**	**171.3**	**513.8**	**856.3**
(10 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACCL. + 107 KNOTS WIND	1.64	4.93	8.21	**0.93**	2.78	4.63
API-4F ACCL. + 50.9 KNOTS WIND	3.06	9.18	15.30	1.26	3.78	6.30
TIME DOM.ACC.+ 50.9.9 KNOTS WIND	3.20	9.60	16.00	1.34	4.01	6.68
PRETENSION=225 kips						
COEFFICIENT OF FRICTION	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
SLIP CAPACITY (kips)	**193.8**	**581.3**	**968.8**	**231.3**	**693.8**	**1156.3**
(10 YR) REACTIONS FROM:	FACTOR OF SAFETY			FACTOR OF SAFETY		
API-4F ACCL. + 107 KNOTS WIND	2.38	7.14	11.90	1.25	3.75	6.26
API-4F ACCL. + 50.9 KNOTS WIND	4.43	13.29	22.16	1.70	5.11	8.51
TIME DOM.ACC.+ 50.9.9 KNOTS WIND	4.64	13.91	23.18	1.80	5.41	9.02

6.3.3 Bolts Tension Loading & Capacity Check

Table 46 Bolt Tension Calculations & FS per Connection (10 YR) for 137.3 kips Pretension

BOLT TENSILE CAPACITY: 109.9 kips

LOAD COMBIN.	(10 YR) REACTIONS				TENSION FORCES			FACTOR
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	FACTOR OF SAFETY
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	407.37	21.47	21.47	50.92	0.54	0.24	**51.70**	**2.13**
API-4F ACCEL. & 50.9 KNOTS WIND	75.75	19.88	19.88	9.47	0.50	0.23	**10.19**	**10.79**
TIME-DM ACCEL. & 50.9 KNOTS WIND	68.69	16.76	16.76	8.59	0.42	0.19	**9.20**	**11.96**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	382.25	379.90	126.25	47.78	3.16	4.32	**55.25**	**1.99**
API-4F ACCEL. & 50.9 KNOTS WIND	35.93	379.11	123.67	4.49	3.09	4.31	**11.89**	**9.25**
TIME-DM ACCEL. & 50.9 KNOTS WIND	58.48	377.98	113.53	7.31	2.84	4.30	**14.44**	**7.61**

Table 47 Bolt Tension Calculations & FS per Connection (10 YR) for 75 kips Pretension

BOLT TENSILE CAPACITY: 172.3 kips

LOAD COMBIN.	(10 YR) REACTIONS				TENSION FORCES			FACTOR
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	FACTOR OF SAFETY
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	407.37	21.47	21.47	50.92	0.54	0.24	**51.70**	**3.33**
API-4F ACCEL. & 50.9 KNOTS WIND	75.75	19.88	19.88	9.47	0.50	0.23	**10.19**	**16.90**
TIME-DM ACCEL. & 50.9 KNOTS WIND	68.69	16.76	16.76	8.59	0.42	0.19	**9.20**	**18.73**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	382.25	379.90	126.25	47.78	3.16	4.32	**55.25**	**3.12**
API-4F ACCEL. & 50.9 KNOTS WIND	35.93	379.11	123.67	4.49	3.09	4.31	**11.89**	**14.49**
TIME-DM ACCEL. & 50.9 KNOTS WIND	58.48	377.98	113.53	7.31	2.84	4.30	**14.44**	**11.93**

Table 48 Bolt Tension Calculations & FS per Connection (10 YR) for 150 kips Pretension

BOLT TENSILE CAPACITY: 97.3 kips

LOAD COMBIN.	(10 YR) REACTIONS				TENSION FORCES			FACTOR
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	FACTOR OF SAFETY
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	407.37	21.47	21.47	50.92	0.54	0.24	**51.70**	**1.88**
API-4F ACCEL. & 50.9 KNOTS WIND	75.75	19.88	19.88	9.47	0.50	0.23	**10.19**	**9.54**
TIME-DM ACCEL. & 50.9 KNOTS WIND	68.69	16.76	16.76	8.59	0.42	0.19	**9.20**	**10.58**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	382.25	379.90	126.25	47.78	3.16	4.32	**55.25**	**1.76**
API-4F ACCEL. & 50.9 KNOTS WIND	35.93	379.11	123.67	4.49	3.09	4.31	**11.89**	**8.18**
TIME-DM ACCEL. & 50.9 KNOTS WIND	58.48	377.98	113.53	7.31	2.84	4.30	**14.44**	**6.73**

Table 49 Bolt Tension Calculations & FS per Connection (10 YR) for 225 kips Pretension

BOLT TENSILE CAPACITY: 22.3 kips

LOAD COMBIN.	(10 YR) REACTIONS				TENSION FORCES			FACTOR
	FZ kips	MX kip-in	MY kip-in	T1 kips	T2 kips	T3 kips	T kips	FACTOR OF SAFETY
UPPER DERRICK								
API-4F ACCEL. & 107 KNOTS WIND	407.37	21.47	21.47	50.92	0.54	0.24	**51.70**	**0.43**
API-4F ACCEL. & 50.9 KNOTS WIND	75.75	19.88	19.88	9.47	0.50	0.23	**10.19**	**2.19**
TIME-DM ACCEL. & 50.9 KNOTS WIND	68.69	16.76	16.76	8.59	0.42	0.19	**9.20**	**2.42**
SUBSTRUCTURE								
API-4F ACCEL. & 107 KNOTS WIND	382.25	379.90	126.25	47.78	3.16	4.32	**55.25**	**0.40**
API-4F ACCEL. & 50.9 KNOTS WIND	35.93	379.11	123.67	4.49	3.09	4.31	**11.89**	**1.87**
TIME-DM ACCEL. & 50.9 KNOTS WIND	58.48	377.98	113.53	7.31	2.84	4.30	**14.44**	**1.54**

A summary of the factors of safety associated with the three wind and dynamic loading directions for the 10 Year hurricane case is given below.

Table 50 Summary of Tensile Factors of Safety: 10-Year Hurricane Load Case

LOADING DIRECTION	45-DEGREE LOADING				0-DEGREE LOADING				90-DEGREE LOADING			
BOLT TENSILE CAPACITY	109.9 kips	172.3 kips	97.3 kips	22.3 kips	109.9 kips	172.3 kips	97.3 kips	22.3 kips	109.9 kips	172.3 kips	97.3 kips	22.3 kips
LOAD COMBINATION	FACTOR OF SAFETY				FACTOR OF SAFETY				FACTOR OF SAFETY			
	UPPER DERRICK FOOTINGS				UPPER DERRICK FOOTINGS				UPPER DERRICK FOOTINGS			
API-4F ACCEL. & 107 KNOTS WIND	2.13	3.33	1.88	0.43	6.27	9.82	5.55	1.27	6.32	9.90	5.59	1.28
API-4F ACCEL. & 50.9 KNOTS WIND	10.79	16.90	9.54	2.19	176.19	276.08	155.89	35.70	238.92	374.37	211.39	48.41
TIME-DM ACCEL. & 50.9 KNOTS WIND	11.96	18.73	10.58	2.42	179.34	281.02	158.68	36.33	270.33	423.59	239.18	54.77
	SUBSTRUCTURE FOOTINGS				SUBSTRUCTURE FOOTINGS				SUBSTRUCTURE FOOTINGS			
API-4F ACCEL. & 107 KNOTS WIND	1.99	3.12	1.76	0.40	7.79	12.21	6.89	1.58	22.38	35.07	19.80	4.53
API-4F ACCEL. & 50.9 KNOTS WIND	9.25	14.49	8.18	1.87	17.85	27.97	15.79	3.62	22.43	35.15	19.85	4.54
TIME-DM ACCEL. & 50.9 KNOTS WIND	7.61	11.93	6.73	1.54	18.39	28.82	16.27	3.73	22.38	35.07	19.80	4.53

7. SPAR VS TLP ANALYSIS

7.1 General

An analysis, similar to that outlined in the previous sections for Spar rigs, is performed with the aid of the STRUCAD software using the TLP motions presented in the following Table.

Table 51 TLP Platform Accelerations

ENVIRONMENTAL CONDITION	MAXIMUM ACCELERATION (g)	
	LATERAL	VERTICAL
10 YEAR	0.15	0.02
100 YEAR	0.2	0.04
IVAN	0.26	0.05

The structure (derrick & substructure) geometry, wind areas and masses remain the same. **The clamp connections are assumed to be fixed (as opposed to pinned).**

7.2 Tensile, Shear & Slip Results for TLP Rig Clamps

The TLP rig clamp reaction forces and moments and associated factors of safety are calculated in a similar fashion to that described previously. The results are summarised in the following Tables.

Table 52 TLP Substructure Clamp Loads Pertaining to Bolts Tension

ENVIRONMENTAL CONDITION	X DIRECTION LOADING				45°- DIRECTION LOADING			
	MAX. FZ kips	MIN. FZ** kips	MX kip-in	MY kip-in	MAX. FZ kips	MIN. FZ** kips	MX kip-in	MY kip-in
10 YEAR	730.757		395.599	118.976	857.906		363.877	138.115
		273.743	343.396	52.734		146.594	375.118	71.873
100 YEAR	892.430		396.750	147.838	1115.161		354.179	173.356
		91.570	327.155	82.948		**-131.161**	369.735	108.466
1000 YEAR	981.148		403.429	181.866	1256.093		348.153	215.039
		-7.398	312.944	117.651		**-282.300**	368.220	150.824

** POSITIVE NUMBER= COMPRESSION FORCE ON BOLTS

Table 53 TLP Upper Derrick Clamp Loads Pertaining to Bolts Tension

ENVIRONMENTAL CONDITION	X OR Y DIRECTION LOADING				45°- DIRECTION LOADING			
	MAX. FZ kips	MIN. FZ** kips	MX kip-in	MY kip-in	MAX. FZ kips	MIN. FZ** kips	MX kip-in	MY kip-in
10 YEAR	221.019		38.500	58.120	307.300		65.278	65.278
		48.480	24.194	4.577		**-37.789**	2.579	2.579
100 YEAR	306.060		40.250	66.974	480.173		76.515	76.515
		-42.086	21.169	5.554		**-216.173**	15.095	15.095
1000 YEAR	340.724		77.377	42.793	550.823		89.780	89.780
		-79.474	17.987	16.598		**-289.573**	29.001	29.001

** POSITIVE NUMBER= COMPRESSION FORCE ON BOLTS

Given that the most critical direction for wind & Inertia loading on the structure is at 45° angle, the related clamps factors of safety are calculated and provided below.

Table 54 TLP-Clamp Bolts Tensile Factors of Safety for 45° Loading Direction

ENVIRONMENT	BOLT PRETENSION (kips)			
	75.0	137.3	150.0	225.0
	CLAMP TENSILE FACTOR OF SAFETY			
UPPER DERRICK				
IVAN	4.62	2.95	2.61	**0.60**
100 YR	6.25	3.99	3.53	**0.81**
10 YR	35.75	22.82	20.19	4.62
SUBSTRUCTURE				
IVAN	3.98	2.54	2.25	**0.52**
100 YR	7.39	4.72	4.17	**0.96**
10 YR	28.43	18.14	16.05	3.68

Clamps slip and bolts shear factors of safety are also calculated as follows.

Table 55 TLP-Substructure Clamp Shear Forces & Factors of Safety

SUBSTRUCTURE		
ENVIRONMENT	CLAMP SHEAR FORCE (kips)	FACTOR OF SAFETY
IVAN	189.1	4.32
100-YEAR	151.6	5.39
10-YEAR	103.5	7.9

Table 56 TLP-Upper Derrick Clamp Shear Forces & Factors of Safety

ENVIRONMENT	UPPER DERRICK CLAMP SHEAR FORCE (kips)	UPPER DERRICK FACTOR OF SAFETY
IVAN	69.70	11.73
100-YEAR	56.65	14.43
10-YEAR	32.64	25.0

Table 57 TLP-Substructure Clamp Slip Forces & Factors of Safety

SUBSTRUCTURE						
BOLT PRETENSION: (kips)			75	137.3	150	225
ENVIRONMENT	SLIP LOAD (kips)	COF	FACTOR OF SAFETY			
IVAN	177.8	0.1	0.63	0.91	0.96	1.30
		0.3	1.88	2.72	2.89	3.88
		0.5	3.13	4.53	4.82	6.50
100-YEAR	141.2	0.1	0.79	1.14	1.21	1.64
		0.3	2.36	3.42	3.64	4.89
		0.5	3.94	5.70	6.06	8.19
10-YEAR	93.65	0.1	1.19	1.72	1.83	2.47
		0.3	3.56	5.16	5.49	7.37
		0.5	5.94	8.60	9.14	12.35

Table 58 TLP-Derrick Clamp Slip Forces & Factors of Safety

DERRICK						
BOLT PRETENSION: (kips)			75	137.3	150	225
ENVIRONMENT	SLIP LOAD (kips)	COF	FACTOR OF SAFETY			
IVAN	69.698	0.1	1.06	1.77	1.92	2.78
		0.3	3.18	5.32	5.76	8.34
		0.5	5.29	8.87	9.60	13.90
100-YEAR	56.646	0.1	1.30	2.18	2.36	3.42
		0.3	3.91	6.55	7.08	10.26
		0.5	6.51	10.91	11.81	17.10
10-YEAR	32.64	0.1	2.26	3.79	4.10	5.94
		0.3	6.78	11.36	12.29	17.81
		0.5	11.30	18.93	20.49	29.68

7.3 Structure Overturning Moments Vs. Maximum Uplift Forces

As demonstrated in the previous Sections, Inertia & wind loading generate moments at the upper derrick and substructure footings, which result in uplift forces that can exceed the compression forces exerted by the dead weight of the structure.

When this happens, the clamp bolts are subject to tensile loading. This section depicts the relationship between clamp max. uplift forces and the structure global overturning moments. The results for Spar rigs are derived using Time Domain accelerations.

7.3.1 Results for Spar Rig

Table 59 Spar Derrick Clamp Maximum Uplift Forces & Global Overturning Moments

ENVIRONMENT	LOAD-DIRECTION			LOAD DIRECTION								
	X-DIRECT.	Y-DIRECT.	45 deg	X-DIRECTION			Y-DIRECTION			45°-DIRECTION		
	MAX. UPLIFT CLAMP LOAD (FZ) (kips)			DERRICK GLOBAL MOMENTS (AT DERRICK FOOTINGS LEVEL) (kip-ft)								
				M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
NONE (STATIC)	UPLIFT=0.0 kips *DEAD LOAD/CLAMP= -137.5 kips*			0.00								
10 YEAR	-34.20	-34.20	**68.69**	2732.40	1212.42	**3944.82**	2732.40	1212.42	**3944.82**	3864.20	1714.62	**5578.82**
100 YEAR	**85.60**	**85.60**	**308.29**	4971.45	3093.20	**8064.65**	4971.45	3093.20	**8064.65**	7030.69	4374.45	**11405.14**
IVAN	**137.12**	**137.12**	**409.67**	6426.20	3615.81	**10042.01**	6426.20	3615.81	**10042.01**	9088.02	5113.53	**14201.55**

*** $M_T = M_{accel} + M_{wind}$**

Table 60 Spar Substructure Clamp Maximum Uplift Forces & Global Overturning Moments

ENVIRONMENT	LOAD-DIRECTION			LOAD DIRECTION								
	X-DIRECT.	Y-DIRECT.	45 deg	X-DIRECTION			Y-DIRECTION			45°-DIRECTION		
	MAX. UPLIFT CLAMP LOAD (FZ) (kips)			(DERRICK+SUB.) GLOBAL MOMENTS (AT SUBSTRUCTURE FOOTINGS LEVEL) (kip-ft)								
				M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
NONE (STATIC)	UPLIFT=0.0 kips *DEAD LOAD/CLAMP= -512.5 kips*			0.00								
10 YEAR	-220.26	-349.18	-58.48	10643.40	1965.73	**12609.13**	10643.40	1965.73	**12609.13**	15052.04	2779.96	**17832.00**
100 YEAR	**76.05**	-184.32	**402.70**	19393.95	5014.98	**24408.93**	19393.95	5014.98	**24408.93**	27427.19	7092.26	**34519.44**
IVAN	**229.75**	-133.37	**638.52**	25098.20	5862.27	**30960.47**	25098.20	5862.27	**30960.47**	35494.21	8290.50	**43784.72**

*** $M_T = M_{accel} + M_{wind}$**

These results are shown in the following Figures.

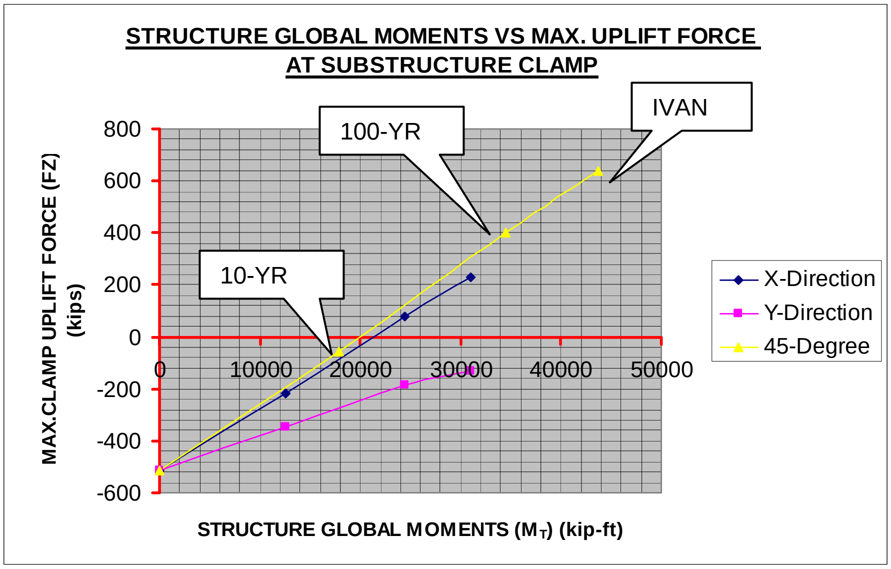

Figure 13 Spar Substructure Clamp Uplift Forces VS Global Overturning Moments

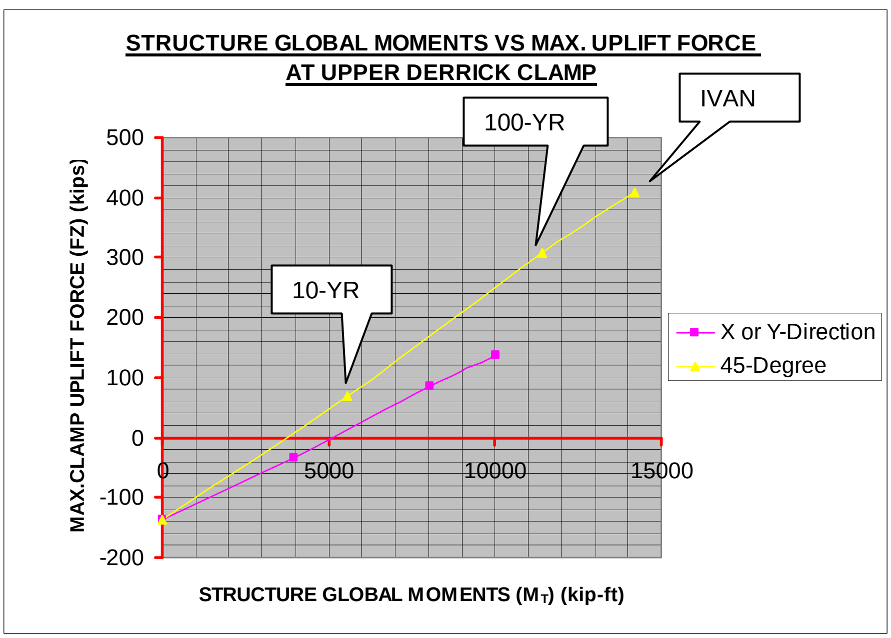

Figure 14 Spar Derrick Clamp Uplift Forces VS Global Overturning Moments

7.3.2 Results for TLP Rig

Table 61 TLP Derrick Clamp Maximum Uplift Forces & Global Overturning Moments

ENVIRONMENT	LOAD-DIRECTION			LOAD DIRECTION								
	X-DIRECT.	Y-DIRECT.	45 deg	X-DIRECTION			Y-DIRECTION			45°-DIRECTION		
	MAX. UPLIFT CLAMP LOAD (FZ) (kips)			DERRICK GLOBAL MOMENTS (AT DERRICK FOOTINGS LEVEL) (kip-ft)								
				M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
NONE (STATIC)	UPLIFT=0.0 kips *DEAD LOAD/CLAMP= -137.5 kips*			0.00								
10 YEAR	-48.48	-48.48	**37.79**	1897.50	1212.42	**3109.92**	1897.50	1212.42	**3109.92**	2683.47	1714.62	**4398.09**
100 YEAR	**42.09**	**42.09**	**216.17**	2530.00	3093.20	**5623.20**	2530.00	3093.20	**5623.20**	3577.96	4374.45	**7952.41**
IVAN	**79.47**	**79.47**	**289.57**	3289.00	3615.81	**6904.81**	3289.00	3615.81	**6904.81**	4651.35	5113.53	**9764.88**

*** M_T= M_{accel}+M_{wind}**

Table 62 TLP Substructure Clamp Maximum Uplift Forces & Global Overturning Moments

ENVIRONMENT	LOAD-DIRECTION			LOAD DIRECTION								
	X-DIRECT.	Y-DIRECT.	45 deg	X-DIRECTION			Y-DIRECTION			45°-DIRECTION		
	MAX. UPLIFT CLAMP LOAD (FZ) (kips)			(DERRICK+SUB.) GLOBAL MOMENTS (AT SUBSTRUCTURE FOOTINGS LEVEL) (kip-ft)								
				M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*	M_{accel}	M_{wind}	M_T*
NONE (STATIC)	UPLIFT=0.0 kips *DEAD LOAD/CLAMP= -512.5 kips*			0.00								
10 YEAR	-273.74	-379.50	-146.59	7522.50	1965.73	**9488.23**	7522.50	1965.73	**9488.23**	10638.42	2779.96	**13418.38**
100 YEAR	-91.57	-269.70	**131.16**	10030.00	5014.98	**15044.98**	10030.00	5014.98	**15044.98**	14184.56	7092.25	**21276.82**
IVAN	**7.40**	-209.90	**282.30**	13039.00	5862.27	**18901.27**	13039.00	5862.27	**18901.27**	18439.93	8290.50	**26730.43**

*** M_T= M_{accel}+M_{wind}**

These results are illustrated in the following Figures.

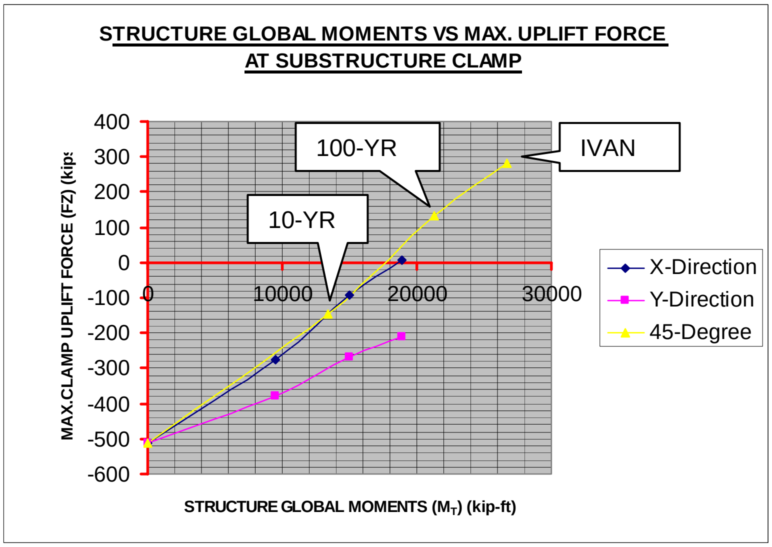

Figure 15 TLP Substructure Clamp Uplift Forces VS Global Overturning Moments

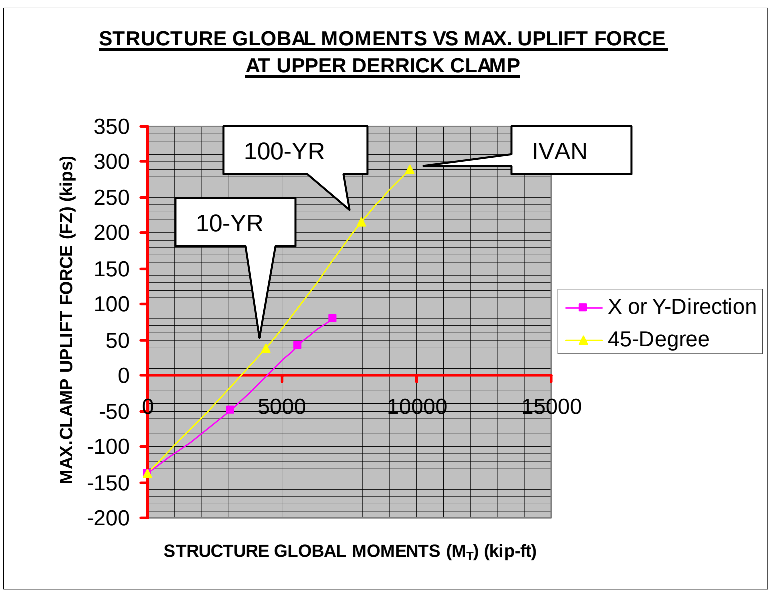

Figure 16 TLP Derrick Clamp Uplift Forces VS Global Overturning Moments

8. SUMMARY OF FINDINGS & CONCLUSIONS

The analysis included in this document focuses on the Tie-Down clamps of a drilling rig mounted on a Spar. The analysis has two main objectives. The first objective is to compare the accelerations calculated based on API-4F specifications to those resulting from Time Domain analysis. The second objective is to analyse the capability of the clamped connections at the upper derrick and substructure footings levels to withstand various environmental loading conditions, namely those associated with Ivan, 100 year and 10 year hurricanes.

Detailed calculations included in Section 2 of this document proved that for a Spar Rig the accelerations derived according to API-4F specifications are consistently more conservative than those obtained from the Time Domain analysis. The latter was exceeded by 4.5% to 6.5% for the case of lateral accelerations. For vertical accelerations, API-4F gives a range of values that reach 2.5 times the corresponding value from Time Domain analysis specifically for the 100 year hurricane case. It is important to note that the vertical accelerations employed for the comparison from Time Domain Analysis, are those associated with maximum lateral accelerations.

To address the second objective of this analysis, several steps were undertaken.
1- Rigid models simulating the upper derrick and substructure masses were developed and subjected to the three different environmental conditions. Reaction forces and moments at the upper derrick and substructure footings were extracted from those models.
2- The clamped connections ultimate strength with respect to bolt shear, slip resistance and tension were determined with respect to corresponding varying parameters.
3- Connections actual shear, slip and tension loads were calculated from the reactions for the three environmental load cases.
4- The ratio of connection ultimate strength to actual loading were determined and documented as the connection factor of safety with respect to each mode of bolt failure.

The analysis demonstrates that the integrity of the clamped connections is highly specific and varies due to the many varying parameters involved. These parameters vary with respect to the mode of failure under consideration. Moreover, for the same mode of failure a second set of parameters affect the outcome of the analysis. As an example, the slip resistance of a connection depends on bolts pretension and coefficient of friction for a given load case.

The specifics of the bolts failure analysis are included in details in this document. A general overview of the results suggests that within the limits of this study:

1- Shear failure does not occur for bolts.

2- **Slip resistance failure occurs in several occasions. Out of a total number of 36 varying combinations of loading conditions and parameters, the number of reported failure cases for a Spar rig are shown in the following graph:**

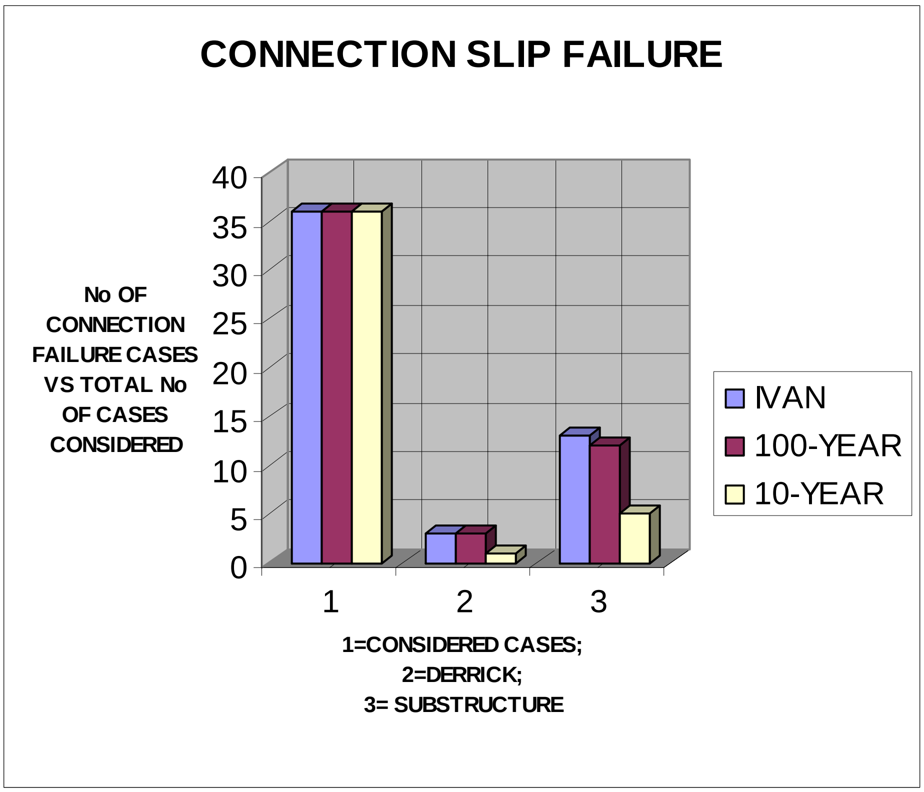

Figure 17 Number of Bolt Slip Failure cases in the analysis of a Spar Rig

3- **Similarly, the number of connection tensile failure cases, reported in this study for a Spar rig, is graphically represented below. These are cases where the actual load exceeds the corresponding ultimate capacity of the clamp (factors of safety less than one).**

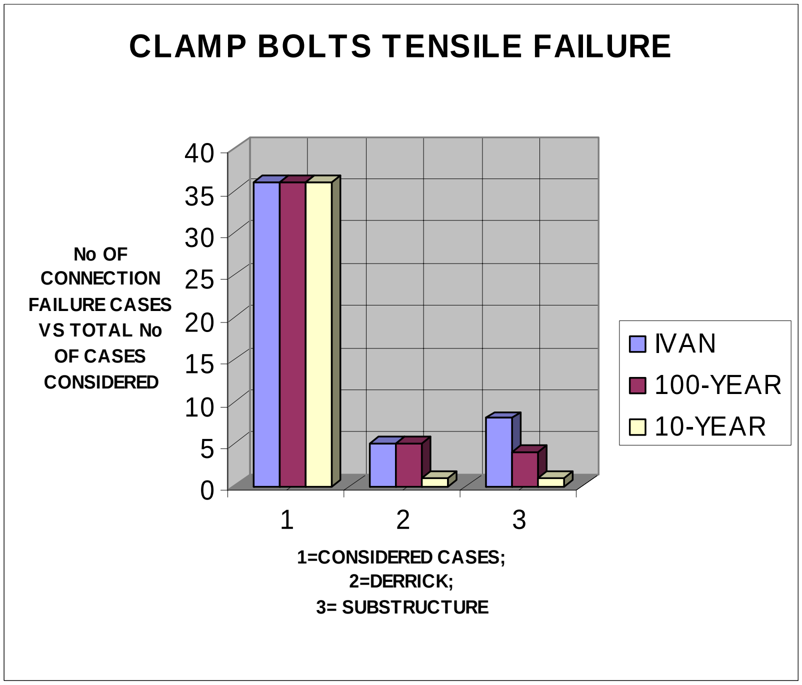

Figure 18 Number of Bolt Tensile Failure cases in the analysis of a Spar Rig

A comparative analysis performed between Spar and TLP rig tie-down clamps, where the only varying parameter is the dynamic loading on the structure, demonstrates the higher vulnerability of the Spar rigs for clamp slip and bolt tensile failures.

In conclusion, the analysis demonstrates that:

1. **The clamp connections, particularly at the substructure footings level and during severe environmental conditions, such as Ivan hurricane, are more likely to fail due to inadequate slip resistance and/or bolt tensile failure than due to shear failure of the bolts.**

2. **There is a need to address the clamp design issue while taking into consideration the particulars of the offshore floating structures on which the drilling rigs are mounted.**

It is important to finally note that the analyses in this document address the clamp actual load VS the ultimate strength of the connections and not VS the allowable design loads (or stresses) for shear, slip and tension.

Comparing actual loads to the latter would show a higher number of cases designated as “not acceptable” due to exceeding the allowable design forces and stresses defined by the AISC. and other industry standards and specifications.

9. REFERENCES

1- American Petroleum Institute, “Specification for Drilling and Well Servicing Structures”, API Specification 4F, Second Edition, June, 1995.

2- Li, Zhanqing & Xu, Qi, “Spar Motion Analysis Results for MMS Rig Tie- Down Study”, Internal Memorandum, Technip USA, June 28, 2006.

3- Interface Solutions Inc., “Flange Pressure”, page2.

4- Salmon, Charles G. and Johnson, John E., “Steel Structures Design and Behavior”, Fourth Edition.

5- Manual of Steel Construction, “Allowable Stress Design”, Ninth Edition.

Appendix B

Assessment of the Performance of Tie-Down Clamps for a Drilling Rig on a TLP in Severe Hurricane Environments

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January 2007

Global Motion of Deep Star TLP
and the Corresponding Load at the Connection of Derrick and Substructure in Extreme Survival Condition

Prepared

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August, 2006

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1.0 SUMMARY

1.1 Scope

This report summarizes the results of the global motion analysis of the Deep Star TLP in 1000 year hurricane condition as well as in 10 year and 100 year hurricane. WAMIT, a second order diffraction/radiation program, was utilized to calculate the frequency dependent hydrodynamic coefficients and the first-order and the second-order sum and difference frequency wave excitation forces. Due to the stiff tendon system of TLP, the heave, roll and pitch natural periods are around 3-4 seconds and the surge and sway natural periods are about 100-160 seconds, which are out of the wave frequency range. Thus, the second order wave loads of sum and difference frequencies are so important that they may not be ignored. Three hour time domain simulation were carried out by a TAMU hull/mooring/riser coupled dynamics analysis program, in the 10 year, 100 year and 1000 year hurricane condition. The force components, such as wind, gravitational and inertia forces, acting on a derrick are obtained through the global motion of the hull to calculate the shear and axial reaction forces at the derrick footing. The calculation is to evaluate the maximum load on the tie-down equipment in the extreme survival condition.

2.0 INTRODUCTION

Many platforms have been designed and installed in GOM (Gulf of Mexico) since the offshore oil and gas industry was born off in 1940's. Most of them have been designed for 100 year return hurricane as the environmental criteria according to API RP2A[1], while the others are designed to survive in 1000 year return hurricane. Recently, there were several severe hurricanes, such as Ivan, Katrina and Rita, which caused the minor and major damages of the platforms. The recent successive severe hurricane events raised the question whether the current design criteria is suitable or not. This study is based on such demands to investigate the robustness of the design criteria in GOM.

A global motion analysis of a typical TLP in GOM, the Deep Star TLP, is performed in severe environmental condition using Charm3D, a computer program of hull and mooring/riser coupled analysis in frequency and time domain[2]. Ten year, 100 year and 1000 year return hurricanes are considered as environmental conditions.

WAMIT[3] is used to calculate the hydrodynamic coefficients such as added mass and hydrodynamic damping and the first and second wave excitation forces. The external stiffness due to tendon and riser is calculated and included in addition to the hydrostatic stiffness due to hull geometry in WAMIT computation so that more accurate motions are obtained in frequency domain because the second order wave excitation force in frequency domain is motion-dependent. The Charm3D is based on the hybrid model of Morison members and a panelized body. The potential forces on column and pontoon are obtained from WAMIT while the viscous effects are considered through the Morison equation.

To calculate the reaction shear and axial forces at a derrick base, equations of force and moment equilibrium of derrick are set up and solved. The results are examined and discussed in the view point of the safety of a top side component in the severe hurricane condition.

3.0 SPECIFICATION OF DEEP STAR TLP

The principal dimensions of the platform are tabulated in Table 1, which are based on Ref. [4]. The TLP consists of four circular columns of 54 ft. outer diameter which are connected at the keel by rectangular pontoons of 27 ft. width and 24 ft. height. The center to center distance is 200 ft. The hull is attached to eight tendons (two tendons at each column), and one drilling TTR and seven production. TTRs are connected to the hull by hydraulic pneumatic tensioners at 120.08 ft. above the mean water level (MWL). The detailed configurations are shown in Figure 1 by the side and the plan views of it.

The In-Place draft, 80 ft., is selected as a base case to estimate the hydrostatic and mass properties. The load condition and corresponding values are shown in Table 2. The total weight is 53,256 kips, the total tendon pretension at the top (porch) is 15,500 kips, and the riser total pretension at the top is 3,500 kips. Vertical center of gravity (COG) is at 28.1 ft. above MWL and vertical center of buoyancy (COB) is at 49.8 ft. below MWL. The roll and pitch radii of gyration are 108.9 ft. and the yaw radius of gyration is 106.3 ft.

The wind load coefficient is $C_{eff} = F_w / V_{10}^2$ =0.0665 kips/(ft/sec)^2 at the center of pressure 125 ft. from MWL, where F_w is total wind force on the hull above MWL and V_{10} is the 1 hour averaged wind speed at 10m level above MWL.

12 spread mooring lines, 6 SCRs and 8 TTRs are modeled. The 8 TTRs are modeled as an equivalent one. The tensioner stiffness of a TTR is assumed to be 25 kips/ft. The mooring and riser configuration is shown in Table 3.

Table 1. Principal Dimensions

Water Depth(ft)	3000
Number of Column	4
Column Cross Section Diameter (ft)	54
Column Center to Center Distance (ft)	200
Column Freeboard (ft)	67
Pontoon Breadth (ft)	27
Pontoon Height (ft)	24
Height of Deck Bottom from MWL (ft)	75
Deck Height (ft)	40

Table 2. Hull Load Condition at In-Place Draft

Draft (ft)	80.0
Total weight (kips)	53,256
Tendon Pretension at the top (kips)	15,500
Riser Pretension at the top (kips)	3,500
Displacements (kips)	72,256
Vertical Center of Gravity from MWL(ft)	28.1
Vertical Center of Buoyancy from MWL(ft)	-49.8
Roll Radius of Gyration (ft)	108.9
Pitch Radius of Gyration (ft)	108.9
Yaw Radius of Gyration (ft)	106.3
Wind Load Coefficient(kips/(ft/sec)^2)	0.0665
Center of Pressure from MWL (ft)	125.0

Table 3. Configuration of the Mooring Line.

