SIMULATED FATIGUE DAMAGE INDEX ON MOORING LINES OF A GULF OF MEXICO TRUSS SPAR DETERMINED FROM RECORDED FIELD DATA

A Thesis

by

ADAM FULLER KIECKE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Ocean Engineering

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Approved by:

Chair of Committee,	Jun Zhang
Committee Members,	Richard Mercier
	Steven DiMarco
Head of Department,	John Niedzwecki

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ABSTRACT

Simulated Fatigue Damage Index on Mooring Lines of a Gulf of Mexico Truss Spar Determined from Recorded Field Data. (May 2012)

Adam Fuller Kiecke, B.A., Texas A&M University

Chair of Advisory Committee: Dr. Jun Zhang

The Constitution Truss Spar, operated by Anadarko Petroleum Corporation (APC), is located in Green Canyon Block 679 and 680 in a water depth of 1,500 m. It was installed in October of 2006 and has since weathered multiple hurricanes and other storms. The platform is equipped with an Environmental Platform Response Monitoring System (EPRMS) which records real-time motions, environmental parameters and loads. These measurements were used to hind-cast the platform mooring tensions and estimate fatigue damage index accrued over the short life (install to start of study, July 2010) of the platform. The study found that extreme events such as Hurricane Ike (~100 yr storm) accounted for considerably higher fatigue damage index than the total caused by other small storms likely to occur in the 20 year service life of the vessel. It is therefore a recommendation of this study that a design criterion for fatigue damage accrued during extreme events such as 100 yr hurricanes be considered in the design of station keeping systems in a similar manner to the guidelines found in API RP 2T (2010) for design of tension leg platforms.

DEDICATION

To my wife, for all the love and support I received through this journey.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Zhang, my committee members, Dr. Mercier and Dr. DiMarco and Dr. Randall, for their guidance and support throughout the course of this research. I would also like to thank Dr. Paul Jacob, Americas representative of Orcina Ltd., for his continual support in OrcaFlex and consultation on the study.

Thanks also to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to Anadarko Petroleum Company for providing the data, and especially Ms. Jenifer Tule of Anadarko who always provided any additional data or guidance needed.

Finally, thanks to my mother and father for their encouragement and to my wife for her patience and love.

NOMENCLATURE

DoF	Degrees of Freedom
APC	Anadarko Petroleum Company
API	American Petroleum Institute
BMT	British Maritime Technology
EPRMS	Environment and Platform Response Monitoring System
FDI	Fatigue Damage Index
GOM	Gulf of Mexico
GPS	Global Positioning System
IMMS	Integrated Marine Monitoring System
RP	Recommended Practice
SWL	Still Water Level
TLP	Tension Leg Platform
VIM	Vortex Induced Motion
WAFO	Wave Analysis for Fatigue and Oceanography

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1. INTRODUCTION

The Constitution Truss Spar (the platform) was installed in the Gulf of Mexico in October of 2006 and is located at 90 miles south of Morgan City, LA (90°58' 4.8" West Longitude and 27°17'31.9" North Latitude). It has since weathered multiple hurricanes and other storms. After platform installation, British Maritime Technology (BMT) installed an Environmental Platform Response Monitoring System (EPRMS). The EPRMS is an integrated system collecting a myriad of data that include the motions of the spar in six-degrees of freedom, the tensions in its mooring lines and top-tensioned risers, and wave height, current and wind in the vicinity of the spar. With the permission from Anadarko Petroleum Company (APC), these data were made available to the Ocean Engineering Program of the Civil Engineering Department at Texas A&M University.

These data provide a unique opportunity to analyze storms of different magnitudes. The availability of environment, motions and loads during specific and violent storms is a great opportunity to learn about the platform response as if it were a full scale model. It is interesting to examine how much fatigue damage the mooring lines may have accumulated during these specific storms, how the fatigue damage accrued by one storm compares to another and how the number of occurrences of such storms compares to the design criteria for the platform.