	#	X (ft)	Y (ft)	Z (ft)	X (ft)	Y (ft)	Z (ft)	To(kips)
Tendon	1	108.29	130.92	-72.51	108.29	130.92	-3000.15	1.94E+03
	2	130.92	108.29	-72.51	130.92	108.29	-3000.15	1.94E+03
	3	130.92	-108.29	-72.51	130.92	-108.29	-3000.15	1.94E+03
	4	108.29	-130.92	-72.51	108.29	-130.92	-3000.15	1.94E+03
	5	-108.29	-130.92	-72.51	-108.29	-130.92	-3000.15	1.94E+03
	6	-130.92	-108.29	-72.51	-130.92	-108.29	-3000.15	1.94E+03
	7	-130.92	108.29	-72.51	-130.92	108.29	-3000.15	1.94E+03
	8	-108.29	130.92	-72.51	-108.29	130.92	-3000.15	1.94E+03
Drill Riser	1	-7.5	-7.5	120.08	-7.5	-7.5	-3000.15	4.54E+02
Production Riser	1	7.5	7.5	120.08	7.5	7.5	-3000.15	2.30E+02
	2	22.5	7.5	120.08	22.5	7.5	-3000.15	2.30E+02
	3	22.5	-7.5	120.08	22.5	-7.5	-3000.15	2.30E+02
	4	7.5	-7.5	120.08	7.5	-7.5	-3000.15	2.30E+02
	5	-22.5	-7.5	120.08	-22.5	-7.5	-3000.15	2.30E+02
	6	-22.5	7.5	120.08	-22.5	7.5	-3000.15	2.30E+02
	7	-7.5	7.5	120.08	-7.5	7.5	-3000.15	2.30E+02

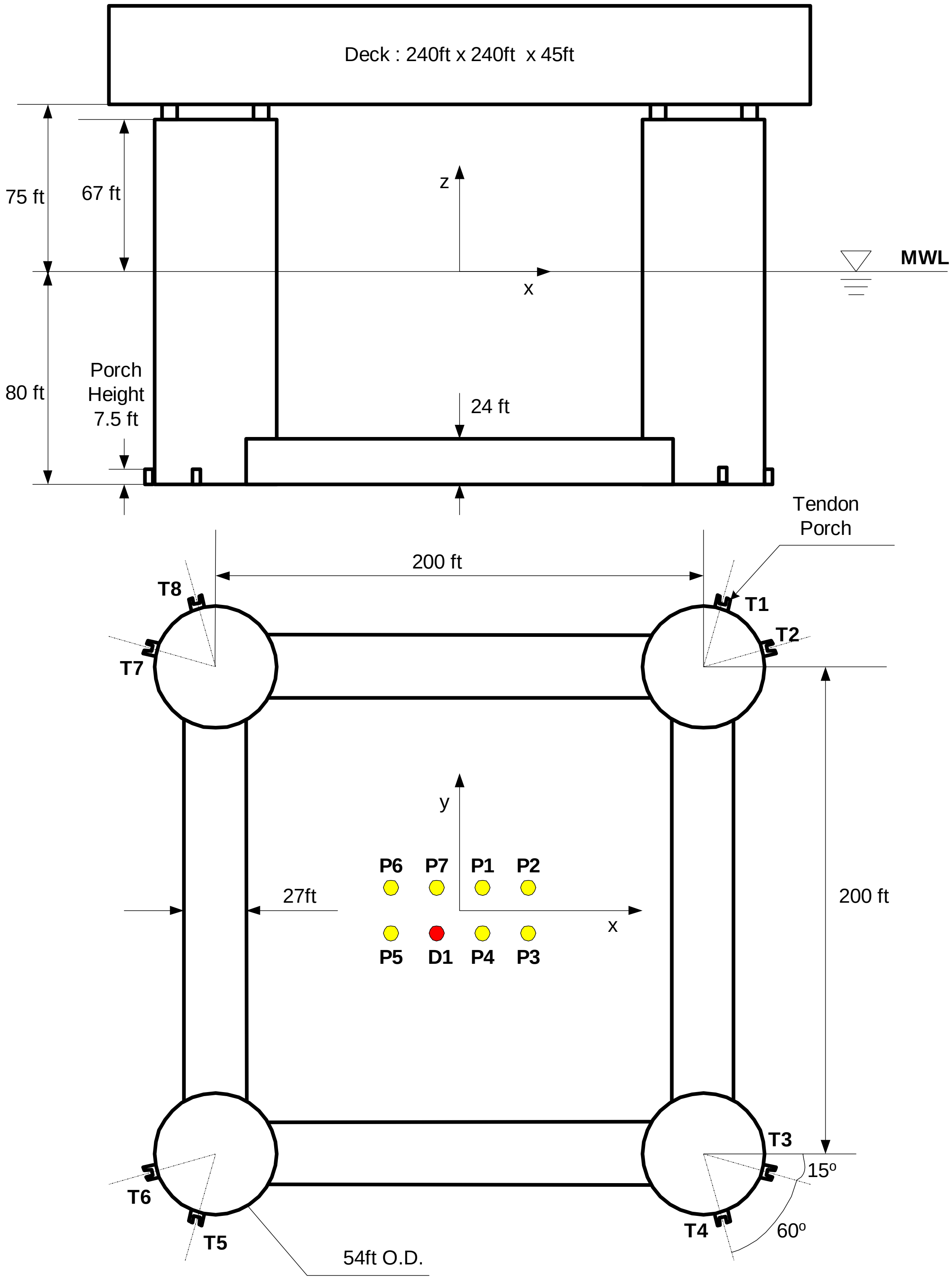


Figure 1. Configuration of the TLP Hull

4.0 NUMERICAL MODELING OF HULL, TENDONS AND RISERS

4.1 Hydrodynamic Modeling with WAMIT

The added mass and radiation damping coefficients, first-order wave excitation forces, and second order sum and difference frequency forces are calculated by the second-order diffraction/radiation program, WAMIT[2]. The tendons and the TTRs are considered as an external stiffness in the frequency domain calculation. The stiffness is added to the hydrostatic stiffness due to the hull geometry, which increases the accuracy of the motion response and the second order forces as well. All the hydrodynamic coefficients are calculated in the frequency domain, and the corresponding forces are converted to the time domain using two-term Volterra series expansion [3]. The frequency-dependent radiation damping was included in the form of convolution integral in the time domain simulation. In Figure 2, the panel configuration for the WAMIT is shown. The body fixed coordinate reference is on the free surface at the centroid of water plane area of the columns. The x-axis is parallel to the pontoon and the z-axis is upward positive. The TLP hull is discretized by 1420 panels and the free surface is discretized by 1070 panels inside a truncation radius.

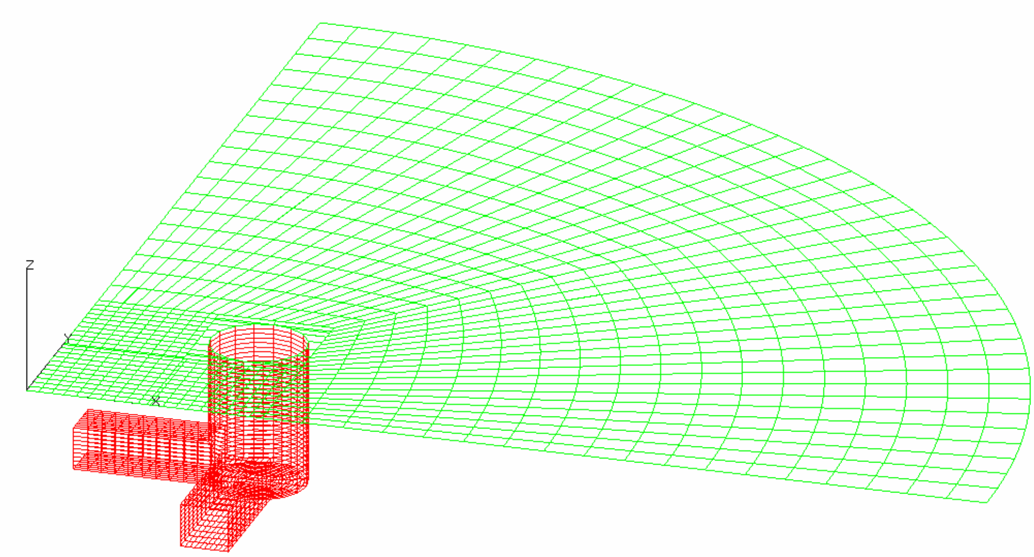


Figure 2. Panel for Hydrodynamic Computation by WAMIT and Body Fixed Coordinate System

4.2 Fully Coupled Analysis Modeling with HARP

Figure 3 shows the global configuration of the platform and tendon/riser coupled system. The water depth is 3000 ft., and the tendons and the risers are all attached down to the sea bed with linear spring. The tendons are also coupled with the hull by the linear spring, while the TTRs are couple with it by numerical pneumatic tensioner model. The relation between tension and the stroke of the tensioner model is obtained through the following nonlinear relation.

$$T = \frac{T_0}{\left(1 + z / z_0\right)^n} \qquad (1)$$

, where

z : stroke of the piston with upward direction positive,

z_0 : effective length of gas in the associated accumulator,

T_0 : Initial top tension at stroke z=0.

n : gas constant.

Figure 3 shows the zoom-in feature near the platform. The centerlines of the columns and the pontoons represent the Morrison tubular members to model the drag force of the columns and the pontoons.

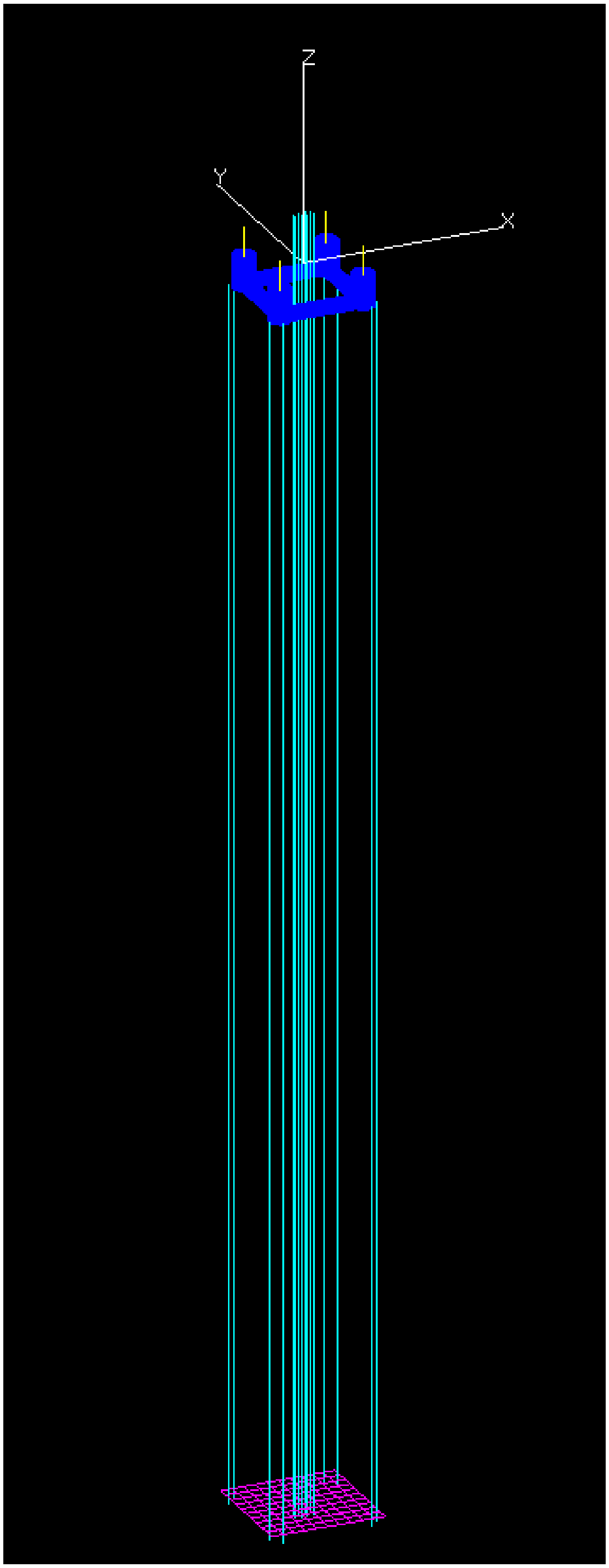


Figure 3. Global Configuration of the Hull/Mooring Line/Riser

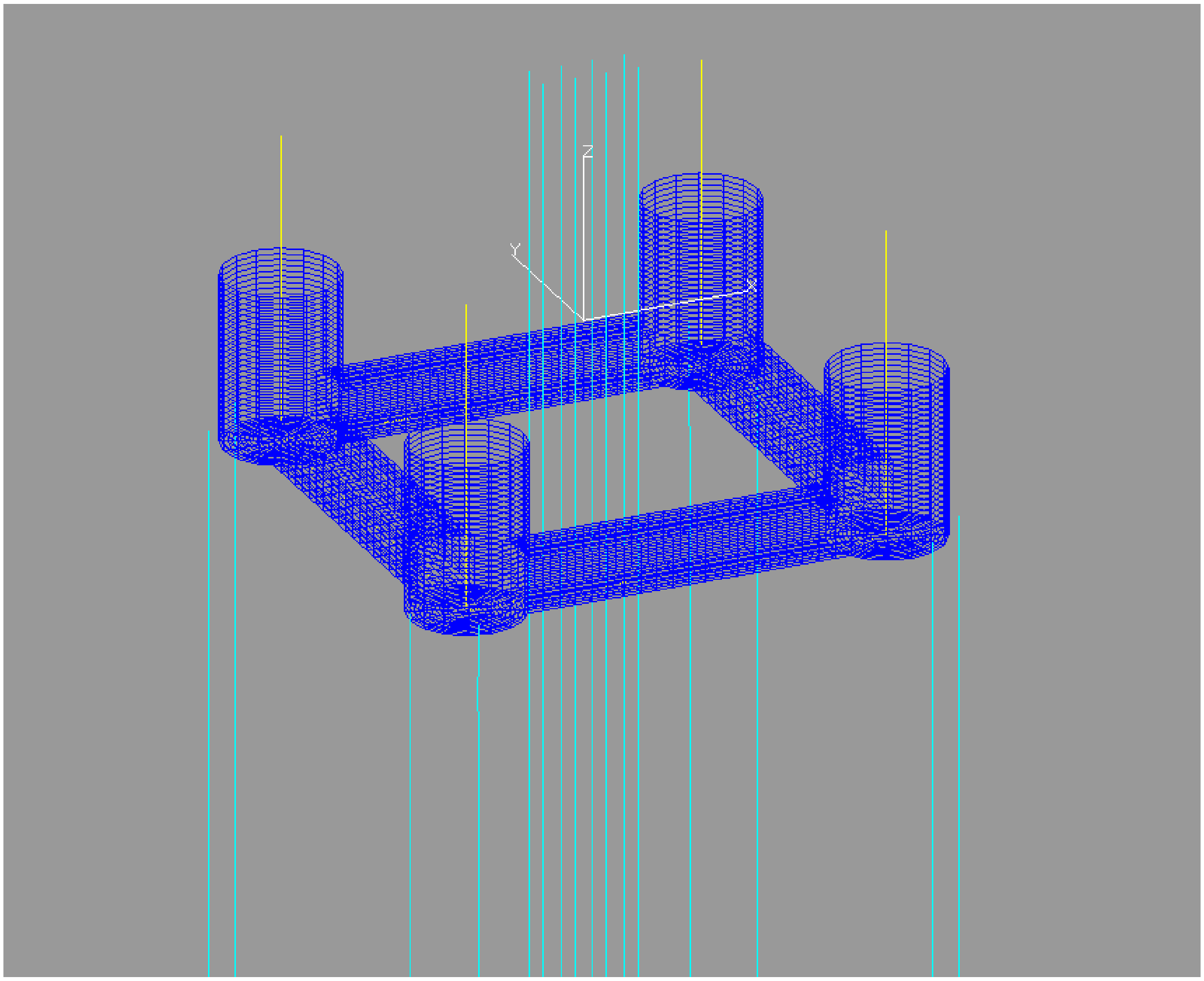


Figure 4. Zoom in of the Global Configuration of the System

5.0 ENVIRONMENTAL CONDITION

Ten year, 100 year and 1000 year return hurricane events are selected as environmental conditions. Table 4. shows the typical wave, wind and current characteristics of each environmental condition. JONSWAP spectrum is used for the long crested irregular wave generation with the given stiffness parameter, γ. Time varying wind speed is generated by using the API spectrum. Wave incident angle is 180 degrees, and the wind and the current are associated with the wave in the direction.

Table 4. Environmental Conditions

Return Period	10 year		100 year		Ivan	
Hs (ft)	24.9		40.0		51.1	
Tp (sec)	11.9		14.0		15.6	
γ *	2.4		2.4		3.0	
Wind Speed** (knot)	50.9		81.3		87.9	
Current Profile	Depth(ft)	Speed(ft/s)	Depth(ft)	Speed(ft/s)	Depth(ft)	Speed(ft/s)
	0.0	2.59	0.0	4.92	0.0	8.19
	98.4	1.97	98.4	3.77	16.4	8.19
	196.9	0.95	196.9	1.84	82.0	3.92
	295.3	0.33	295.3	0.33	164.1	3.69
	3000.0	0.33	3000.0	0.33	264.1	2.44
					328.1	1.02
					492.2	0.95
					984.3	0.88
					3000.0	0.00

* JONSWAP spectrum is used for the irregular wave generation with the given γ

** The wind speed is 1 hour averaged one at 10m above MWL, and API wind spectrum is used for the time varying wind speed generation.

6.0 REACTION FORCE ON THE DERRICK BASE

Let the inertia coordinate system ($\underline{x}_1$, $\underline{x}_2$, $\underline{x}_3$), then the body fixed coordinate system ($\underline{b}_1$, $\underline{b}_2$, $\underline{b}_3$) experience the translational motion ${}^N\underline{x}_t$ and the rotational motion $\underline{\theta}_{B/N}$ with respect to the inertia coordinate system (Refer to Figure 5.), where superscript N means "with respect to the inertia frame" and superscript B means "with respect to the body fixed coordinate system". Assume the derrick is on the deck by the four point support at $\underline{p}^1$, $\underline{p}^2$, $\underline{p}^3$ and $\underline{p}^4$, and that each support has the substructure tied-down by bolts as in Figure 6.

The velocity of the point, ${}^B\underline{r}$ or ${}^N\underline{R}$, on the platform is obtained by the time derivative in the inertia frame as :

$$ {}^N\frac{d\underline{R}}{dt} = \underline{\dot{x}}_t + \underline{\dot{\theta}}_{B/N} \times {}^B\underline{r} \tag{2} $$

The inertial acceleration is found by taking the inertial derivative of velocity as:

$$ {}^N\frac{d^2\underline{R}}{dt^2} = \underline{\ddot{x}}_t + \underline{\ddot{\theta}}_{B/N} \times {}^B\underline{r} + \underline{\dot{\theta}}_{B/N} \times \left(\underline{\dot{\theta}}_{B/N} \times {}^B\underline{r}\right) \tag{3} $$

Integrating the infinitesimal linear inertial force contributions over the entire body, the total linear inertia force is given by:

$$ \int_B {}^N\frac{d^2\underline{R}}{dt^2} dm = \left[M\right]\underline{\ddot{x}}_t - \left[\underline{r}_g{}^{\times}\right]\left\{\underline{\ddot{\theta}}_{B/N}\right\} - \left[\underline{\dot{\theta}}_{B/N}{}^{\times}\right]\left(\left[\underline{r}_g{}^{\times}\right]\left\{\underline{\dot{\theta}}_{B/N}\right\}\right) \tag{4} $$

where

$$ \left[M\right] = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix}, $$

$$ \left[\underline{mr}_g{}^{\times}\right] = \int_M \left[\underline{r}^{\times}\right] dm \, , $$

The angular momentum is obtained by integrating the infinitesimal angular momentum contributions over the entire body.

$$ \underline{H} = \int_M \underline{r} \times {}^N\frac{d\underline{R}}{dt} dm = \int_M \underline{r} dm \times \underline{\dot{x}}_t + \int_M -\left[\underline{r}^{\times}\right]\left[\underline{r}^{\times}\right] dm \left\{\underline{\dot{\theta}}_{B/N}\right\} \tag{5} $$

Taking the time derivative of angular momentum gives

$$\frac{d\underline{L}}{dt} = \left[\underline{mr}_g^{\times}\right]\left\{\underline{\ddot{x}}_t\right\} + \left[I\right]\left\{\underline{\ddot{\theta}}_{B/N}\right\} \tag{6}$$

, where

$$\left[I\right] = \int_M -\left[\underline{r}^{\times}\right]\left[\underline{r}^{\times}\right] dm\,.$$

Thus, the force equilibrium from the free body diagram at Figure 5. is written as:

$$\left[M\right]\underline{\ddot{x}}_t - \left[\underline{mr}_g^{\times}\right]\left\{\underline{\ddot{\theta}}_{B/N}\right\} - \left[\underline{\dot{\theta}}_{B/N}^{\times}\right]\left(\left[\underline{r}_g^{\times}\right]\left\{\underline{\dot{\theta}}_{B/N}\right\}\right) = \left\{\underline{f}_g\right\} + \left\{\underline{f}_{wind}\right\} + \sum_{i=1}^{4}\left\{\underline{f}_r^{\,i}\right\} \tag{7}$$

where

$\underline{f}_g$ = gravitational force,

$\underline{f}_{wind}$ = wind force,

$\underline{f}_r^{\,i}$ = reaction force at the bolting point $\underline{p}^i$.

The moment equilibrium around the body reference point goes to

$$\left[\underline{mr}_g^{\times}\right]\left\{\underline{\ddot{x}}_t\right\} + \left[I\right]\left\{\underline{\ddot{\theta}}_{B/N}\right\} = \left[\underline{r}_g^{\times}\right]\left\{\underline{f}_g\right\} + \left[\underline{r}_{wind}^{\times}\right]\left\{\underline{f}_{wind}\right\} + \sum_{i=1}^{4}\left[\underline{p}^{i\times}\right]\left\{\underline{f}_r^{\,i}\right\} \tag{8}$$

The wind force and the gravitational force are expressed in global coordinate. Thus, coordinate transformation is necessary to express them in the body fixed coordinate. The Euler angle representation of the transformation is used.

The standard yaw-pitch-roll angles are selected as a sequence of rotational angles. Then, resultant transform matrix is obtained in Equation (12).

$$\left\{\underline{b}\right\} = \begin{Bmatrix} \underline{b}_1 \\ \underline{b}_2 \\ \underline{b}_3 \end{Bmatrix} = \begin{bmatrix} c\theta_3 & s\theta_3 & 0 \\ -s\theta_3 & c\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \underline{x}_1 \\ \underline{x}_2 \\ \underline{x}_3 \end{Bmatrix} = \left[E\left(\theta_3\right)\right]\left\{\underline{x}\right\} \tag{9}$$

$$\{\underline{b}\} = \begin{Bmatrix} \underline{b}_1 \\ \underline{b}_2 \\ \underline{b}_3 \end{Bmatrix} = \begin{bmatrix} c\theta_2 & 0 & -s\theta_2 \\ 0 & 1 & 0 \\ s\theta_2 & 0 & c\theta_2 \end{bmatrix} \begin{Bmatrix} \underline{x}_1 \\ \underline{x}_2 \\ \underline{x}_3 \end{Bmatrix} = \left[E(\theta_2)\right]\{\underline{x}\} \tag{10}$$

$$\{\underline{b}\} = \begin{Bmatrix} \underline{b}_1 \\ \underline{b}_2 \\ \underline{b}_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\theta_1 & s\theta_1 \\ 0 & -s\theta_1 & c\theta_1 \end{bmatrix} \begin{Bmatrix} \underline{x}_1 \\ \underline{x}_2 \\ \underline{x}_3 \end{Bmatrix} = \left[E(\theta_1)\right]\{\underline{x}\} \tag{11}$$

$$\{\underline{b}\} = \left[E(\theta_1)\right]\left[E(\theta_2)\right]\left[E(\theta_3)\right]\{\underline{x}\} = \left[E(\underline{\theta})\right]\{\underline{x}\} \tag{12}$$

where

$$\begin{aligned} \left[E(\underline{\theta})\right] &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\theta_1 & s\theta_1 \\ 0 & -s\theta_1 & c\theta_1 \end{bmatrix} \begin{bmatrix} c\theta_2 & 0 & -s\theta_2 \\ 0 & 1 & 0 \\ s\theta_2 & 0 & c\theta_2 \end{bmatrix} \begin{bmatrix} c\theta_3 & s\theta_3 & 0 \\ -s\theta_3 & c\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} c\theta_2 c\theta_3 & c\theta_2 s\theta_3 & -s\theta_2 \\ s\theta_1 s\theta_2 c\theta_3 - c\theta_1 s\theta_3 & s\theta_1 s\theta_2 s\theta_3 + c\theta_1 c\theta_3 & s\theta_1 c\theta_2 \\ c\theta_1 s\theta_2 c\theta_3 + s\theta_1 s\theta_3 & c\theta_1 s\theta_2 s\theta_3 - s\theta_1 c\theta_3 & c\theta_1 c\theta_2 \end{bmatrix} \end{aligned}$$

The body force is gravitational force acting on the center of gravity represented in the body fixed coordinate system is

$$\left\{\underline{f}_g\right\} = \left[E(\underline{\theta})\right] \begin{Bmatrix} 0 \\ 0 \\ -mg \end{Bmatrix} \text{ at } \{r_g\} = \begin{Bmatrix} x_g \\ y_g \\ z_g \end{Bmatrix} \tag{13}$$

The environmental forces on the derrick is the wind which is only in horizontal plane in the global coordinate system. Transforming the wind force to the body fixed coordinate system is

$$\left\{\underline{f}_w\right\} = \left[E(\underline{\theta})\right] \begin{Bmatrix} f_{wx} \\ f_{wy} \\ 0 \end{Bmatrix} \text{ at } \{r_w\} = \begin{Bmatrix} x_w \\ y_w \\ z_w \end{Bmatrix} \tag{14}$$

The reaction forces are at the four corners and they consist of normal force and the shear forces.

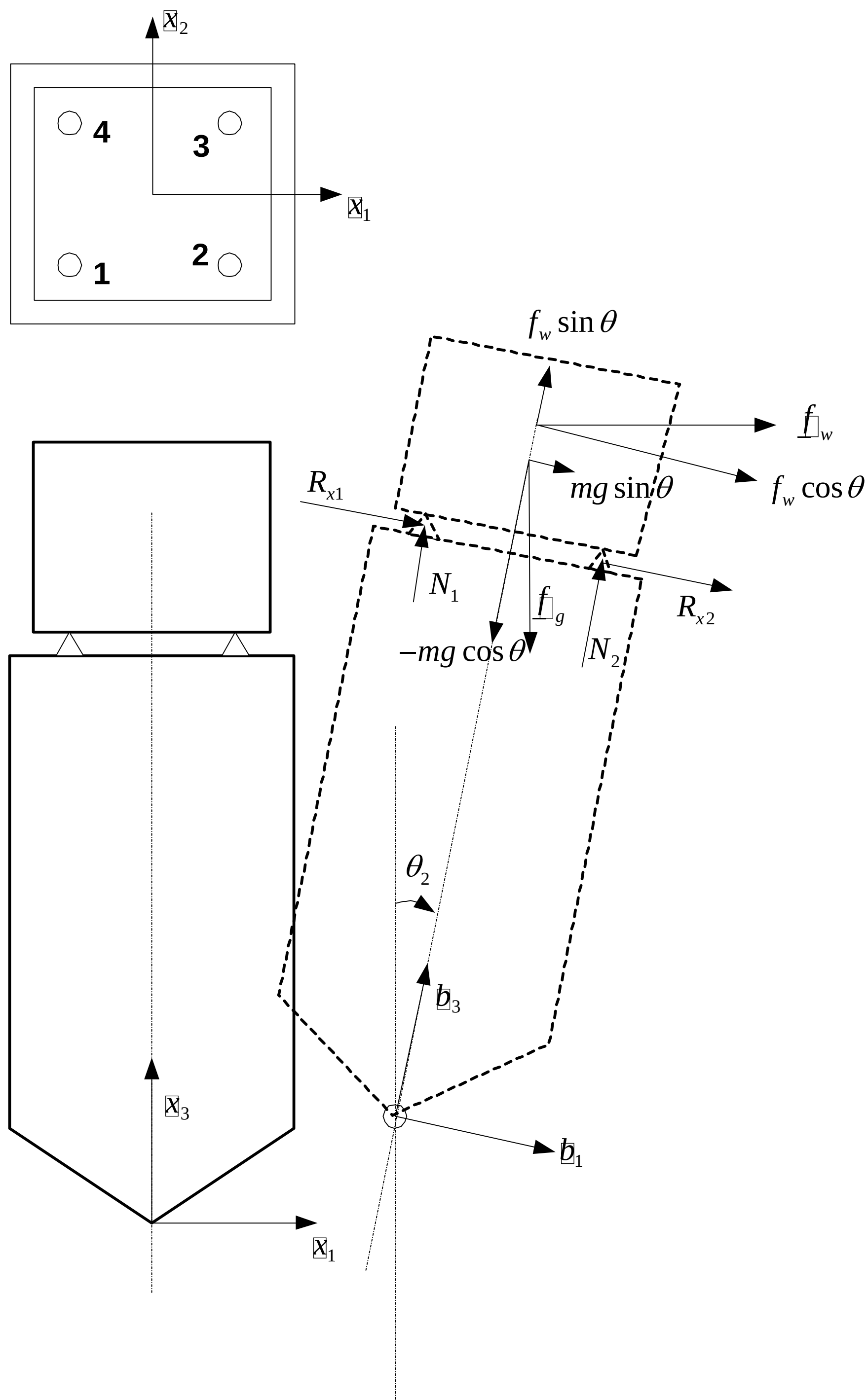


Figure 5. Definition Sketch of the Coordinate System and Free Body Diagram of the Derrick

7.0 RESULTS

The reaction forces and the moments on the derrick and the substructure footing points are calculated with the formula given at the previous section. The corresponding slip force and the shear and the tensile forces acting on each bolt are calculated to give the safety factor of the footing against the environmental loadings.

The configuration of the derrick and the substructure is shown in Figure 6. The derrick is connected to the deck through the substructure. The footings of derrick connect the derrick and the substructure, and the substructure footings support the derrick and the substructure. A plan view of the footing layout is in Figure 7. The upper derrick footings are on the rail which is parallel to the y-axis to allow the slip only in y-direction. The shear force in x-direction is transferred to the bolt directly and the bolts need to resist the shear force. On the contrary, the substructure footings are laid on the rail parallel to x-direction to allow the slip in x-direction. Thus, the y-directional shear forces are totally transferred to the bolts.

Each footing has the eight bolts to give the pretension for the slip capacity as in Figure 8. Due to the layout of the bolts, the shear force is applied only to 4 bolts, while the tensile force is uniformly applied to 8 bolts. Therefore, the capacity of the shear force for a footing is determined by the those of 4 bolts and the tensile capacity is by 8 bolts. 1-1/2 inch bolts are used to tie down the structure and the corresponding shear and the tensile capacities for each bolt are estimated through the material property(Refer to Ref.3).

The derrick and the substructure are assumed to be positioned at the center of the deck, i.e. at the CG of the TLP, and the vertical CGs of the derrick and the substructure are shown in Table 5. The center of pressure of the wind force and the wind area of derrick and the substructure are also shown in the table. For the derrick, the projected area in x-direction is 1470 $ft.^2$, but the front part does not shade the area at the down stream. Thus, the double of the projected area(=2940 $ft.^2$) is used. The resultant total wind area and the center of wind pressure at the last column are used to calculated the reaction forces on the substructure footings. The radius of gyrations are assumed and given in the table.

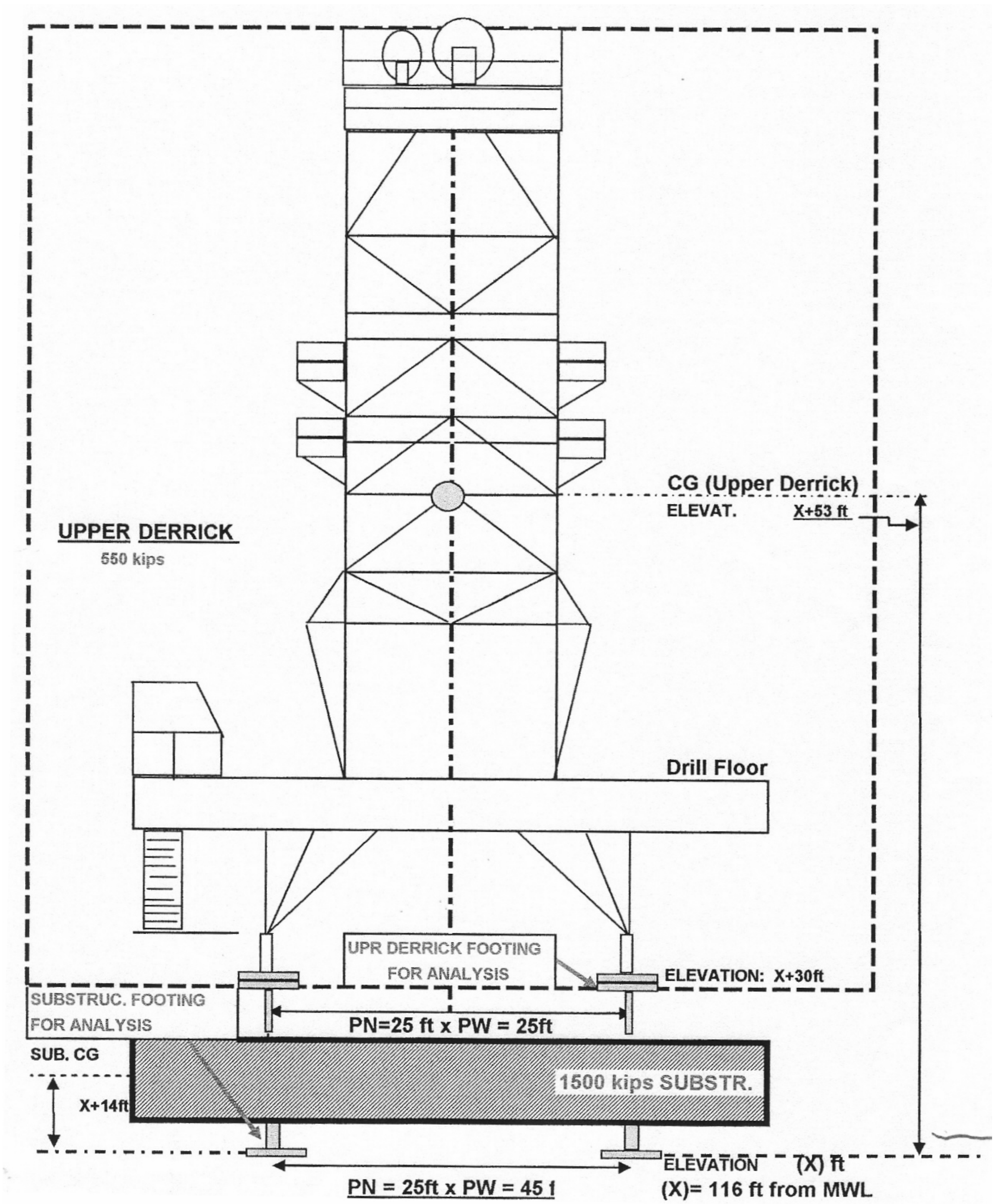


Figure 6. The Configuration of Derrick and Substructure

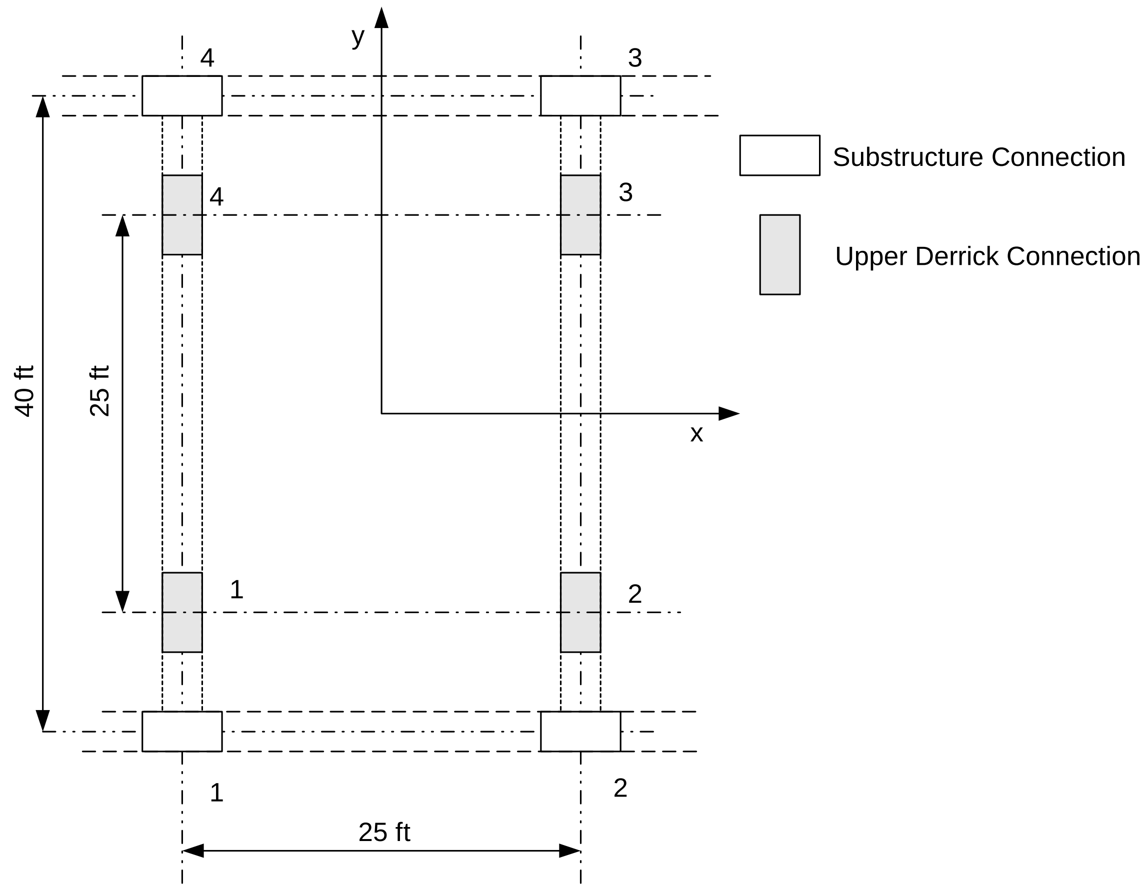


Figure 7. Configuration of the Upper Derrick and the Substructure Footings

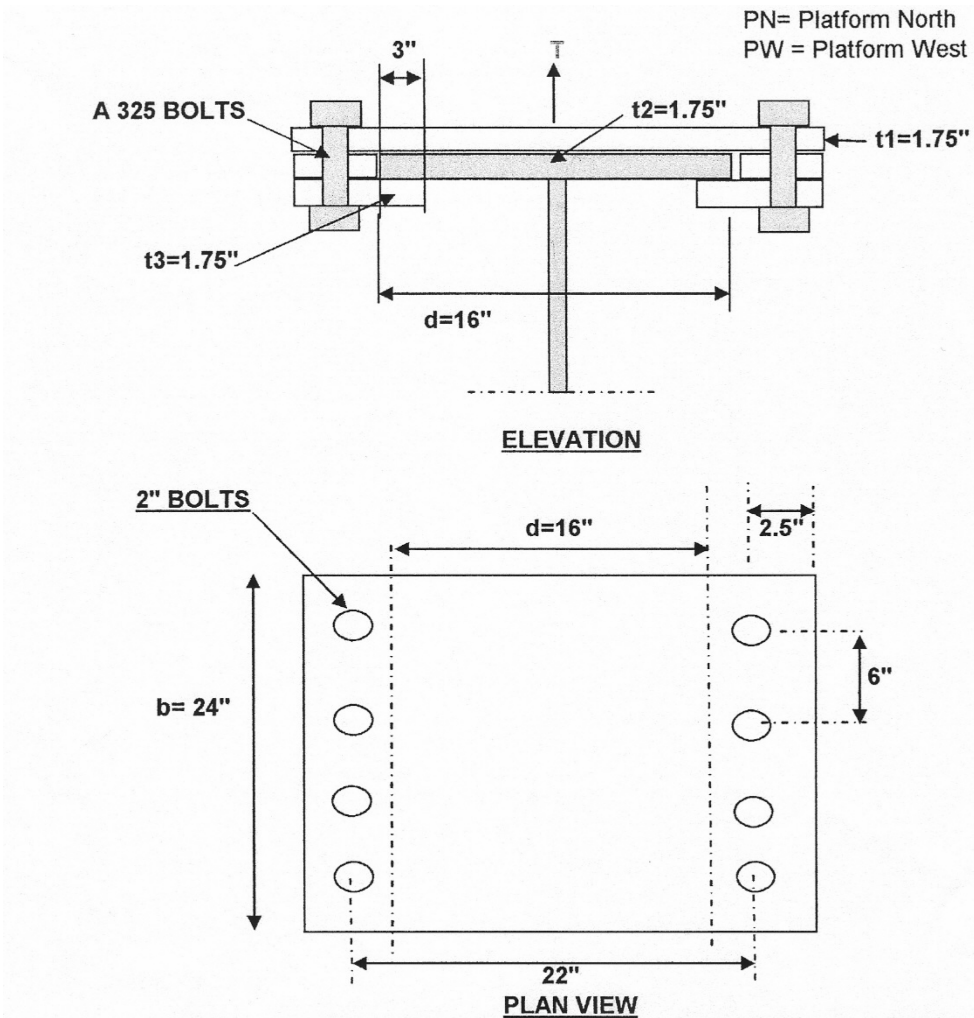


Figure 8. A Typical Connection at Derrick Base & at Substructure base

Table 5. Specifications of Upper Derrick

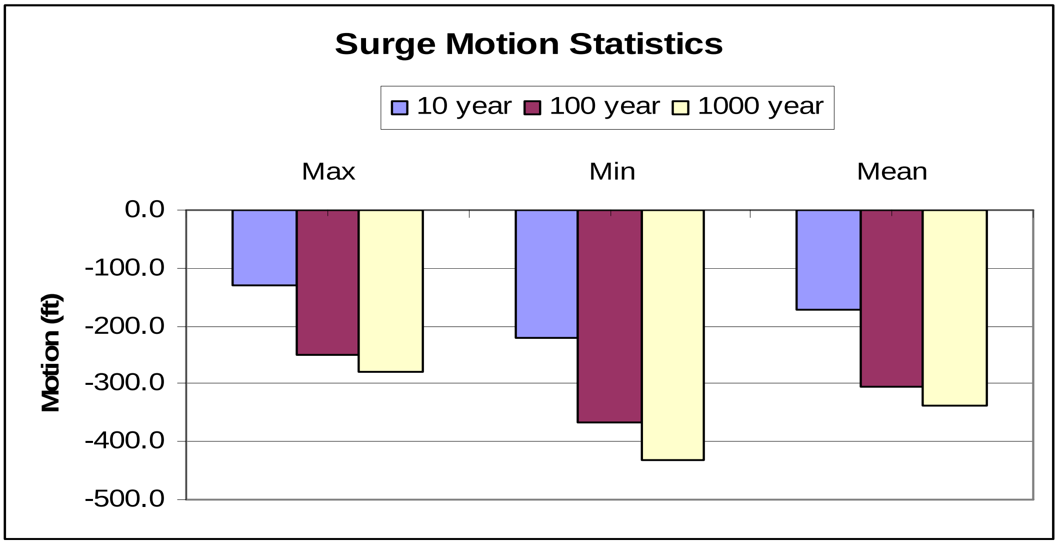
	Upper Derrick	Substructure	Total
Weight (kips)	550	1500	2050
Projected Area (ft^2)	2940	500	3440
Center of Pressure from MWL (ft)	201	130	190
Center of Gravity from MWL (ft)	169	130	140.5
Height Coefficient(C_h)*	1.37	1.19	1.24
Shape Coefficient(C_s)*	1.25	1.25	1.25
Radius of Gyration around CG** (ft)	15/15/10	15/15/10	20/20/10

* Wind force is calculated by $F_{wind} = 1/2 \rho_{air} A_{project} C_h C_s V_{10m}^2$ (Refer to Technip Report)

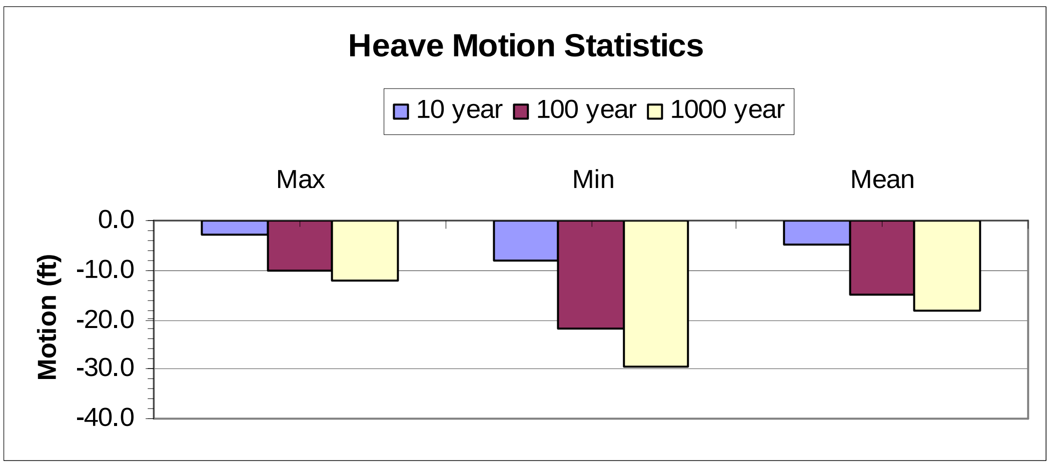
** Assumed for the exact inertia force calculation through motion.

7.1 Derrick Motion

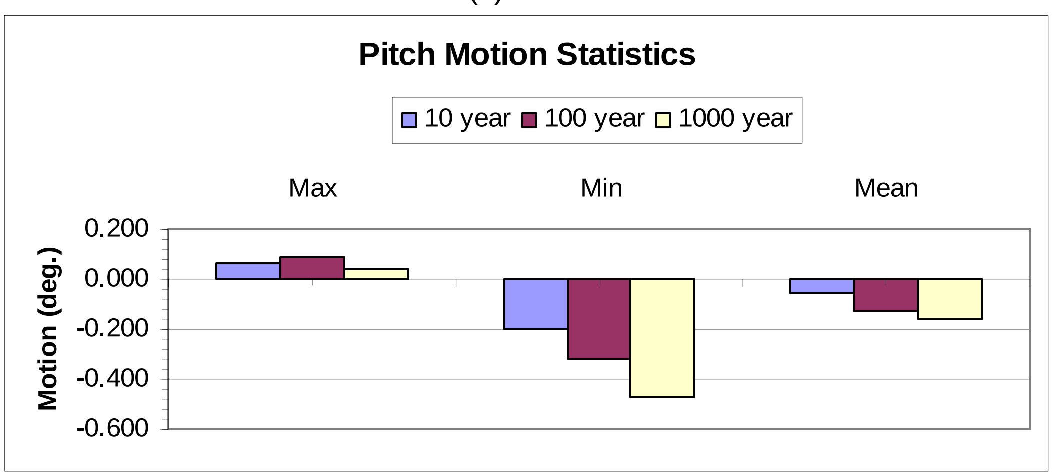
Derrick Motions are shown in Figure A-1 through A-12 in Appendix A. The Statistics of surge, heave and pitch are in figure 8, and the statistics of the accelerations in the directions are in figure 9.



(a) Surge Motion

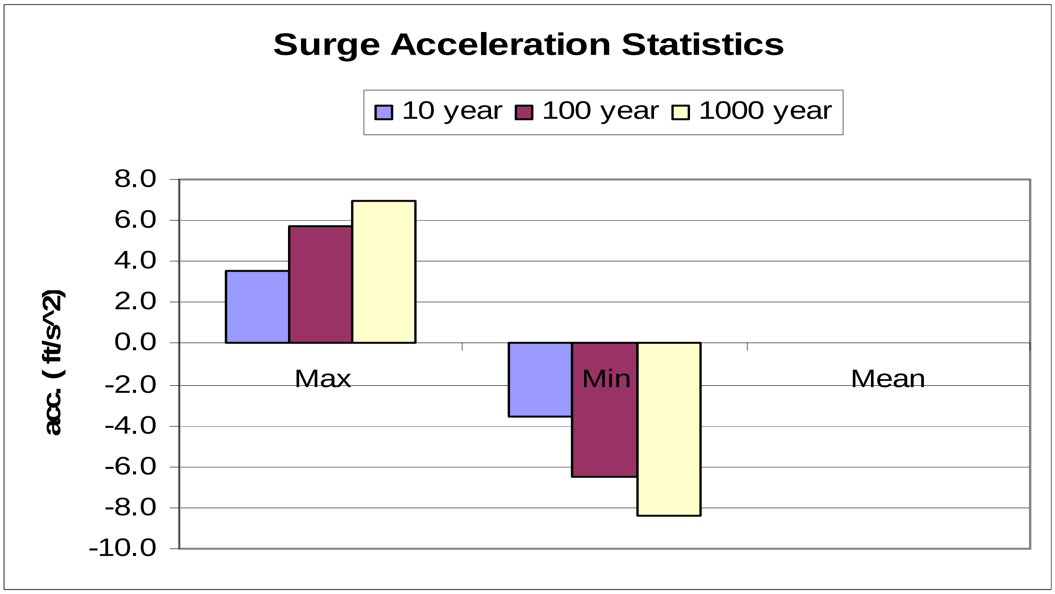


(b) Heave Motion

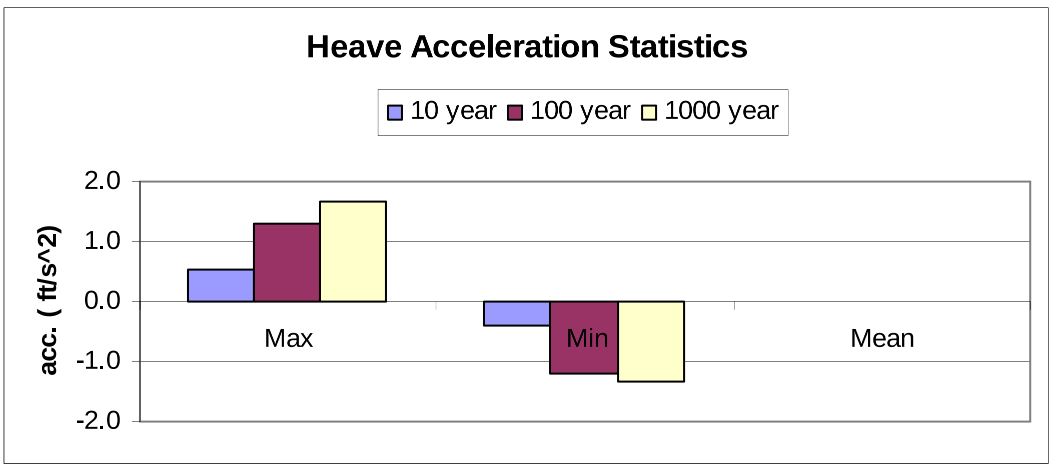


(c) Pitch Motion

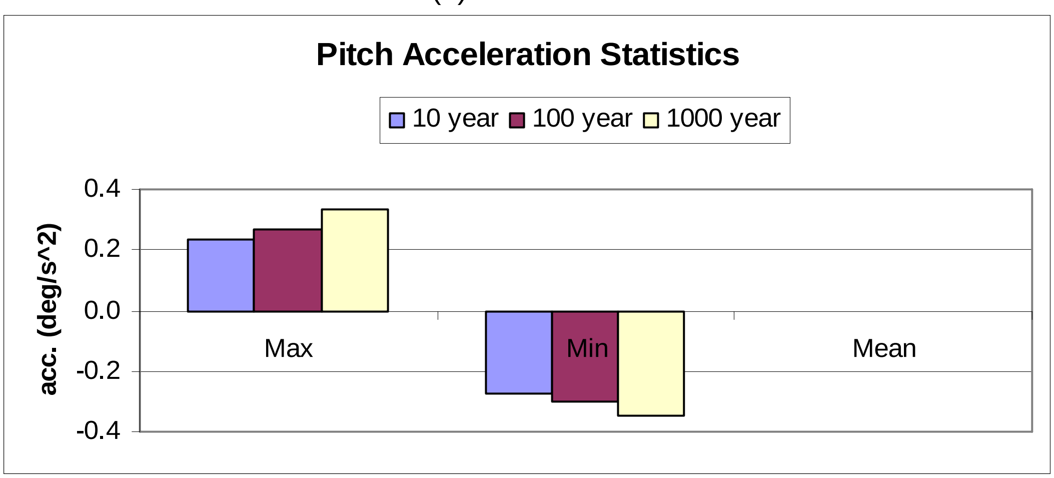
Figure 9. Statistics of Derrick COG Motion - Three Main Modes for 180 Degree Incident Angle



(a) Surge Acceleration



(b) Heave Acceleration



(c) Pitch Acceleration

Figure 10. Statistics of Derrick COG Acceleration - Three Main Modes for 180 Degree Incident Angle

7.2 Dynamic Forces on Derrick and Substructure

Table 6. Statistics of Dynamic Forces on the Derrick for 10 Year Hurricane

Surge(kips)

	Inertia	Gravitational	Wind	Total
Max	61.73	0.65	-18.50	21.80
Min	-61.22	-1.94	-97.31	-141.27
Mean	0.00	-0.54	-52.20	-52.75

Heave(kips)

	Inertia	Gravitational	Wind	Total
Max	10.95	-554.00	0.26	-540.75
Min	-13.25	-554.00	-0.08	-564.95
Mean	0.01	-554.00	0.05	-553.96

Pitch (kips-ft)

	Inertia	Gravitational	Wind	Total
Max	1423.30	15.10	-1017.70	-265.30
Min	-1425.90	-44.50	-5351.80	-6184.80
Mean	0.00	-12.50	-2871.20	-2883.60

Table 7. Statistics of Dynamic Forces on the Derrick for 100 Year Hurricane

Surge(kips)

	Inertia	Gravitational	Wind	Total
Max	98.98	0.88	-46.74	32.36
Min	-112.08	-3.11	-199.69	-252.01
Mean	0.00	-1.19	-113.91	-115.11

Heave(kips)

	Inertia	Gravitational	Wind	Total
Max	22.34	-553.99	0.91	-533.38
Min	-20.55	-554.00	-0.19	-576.16
Mean	-0.04	-554.00	0.25	-553.71

Pitch (kips-ft)

	Inertia	Gravitational	Wind	Total
Max	2287.00	20.00	-2571.00	-1489.00
Min	-2606.00	-72.00	-10983.00	-11543.00
Mean	0.00	-27.00	-6265.00	-6293.00

Table 8. Statistics of Dynamic Forces on the Derrick for 1000 Year Hurricane

Surge(kips)

	Inertia	Gravitational	Wind	Total
Max	122.46	0.44	-47.20	17.72
Min	-144.24	-4.53	-248.25	-299.01
Mean	0.08	-1.53	-133.22	-134.83

Heave(kips)

	Inertia	Gravitational	Wind	Total
Max	27.06	-553.98	1.41	-529.89
Min	-23.86	-554.00	-0.09	-580.60
Mean	0.44	-554.00	0.37	-554.06

Pitch (kips-ft)

	Inertia	Gravitational	Wind	Total
Max	2818.00	10.00	-2596.00	-1446.00
Min	-3343.00	-104.00	-13654.00	-14388.00
Mean	2.00	-35.00	-7327.00	-7364.00

Table 9. Statistics of Dynamic Forces on the Derrick and the Substructure for 10 Year Hurricane

Surge(kips)

	Inertia	Gravitational	Wind	Total
Max	227.24	2.42	-19.60	174.34
Min	-220.77	-7.16	-103.05	-281.35
Mean	0.00	-2.01	-55.29	-57.29

Heave(kips)

	Inertia	Gravitational	Wind	Total
Max	40.50	-2050.00	0.30	-2001.00
Min	-49.00	-2050.00	-0.10	-2090.50
Mean	0.00	-2050.00	0.10	-2050.00

Pitch(kips-ft)

	Inertia	Gravitational	Wind	Total
Max	5588.00	59.00	-1450.00	2277.00
Min	-5510.00	-176.00	-7626.00	-11660.00
Mean	0.00	-49.00	-4091.00	-4140.00

Table 10. Statistics of Dynamic Forces on the Derrick and the Substructure for 100 Year Hurricane

Surge(kips)

	Inertia	Gravitational	Wind	Total
Max	362.78	3.24	-49.50	318.81
Min	-405.48	-11.52	-211.48	-523.80
Mean	0.01	-4.42	-120.64	-125.07

Heave(kips)

	Inertia	Gravitational	Wind	Total
Max	82.60	-2050.00	1.00	-1973.90
Min	-76.10	-2050.00	-0.20	-2132.50
Mean	-0.10	-2050.00	0.30	-2049.60

Pitch(kips-ft)

	Inertia	Gravitational	Wind	Total
Max	8949.00	79.00	-3663.00	3839.00
Min	-10097.00	-282.00	-15649.00	-20945.00
Mean	0.00	-108.00	-8927.00	-9036.00

Table 11. Statistics of Dynamic Forces on the Derrick and the Substructure for 1000 Year Hurricane

Surge(kips)

	Inertia	Gravitational	Wind	Total
Max	452.75	1.63	-49.99	362.90
Min	-525.36	-16.77	-262.90	-597.29
Mean	0.25	-5.65	-141.08	-146.98

Heave(kips)

	Inertia	Gravitational	Wind	Total
Max	100.10	-2049.90	1.50	-1961.40
Min	-88.30	-2050.00	-0.10	-2149.60
Mean	1.60	-2050.00	0.40	-2051.20

Pitch(kips-ft)

	Inertia	Gravitational	Wind	Total
Max	11099.00	40.00	-3699.00	2293.00
Min	-13018.00	-411.00	-19455.00	-24482.00
Mean	7.00	-138.00	-10440.00	-10586.00

7.3 Reaction Forces on the Footings

Table 12. Reaction Forces on Upper Derrick Footing for 10 Year Hurricane

	Fx	N1,N4	N2,N3
Max	35.32	132.31	263.11
Min	-5.45	15.23	142.92
Mean	13.19	80.82	196.16

Table 13. Reaction Forces on Upper Derrick Footing for 100 Year Hurricane

	Fx	N1,N4	N2,N3
Max	63.00	107.50	368.51
Min	-8.09	-93.19	167.08
Mean	28.78	12.57	264.28

Table 14. Reaction Forces on Upper Derrick Footing for 1000 Year Hurricane

	Fx	N1,N4	N2,N3
Max	74.75	109.10	425.18
Min	-4.43	-150.36	166.94
Mean	33.71	-8.77	285.80

Table 15. Reaction Forces on Substructure Footing for 10 Year Hurricane

	Fx	N1,N4	N2,N3
Max	73.23	553.40	754.49
Min	-41.96	275.46	465.11
Mean	16.33	426.66	598.33

Table 16. Reaction Forces on Substructure Footing for 100 Year Hurricane

	Fx	N1,N4	N2,N3
Max	130.95	581.38	939.28
Min	-79.70	101.50	427.82
Mean	31.27	331.68	693.11

Table 17. Reaction Forces on Substructure Footing for 1000 Year Hurricane

	Fx	N1,N4	N2,N3
Max	149.30	556.80	1009.20
Min	-90.70	29.90	463.60
Mean	36.70	301.10	724.50

7.4 Connection Capacity and Safety Factors

Table 18. Friction Resistance Capacity (Slip Capacity)

Torq (lb-ft)	T0 (kips)	Friction Coeff	P_0 (kips)	Ptot	Pder	Pder_tot	Psub	Psub_tot
2500	75	0.1	7.50	60.00	13.75	73.75	51.25	111.25
		0.3	22.50	180.00	41.25	221.25	153.75	333.75
		0.5	37.50	300.00	68.75	368.75	256.25	556.25
4576.7	137.301	0.1	13.73	109.84	13.75	123.59	51.25	161.09
		0.3	41.19	329.52	41.25	370.77	153.75	483.27
		0.5	68.65	549.20	68.75	617.95	256.25	805.45
5000	150	0.1	15.00	120.00	13.75	133.75	51.25	171.25
		0.3	45.00	360.00	41.25	401.25	153.75	513.75
		0.5	75.00	600.00	68.75	668.75	256.25	856.25
7500	225	0.1	22.50	180.00	13.75	193.75	51.25	231.25
		0.3	67.50	540.00	41.25	581.25	153.75	693.75
		0.5	112.50	900.00	68.75	968.75	256.25	1156.25

Table 19. Tensile Capacity with Pretension

Rn (kips)	Bolt Pretension (kips)	Ten. Cap. per Bolt (kips)	Total Capacity (kips)
247.4004	75.000	172.400	1379.203
247.4004	137.301	110.099	880.795
247.4004	150.000	97.400	779.203
247.4004	225.000	22.400	179.203

Table 20. Shear Capacity of bolts

Shear Capacity per Bolt =	Rn =	204.518	kips
Total Connection Shear Capacity =	(N/2)*Rn=	818.071	kips

Table 21. Shear and Slip Safety Factor of the Upper Derrick Footing for 10 year Hurricane Load Condition

Pretension (kips)	Fx (kips) SHEAR	Fy(kips) SLIP	Bolt Shear Fact. of Safety	Bolt Slip Fact. Of Safety (when Fy=Fx) 0.1	0.3	0.5
137.3	35.318	0.000	23.163	3.5	10.6	17.6
75	35.318	0.000	23.163	2.1	6.3	10.5
150	35.318	0.000	23.163	3.8	11.4	19.1
225	35.318	0.000	23.163	5.5	16.6	27.7

Table 22. Shear and Slip Safety Factor of the Substructure Footing for 10 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension	Fx (kips)	Fy(kips)	Bolt Shear Fact.	Bolt Slip Fact. Of Safety		
(kips)	SLIP	SHEAR	of Safety(when Fy=Fx)	0.1	0.3	0.5
137.3	70.339	0.000	11.2	2.290	6.871	11.451
75	70.339	0.000	11.2	1.582	4.745	7.908
150	70.339	0.000	11.2	2.435	7.304	12.173
225	70.339	0.000	11.2	3.288	9.863	16.438

Table 23. Minimum Tension Safety Factor for 10 year Hurricane Load Condition (- means no tensile loading)

	Fz	T	Torque(lb-ft)	4576.7	2500	5000	7500
	(kips)	(kips)	T0(in kips) =	137.3	75	150	225
Upper Der	15.231	1.904	Safety Factors	-	-	-	-
Substruct	280.734	35.092		-	-	-	-

*Positive Fz is compression with the view point of the bolt, and does not add the tensile force to it. Only negative reaction force adds the tensile force to the bolt.

Table 24. Shear and Slip Safety Factor of the Upper Derrick Footing for 100 year Hurricane Load Condition

Pretension	Fx (kips)	Fy (kips)	Bolt Shear Fact.	Bolt Slip Fact. Of Safety(when Fy=Fx)		
(kips)	SHEAR	SLIP	of Safety(when Fy=Fx)	0.1	0.3	0.5
137.3	63.001	0.000	12.985	1.9	5.9	9.8
75	63.001	0.000	12.985	1.2	3.5	5.8
150	63.001	0.000	12.985	2.1	6.4	10.6
225	63.001	0.000	12.985	3.0	9.2	15.3

Table 25. Shear and Slip Safety Factor of the Substructure Footing for 100 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension	Fx (kips)	Fy(kips)	Bolt Shear Fact.	Bolt Slip Fact. Of Safety		
(kips)	SLIP	SHEAR	of Safety(when Fy=Fx)	0.1	0.3	0.5
137.3	130.950	0.000	6.3	1.230	3.691	6.151
75	130.950	0.000	6.3	0.850	2.549	4.248
150	130.950	0.000	6.3	1.308	3.923	6.539
225	130.950	0.000	6.3	1.766	5.298	8.830

Table 26. Minimum Tension Safety Factor for 100 year Hurricane Load Condition

	Fz	T	Torque (lb-ft)	4576.7	2500	5000	7500
	(kips)	(kips)	T0 (in kips) =	137.3	75	150	225
Upper Der	-93.189	-11.649	Safety Factors	9.452	14.800	8.362	1.923
Substruct	101.501	12.688		-	-	-	-

*Positive Fz is compression with the view point of the bolt, and does not add the tensile force to it. Only negative reaction force adds the tensile force to the bolt.

Table 27. Shear and Slip Safety Factor of the Upper Derrick Footing for 1000 year Hurricane Load Condition

Pretension	Fx (kips)	Fy (kips)	Bolt Shear Fact.	Bolt Slip Fact. Of Safety (when Fy=Fx)		
(kips)	SHEAR	SLIP	of Safety	0.1	0.3	0.5
137.3	74.753	0.000	10.944	1.6	4.9	8.2
75	74.753	0.000	10.944	0.98	2.9	4.9
150	74.753	0.000	10.944	1.8	5.3	8.9
225	74.753	0.000	10.944	2.6	7.7	12.9

Table 28. Shear and Slip Safety Factor of the Substructure Footing for 1000 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension	Fx (kips)	Fy (kips)	Bolt Shear Fact.	Bolt Slip Fact. Of Safety		
(kips)	SLIP	SHEAR	of Safety (when Fy=Fx)	0.1	0.3	0.5
137.3	149.300	0.000	5.5	1.079	3.237	5.395
75	149.300	0.000	5.5	0.745	2.235	3.726
150	149.300	0.000	5.5	1.147	3.441	5.735
225	149.300	0.000	5.5	1.549	4.647	7.744

Table 29. Minimum Tension Safety Factor for 1000 year Hurricane Load Condition

	Fz	T	Torque (lb-ft)	4576.7	2500	5000	7500
	(kips)	(kips)	T0 (in kips) =	137.3	75	150	225
Upper Der	-150.356	-18.795	Safety Factors	5.858	9.173	5.182	1.192
Substruct	29.900	3.738		-	-	-	-

*Positive Fz is compression with the view point of the bolt, and does not add the tensile force to it. Only negative reaction force adds the tensile force to the bolt.

8.0 INTERPRETATION AND DISCUSSION OF THE RESULTS

This case study is for a Deepstar TLP (3000 ft.) with the collinear wind, wave, and current from X direction. Three different environmental conditions, 10yr, 1000yr, 1000yr (IVAN), are considered. We check the possibility of slip and tensile failure at upper-derrick and substructure footings.

We first simulated the global motion of the TLP by using hull-mooring-riser coupled dynamic time-domain analysis program, WINPOST. Then, the platform motion and acceleration time series are inputted to the exact dynamic equations for a derrick to obtain the maximum shear force causing slip and maximum separation force causing additional tensile loading on bolts.

The exact results are compared with the current industry methodology based on API-4F.
API-4F recommendation for the dynamic loading estimation is based on a simple formula neglecting phase differences between accelerations and forces hoping that it will lead to conservative results. Furthermore, API formula neglects the effects of rotational inertia and centrifugal forces, which turned out to be insignificant in the present example.

One of the drawbacks of the current API-4F recommendation is the calculation methodology of the maximum acceleration, which is to be calculated by maximum motion amplitude multiplied by peak frequency (of input spectrum) squared. In the case of TLP, the actual peak frequency of pitch acceleration is quite different from the input-spectrum peak frequency. Therefore, in this kind of case, the maximum acceleration values read directly from the acceleration time series had better to be used.

Example spectrum peak frequency=0.4 rad/s, pitch acceleration peak frequency=2 rad/s, surge acceleration peak frequency= 0.4 rad/s (see attached figures)

In the following, we summarize the results only for the case of IVAN.

(1) At Upper Derrick Footing

We follow the same procedure as Technip for the slip and tensile capacity of the derrick connection by bolts. In reality, the actual normal force causing frictional resistance can be smaller than the pretension of the bolts, so the slip capacity is actually smaller than the given numbers by Technip. In tensile and slip capability, the flexibility of the plates can play a role but in the present case, it is assumed that they are all rigid.

In calculating the exact dynamic equation of the upper derrick, the pitch-roll radius of gyration of the upper derrick is assumed to be 15 ft.

In all cases, the shear loading is much smaller than the bolt shear capacity (per connection=818 kips), therefore there is no chance of bolt shear failure at upper-derrick footing.

[Dynamic Loading by simple(API4F) formulas]

Shear

1. API with accel time series: m(r x pit accel + hor accel)= 17080 x (0.006 x 169+8)=17080 x 9=154 kips (38 kips per connection)

2. API4F original : hor accel=0.16x20=3.2 ; 17080 x (0.001 x 169 + 3) = 51 kips (13 kips per connection)

It is clearly seen that the original API 4F formula underestimates the dynamic X loading by factor of 3 in the case of TLP.

Then using API4F with accel time series:

> Shear per connection: by wind = 62kips, by dynamics=36kips, by grav=1 kips : total=**99 kips**
>
> Tensile per connection: by wind = 272kips, by dynamics=66kips, by grav=-137 kips : total=**201 kips**

This simple formula does not consider phase differences between constituent forces.

[Exact Method]

By using the exact dynamic equation of upper derrick and acceleration time series of platform, we obtain the following results (see attached table and time series).

Shear per connection = **75 kips**

Tensile per connection=**150 kips**

Using the same Shear and Tensile Capacity of Technip (per connection)

Slip failure occurs when bolt pretension=75 kips and friction coef=0.1(capacity=74 kips)

Tensile failure does not occur even for the smallest tensile capacity case (capacity=178 kips)

[Possible Increase by 45-deg heading]

We can do/repeat the same simulation and analysis for 45-deg heading. Here, we use simple estimation based on the load and arm increase.

It is likely that the wind and dynamic loading are increased by factor of 1.414.
Similarly, the maximum tensile force is increased by factor of 1.414 x 1.43=2
(1.43= 25 x 2 / 35: 1 bolt resists instead of 2 bolts and the new arm is 35 ft. instead of 25 ft.)

(for 45-deg heading)

Shear per connection = **106 kips**

Tensile per connection=**300 kips**

In this case,

Slip failure occurs when bolt pretension=75 kips and friction coef=0.1 (capacity=74 kips)

Tensile failure occurs when bolt-pretension= 225 kips. (capacity=178 kips)

(2) At Substructure Footing

We assume that the weight of substructure=1500 kips and the CG is located 130 ft. above MWL. Its wind projected area= 500 ft.^2 and wind CP=CG. We follow the same procedure as Technip for the slip and tensile capacity of the derrick connection by bolts.

In calculating the exact dynamic equation of the upper derrick, the pitch-roll radius of gyration of the upper derrick + substructure is assumed to be 20 ft. The new center of gravity and center of pressure of the upper+lower deck structure are 140.5 ft. and 190 ft. above MWL.

In all cases, the shear loading is much smaller than the bolt shear capacity (per connection=818 kips), therefore there is no chance of bolt shear failure at substructure footing.

[Dynamic Loading by simple(API4F) formulas]

Shear

API with accel time series: m(r x pit accel + hor accel)= 63664 x (0.006 x 141+8)=17080 x 9=563 kips (141kips per connection)

Then using API4F with accel time series:

Shear per connection: by wind = 66 kips, by dynamics=141 kips, by grav=2 kips : total=**209 kips**

Tensile per connection: by wind = 387 kips, by dynamics=262 kips, by grav=-512 kips : total=**137 kips**

The minus sign means compressional (not tensile) loading.

At the substructure footing, the shear causing slip is increased (about twice) and the tensile loading is decreased compared to the upper-derrick case. This simple formula does not consider phase differences between constituent forces.

[Exact Method]

By using the exact dynamic equation of upper derrick and acceleration time series of platform, we obtain the following results (see attached table and time series).

Shear per connection = **149 kips**

Tensile per connection=**-29 kips**

Compared to the upper-derrick case, the shear loading causing slip is increased by factor of two but there is no tensile loading on the bolts.

Using the same Shear and Tensile Capacity of Technip (per connection)

Slip failure occurs when (i) bolt pretension=75 kips and friction coef=0.1(capacity=111 kips)

Tensile failure does not occur even for the smallest tensile capacity case (capacity=178 kips)

[Possible Increase by 45-deg heading]

We can do/repeat the same simulation and analysis for 45-deg heading. Here, we use simple estimation based on the load and arm increase.

It is likely that the wind and dynamic loading are increased by factor of 1.414.

(for 45-deg heading)
Shear per connection = **210 kips**
In this case,

Slip failure occurs when (i) bolt pretension=75 kips and friction coef=0.1 (capacity=111 kips) and (ii) bolt pretension=150 kips and friction coef=0.1 (capacity=17 1kips).

Tensile failure does not occur.

8.1 Platform Acceleration Results

In the following, the platform acceleration results can be summarized as follows

Maximum Lateral Acceleration (normalized by g)

	10yr	100yr	1000yr
SPAR	0.2	0.4	0.51
TLP	0.15	0.2	0.26

Maximum Vertical Acceleration (normalized by g)

	10yr	100yr	1000yr
SPAR	0.01	0.015	0.027
TLP	0.02	0.04	0.05

It is seen that the horizontal acceleration of a TLP is about half of that of spar. The vertical acceleration of a TLP is about twice the spar vertical acceleration. From this comparison, it is expected that spars have greater dynamic (inertia) loading than TLPs. Considering the same wind loading and weight for the identical derrick design, spar derrick is less safe that the TP derrick.

8.2 Recommendation based on the present study

If bolt pretension is too small, slip failure is likely to occur. In case bolt pretension is too large, the system is vulnerable to tensile failure. Therefore, maintaining proper middle-range tension especially during the hurricane is important.

It is important to check how much slip capacity can be reduced during the wet weather condition. Can the friction coefficient be as low as 0.1? If so, the safety of the derrick system under this condition should be checked.

Another uncertainty associated with slip failure is to find the actual grip force by bolts to prevent slip. It needs to be checked how much the slip capacity can be reduced by the present bolt-based connection method. If the actual grip force is smaller than the pretension, which value should be used in the derrick design?

Substructure connection is more vulnerable to the slip failure compared to upper-derrick connection, so stronger tightening method needs to be used.

In case of TLP, API4F dynamic loading based on motion amplitude can be significantly smaller than that with accel. time series.

Simple formulas with accel. time series but without considering phase differences between constituent forces tend to be conservative in the case of present example. However, it is not clear whether it is also conservative for other design conditions and other platform types since rotary inertia and centrifugal forces are missing.

A new method using the platform global-motion time series and exact derrick dynamic equations is recommended as a new methodology to check the slip and tensile failure of derrick connection.

9.0 REFERENCES

[1] Lee, C.H., Korsmeyer, F.T. (1999), WAMIT User manual, Dept. of Ocean Engineering, MIT.

[2] Kim, M.H. WINPOST User manual, Texas A&M University.

[3] Kim, M.H., Tahar, A. and Kim, Y.B.(2001), "Variability of TLP Motion Analysis Against Various Design Methodologies/Parameters", Proceedings of 11th ISOPE conference, Stavanger, vol.III, pp.467-473.