This thesis follows the style of Ocean Engineering.

Currently, the guidelines for the design of station keeping systems for offshore platforms set forth by the American Petroleum Institute (API RP 2SK, 2005) have design checks for the 100 yr loop current, the typical wave scatter diagram and 20 yrs of Vortex Induced Motion (VIM) events. There is no explicit provision for fatigue damage associated with the major wind/wave storm events that induce large tension ranges at low (near storm wave frequencies, 0.1 - 0.25 Hz) cyclic frequencies.

However, API RP 2T (2010) (regarding the TLP platform tendons) does give guidelines for such events and states that "Components that are susceptible to low-cycle/high-stress fatigue should be analyzed to assess damage accumulation during rare extreme events that may be of extended duration, such as a 48-hour rise and fall of the 100 yr storm. These discrete events may be found to induce more fatigue damage accumulation over the service life of the platform than is captured by applying the probabilistic wave scatter diagram for these low probability events." This Recommended Practice (RP) further explains that these low-cycle/high-stress events should be considered in the design stage and it is crucial to determine which components of the platform are prone to "excessive" damage in large sea-states. API RP 2T (2010) suggests that the 100 yr storm robustness check should be an un-factored damage accumulation and equal to or less than 0.01. A damage accumulation of 0.01 means that the summation of the damage associated with each tension range of the storm cannot be greater than 1% of the total fatigue life of the tendon. An unfactored load means that no probability or safety factors have been assigned to the loads. As this is meant to be a robustness check, the accumulated damage from the low-cycle/high-stress event is not meant to be added to the scatter diagram fatigue analysis or multiplied by any factors of safety. It is recognized that this API RP 2T (2010) criterion is for the tendons and other appurtenances associated with TLPs, so the above discussion will be treated as an interesting broad comparison and not a like-for-like comparison with the spar. Also, unlike spars, TLPs are not unconditionally stable platforms so the design of TLP tendons would naturally be more stringent than the design of spar mooring lines.

The objective of this study is to analyze the possible mooring line fatigue damage induced from actual extreme storms and compare the fatigue damage with other lesser storms as well as the typical 20 yr fatigue life. The results of this comparison will shed light on the RP 2SK (2005) treatment of extreme wind/wave events and determine if the guidelines should have similar provisions as the recommended practice of API RP 2T (2010) in regards to that subject.

2. BACKGROUND

2.1 Constitution Truss Spar

The Constitution Truss Spar Platform has a diameter of 30 m, a freeboard of 15.2 m, and the total hull length is 169 m. The hard tank and soft tank are connected by a truss structure which incorporates 3 heave plates. The platform properties can be seen below in Table 1 for dimensions, Figure 1 for elevation view and Figure 2 for plan view. Platform North and True North are coincident. The mooring system is a 3 x 3 geometry comprised of ~100m of platform chain, 2,000 m of wire rope and 60m of chain to the seabed where the lines are anchored below the mud line to their suction caissons (see Table 2 and Figure 3.) One mooring triplet is directed towards the east at 98^o, and the other two groups are directed towards the northwest at 329^o and southwest 211^o (see Figure 2). Table 3 shows the drag coefficients for the different line segments. The platform mooring was designed for a fatigue life of 20 years with a safety factor of 10. It should be noted that while mooring properties can be modeled exactly by design documents, as-built anchor locations and line lengths can be slightly deviated from design documents. Actual pile locations can be differ from design positions by tens of meters and actual line lengths can differ from design lengths by meters.