10.0 APPENDIX A: FIGURES FOR THE 180 DEGREE CASE

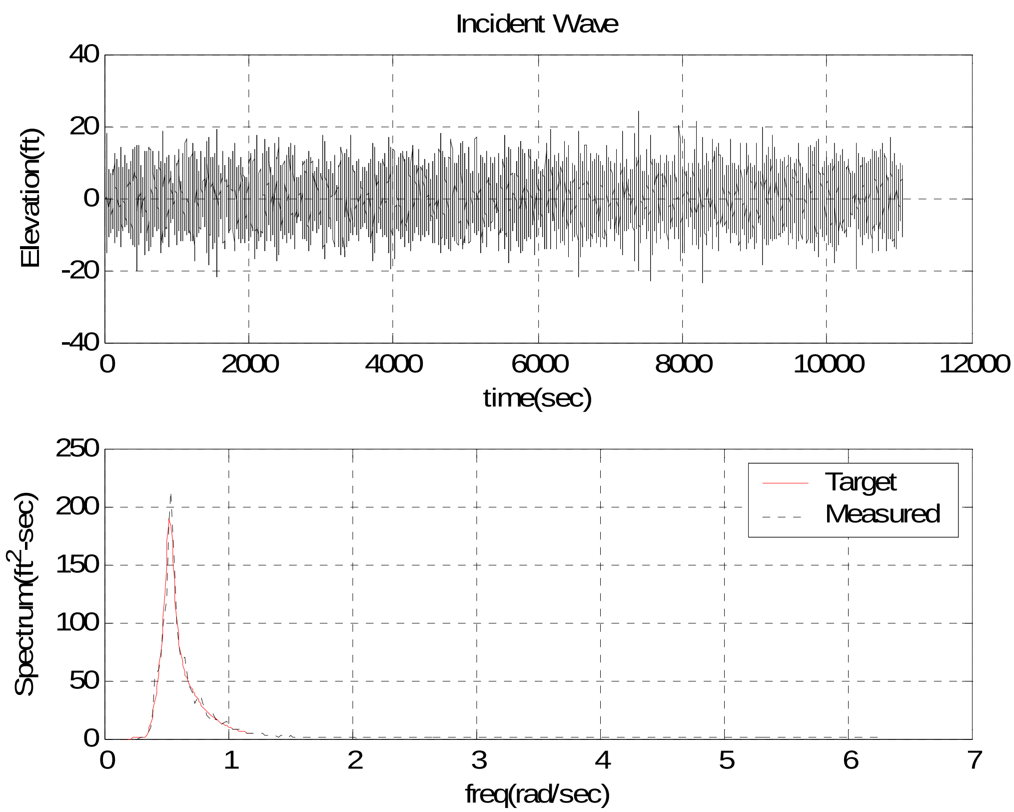
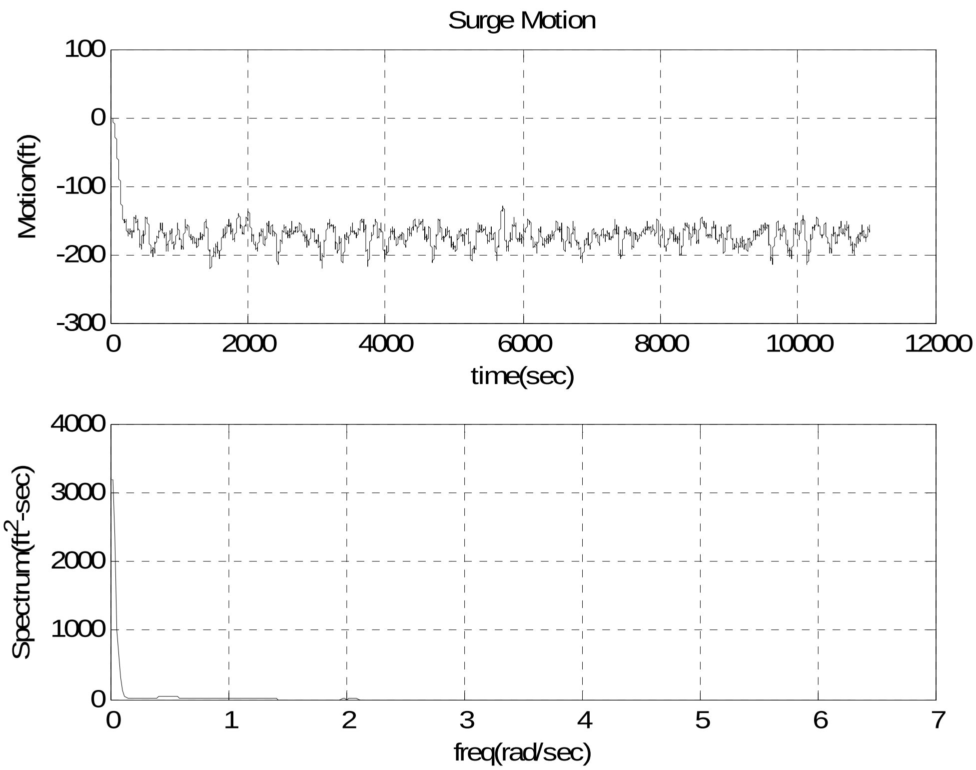
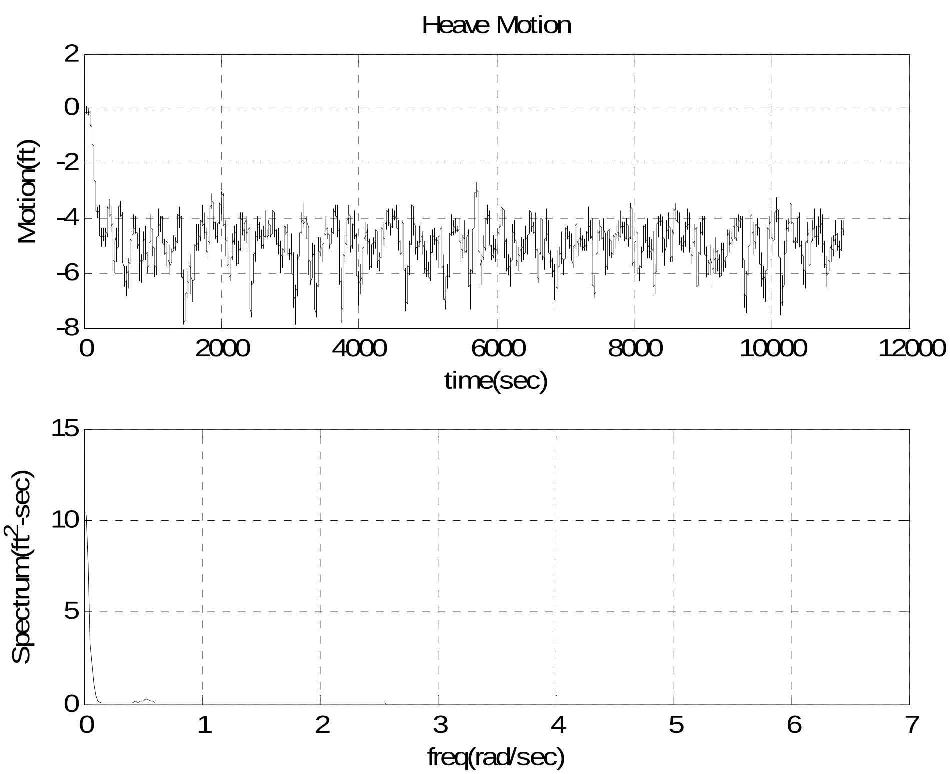


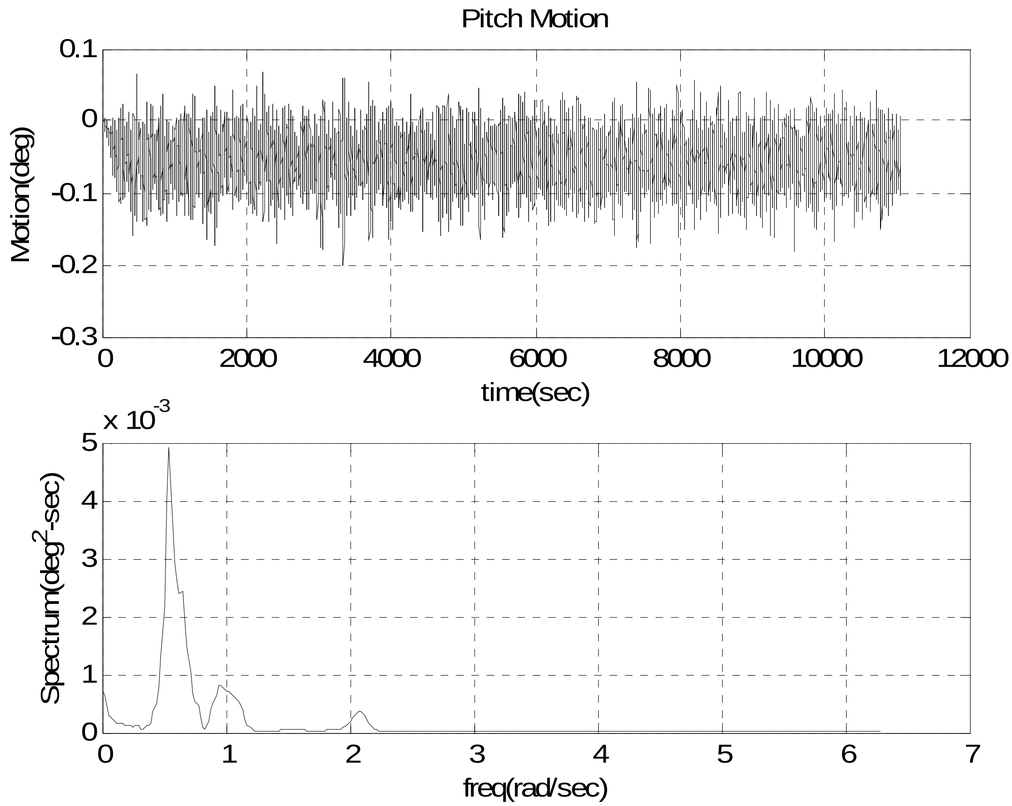
Figure A-1. Incident Wave Time History and Power Spectrum (10 Year Hurricane; Hs=24.9ft, Tp=11.9, γ =2.4)



(a) Surge

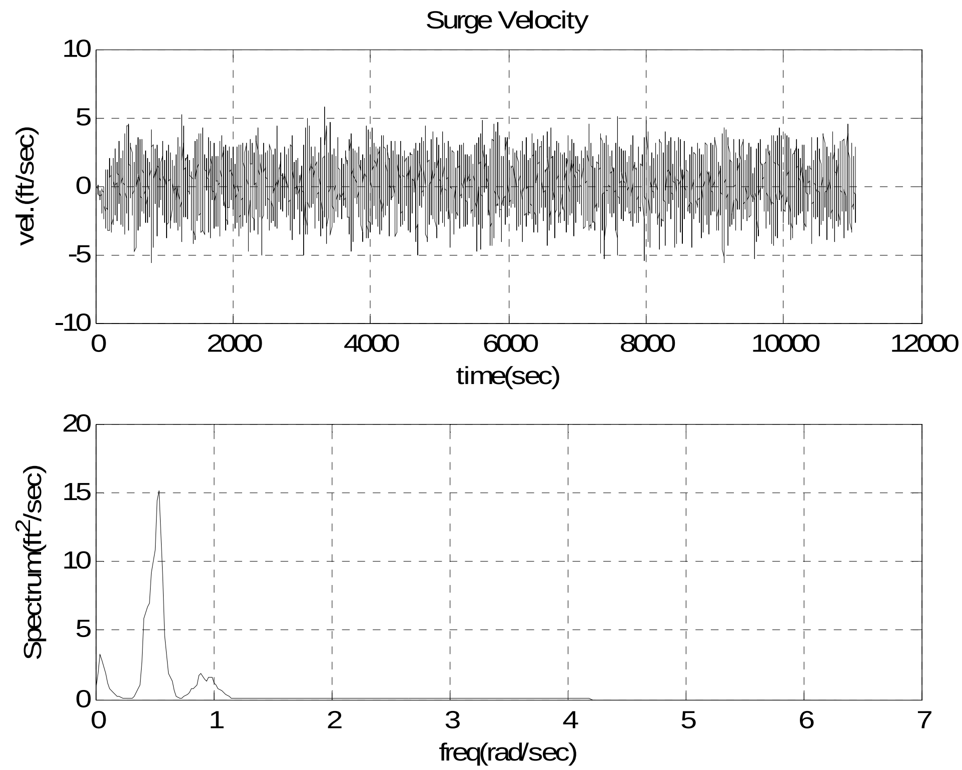


(b) Heave

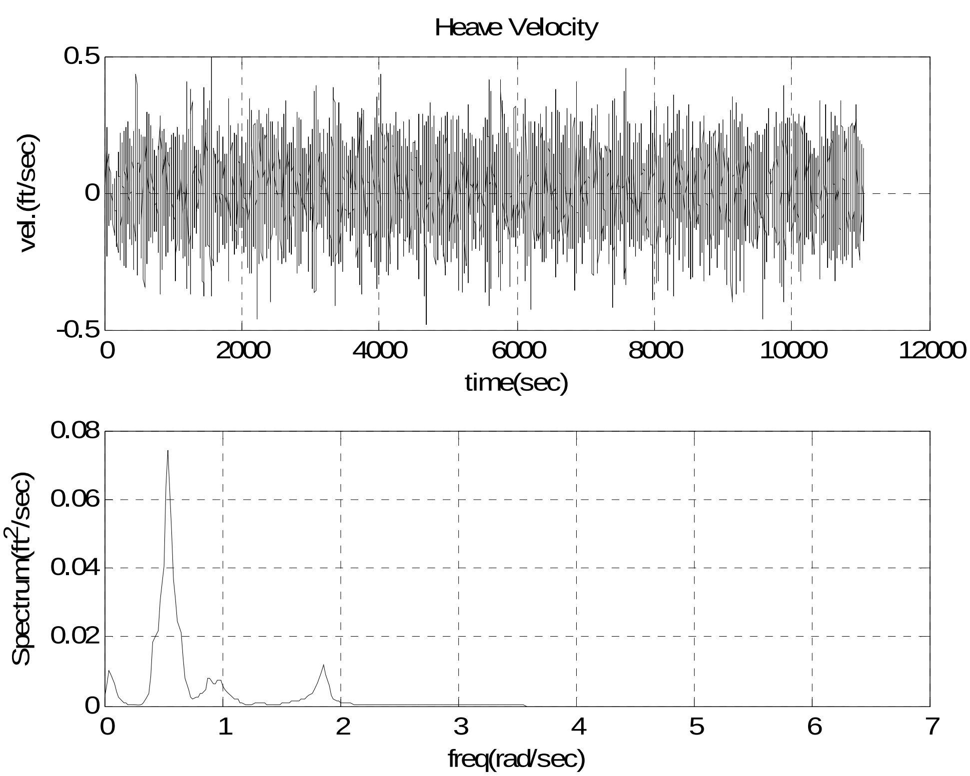


(c) Pitch

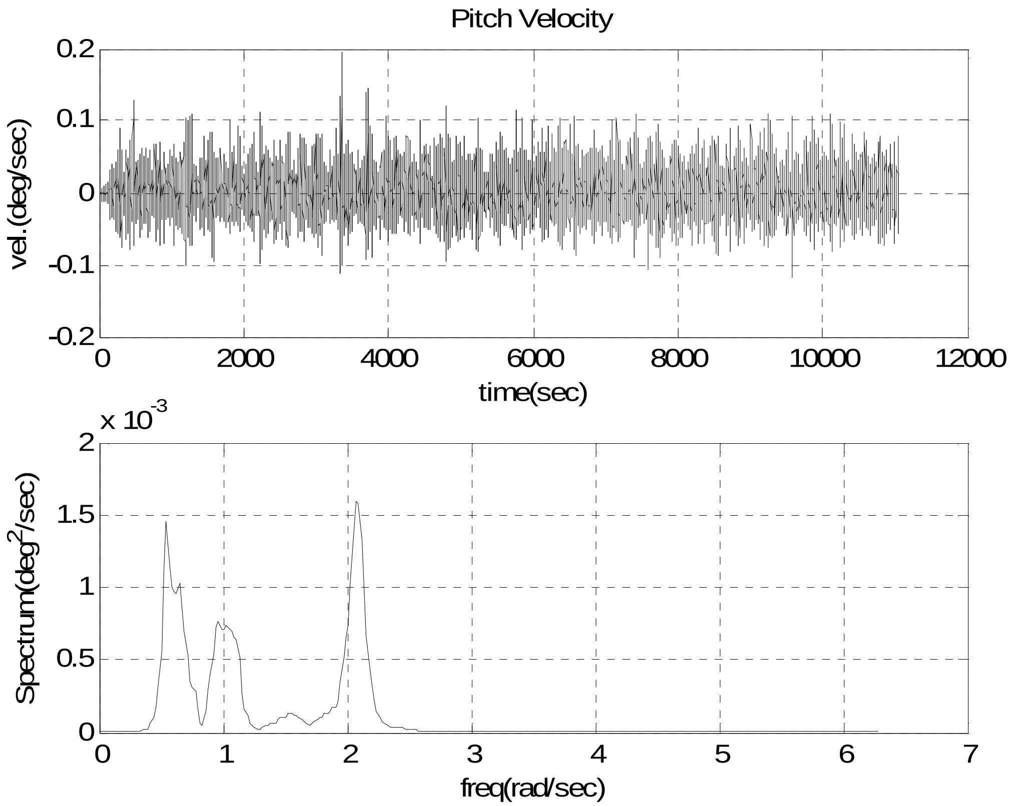
Figure A-2. Motion Time Series and Spectrum at the Upper Derrick CG for 10 Year Hurricane



(a) Surge

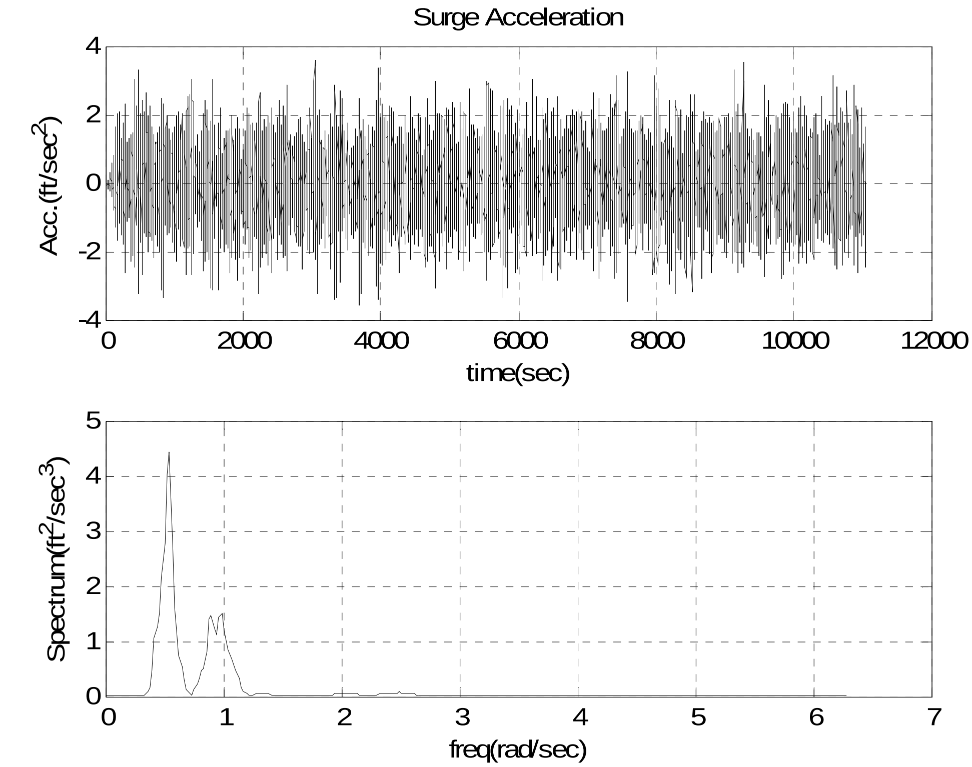


(b) Heave

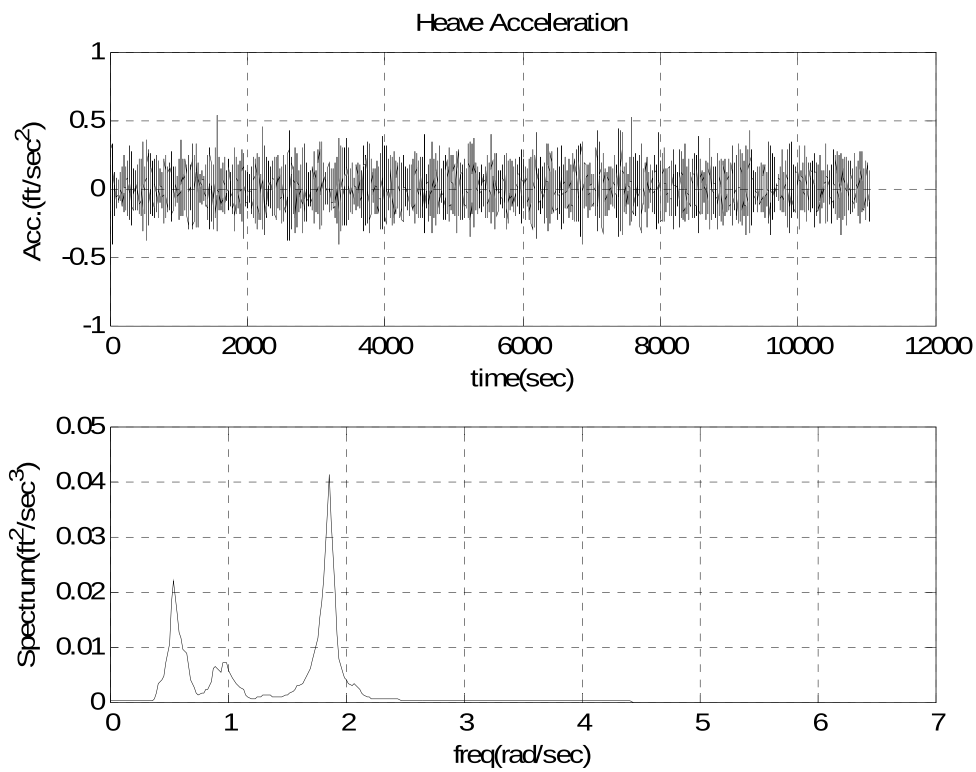


(c) Pitch

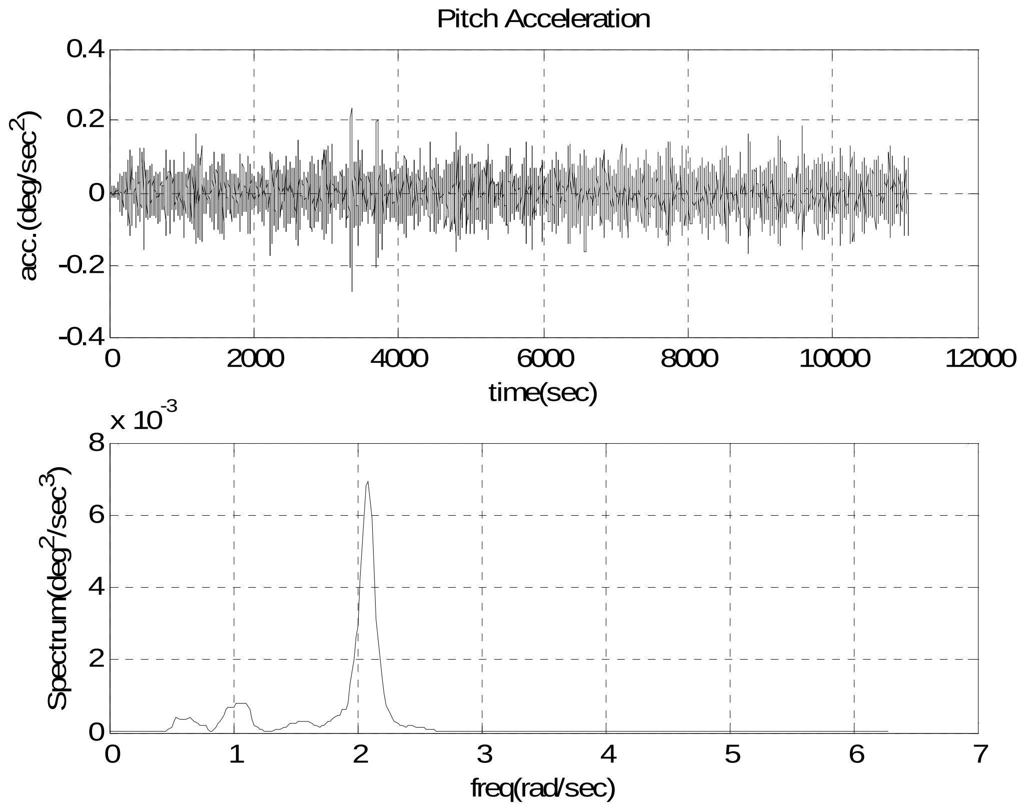
Figure A-3. Velocity Time Series and Spectrum at the Upper Derrick CG for 10 Year Hurricane



(a) Surge



(b) Heave



(c) Pitch

Figure A-4. Acceleration Time Series and Spectrum at the Upper Derrick CG for 10 Year Hurricane

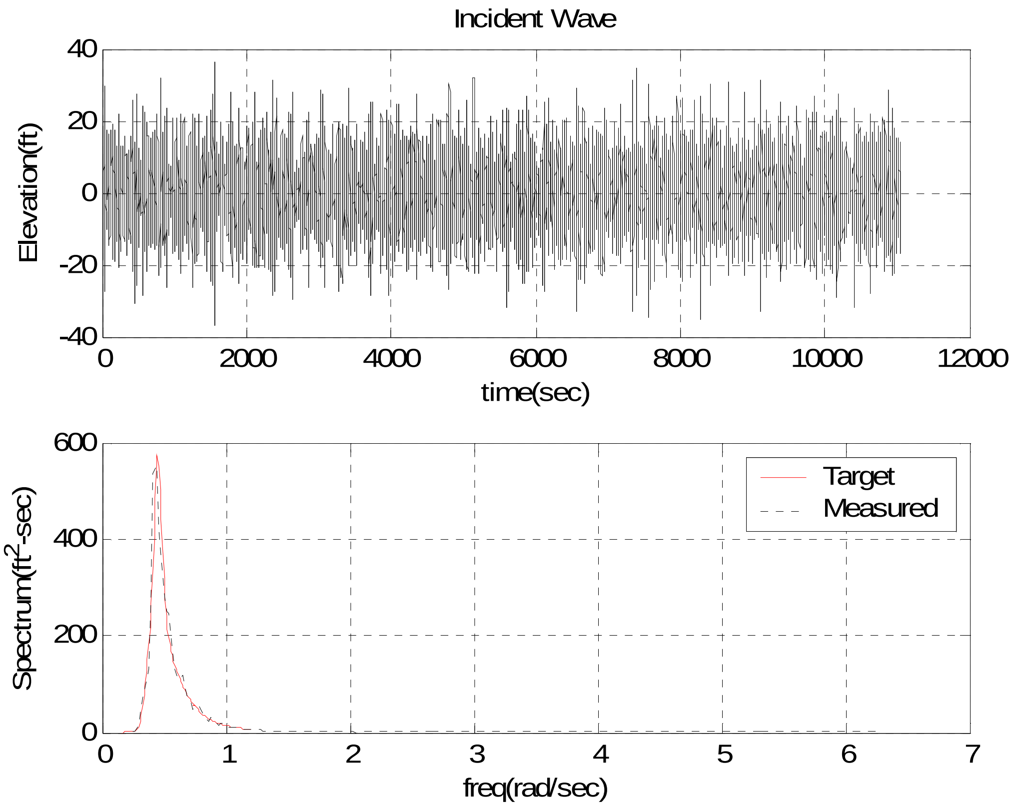
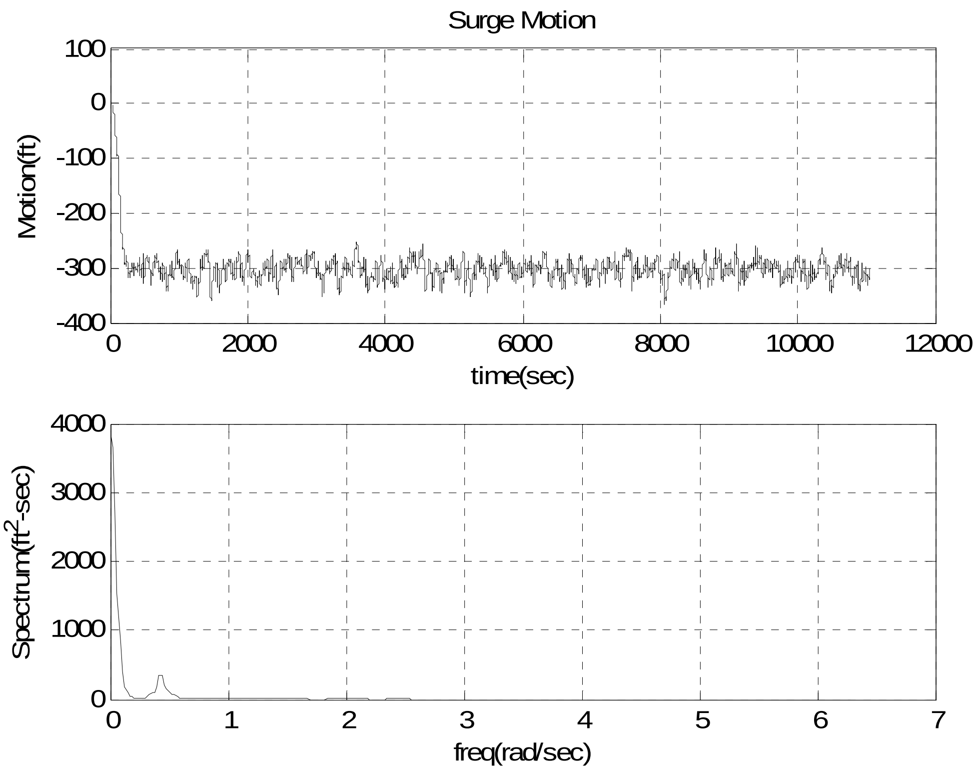
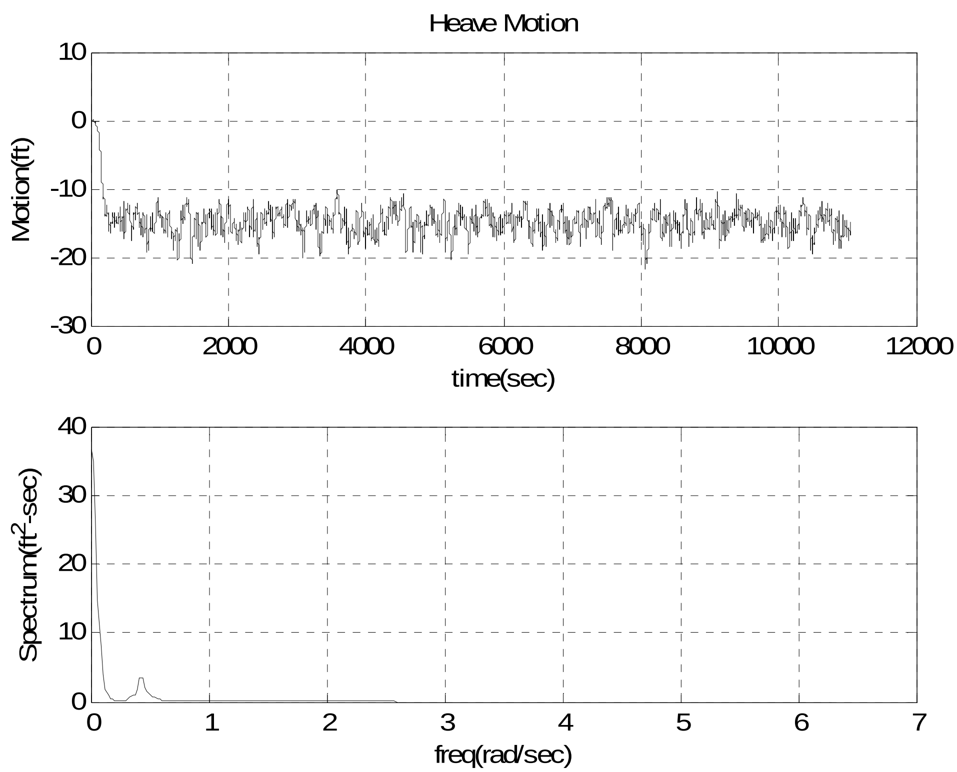


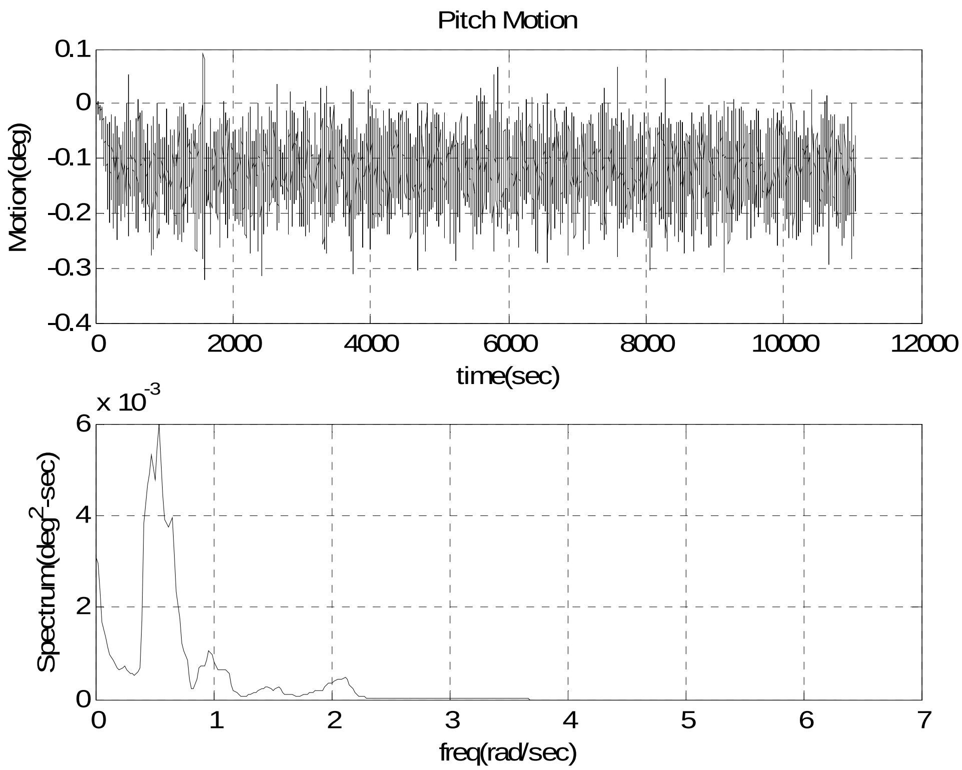
Figure A-5. Incident Wave Time History and Power Spectrum (100 Year Hurricane; Hs=24.9ft, Tp=14.0, γ =2.4)



(a) Surge

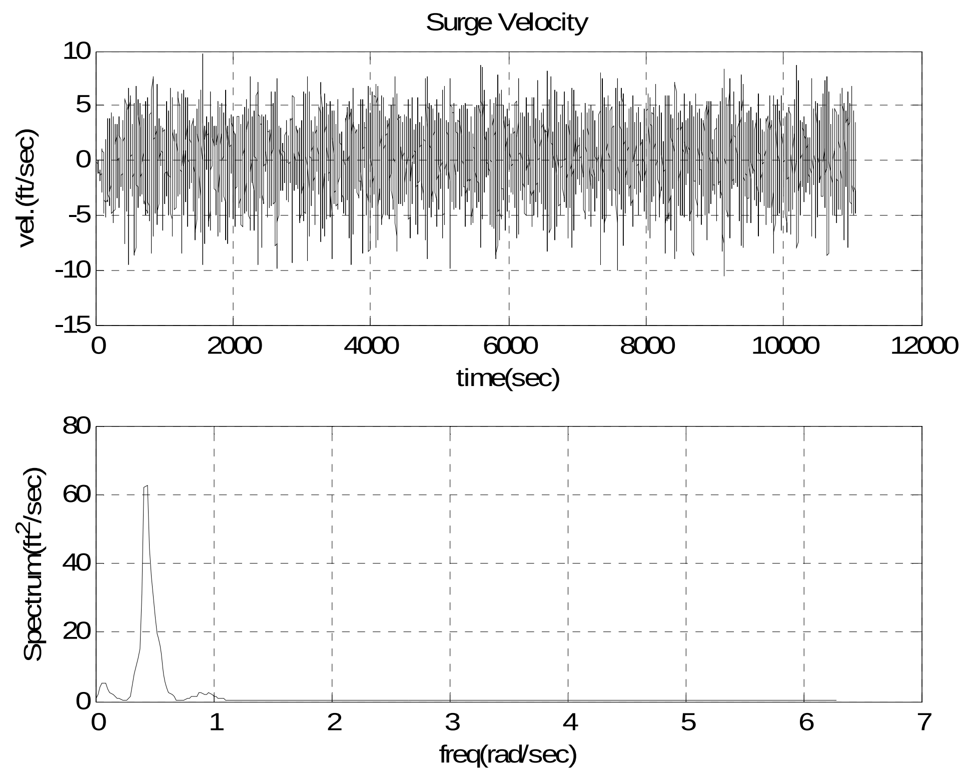


(b) Heave

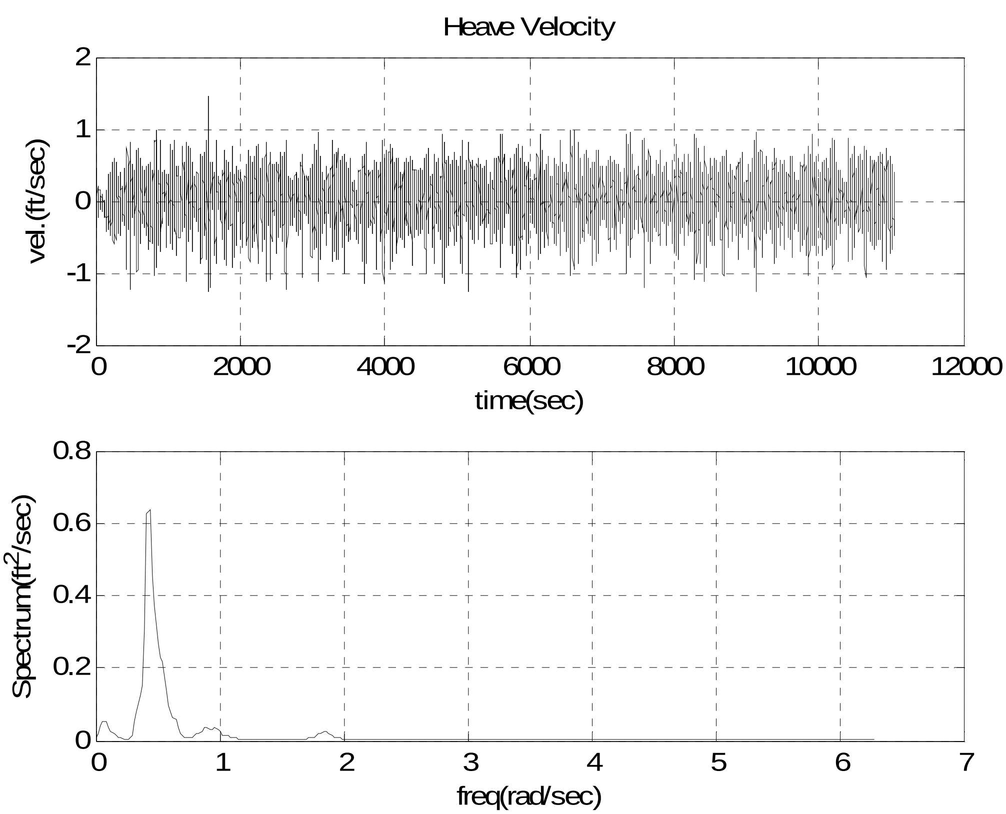


(c) Pitch

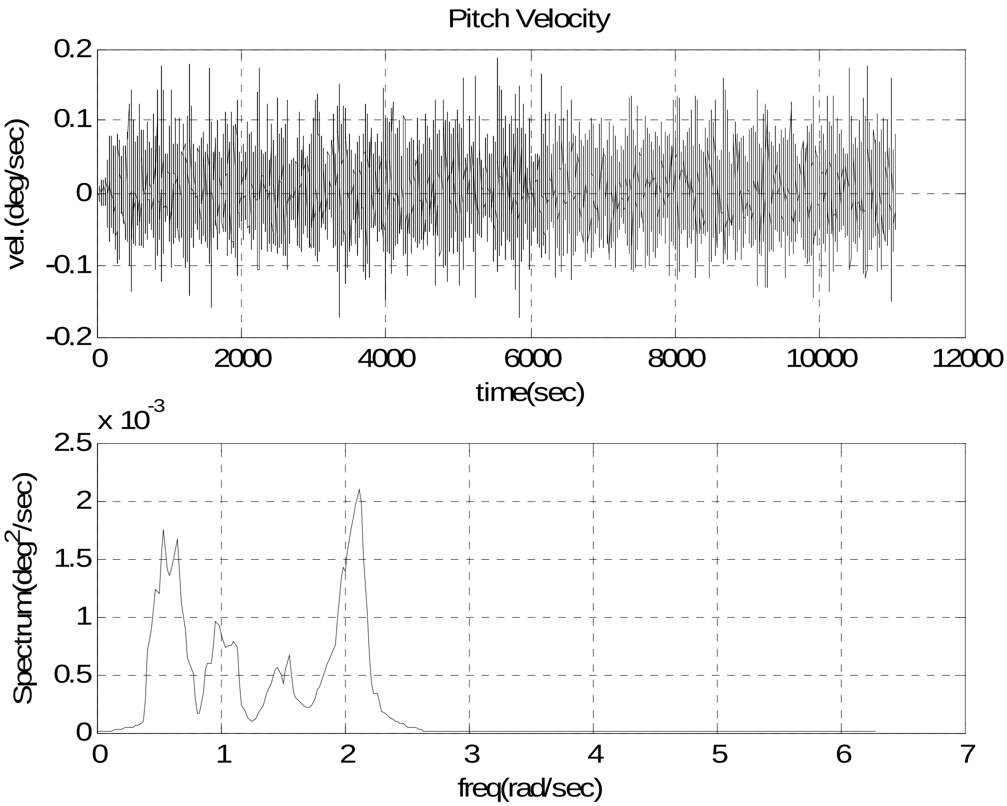
Figure A-6. Motion Time Series and Spectrum at the Upper Derrick CG for 100 Year Hurricane