Table 1 Constitution Spar Dimensions

Mean Water Depth	1,524*m*
Draft	154*m*
Hard Tank Diameter	30*m*
Length Overall	169*m*
Hard Tank Length	74*m*
Soft Tank Length	14*m*
Truss Length	81*m*
Truss Spacing	20*m*
Centerwell Dimensions	12.8 x 12.8*m*
Fairlead Location from Keel	98*m*

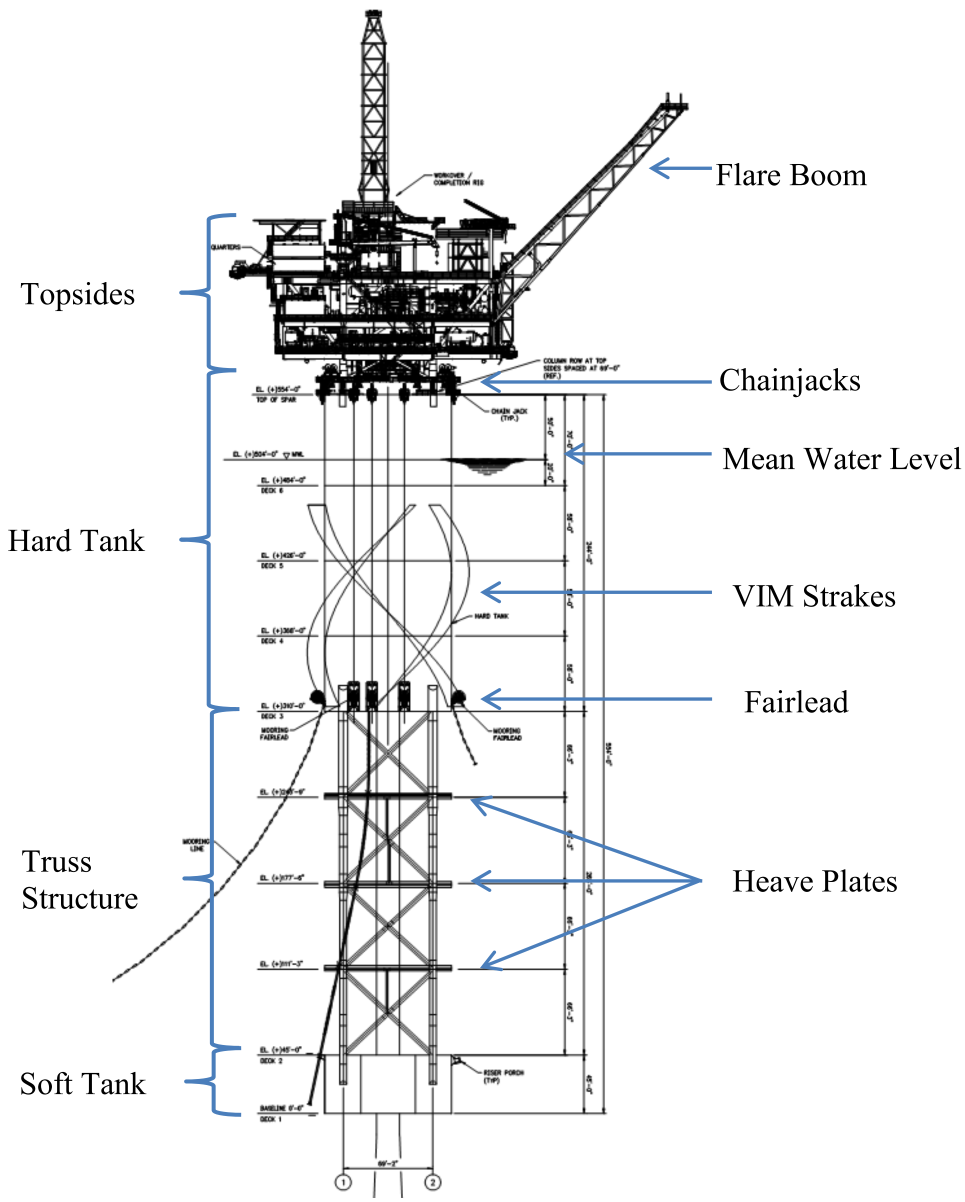

Figure 1 Constitution Spar Elevation

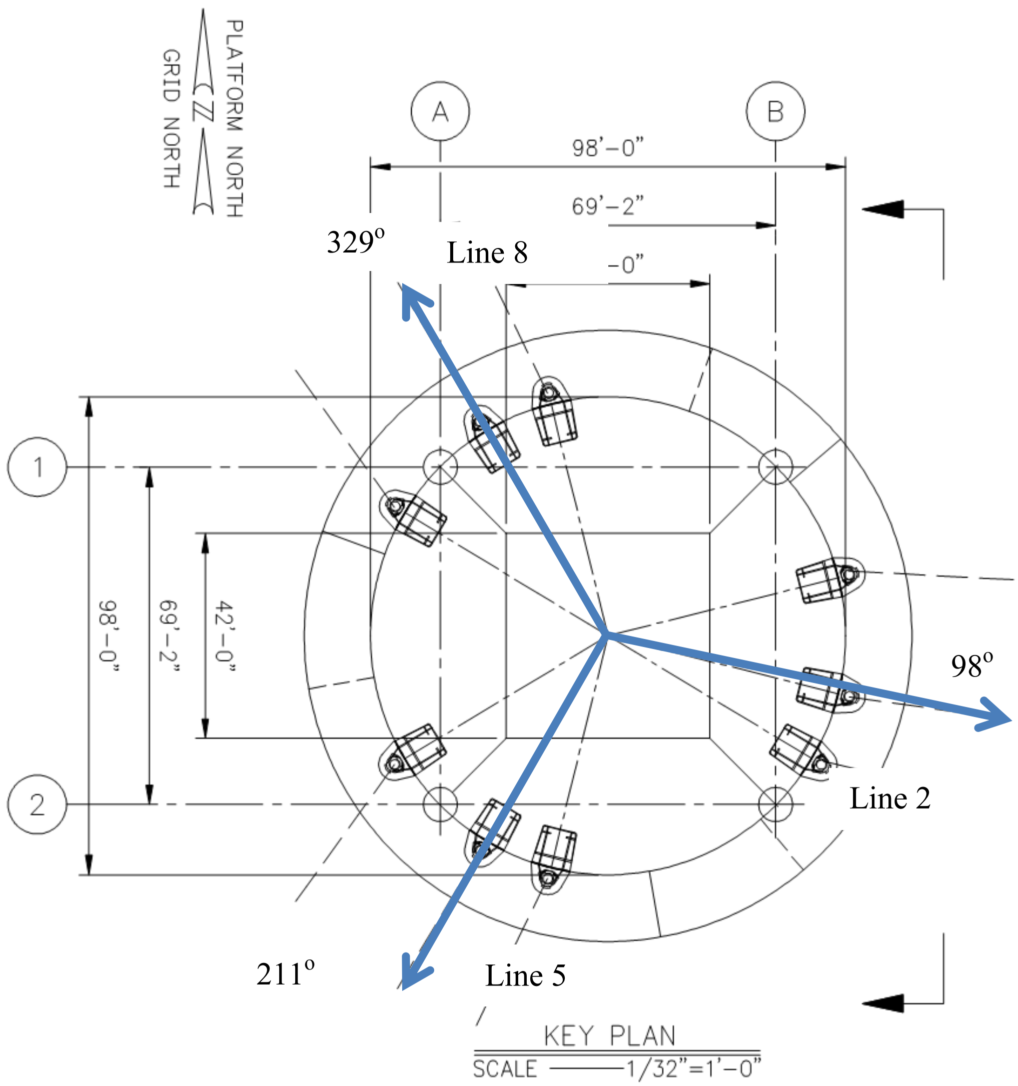

Figure 2 Constitution Truss Spar Plan View

Table 2 Line Properties

	Platform Chain	Spiral Strand	Pile Chain	Units
LineType	R4 Studless	Steel Jacketed Wire	R4 Studless	
Steel Diameter	0.142	0.127	0.142	m
Jacket Thickness	-	0.011	-	m
Weight in Air	3.953	0.824	3.953	kN/m
Weight in Water	3.443	0.647	3.443	kN/m
Nominal Breaking Strength	1,839	1,603	1,839	te
Design Breaking Strength (after 12 mm corrosion allowance)	1,587	-	1,587	te
EA	152,957	151,020	152,957	te