(a) Surge

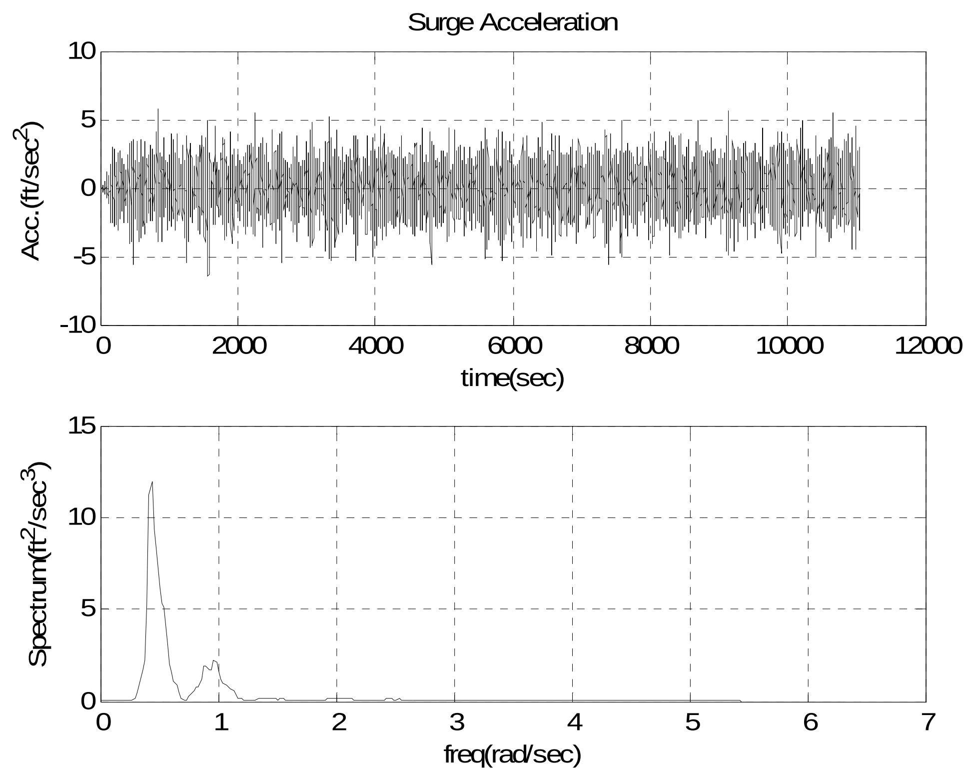


(b) Heave

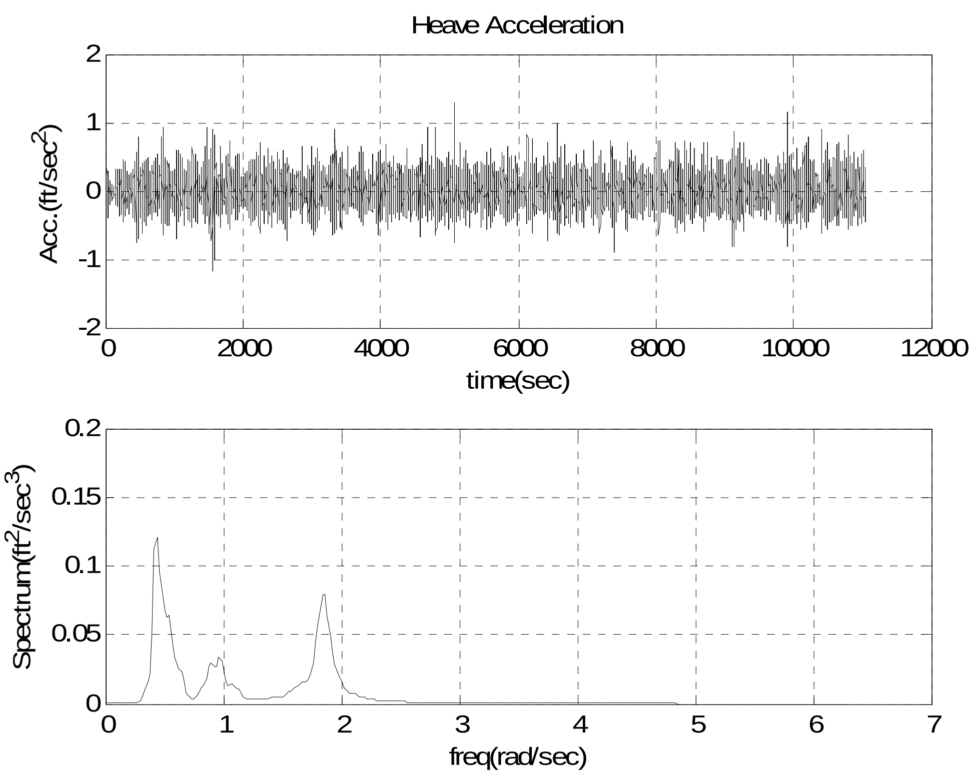


(c) Pitch

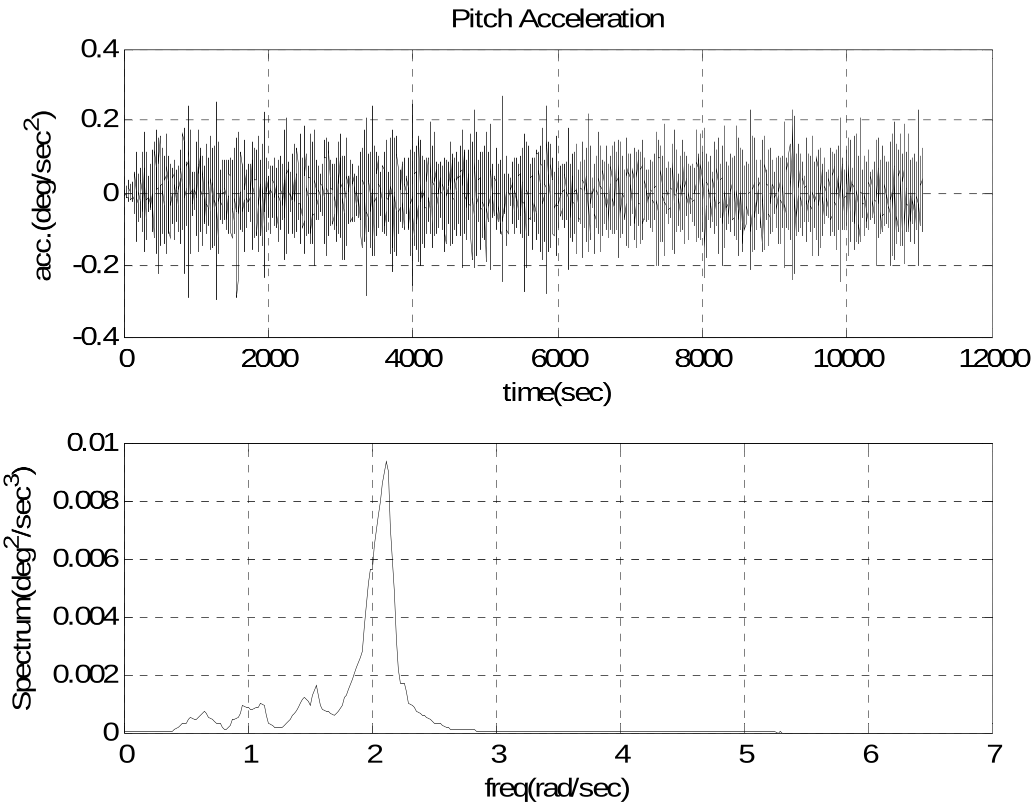
Figure A-7. Velocity Time Series and Spectrum at the Upper Derrick CG for 100 Year Hurricane



(a) Surge



(b) Heave



(c) Pitch

Figure A-8. Acceleration Time Series and Spectrum at the Upper Derrick CG for 100 Year Hurricane

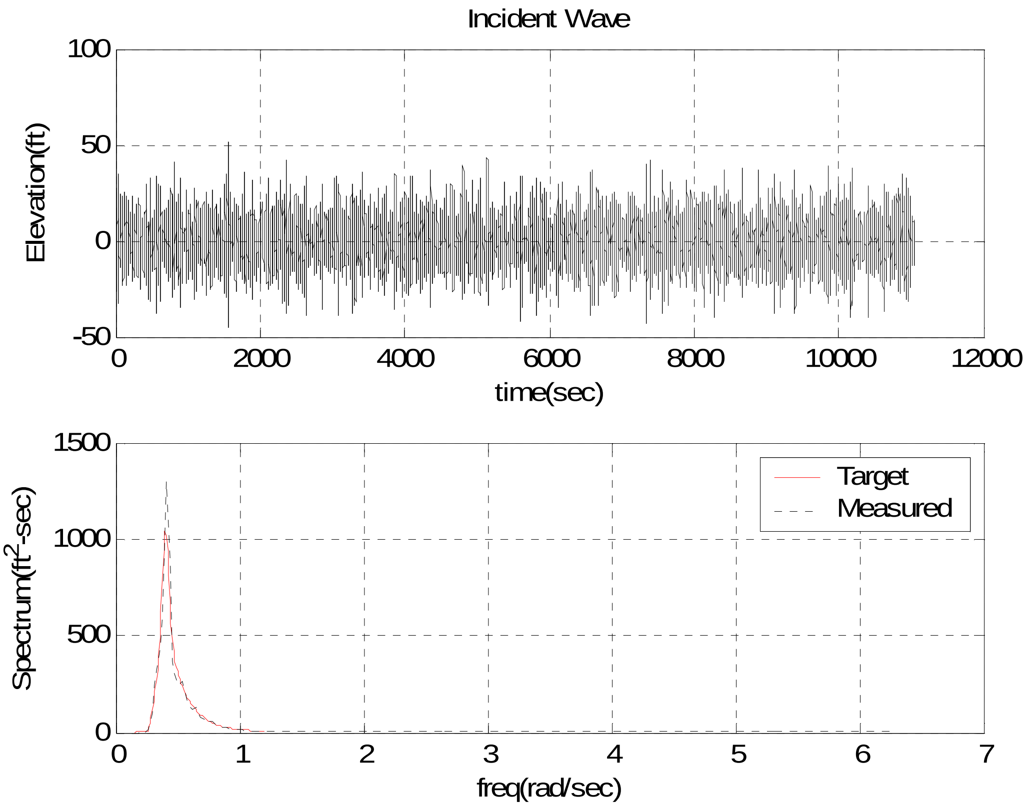
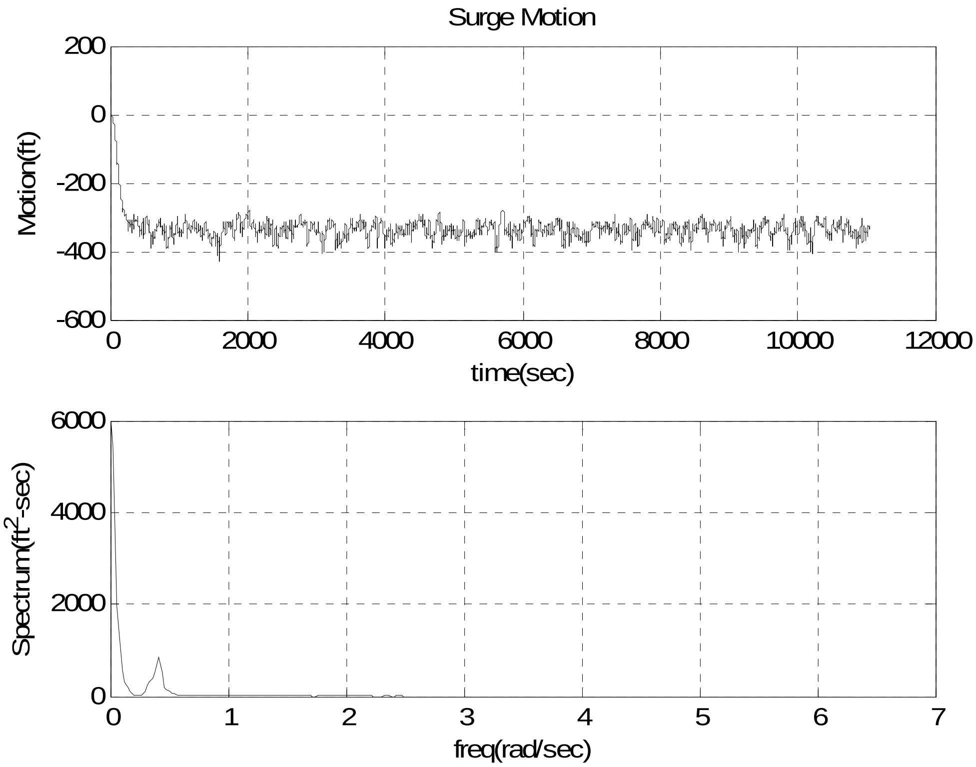
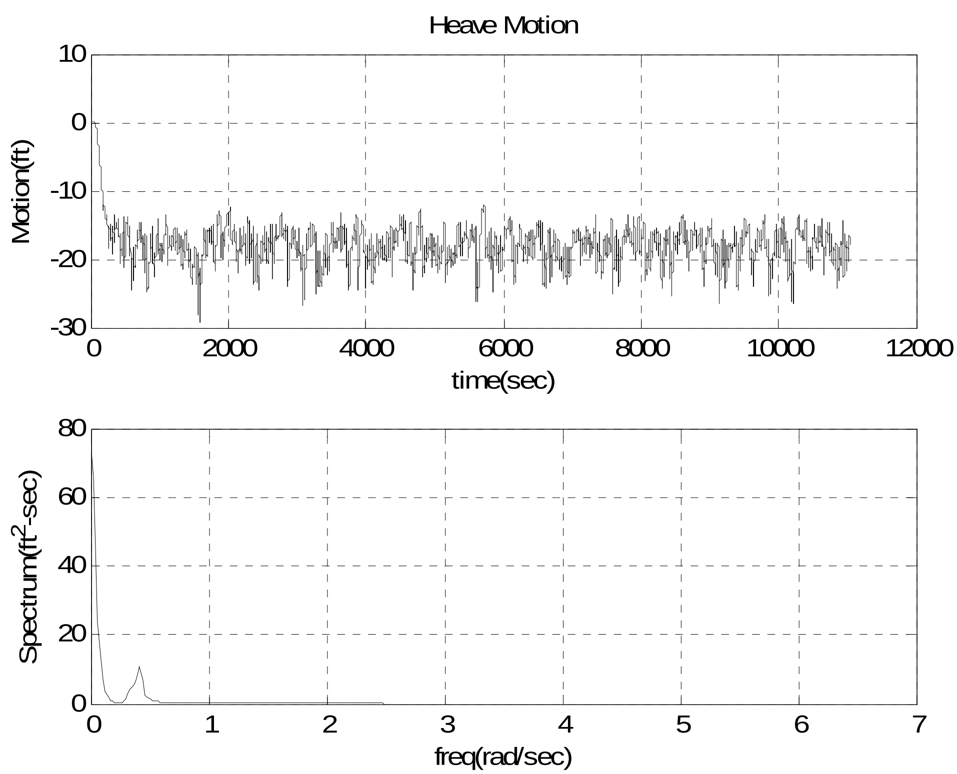


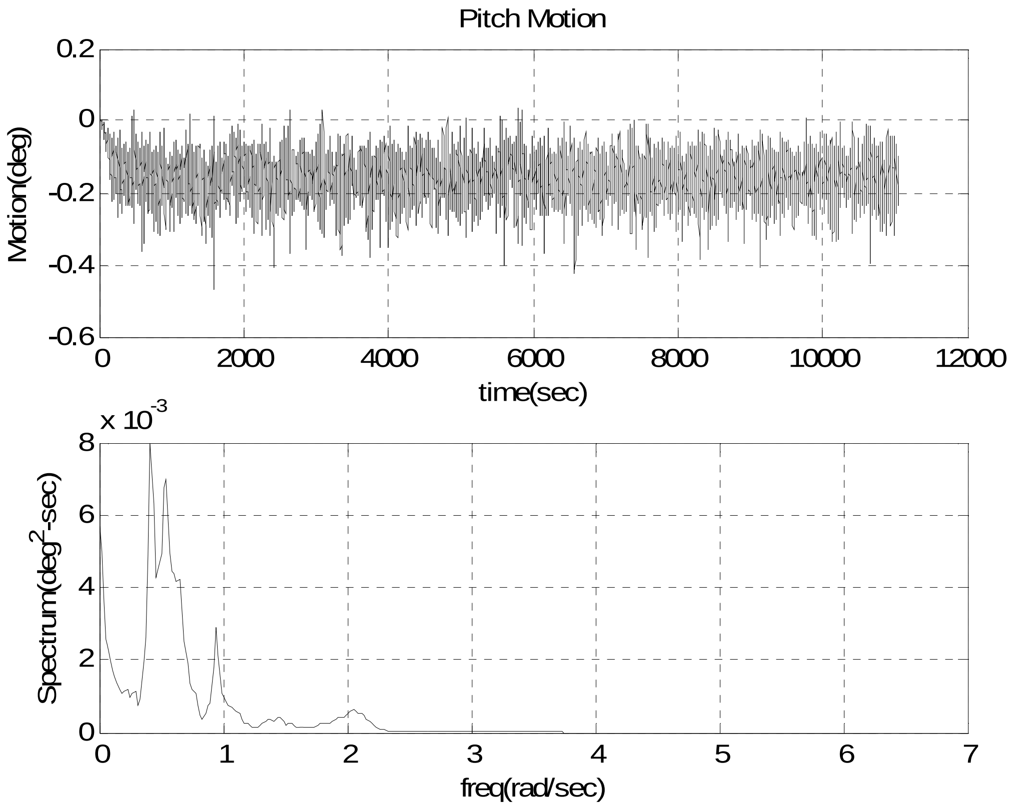
Figure A-9. Incident Wave Time History and Power Spectrum (1000 Year Hurricane; Hs=51.9ft, Tp=15.6, γ =3.0)



(a) Surge

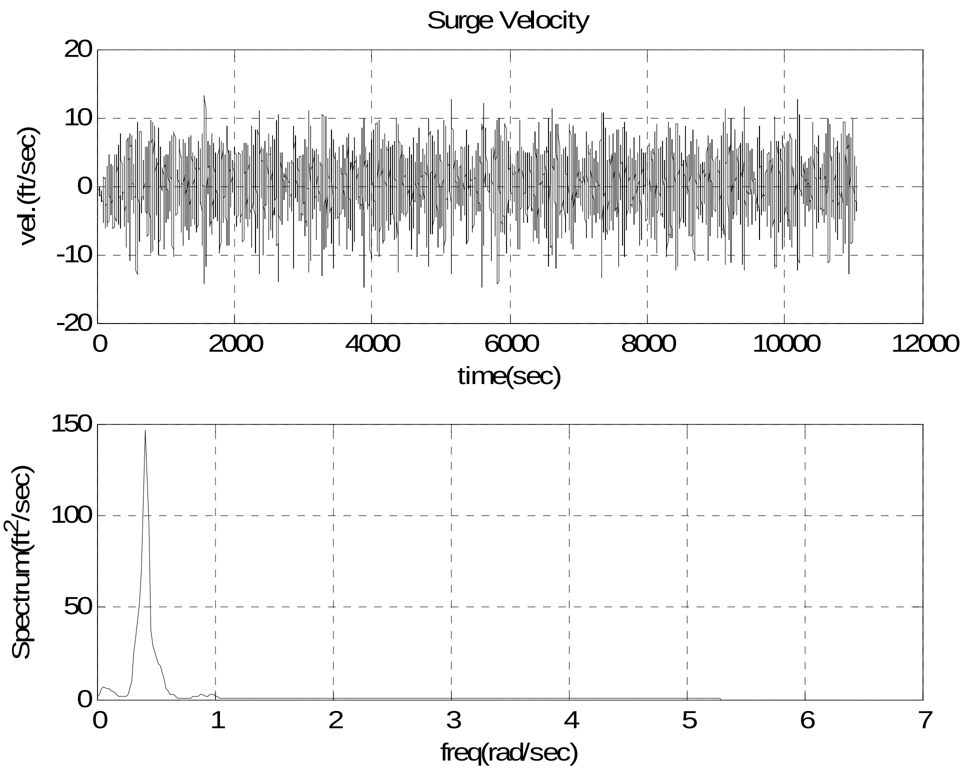


(b) Heave

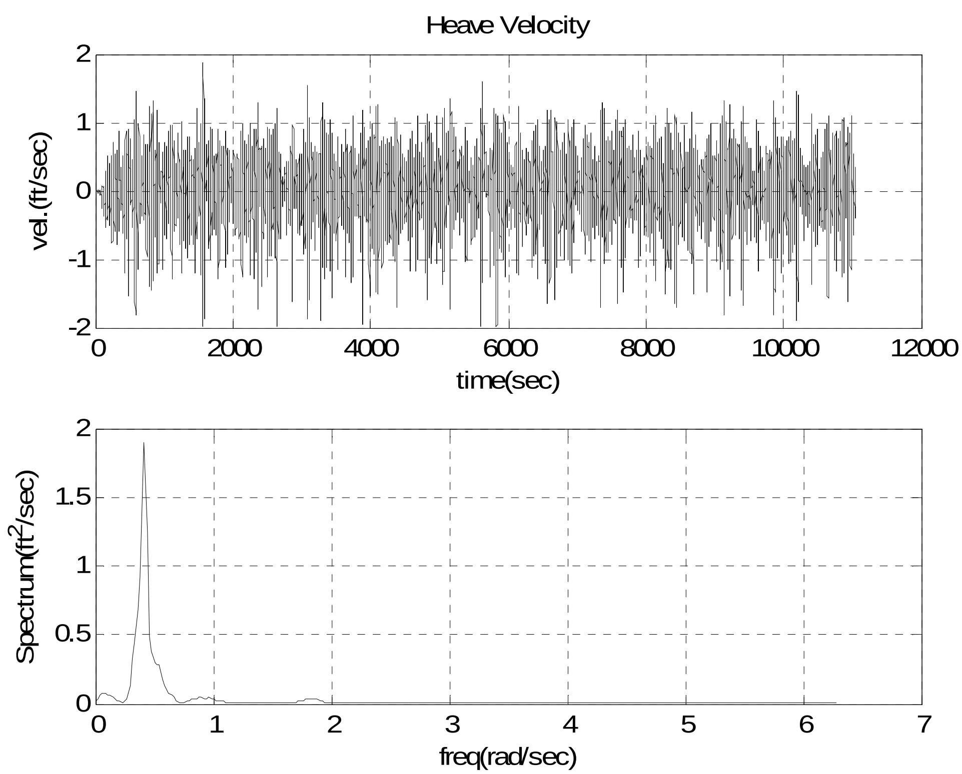


(c) Pitch

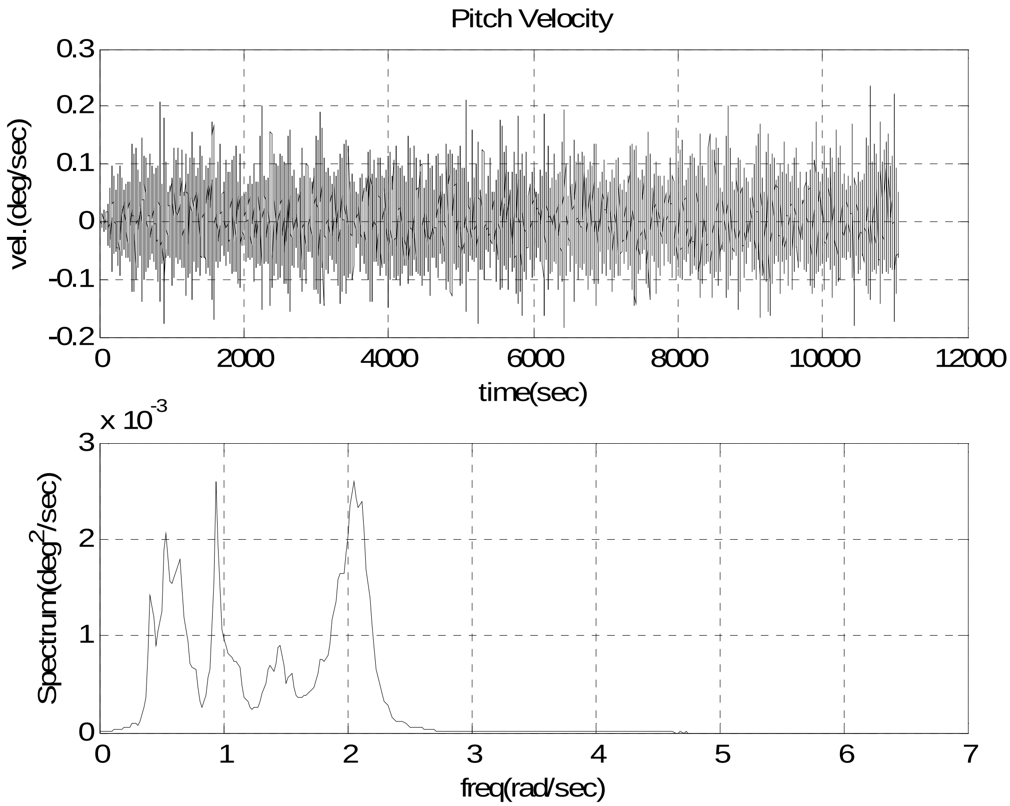
Figure A-10. Motion Time Series and Spectrum at the Upper Derrick CG for 1000 Year Hurricane



(a) Surge

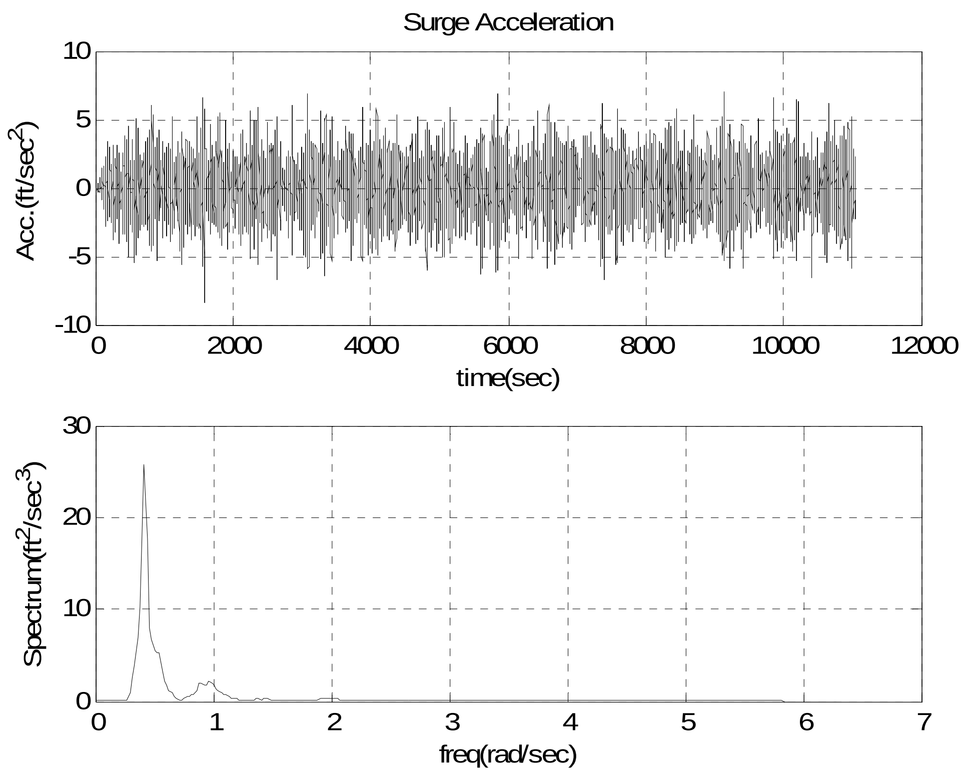


(b) Heave

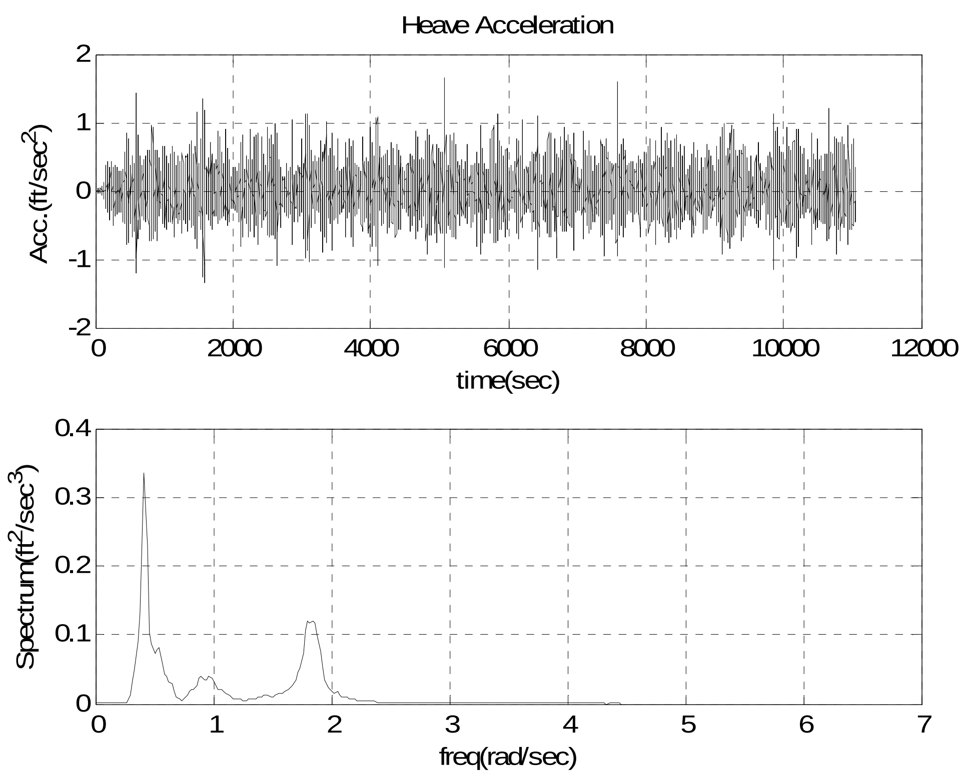


(c) Pitch

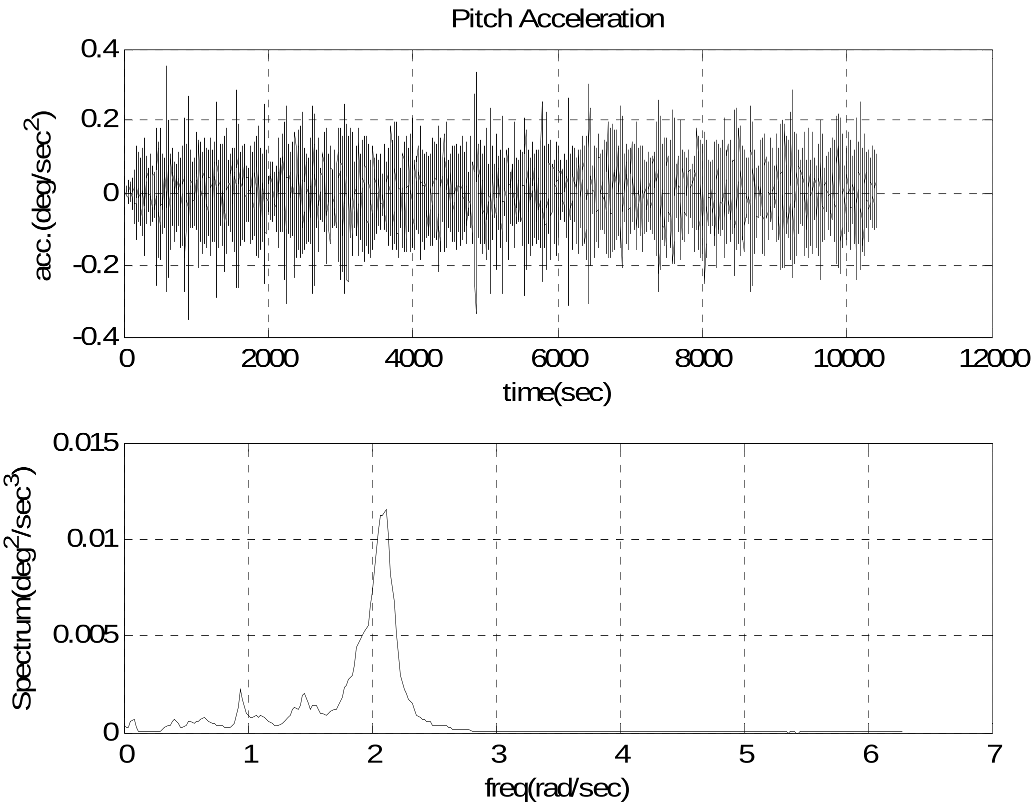
Figure A-11. Velocity Time Series and Spectrum at the Upper Derrick CG for 1000 Year Hurricane



(a) Surge

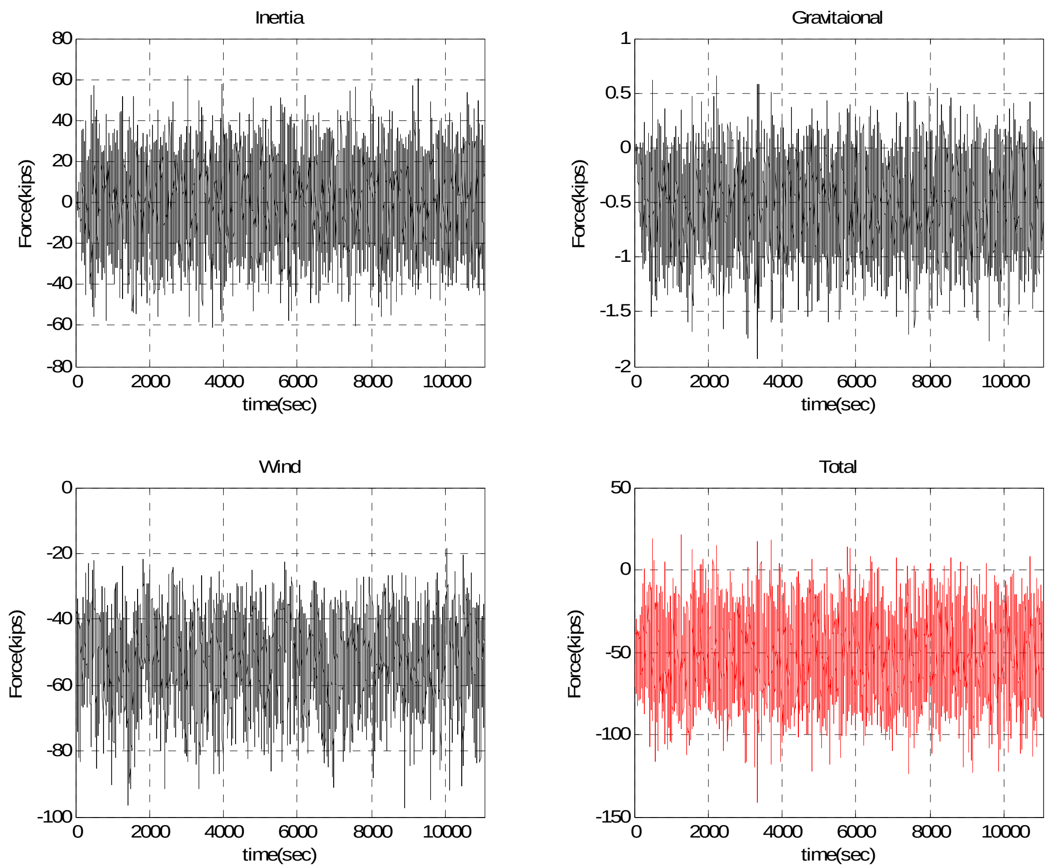


(b) Heave

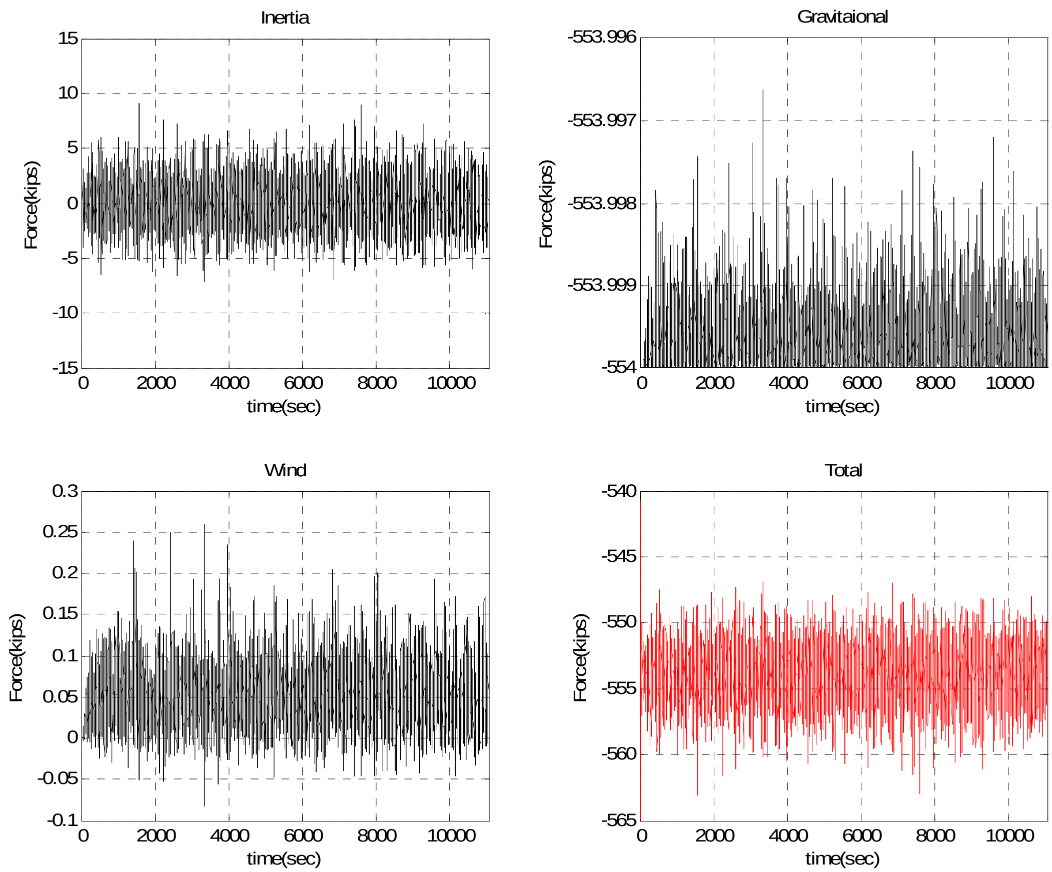


(c) Pitch

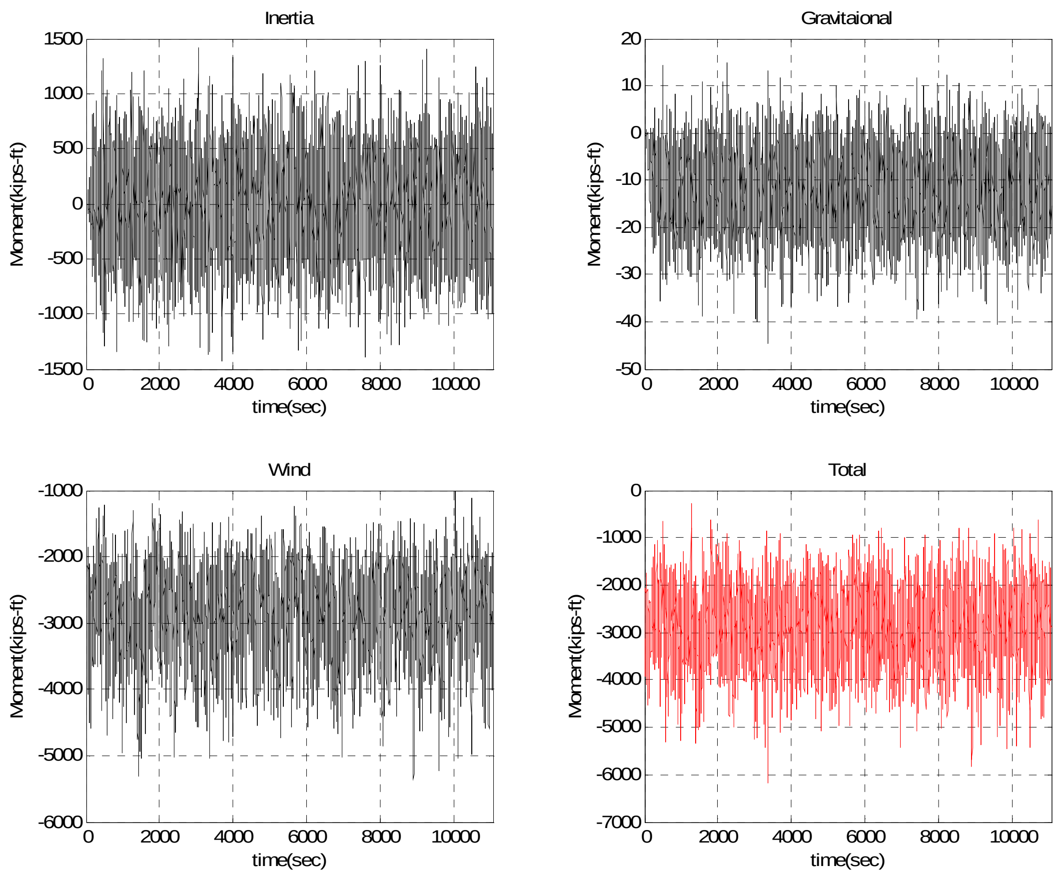
Figure A-12. Acceleration Time Series and Spectrum at the Upper Derrick CG for 1000 Year Hurricane