Table 3 Drag Coefficients

Line Type	Drag Coefficient
Transverse Chain	2.4
Transverse Wire	1.2
Tangential Chain	0.16
Tangential Wire	0.16

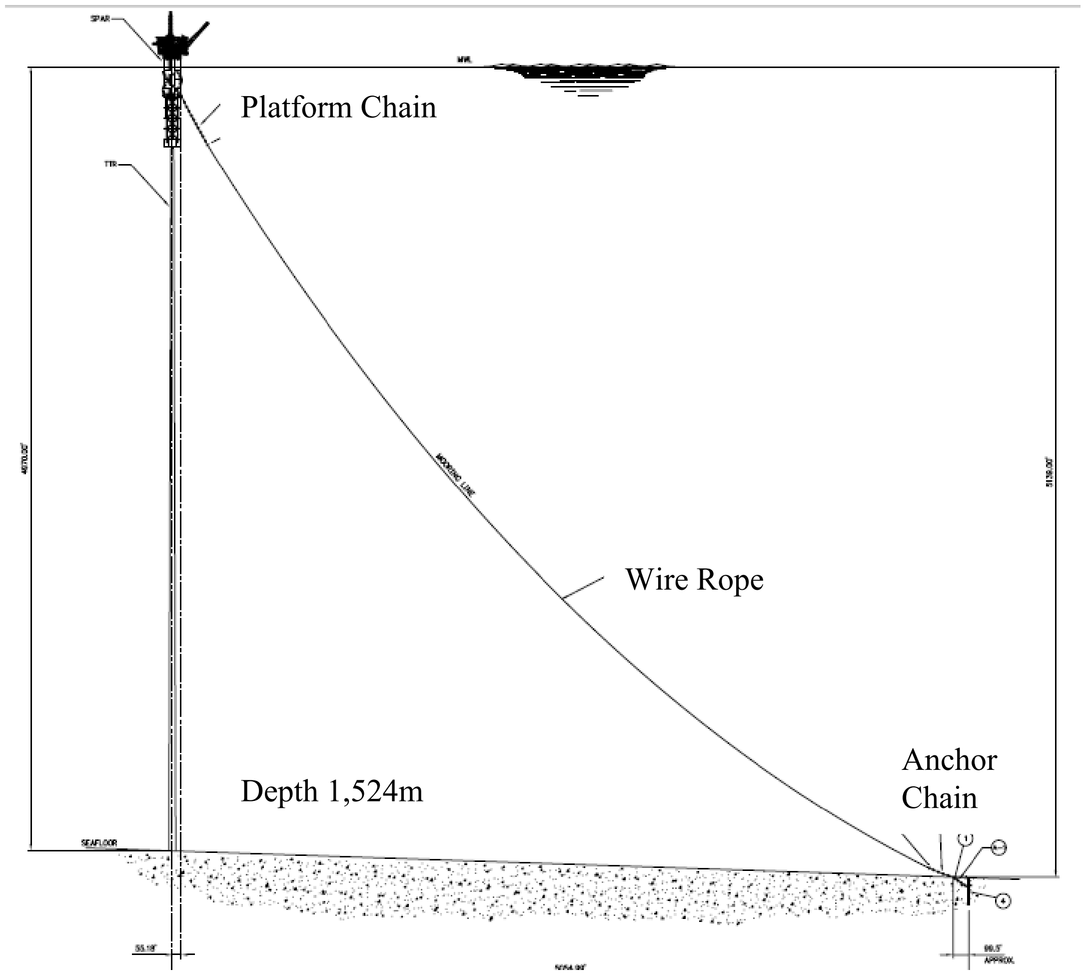

Figure 3 Constitution Truss Spar Mooring Profile

2.2 Field Data

The APC EPRMS collects data at a 4Hz sampling rate, and records over 130 channels of raw environment and platform response data. The data are available to us from June 2007 to July 2010 and hereafter this will be referred to as The Period. A detailed description of this type of monitoring system and its advantages can be found in Irani, et al. (2007) and Prislin, et al. (2005), respectively. All data is appropriately filtered, post-processed, analyzed and quality controlled before release by BMT. The EPRMS data used for this study are:

- 6 Degree of Freedom (6DoF) motions of the spar
- Hourly significant wave height
- Hourly average wind corrected to 10m above SWL
- Surface and deep current (2-point profile) magnitude and direction
- Tensions at the chain jack used for comparison to hind-casted tension
- Mooring line payout was used for general knowledge of when the platform chain was altered

The platform motion and position are measured using a 6DoF and a dual position GPS (gives both location and heading). Motion data used in this study was a combination of low-pass filtered GPS and high-pass filtered 6 DoF data. Since GPS provides accurate motion of the spar at low frequency and accelerometers measure the motion (after double integration) accurately at high frequency range, the combination of these two measurements provides proven and accurate total motion in all six degrees of freedom; surge, sway, heave, roll, pitch and yaw. These filtered motions were extracted to text files by hour of interest and loaded into OrcaFlex for mooring tension simulations. OrcaFlex is the finite element software used to simulate the mooring tensions; it is described in greater detail in Section 2.5.

The airgap (distance between the sea surface elevation and the bottom of the topsides steel) of the platform is measured by a microwave radar attached to the bottom steel of the topsides (platform production facilities located on top of the spar). Post-processing by BMT analysts inverts the measurements, removes the mean and calculates the significant wave height for the hour record. The wave data were not used in the simulations, but similar to the wind, it was used to classify metocean events.

The wind on the platform is recorded by an anemometer on the platform crane. It is understood that the crane and platform heading change with time. However, the final wind direction is derived based on anemometer heading, platform heading and a crane encoder (a pinion gear that measures the rotation of the crane from a specific point). Studies and validations have been performed by BMT to validate the wind speed and direction agree well with nearby platforms and NOAA buoys. The wind was not used in computing tensions in mooring lines as the recorded platform motions captured the effects of the wind on the platform.

The current near the platform is measured at the surface and over a certain depth. The hourly surface current average speed and direction (at 15 m) and the submerged speed and direction at (150 m) are given in the data and used in the computation of the tension. The average hourly current speed and direction are used in the calculation of the average mooring line tension. The surface current value is used as a constant current from the mean water level to the 15m depth where the horizontal current is given. The profile then tapers down to the submerged current at 150m. The current profile tapers further from the submerged current speed at 500m/s to 0 m/s at the 1000m depth.

The mooring tensions were measured at the chain jack and recorded by the EPRMS. For comparison with the simulated fairlead tension, the tensions recorded at the chain jack were corrected by subtracting the dry (66.2 kN above the calm water level) and wet weights (188.4 kN below the calm water level) to get the approximate "measured" tension at the fairlead. Also, it should be noted that Coulomb friction at the fairlead wheel shaft affects the tension right after the fairlead, hence, the tension cannot be measured accurately at the chainjack. Since we had no accurate knowledge of the friction coefficient at the fairlead wheel sheave, no efforts were made to correct the effect of the Coulomb friction on the measured tension.