(a) Surge Direction

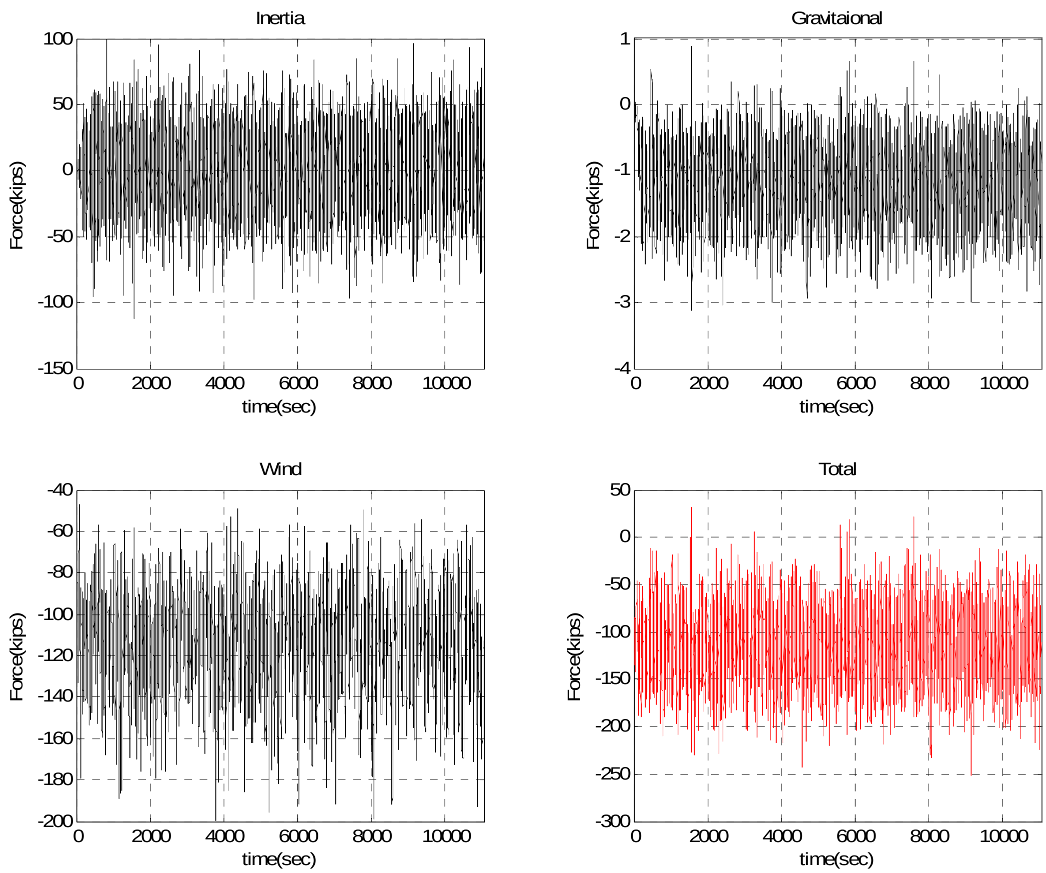


(b) Heave Direction

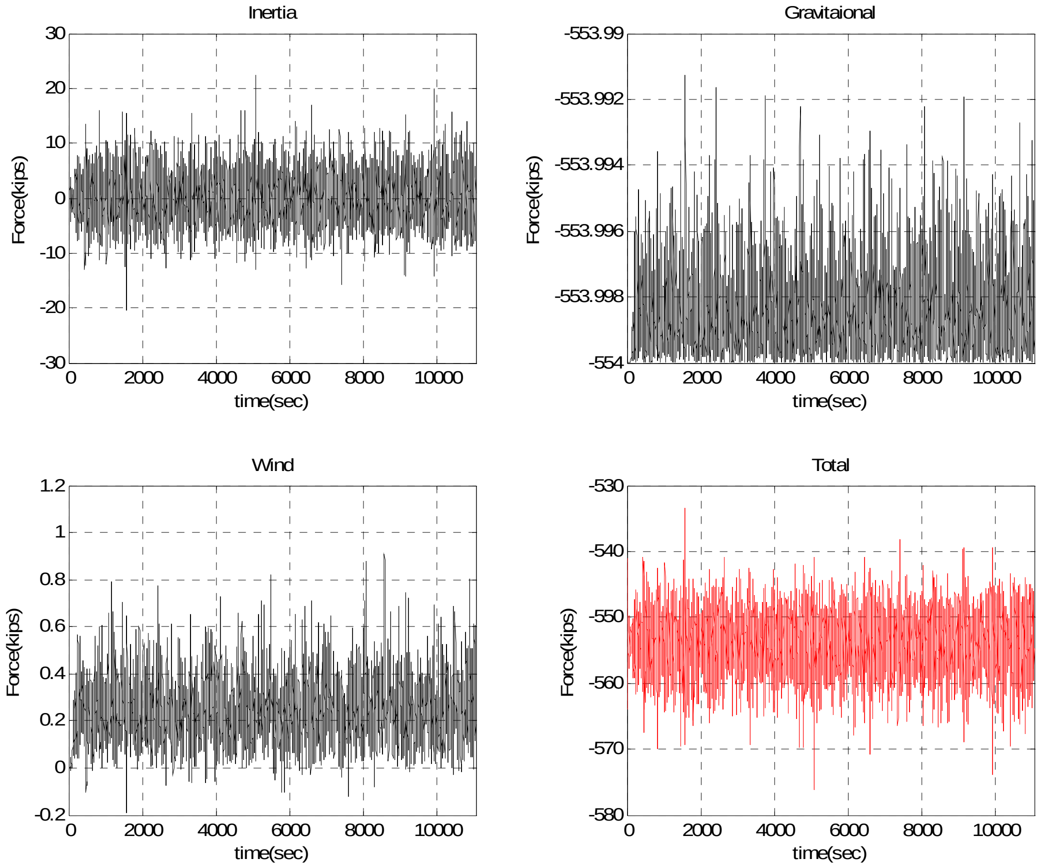


(c) Pitch Direction

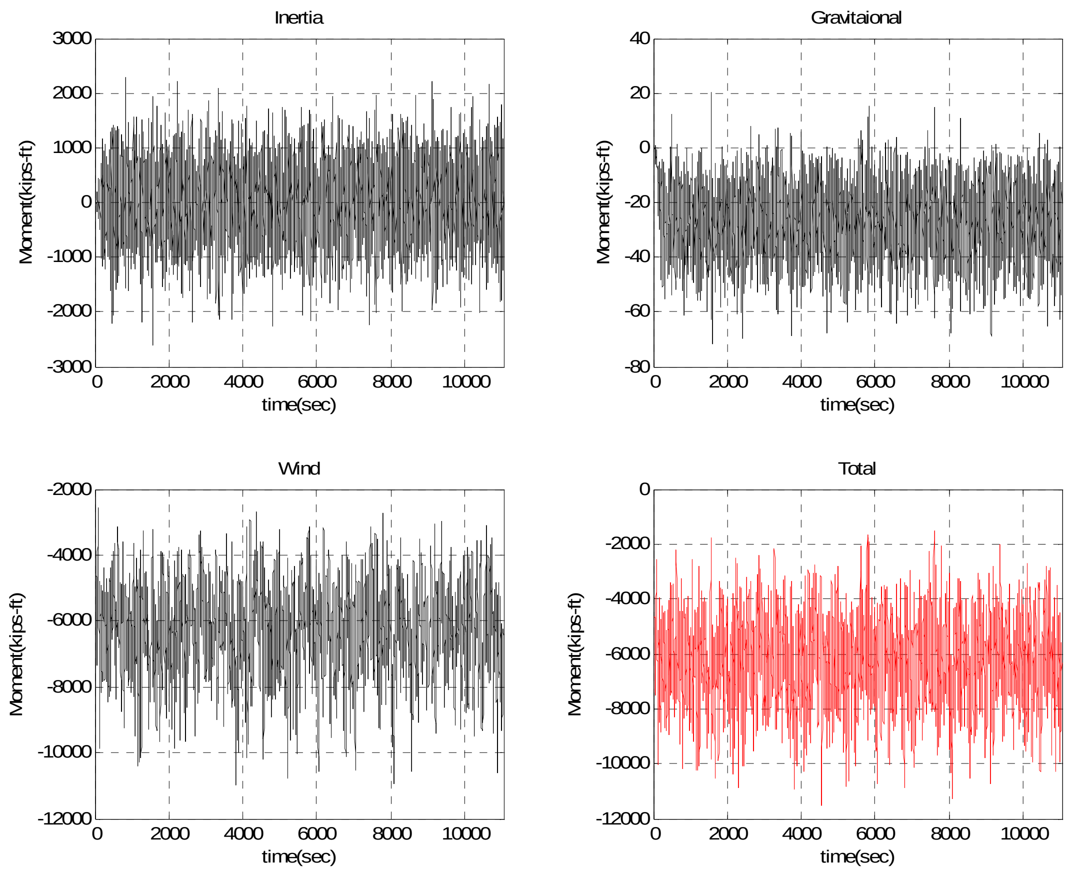
Figure A-13. Resultant Inertia, Gravitational and Wind Forces and Moments Acting on the Upper Derrick for 10 Year Hurricane Condition (Moment is with respect to the Derrick Footing Level)



(a) Surge Direction

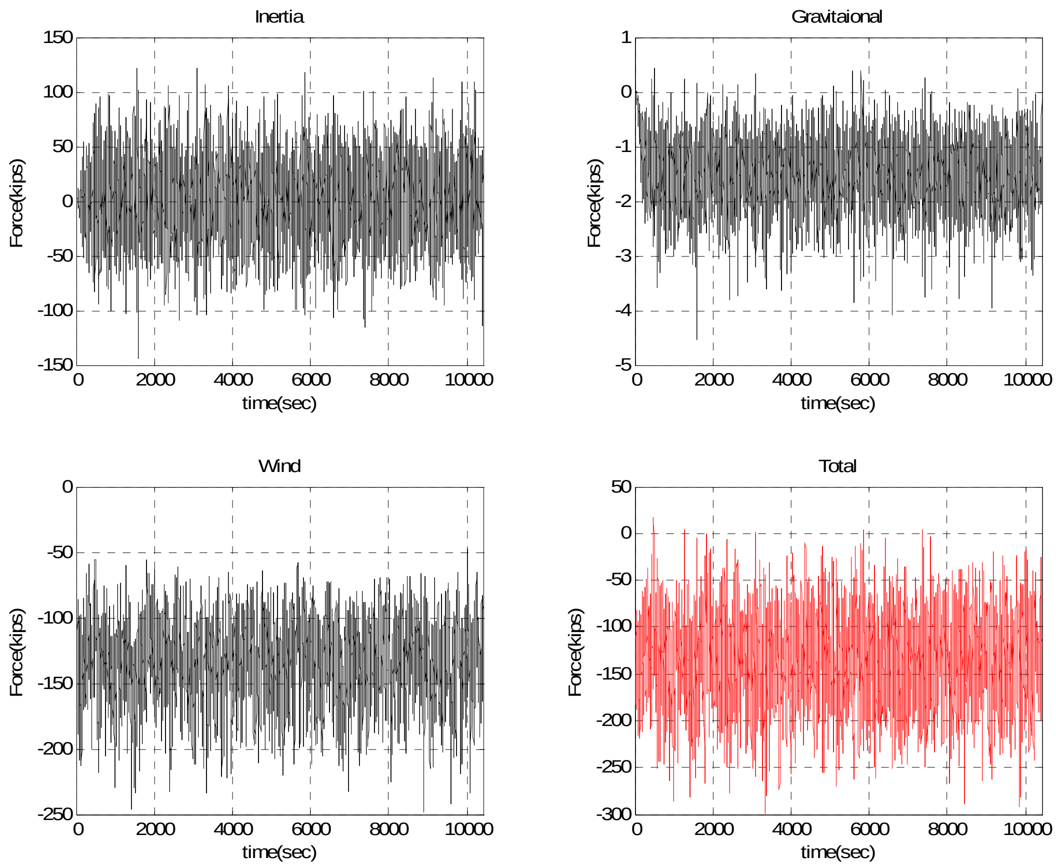


(b) Heave Direction

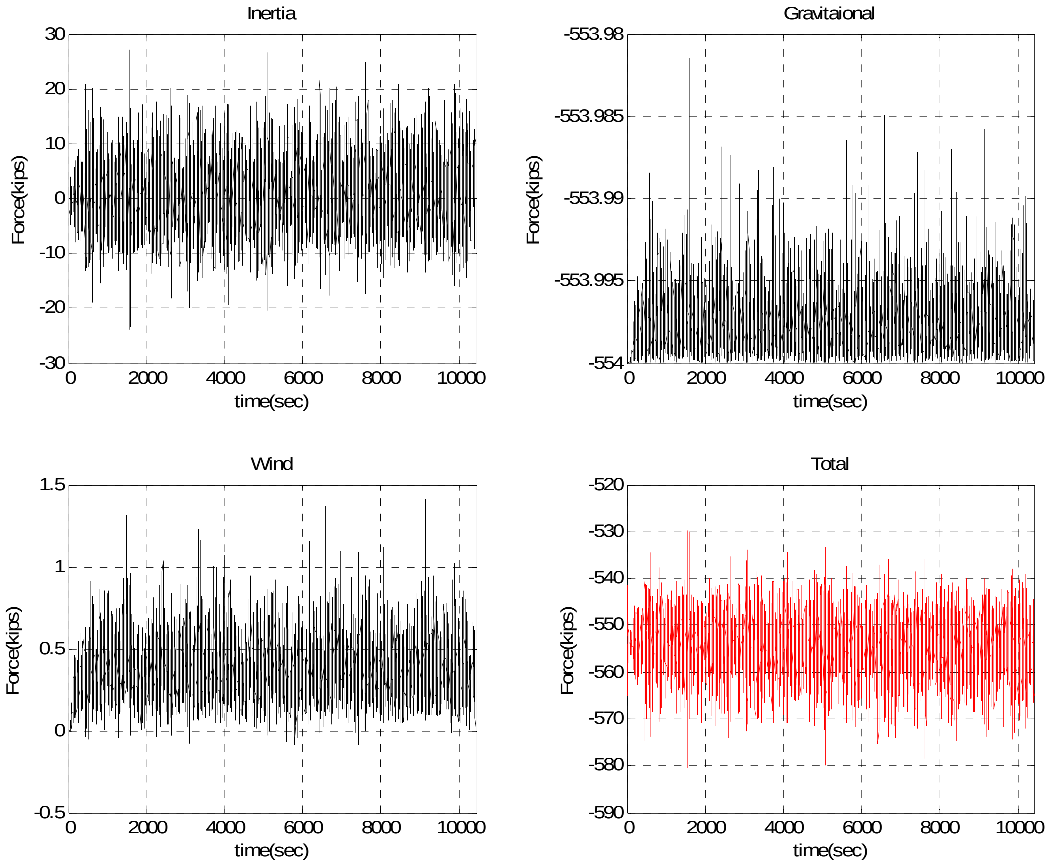


(c) Pitch Direction

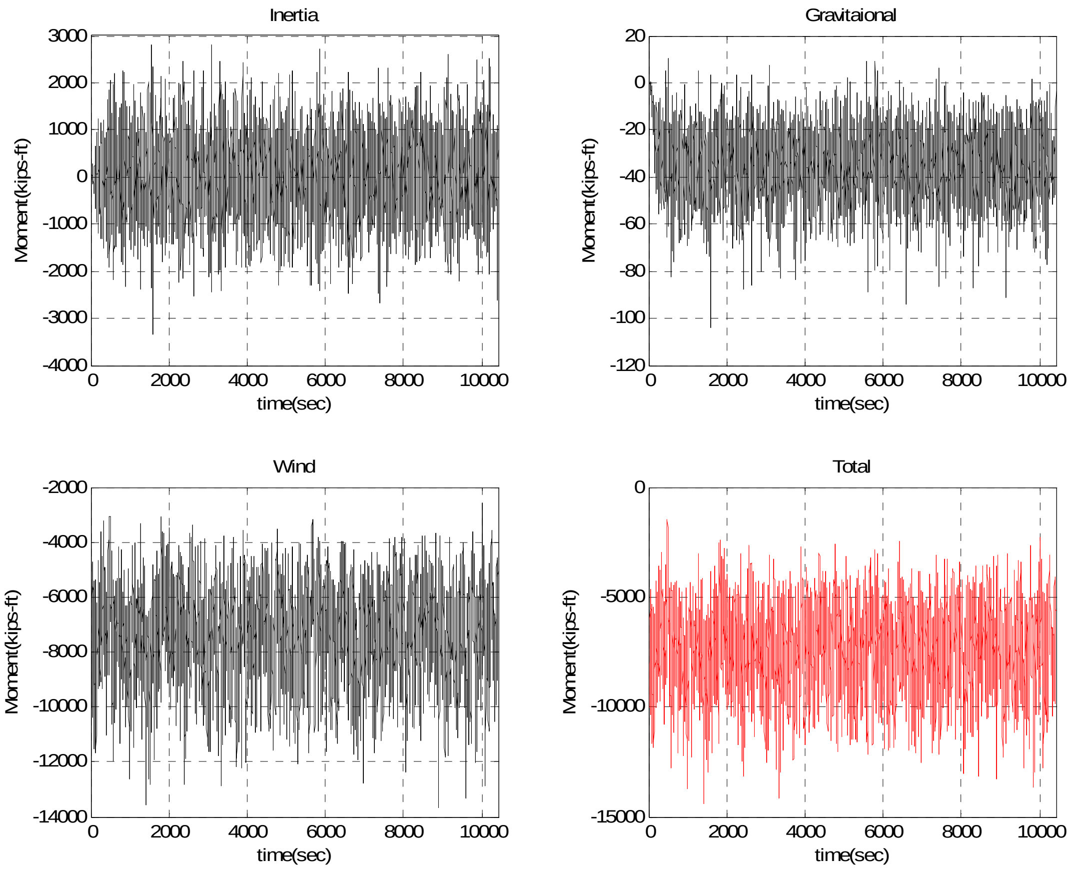
Figure A-14. Resultant Inertia, Gravitational and Wind Forces and Moments Acting on the Upper Derrick for 100 Year Hurricane Condition (Moment is with respect to the Derrick Footing Level)



(a) Surge Direction

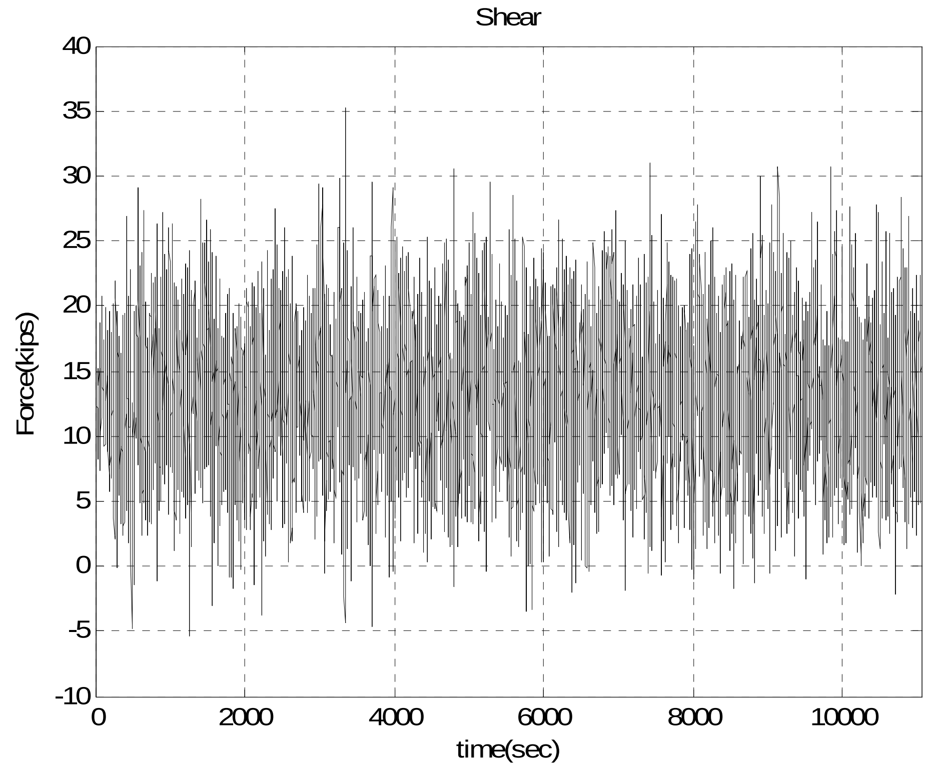


(b) Heave Direction

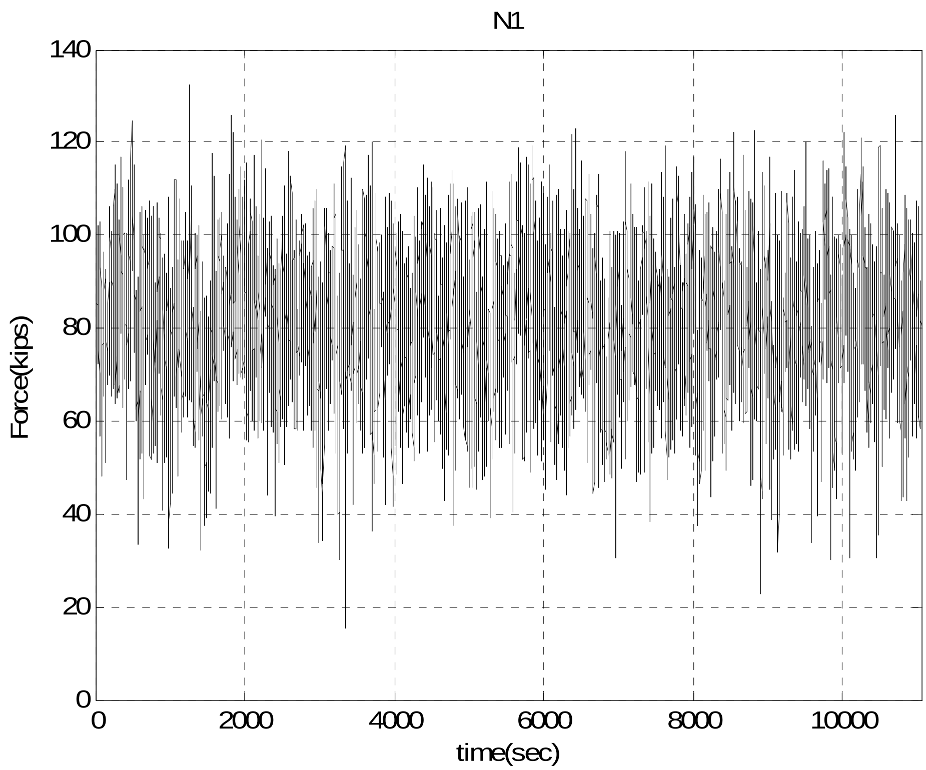


(c) Pitch Direction

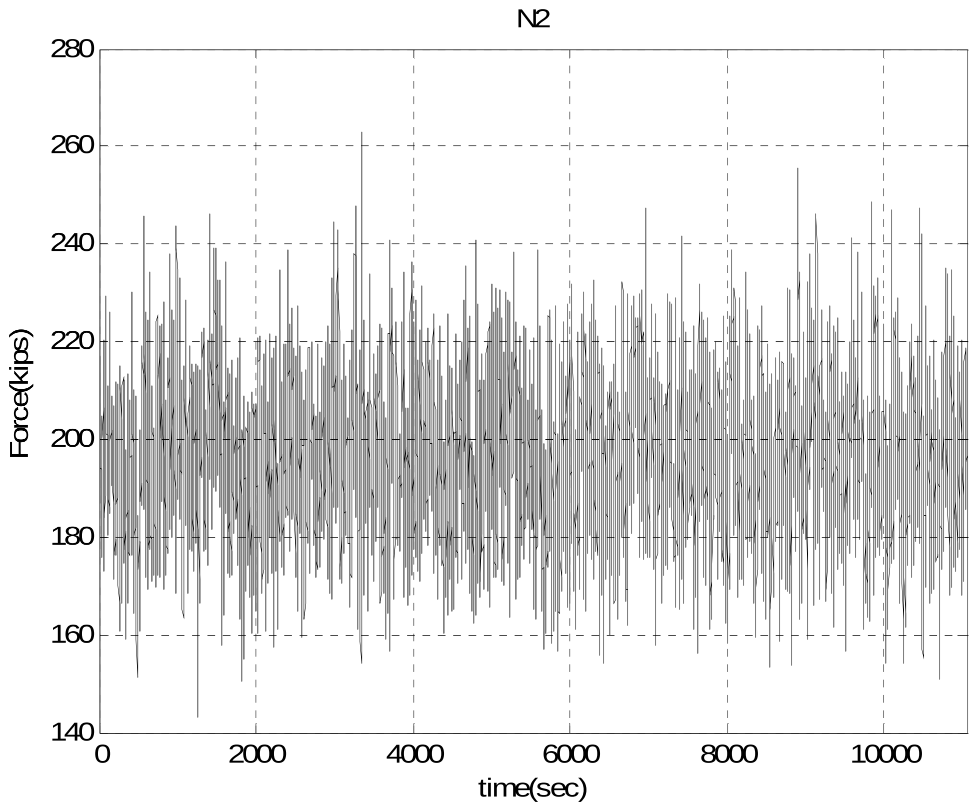
Figure A-15. Resultant Inertia, Gravitational and Wind Forces and Moments Acting on the Upper Derrick for 1000 Year Hurricane Condition (Moment is with respect to the Derrick Footing Level)



(a) Shear Reaction Force acted by the Connection point

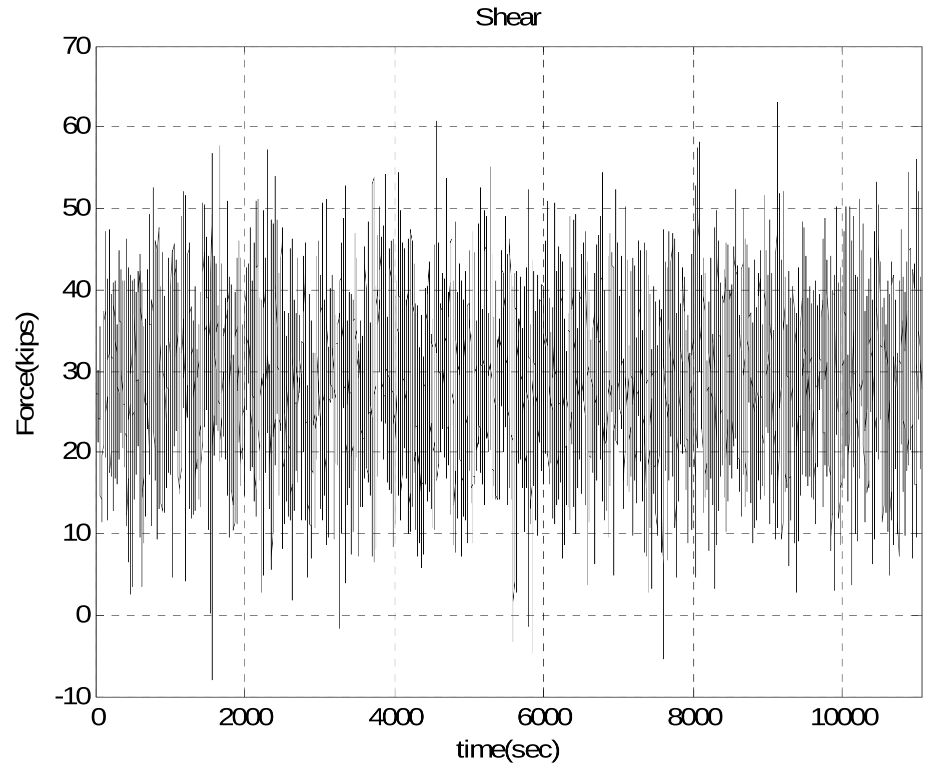


(b) Figure Normal Reaction Force at Footing #1 and #4 (Refer to Figure 5)

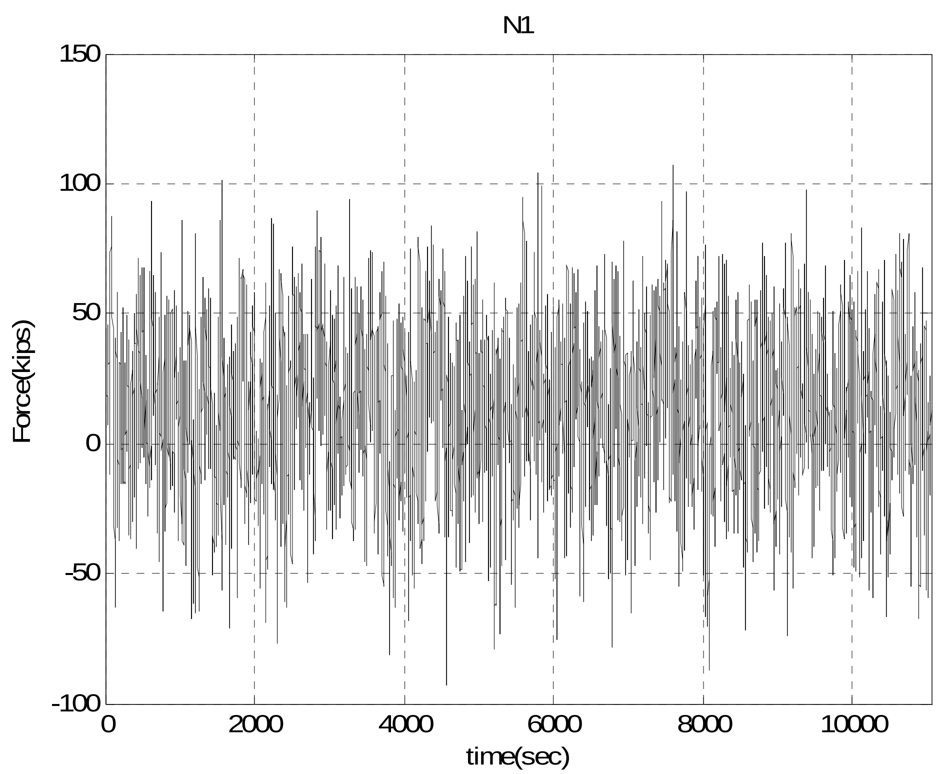


(c) Normal Reaction Force at Footing #2 and #3 (Refer to Figure 5)

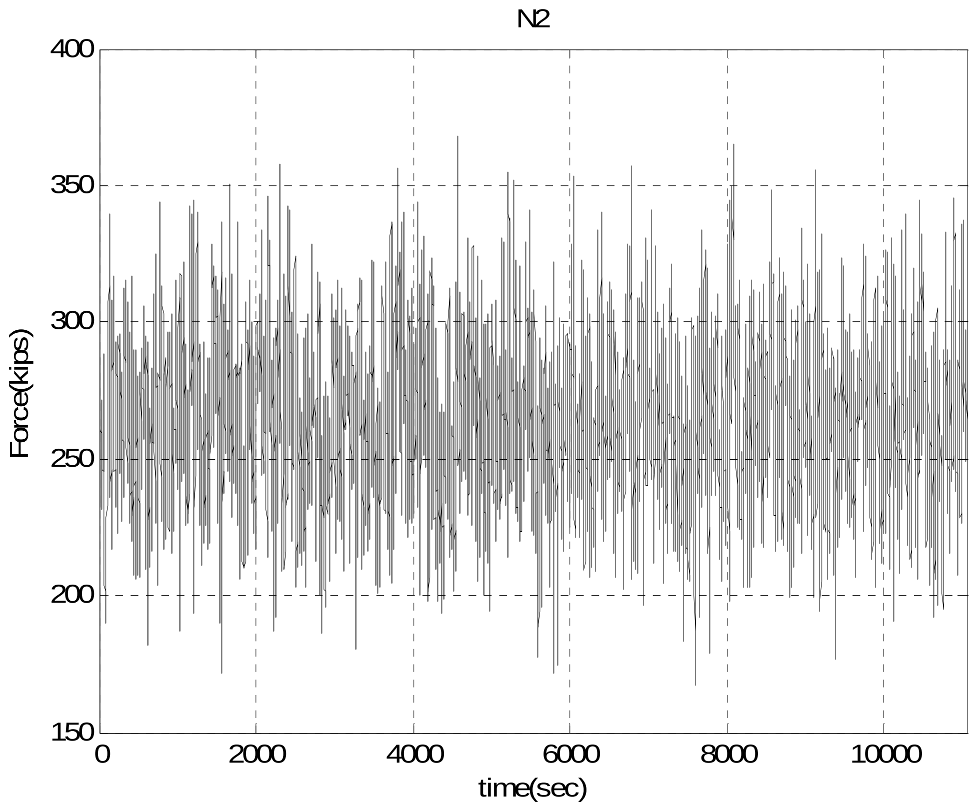
Figure A-16. Reaction Forces at Derrick Point (Positive sign means upward and negative downward direction in the normal reaction force) for 10 Year Hurricane Condition



(a) Shear Reaction Force acted by the Connection point

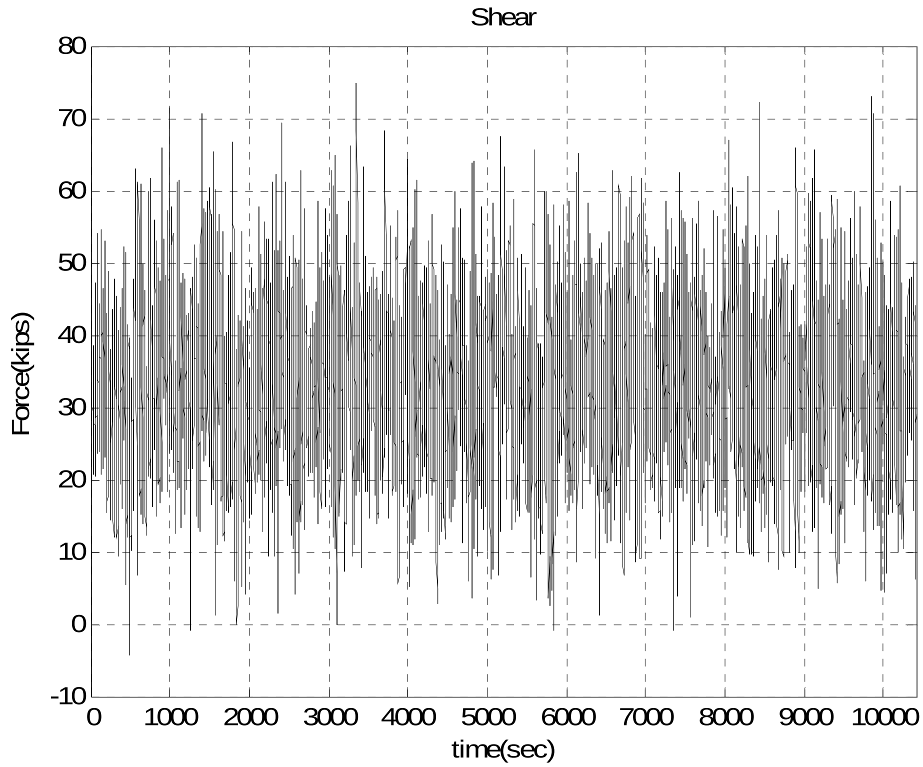


(b) Figure Normal Reaction Force at Footing #1 and #4 (Refer to Figure 5)

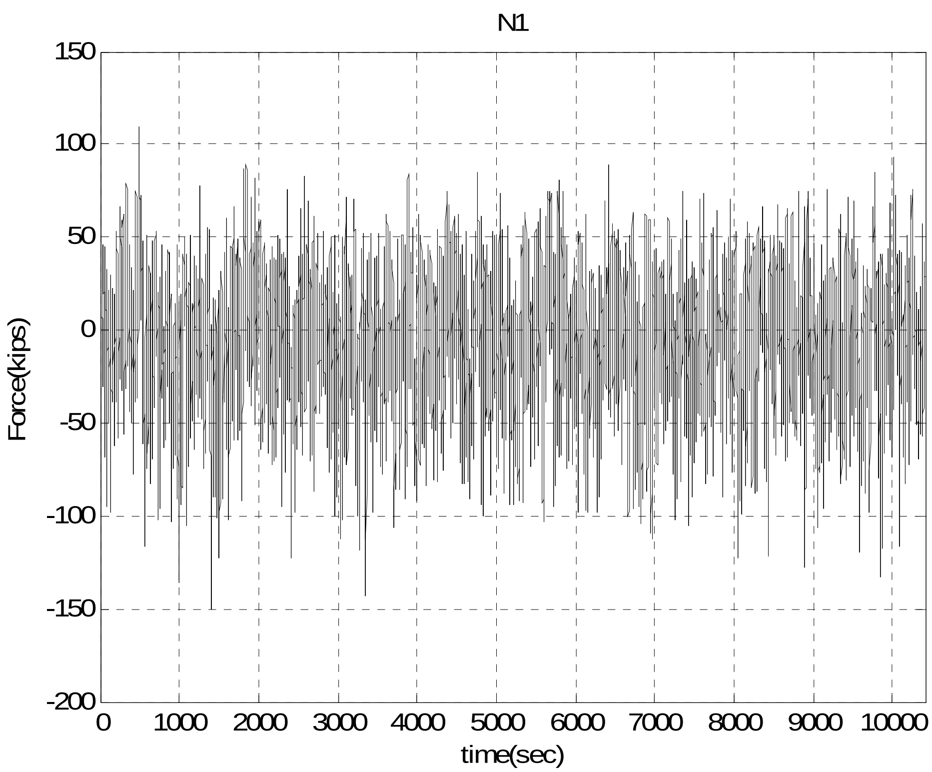


(c) Normal Reaction Force at Footing #2 and #3 (Refer to Figure 5)