2.3 Chain Jack Tensions

The mooring line tensions are measured by a load cell installed near the chain-jack. This tension reading is expected to record less than the tension actually experienced at the fairlead due to Coulomb friction between the fairlead roller bearing and the shaft (Tahar et al., 2005). At the fairlead bearing, there is tension above the fairlead ($T_{inboard}$) with a resultant direction parallel to the platform hull and there is a tension below the bearing in the direction of the mooring line towards the anchor ($T_{outboard}$). Figure 4 shows a diagram of these forces on the fairlead bearing. These two tensions are not equal due to the friction in the bearing. The dynamic tensions in the mooring line below the fairlead bearing must overcome the friction forces in the bearing F_r for the dynamic tensions in the mooring line to be recorded at the chain jack.

$$\text{Tension at chain jack} = T_{outboard} - F_{r*}R_b/R + PC \quad (1)$$

where:

PC = Weight of platform chain (wet and dry)

R_b = Roller bearing radius

R = Radius of the fairlead wheel

The friction in the bearing is a function of the fairlead bearing radius, the normal force to the bearing and the roller bearing coefficient of friction. The coefficient of friction cannot be accurately determined because it depends on the material and the condition of the fairlead system installed in the harsh ocean environment.

$$Fr = N\mu \qquad (2)$$

where:

N = Normal force on the bearing

μ = Coefficient of bearing friction

Although it is possible to know the coefficient at installation, it is difficult to know the coefficient value in service in the harsh offshore environment (Figure 5) as it may change greatly with time. Furthermore, the azimuth angle of the mooring line as it leaves the fairlead will change as the platform position changes, which will also contribute to further unknowns in the system. If the exit angle of the mooring line is not in line with the centerline of the fairlead, then the force needed to overcome the bearing friction would be even greater.

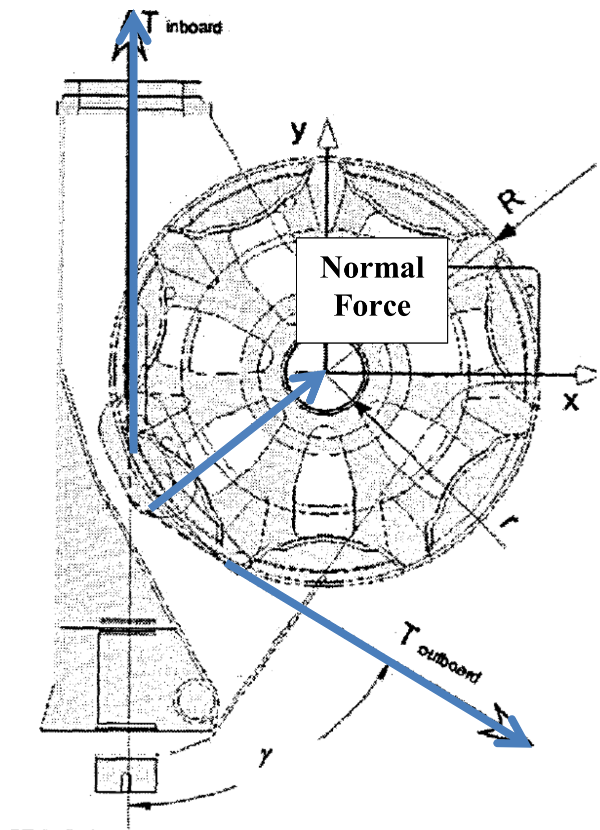

Figure 4: Diagram Showing Loads on Fairlead Bearing

Figure 5: Fairlead Marine Growth After Service Time in the Gulf of Mexico

Tahar et al. (2005) compared measured fairlead mooring tensions and motion measurements taken during Hurricane Isidore with mooring tensions simulated from both analytical predictions of the storm and the recorded motion at the fairlead. Attention focused on the Coulomb friction that occurs between the platform chain and fairlead bearing and the dynamic tension of the mooring lines. Both Tahar et al. (2005) and this study show that neglecting the effects of fairlead friction, as is current offshore practice, may result in under estimation of the tension at the chainjack. Tension measurements can be made more reliable if they were taken by a load cell at some point beneath the fairlead, or even by a load cell in the fairlead itself. Edwards (2003) pointed out that while the measurement in the chain jack is not the most reliable or accurate, it is extremely challenging technically and economically to put mooring tension sensors in such extreme and corrosive environment. Tahar et. al (2005) shows the formulation for the friction correction using the following inputs:

- Dynamic friction coefficient,
- Guide roller radius,
- Bearing radius,
- Normal force at bearing contact,
- Departure angle of mooring line from vertical,
- Mooring tension inboard fairlead,
- Mooring tension outboard fairlead,
- Moment with respect to origin (origin is about the roller bearing),
- Force in x-direction (directly out from fairlead, along mooring line).