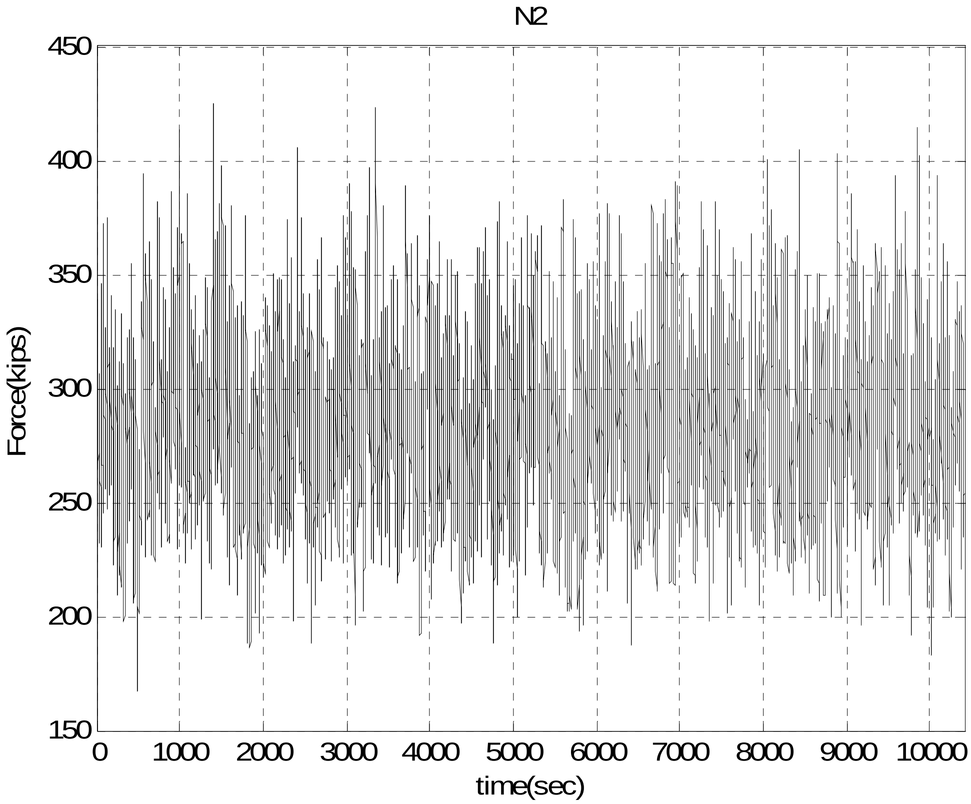
Figure A-17. Reaction Forces at Derrick Footing Point (Positive sign means upward and negative downward direction in the normal reaction force) for 100 Year Hurricane Condition



(a) Shear Reaction Force acted by the Connection point

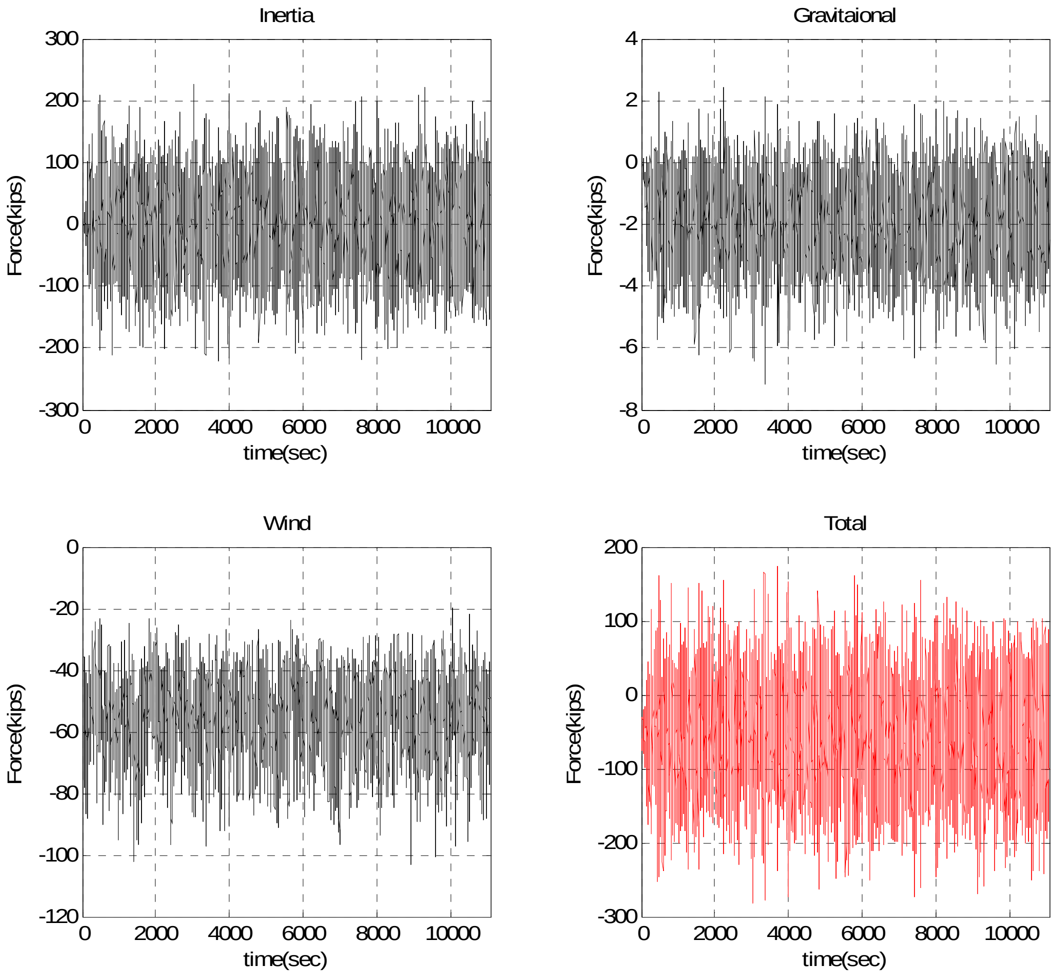


(b) Figure Normal Reaction Force at Footing #1 and #4 (Refer to Figure 5)

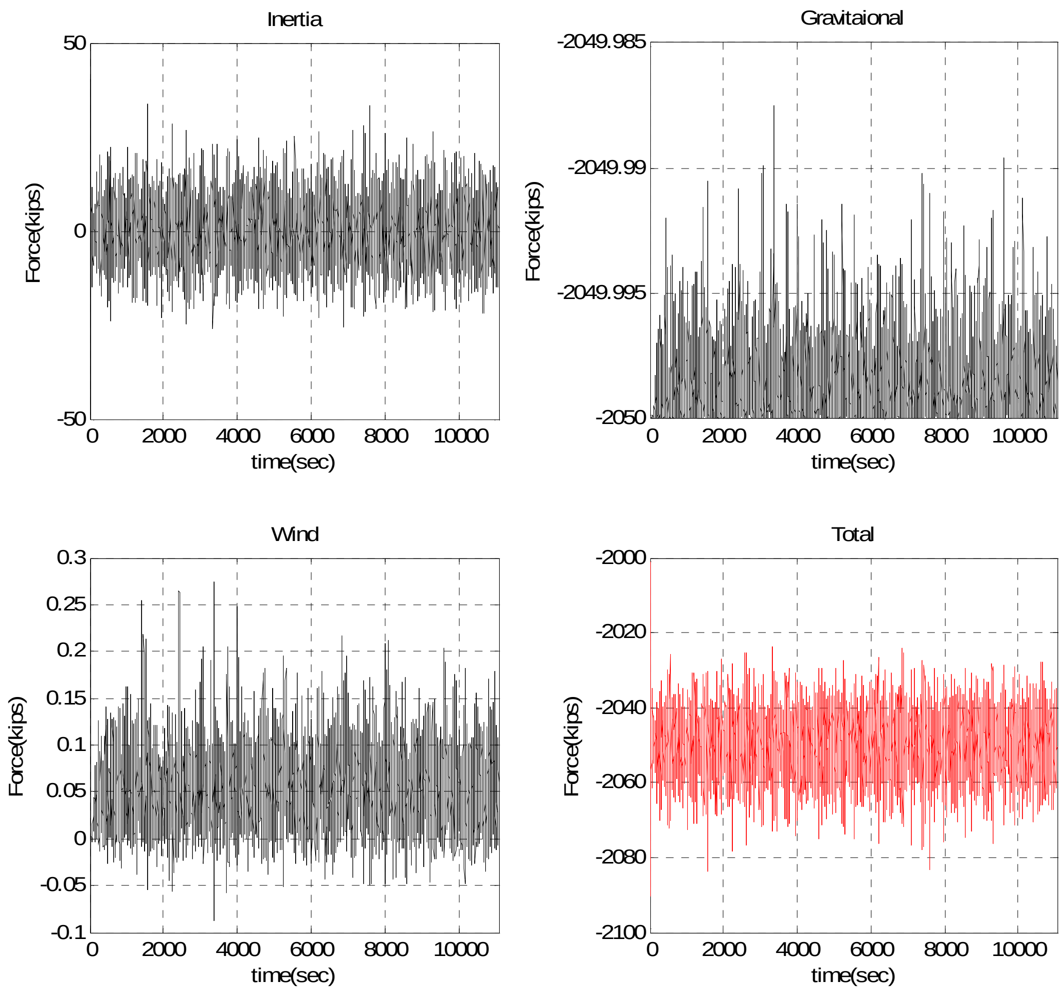


(c) Normal Reaction Force at Footing #2 and #3 (Refer to Figure 5)

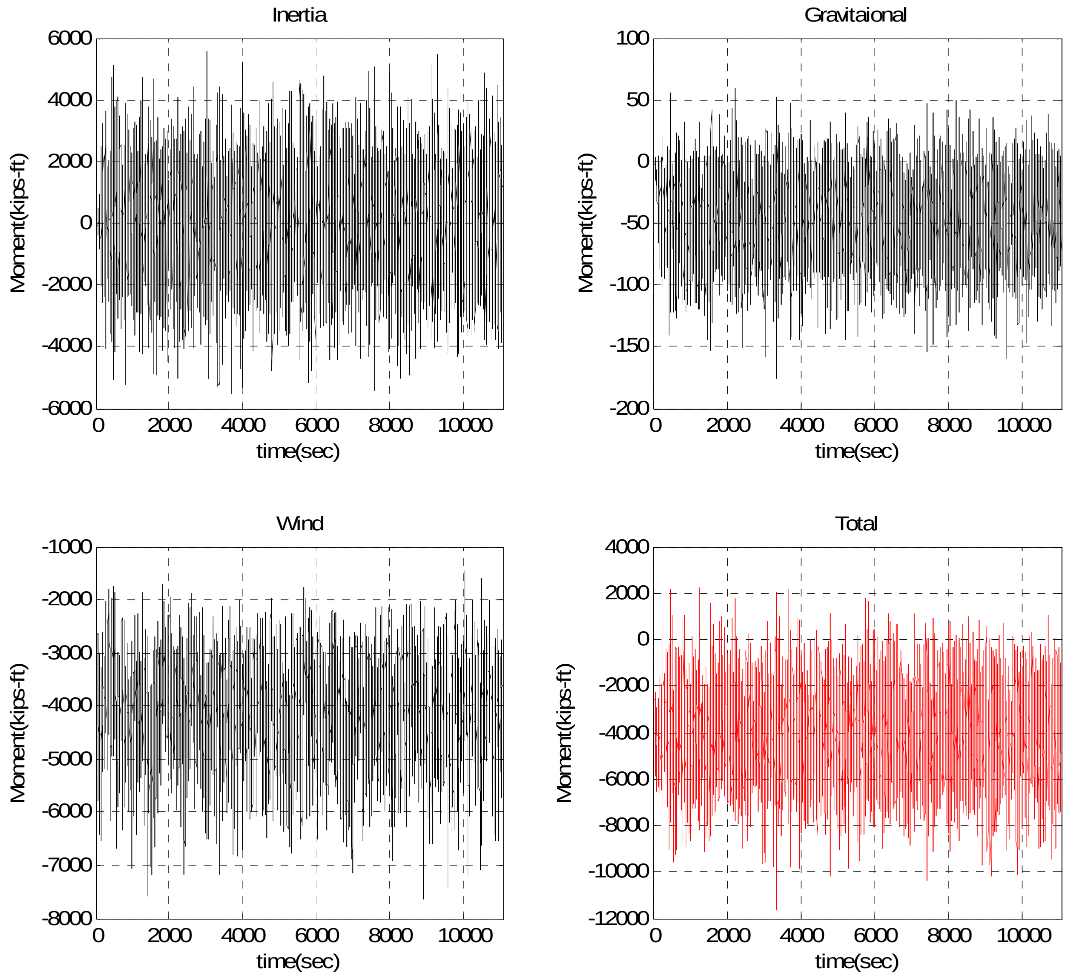
Figure A-18. Reaction Forces at Derrick Footing Point (Positive sign means upward and negative downward direction in the normal reaction force) for 1000 Year Hurricane Condition



(a) Surge Direction

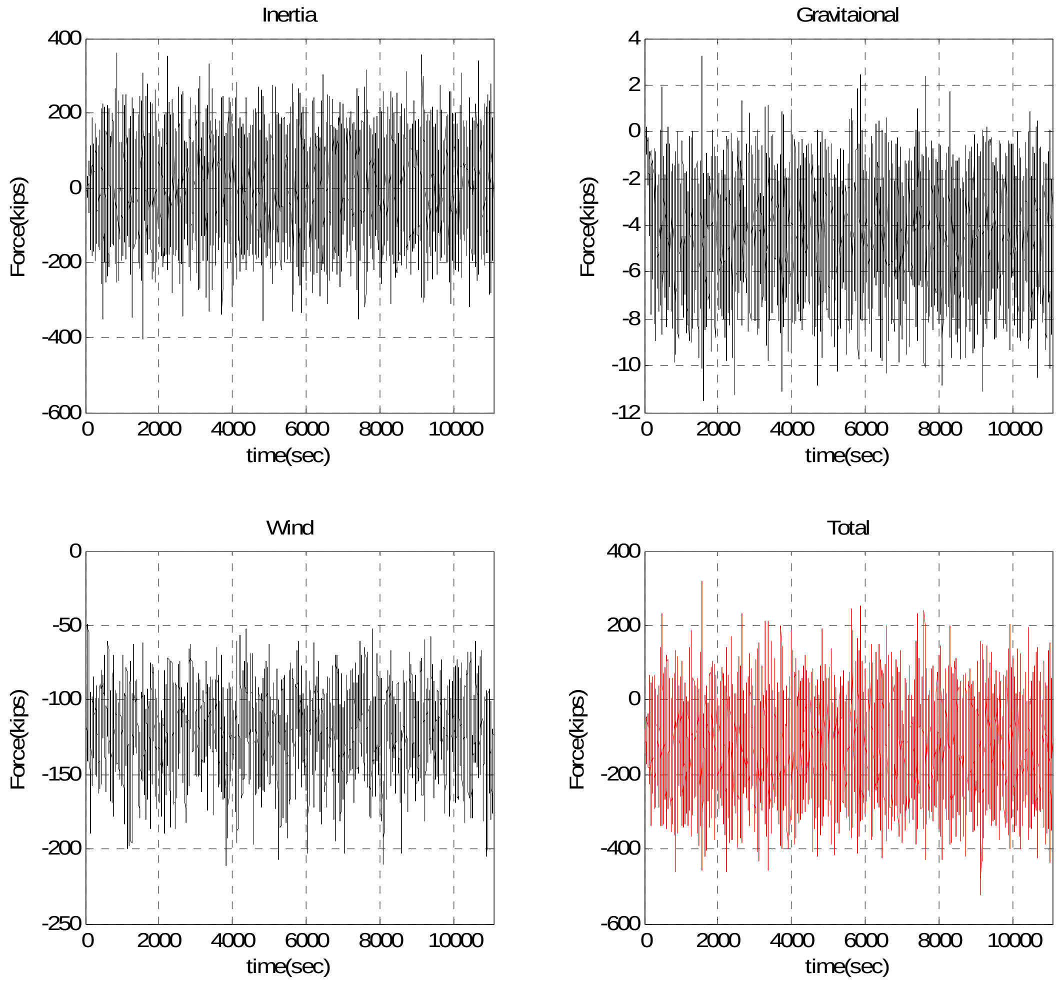


(b) Heave Direction

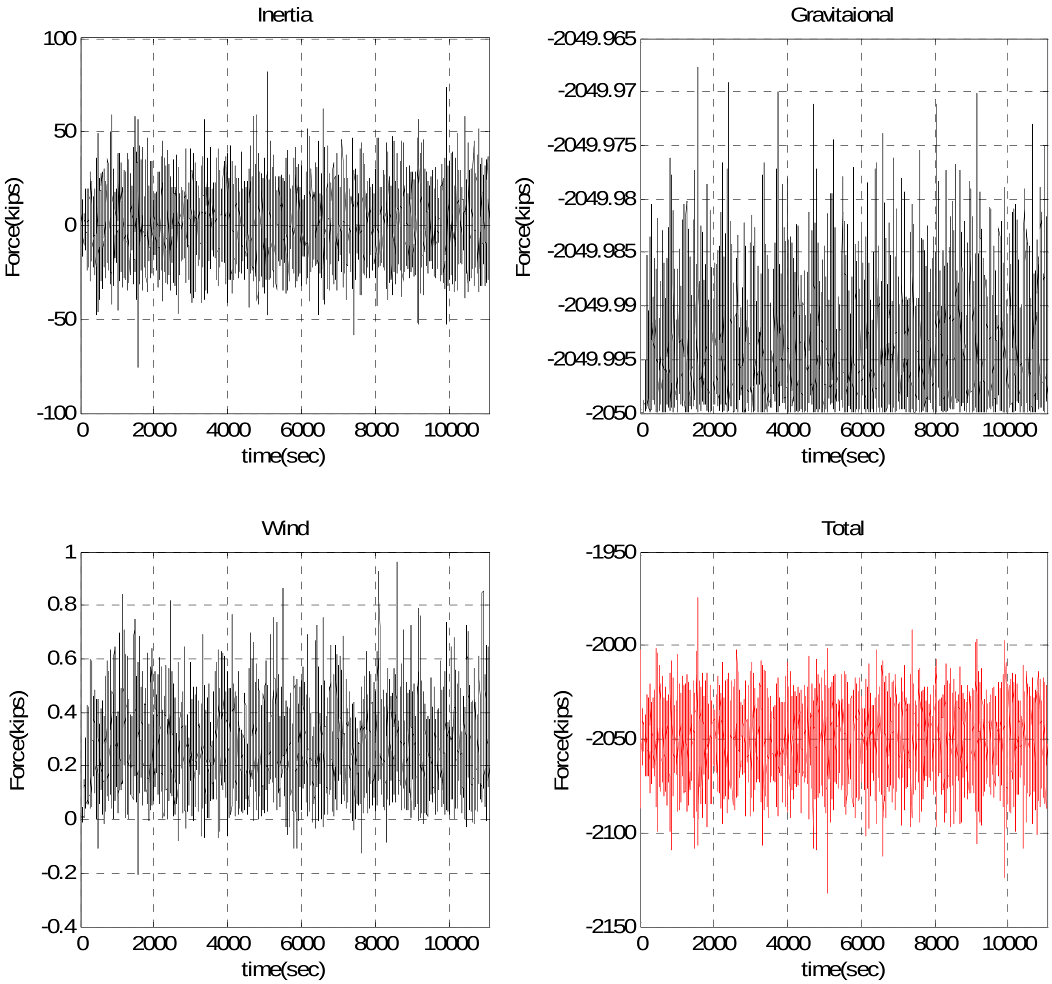


(c) Pitch Direction

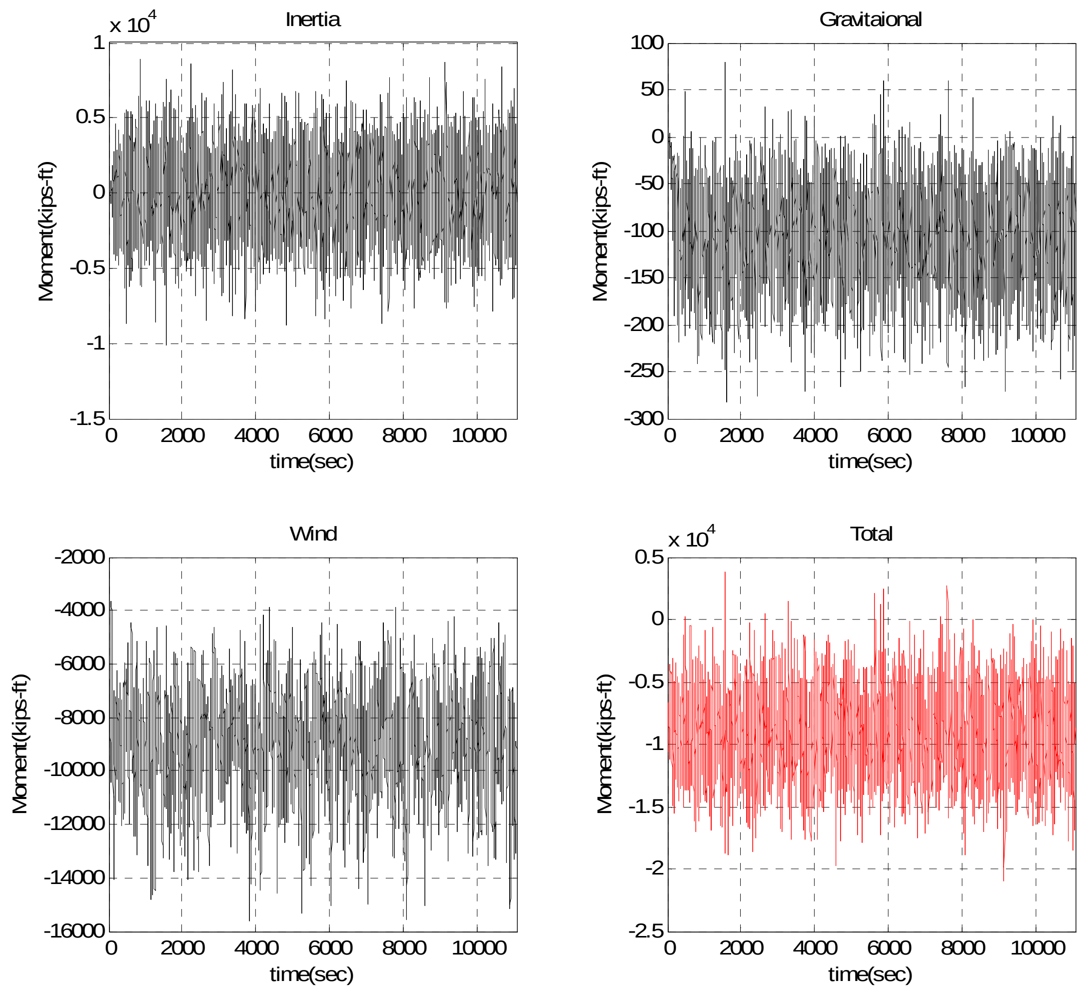
Figure A-19. Resultant Inertia, Gravitational and Wind Forces and Moments Acting on the Upper Derrick and Substructure for 10 Year Hurricane Condition (Moment is with respect to the Substructure Footing Level)



(a) Surge Direction

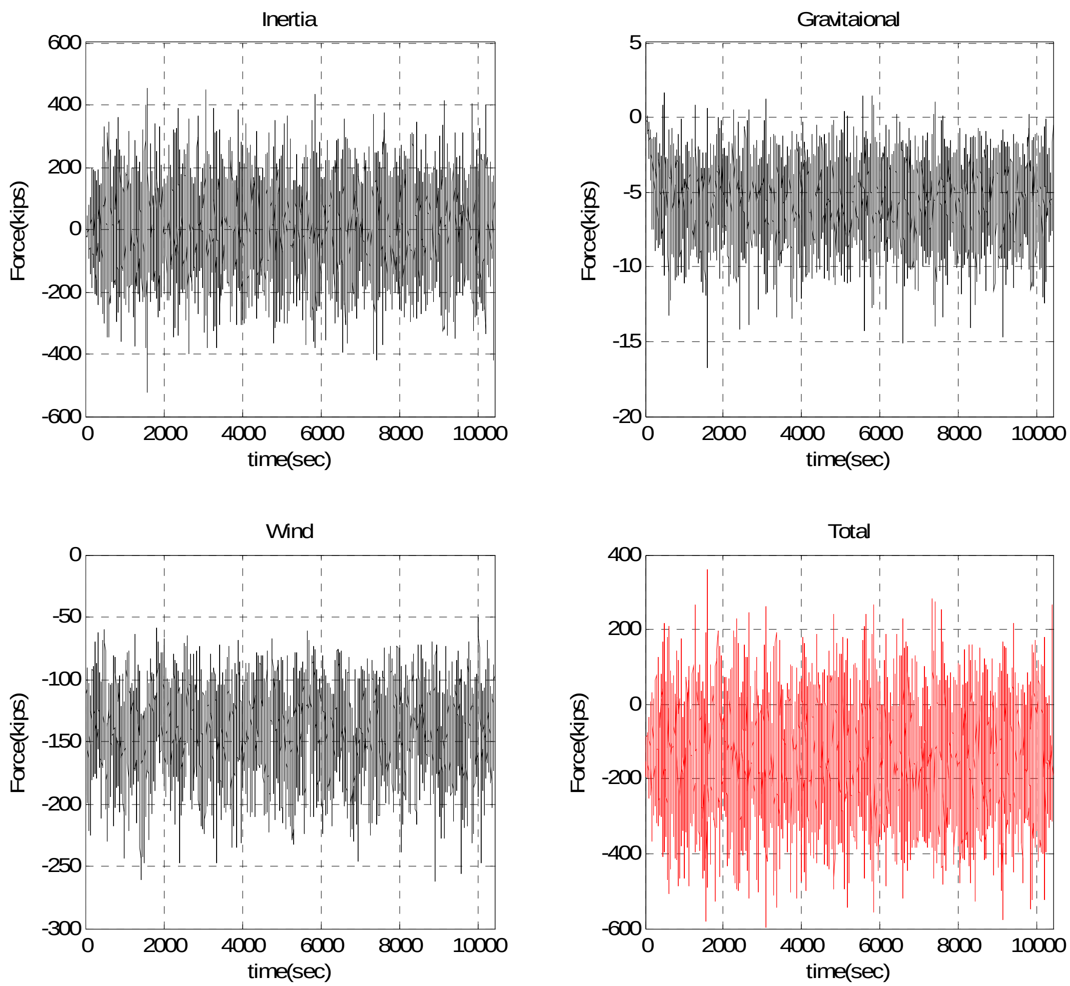


(b) Heave Direction

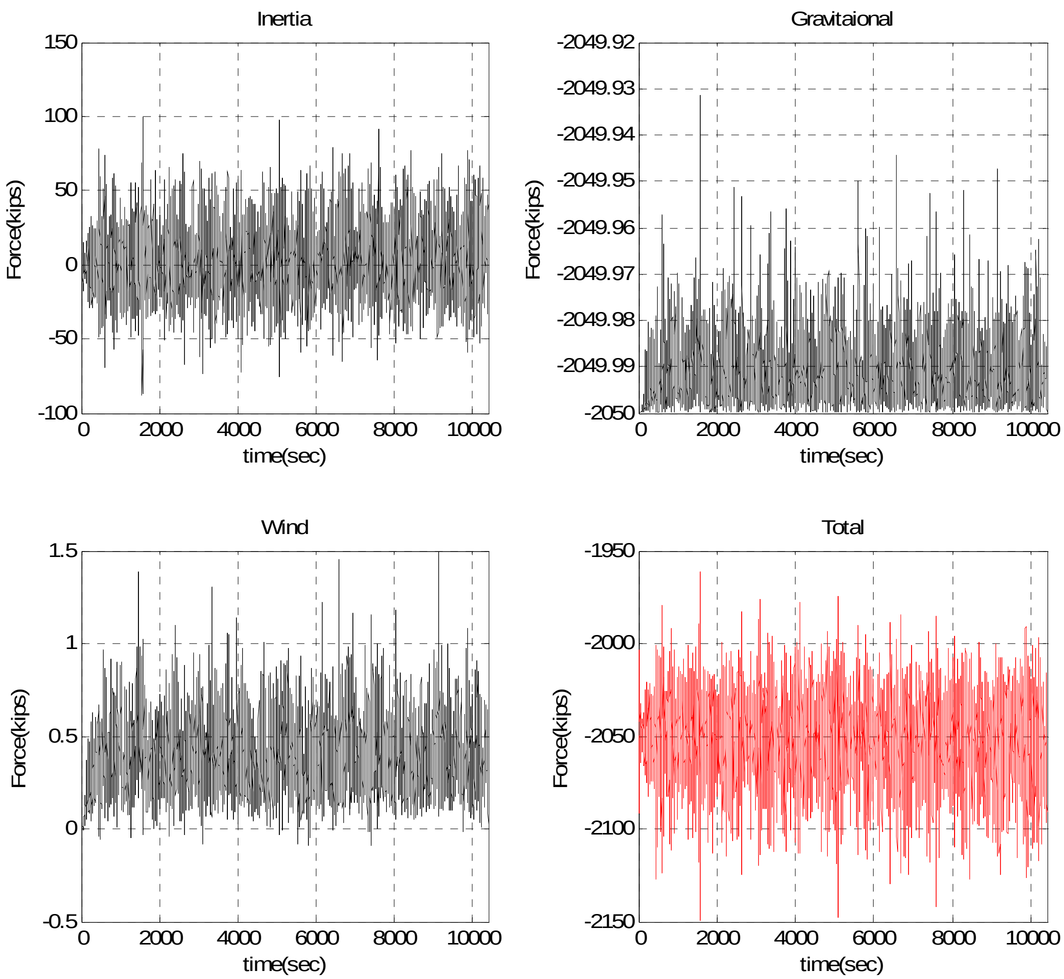


(c) Pitch Direction

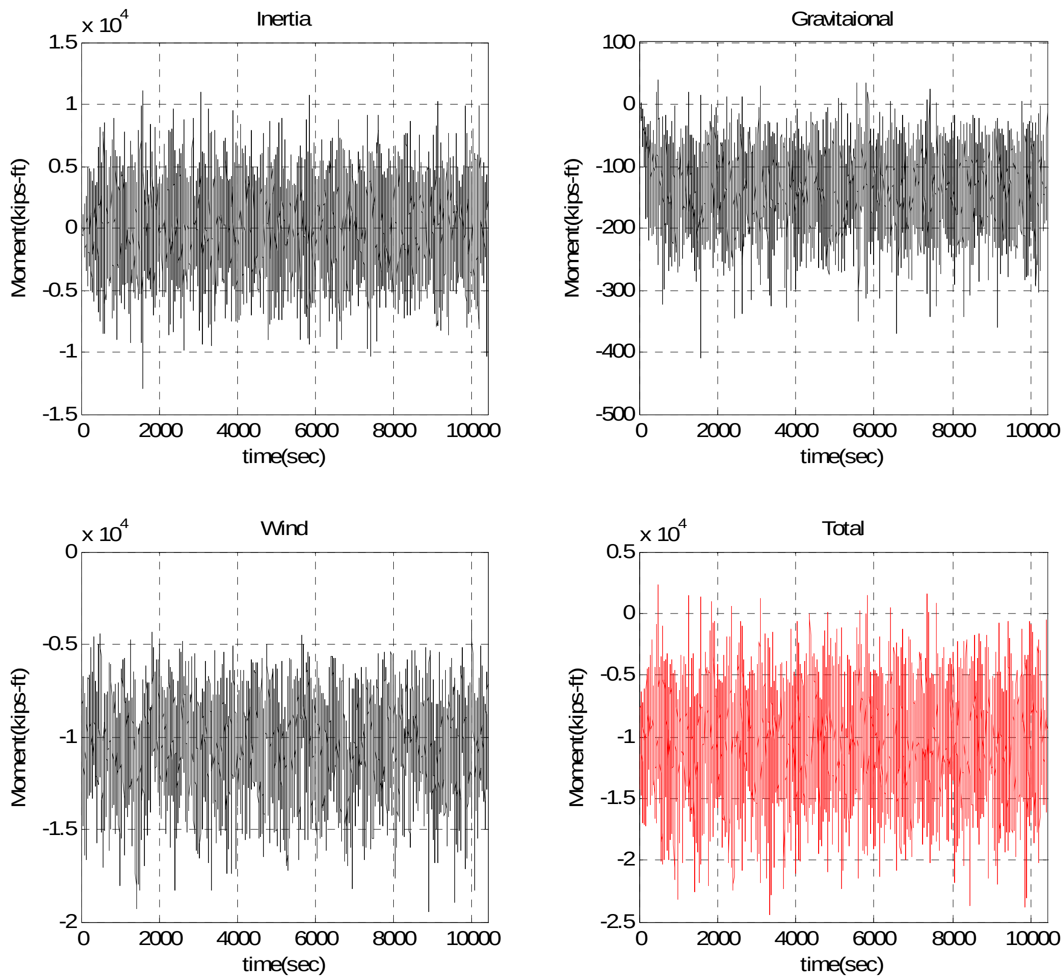
Figure A-20. Resultant Inertia, Gravitational and Wind Forces and Moments Acting on the Upper Derrick and Substructure for 100 Year Hurricane Condition (Moment is with respect to the Substructure Footing Level)



(a) Surge Direction

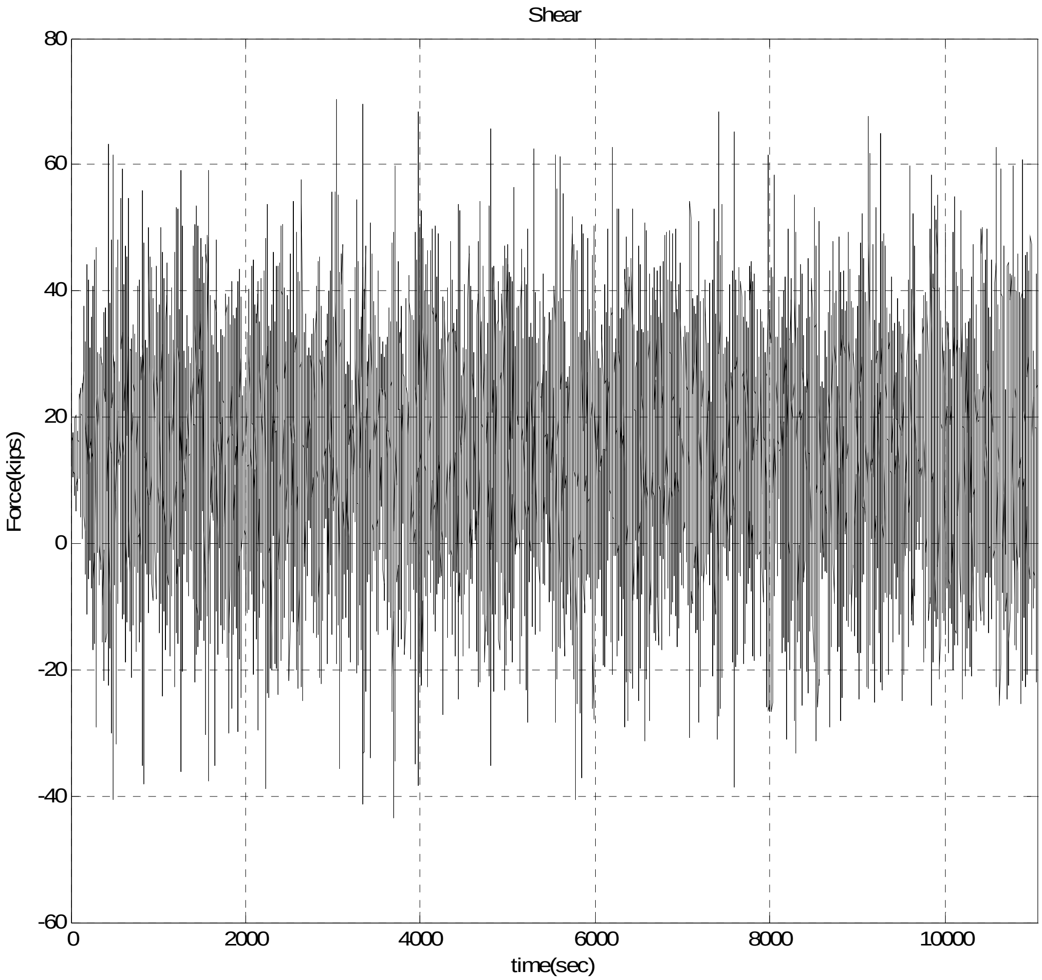


(b) Heave Direction

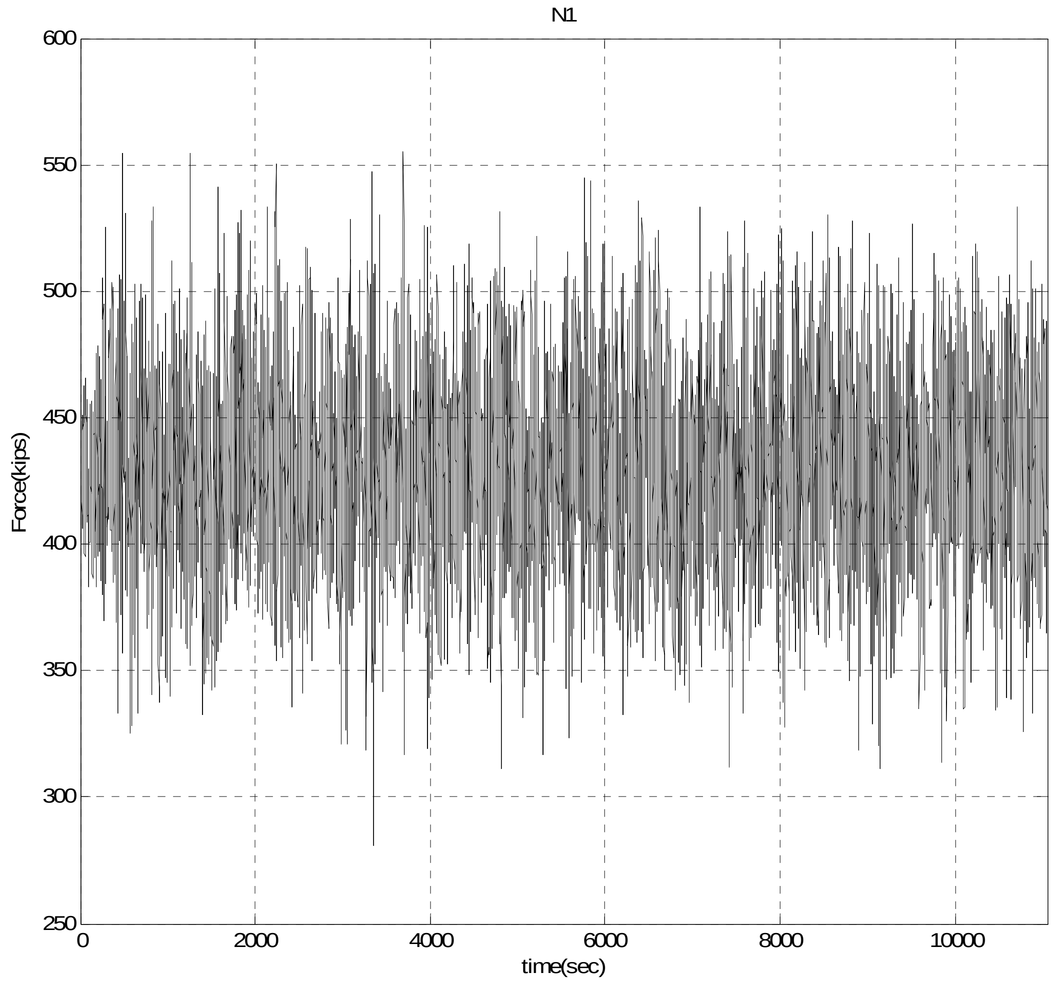


(c) Pitch Direction

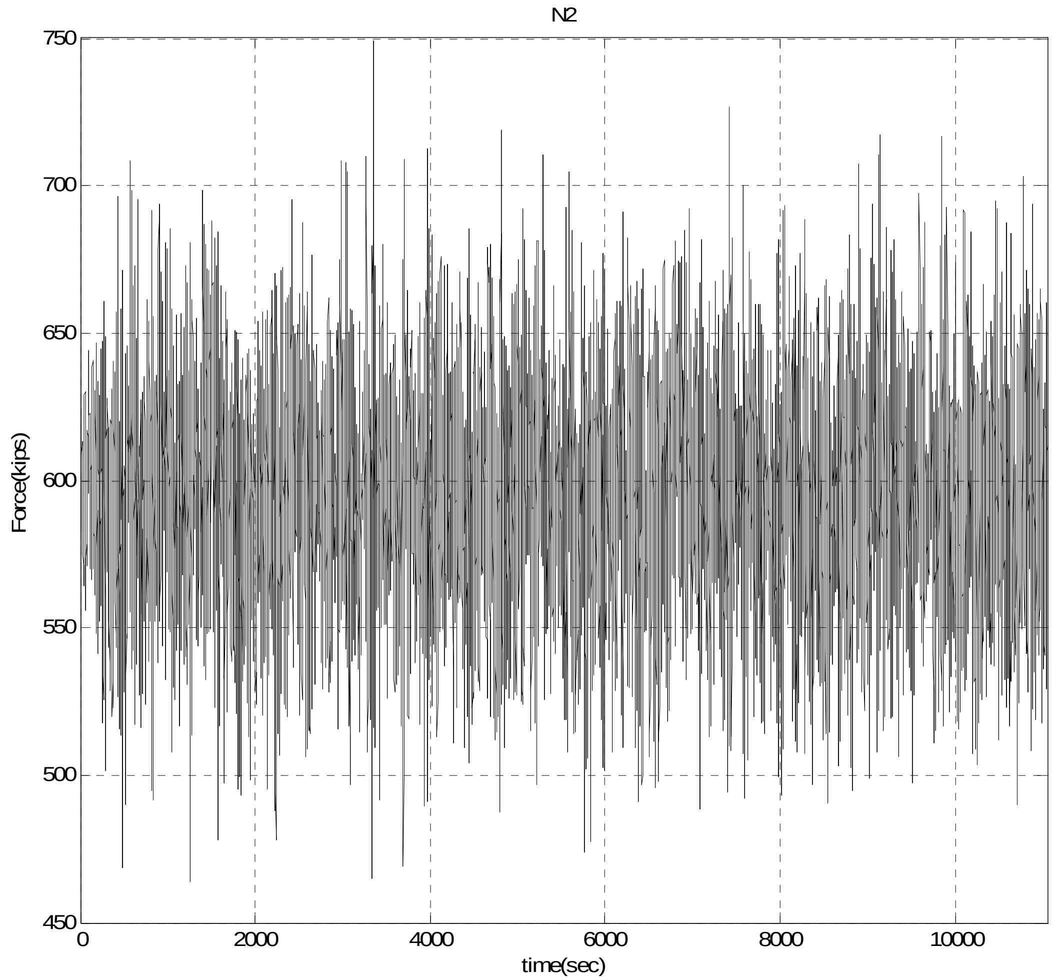
Figure A-21. Resultant Inertia, Gravitational and Wind Forces and Moments Acting on the Upper Derrick and Substructure for 1000 Year Hurricane Condition (Moment is with respect to the Substructure Footing Level)



(a) Shear Reaction Force acted by the Connection point

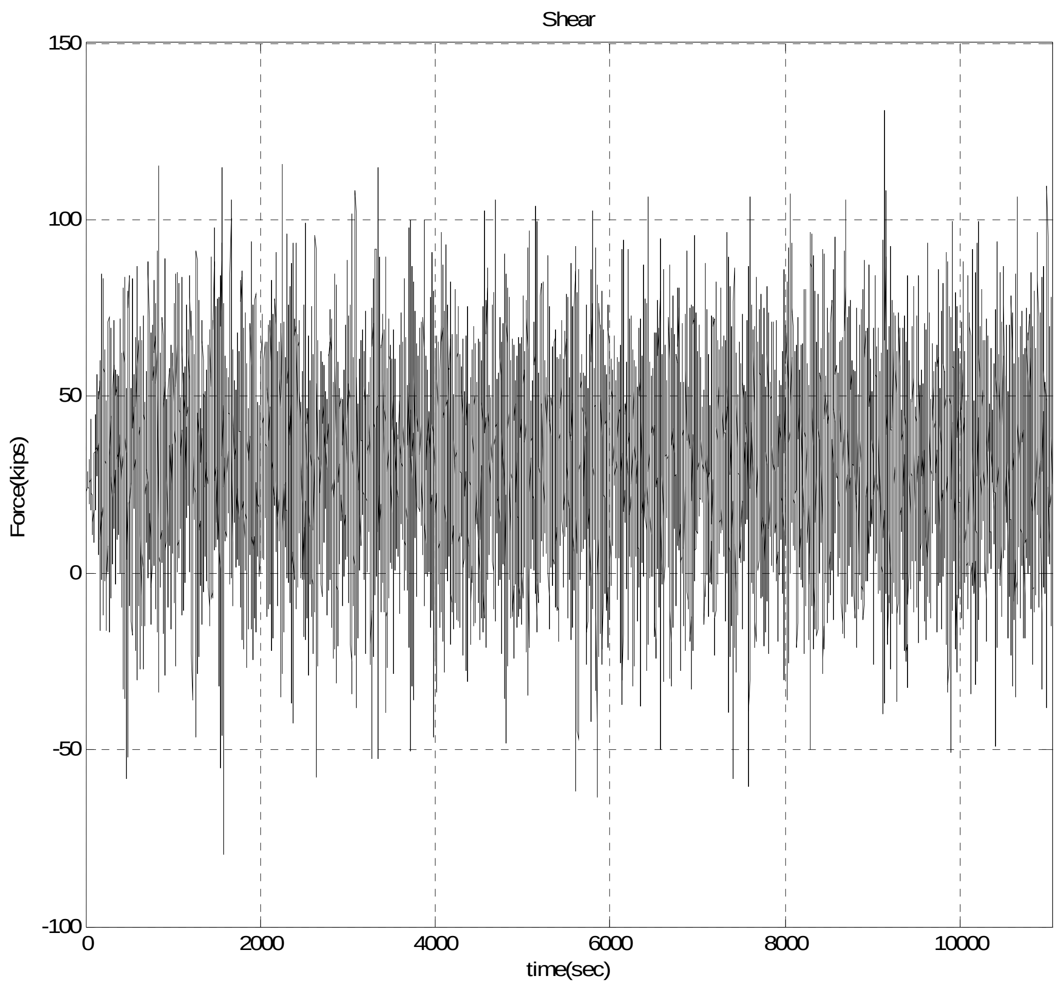


(b) Figure Normal Reaction Force at Footing #1 and #4 (Refer to Figure 5)

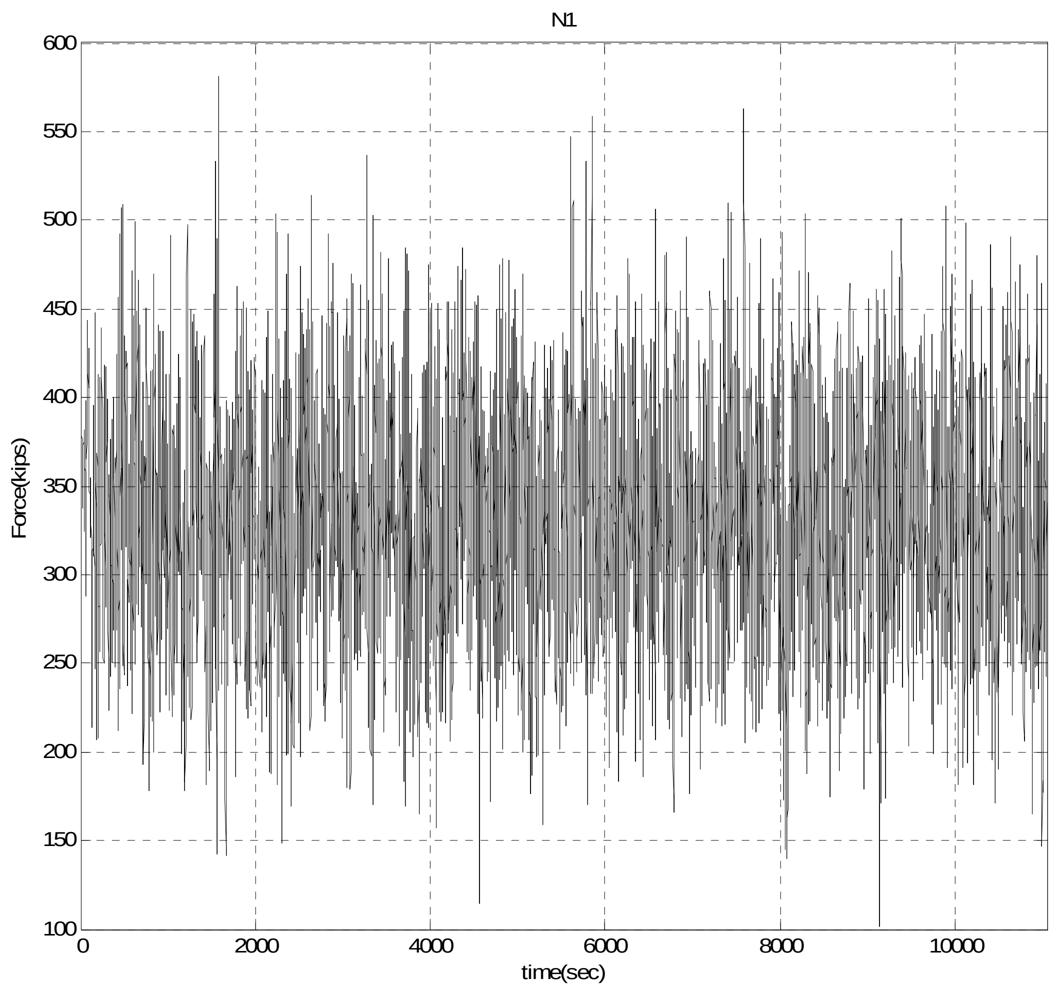


(c) Normal Reaction Force at Footing #2 and #3 (Refer to Figure 5)

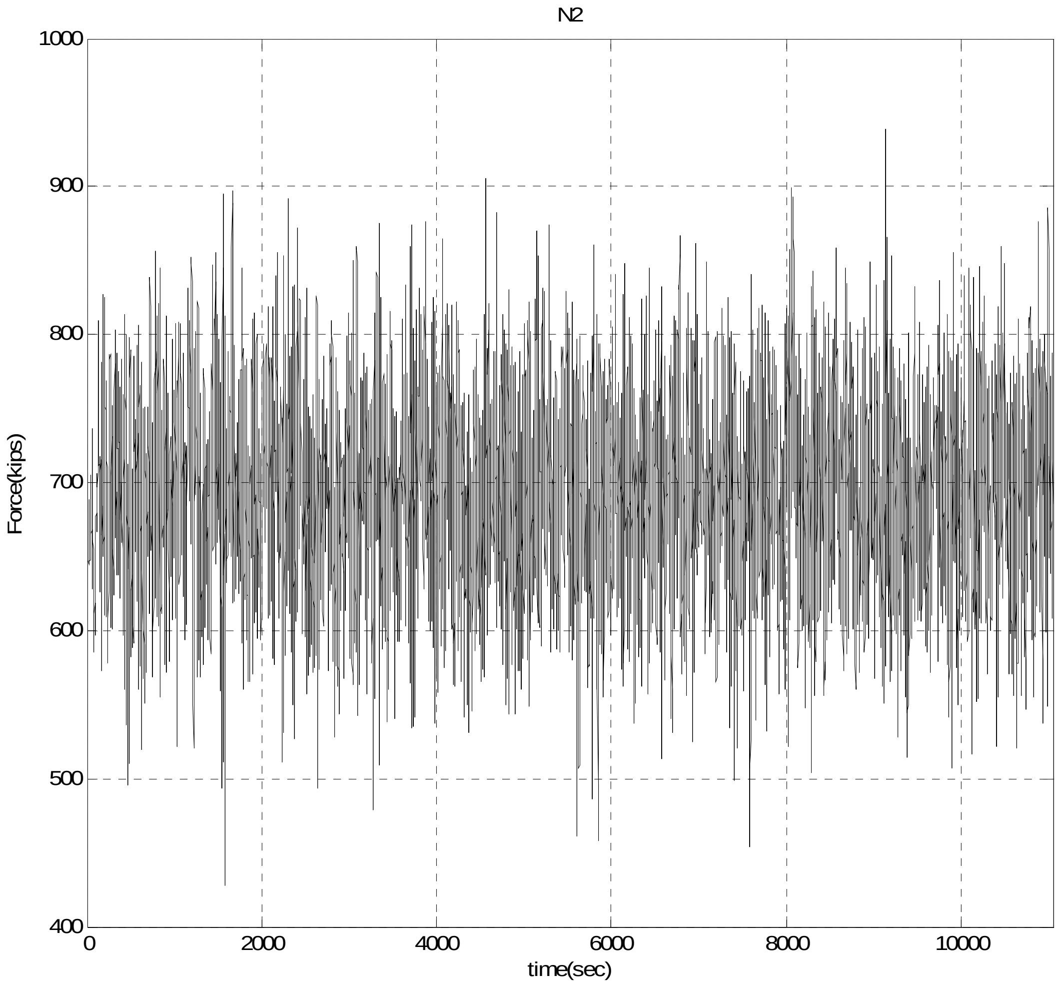
Figure A-22. Reaction Forces at Substructure Footing Point (Positive sign means upward and negative downward direction in the normal reaction force) for 10 Year Hurricane Condition



(a) Shear Reaction Force acted by the Connection point

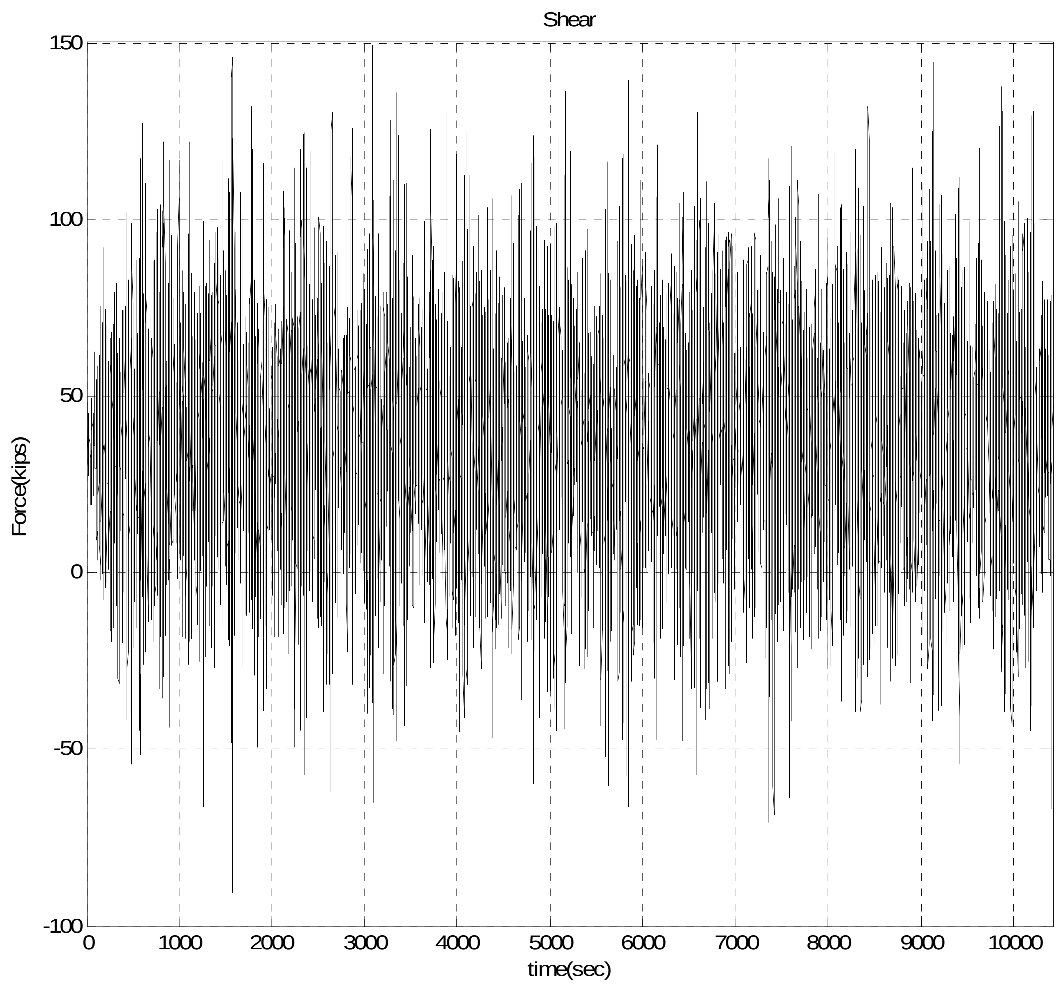


(b) Figure Normal Reaction Force at Footing #1 and #4 (Refer to Figure 5)

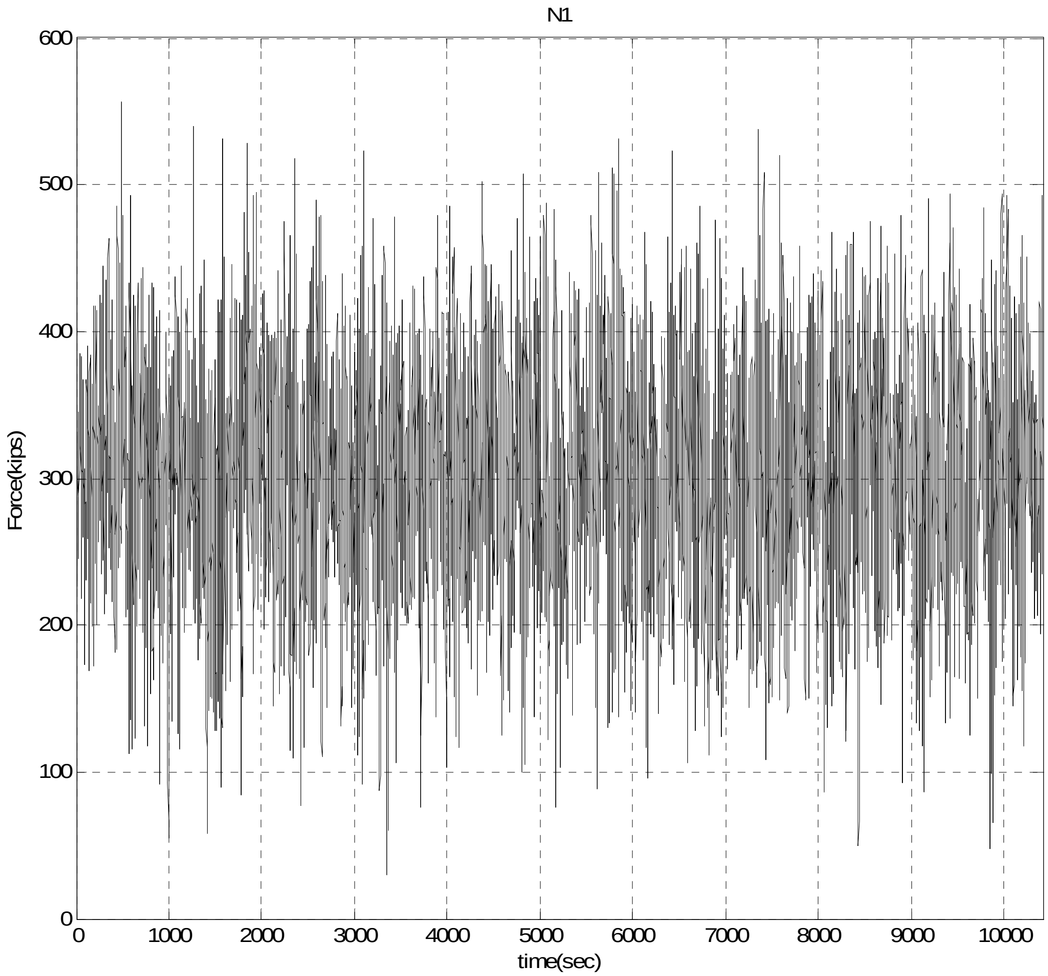


(c) Normal Reaction Force at Footing #2 and #3 (Refer to Figure 5)

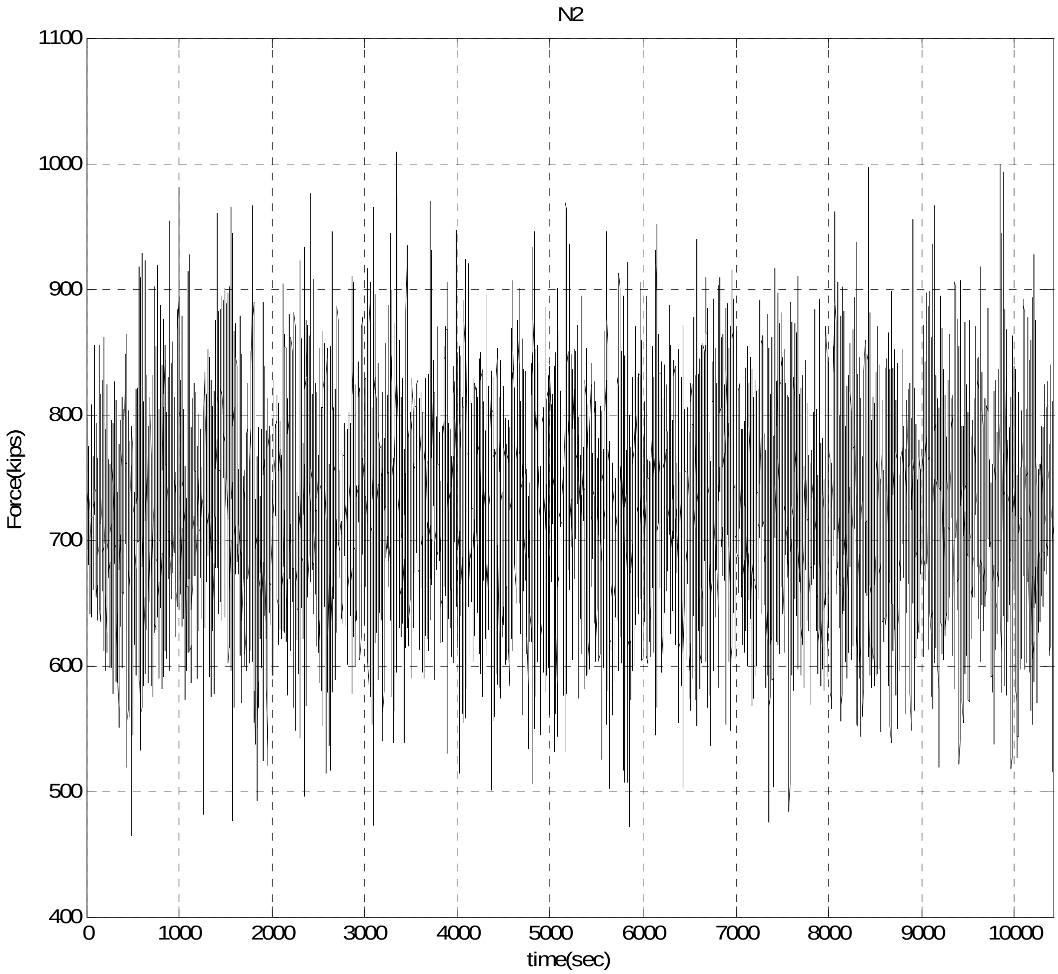
Figure A-23. Reaction Forces at Substructure Footing Point (Positive sign means upward and negative downward direction in the normal reaction force) for 100 Year Hurricane Condition



(a) Shear Reaction Force acted by the Connection point



(b) Figure Normal Reaction Force at Footing #1 and #4 (Refer to Figure 5)



(c) Normal Reaction Force at Footing #2 and #3 (Refer to Figure 5)

Figure A-24. Reaction Forces at Substructure Footing Point (Positive sign means upward and negative downward direction in the normal reaction force) for 1000 Year Hurricane Condition

11.0 APPENDIX B: 135 DEGREE CASE

The 135 degree case is considered by approximating the motions and the forces from the 180 degree results.

First, the sway motions are assume to be the same as those of the 180 degree case but in the opposite direction. The heave, roll and yaw motions are assumed to be the same as those of the pitch motion of 180 degree case. The wind forces in y-direction is in the opposite direction with the magnitude the same as those of 180 degree case. As the wave, wind and current are from foot #2 to foot #4 in 135 degree case, the foot #2 is to have more tension, while foot #4 has more compression force than the others.

- The horizontal slip at substructure footings may occur at the friction coefficient of 0.1 and the pretension of 75 kips for both 100 year and 1000 year hurricane events.

- The maximum tension is found at the footing #2 and the other footings only experience compression.

- The tensile break may occur at the upper derrick footing for 100 year and 1000 year hurricane conditions, when the pretension is 225 kips.

- The tensile break may occur at the substructure footing for 1000 year hurricane condition, when the bolt pretension is 225 kips.

Table B-1. Reaction Forces at the Upper Derrick Footings (10 Year Hurricane)

	Fx	Fy	N1	N2	N3	N4
Max	32.88	6.23	140.22	131.89	140.22	365.41
Min	-6.22	-32.86	134.21	-88.52	134.21	141.38
Mean	11.81	-11.80	137.54	33.57	137.46	241.44

Table B-2. Reaction Forces at the Substructure Footings (10 Year Hurricane)

	Fx	Fy	N1	N2	N3	N4
Max	69.77	42.80	602.62	587.89	528.38	890.85
Min	-42.79	-69.76	491.15	141.17	428.69	430.65
Mean	13.81	-13.80	543.23	379.59	481.79	645.43

Table B-3. Reaction Forces at the Upper Derrick Footings (100 Year Hurricane)

	Fx	Fy	N1	N2	N3	N4
Max	58.87	9.99	143.15	91.19	142.94	558.08
Min	-9.97	-58.83	132.47	-284.51	132.33	181.56
Mean	25.78	-25.76	137.60	-89.31	137.38	364.30

Table B-4. Reaction Forces at the Substructure Footings (100 Year Hurricane)

	Fx	Fy	N1	N2	N3	N4
Max	130.95	78.54	676.90	620.36	538.44	1197.44
Min	-79.70	-129.76	478.03	-156.46	362.15	388.91
Mean	31.27	-30.12	579.55	222.39	445.39	802.55

Table B-5. Reaction Forces at the Upper Derrick Footings (1000 Year Hurricane)

	Fx	Fy	N1	N2	N3	N4
Max	69.39	6.38	144.36	92.97	144.09	658.19
Min	-6.36	-69.33	131.77	-384.87	131.39	181.23
Mean	30.17	-30.13	137.77	-127.65	137.46	402.88

Table B-6. Reaction Forces at the Substructure Footings (1000 Year Hurricane)

	Fx	Fy	N1	N2	N3	N4
Max	147.48	90.44	703.02	588.38	528.77	1311.09
Min	-90.40	-147.44	488.12	-271.79	335.19	433.63
Mean	35.28	-35.23	591.38	173.68	434.44	852.15

Table B-7. Shear and Slip Safety Factor of the Upper Derrick Footing for 10 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension (kips)	Fx (kips) SHEAR	Fy(kips) SLIP	Bolt Shear Fact. of Safety	Bolt Slip 0.1	Fact. Of 0.3	Safety 0.5
137.3	32.882	32.862	24.879	3.761	11.283	18.804
75	32.882	32.862	24.879	2.244	6.733	11.221
150	32.882	32.862	24.879	4.070	12.210	20.350
225	32.882	32.862	24.879	5.896	17.687	29.479

Table B-8. Shear and Slip Safety Factor of the Substructure Footing for 10 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension	Fx (kips)	Fy(kips)	Bolt Shear Fact.	Bolt Slip	Fact. Of	Safety
(kips)	SLIP	SHEAR	of Safety	0.1	0.3	0.5
137.3	69.774	42.802	19.113	2.309	6.926	11.544
75	69.774	42.802	19.113	1.594	4.783	7.972
150	69.774	42.802	19.113	2.454	7.363	12.272
225	69.774	42.802	19.113	3.314	9.943	16.571

Table B-9. Shear and Slip Safety Factor of the Upper Derrick and the Substructure Footing for 10 year Hurricane Load Condition (Evaluated for 4 different pretension condition)

	Fz	T	Torque(lb-ft)	4576.7	2500	5000	7500
	(kips)	(kips)	T0(in kips) =	137.3	75	150	225
Upper Der	-88.522	-11.065	Safety Factors	-9.950	-15.580	-8.802	-2.024
Substruct	141.173	17.647		6.239	9.770	5.519	1.269

- The positive indicates the compression and the negative sign means the tensile force

Table B-10. Shear and Slip Safety Factor of the Upper Derrick Footing for 100 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension	Fx (kips)	Fy(kips)	Bolt Shear Fact.	Bolt Slip	Fact. Of	Safety
(kips)	SHEAR	SLIP	of Safety	0.1	0.3	0.5
137.3	58.867	58.830	13.897	2.101	6.302	10.504
75	58.867	58.830	13.897	1.254	3.761	6.268
150	58.867	58.830	13.897	2.273	6.820	11.367
225	58.867	58.830	13.897	3.293	9.880	16.467

Table B-11. Shear and Slip Safety Factor of the Substructure Footing for 100 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension	Fx (kips)	Fy(kips)	Bolt Shear Fact.	Bolt Slip	Fact. Of	Safety
(kips)	SLIP	SHEAR	of Safety	0.1	0.3	0.5
137.3	130.950	129.757	6.305	1.230	3.691	6.151
75	130.950	129.757	6.305	0.850	2.549	4.248
150	130.950	129.757	6.305	1.308	3.923	6.539
225	130.950	129.757	6.305	1.766	5.298	8.830

Table B-12. Shear and Slip Safety Factor of the Upper Derrick and the Substructure Footing for 100 year Hurricane Load Condition (Evaluated for 4 different pretension condition)

	Fz	T	Torque(lb-ft)	4576.7	2500	5000	7500
	(kips)	(kips)	T0(in kips) =	137.3	75	150	225
Upper Der	-284.510	-35.564	Safety Factors	-3.096	-4.848	-2.739	-0.630
Substruct	-156.461	-19.558		-5.629	-8.815	-4.980	-1.145

- The positive indicates the compression and the negative sign means the tensile force

Table B-13. Shear and Slip Safety Factor of the Upper Derrick Footing for 1000 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension (kips)	Fx (kips) SHEAR	Fy(kips) SLIP	Bolt Shear Fact. of Safety	Bolt Slip 0.1	Fact. Of 0.3	Safety 0.5
137.3	69.390	69.330	11.789	1.783	5.348	8.913
75	69.390	69.330	11.789	1.064	3.191	5.319
150	69.390	69.330	11.789	1.929	5.788	9.646
225	69.390	69.330	11.789	2.795	8.384	13.973

Table B-14 . Shear and Slip Safety Factor of the Substructure Footing for 1000 year Hurricane Load Condition (Evaluated for 4 different pretension condition and 3 friction coeff.)

Pretension (kips)	Fx (kips) SLIP	Fy(kips) SHEAR	Bolt Shear Fact. of Safety	Bolt Slip 0.1	Fact. Of 0.3	Safety 0.5
137.3	147.484	147.443	5.548	1.092	3.277	5.461
75	147.484	147.443	5.548	0.754	2.263	3.772
150	147.484	147.443	5.548	1.161	3.483	5.806
225	147.484	147.443	5.548	1.568	4.704	7.840

Table B-15. Shear and Slip Safety Factor of the Upper Derrick and the Substructure Footing for 1000 year Hurricane Load Condition (Evaluated for 4 different pretension condition)

	Fz	T	Torque(lb-ft)	4576.7	2500	5000	7500
	(kips)	(kips)	T0(in kips) =	137.3	75	150	225
Upper Der	-384.872	-48.109	Safety Factors	-2.289	-3.584	-2.025	-0.466
Substruct	-271.793	-33.974		-3.241	-5.074	-2.867	-0.659

- The positive indicates the compression and the negative sign means the tensile force

12.0 APPENDIX C: SPRING CONNECTION MODEL

Assuming that the body rotational motion is small enough, the point at the body is calculated by the following equation.

$$\{\underline{x}\} = \{\underline{X}\} + \left[\underline{p}^{\times}\right]\{\underline{\theta}\} \tag{C-1}$$

where

$\{\underline{x}\}$ =column vector of a point at the body at the inertia frame,

$\{\underline{X}\}$ =column vector of the linear motion of the body reference point,

$\left[\underline{p}^{\times}\right]$ =cross product matrix of the local coordinate of the point,

$\{\underline{\theta}\}$ =rotational motion of the body in the inertia frame.

The displacement due to the forces in section 6 is obtained by the derivative of equation (C-1)

$$\{\Delta\underline{x}\} = \{\Delta\underline{X}\} + \left[\underline{p}^{\times}\right]\{\Delta\underline{\theta}\} \tag{C-2}$$

The reaction force at the spring is calculated by the spring constant

$$\{Fs\} = -[k]\{\Delta\underline{x}\} = -[k]\{\Delta\underline{X}\} - [k]\left[\underline{p}^{\times}\right]\{\Delta\underline{\theta}\} \tag{C-3}$$

The moment due to the spring reaction force is derived by:

$$\{Ns\} = \left[\underline{p}^{\times}\right]\{Fs\} = -\left[\underline{p}^{\times}\right][k]\{\Delta\underline{X}\} - \left[\underline{p}^{\times}\right][k]\left[\underline{p}^{\times}\right]\{\Delta\underline{\theta}\} \tag{C-4}$$

Resultantly, the global stiffness matrix due to the spring is

$$[K] = \begin{bmatrix} [k] & [k]\left[\underline{p}^{\times}\right] \\ \left[\underline{p}^{\times}\right][k] & \left[\underline{p}^{\times}\right][k]\left[\underline{p}^{\times}\right] \end{bmatrix} \tag{C-5}$$

The body motion can be obtained through the static equilibrium betwen the body forces and the spring force as:

$$\begin{Bmatrix} \Delta\underline{X} \\ \Delta\underline{\theta} \end{Bmatrix} = -[K]^{-1}\begin{Bmatrix} \underline{F} \\ \underline{M} \end{Bmatrix} \tag{C-6}$$

where $\underline{F}$, $\underline{M}$ are the total forces and moments obtained in section 6.

After then, the spring reaction forces are calculated by equation (C-3).

13.0 APPENDIX D: COMPARISON OF HORIZONTAL ACCELERATION BETWEEN EXACT SIMULATION METHOD AND API FORMULA

$$m_0 = \sigma \qquad (1)$$

Where m_0 is the zeroth moment of the motion spectrum and σ is the standard deviation of the time dependent motion.

$$x_{1/1000} = 3.72 m_0 \qquad (2)$$

Assuming the maximum values in 3 hour is $1/1000^{th}$ probability, the maximum in 3 hour can be approximated by equation (2)

The acceleration can be obtained by

$$a_{x\max} = \omega^2 x_{1/1000} \qquad (3)$$

We have wave frequency and low frequency motion which are governed by the incident wave and the wind, respectively. Thus, the peak period of the wave frequency motion is at wave peak period, and the low frequency motion follows the wind spectrum. The low frequency motion peak period is assumed as natural period of surge motion (183.5 sec).

The resultant maximum acceleration is summation of the accelerations from wave frequency and the low frequency motion.

		Wave Frequency			Low Frequency			Total
		RMS	Tp(sec)	$a_{x\max}$ /g	RMS	Tnat(sec)	$a_{x\max}$ /g	$a_{x\max}$ /g
Derrick CG	10yr	2.915	11.900	0.094	13.483	183.500	0.002	0.096
	100yr	8.379	14.000	0.195	15.428	183.500	0.002	0.197
	1000yr	12.484	15.600	0.234	18.463	183.500	0.003	0.237
Substructure CG	10yr	2.896	11.900	0.093	13.464	183.500	0.002	0.095
	100yr	8.349	14.000	0.194	15.399	183.500	0.002	0.197
	1000yr	12.441	15.600	0.233	18.419	183.500	0.002	0.236

14.0 APPENDIX E: COMPARISON BETWEEN MHKIM AND TECHNIP FOR TLP MAXIMUM BOLT TENSION

Table E1. Maximum bolt tension on upper derrick (0-degree heading unit: kips, negative sign=tension on bolt)

	MHKIM	TECHNIP
10-year	15	48
100-year	-93	-42
1000-yr	-150	-80

Table E2. Maximum bolt tension on upper derrick (45-degree heading unit: kips, negative sign=tension on bolt)

	MHKIM	TECHNIP
10-year	-88	-38
100-year	-284	-216
1000-yr	-384	-290

Table E3. Maximum bolt tension on sub-structure footing (0-degree heading unit: kips, negative sign=tension on bolt)

	MHKIM	TECHNIP
10-year	275	273
100-year	101	91
1000-yr	30	-8

Table E4. Maximum bolt tension on sub-structure footing (45-degree heading unit: kips, negative sign=tension on bolt)

	MHKIM	TECHNIP
10-year	141	146
100-year	-156	-132
1000-yr	-271	-283

MHKIM: Direct time domain simulation including all the dynamic forces based on the time-domain motion and acceleration time series results

Technip: Select maximum combined loading from wind force/acceleration force time series and then run statics program STRUCAD.