As mentioned previously it is difficult to determine the static and dynamic coefficients, because the coefficient of friction is affected both by the corrosion of the bearing and the angle of departure of the mooring line. Difficulties were also great in matching the analytical mooring model with the as-built in-situ mooring configuration. Tahar et al. (2005) found that the nominal position of the analytical model based on ship logs was nearly 27 m from the nominal position calculated from as-built information, and expected that this discrepancy would affect their final tension comparison.

At the conclusion of the study, the predicted dynamic tensions for the lines on the most loaded side of the platform were in general greater than the corresponding tension measured at the chainjack (after subtracting the wet and dry weights between the fairlead and the chainjack), but in general the predictions were within 10% of the measured. It should be noted that in the study of Tahar et al. (2005), comparison between modeled tensions and measured tensions was only made after the Coulomb friction was accounted for.

In Theckumpurath et al. (2006), the Horn Mountain Spar was again used in an investigation of the platform response during Hurricane Isidore. The platform motions were simulated using the recorded environment by the Integrated Marine Monitoring System (IMMS). The simulations were performed with a program known as COUPLE and comparison between the recorded motion data and the simulated motions yielded satisfactory agreement. The comparison of the simulated tension showed that the measured maximum tension in the least loaded mooring lines usually agreed well with the maximum simulated tension in the least loaded line. However, the predicted maximum tension for the most loaded line was greater than the measured maximum tension in the most loaded line. In general, the tension standard deviations for the most loaded lines were nearly 100% greater than the measured.

2.4 Metocean Criteria and Recorded Data

For this study, the original environmental design criteria are used for comparison to the actual experienced environment. It is understood that the criteria for this location have changed since installation per API guidelines. However, the interest of this study lies in the design process and the inclusion/exclusion of extreme fatigue events so the original design documents were useful for categorization of events that occurred over the study period. The environmental design criteria for wind, significant wave height and current associated with the different return period storms can be seen in Table 4.

Table 4 Environmental Design Criteria

Return Period (yr)	Type	Hs (m)	1Hr Wind @ 10m (m/s)	Surface Current (m/s)
1	Winter	4.3	14.9	0.2
10	Winter	5.1	18.4	0.2
50	Hurricane	9.8	37.1	0.9
100	Hurricane	12.0	41.3	1.2
1000	Hurricane	14.2	63.6	1.4

A survey of the Hs data was performed to quantify the number wave events that occurred over the period. The "events" were characterized by an established rise and fall of the 1-hour Hs as shown below in Figure 6. For instance in the first half of 2010, there was one event with a max Hs between 4 and 5 m and there were 2 events between 3.5m and 4m. These numbers can also be seen in the 2010 column in Table 5. In the three years of this data period, there occurred one 100 yr hurricane sea state in Hurricane Ike (~12.1m), two 10 yr winter storm seastates in a winter storm (~6.1m) and Hurricane Gustav (~6.1m, not occurring in winter but of equal wave height to a 10 yr winter storm) and eight storms of 1 yr winter storm Hs (see Table 5 and Figure 6). Table 5 shows the percentage of occurrence of each storm in terms of an Hs window. For instance, in 2008 there were 11 occurrences of events where the maximum Hs during that event was between 2.5m and 3.0m, and column 7 shows this, of all the events that registered between 1.5m and 12.1m, 19% were between 2.5m and 3.0m. Figure 7 shows a comparison of the hourly significant wave heights for three different storms that were simulated in this study. In the figure, the storm records are centered about their respective storm peak.

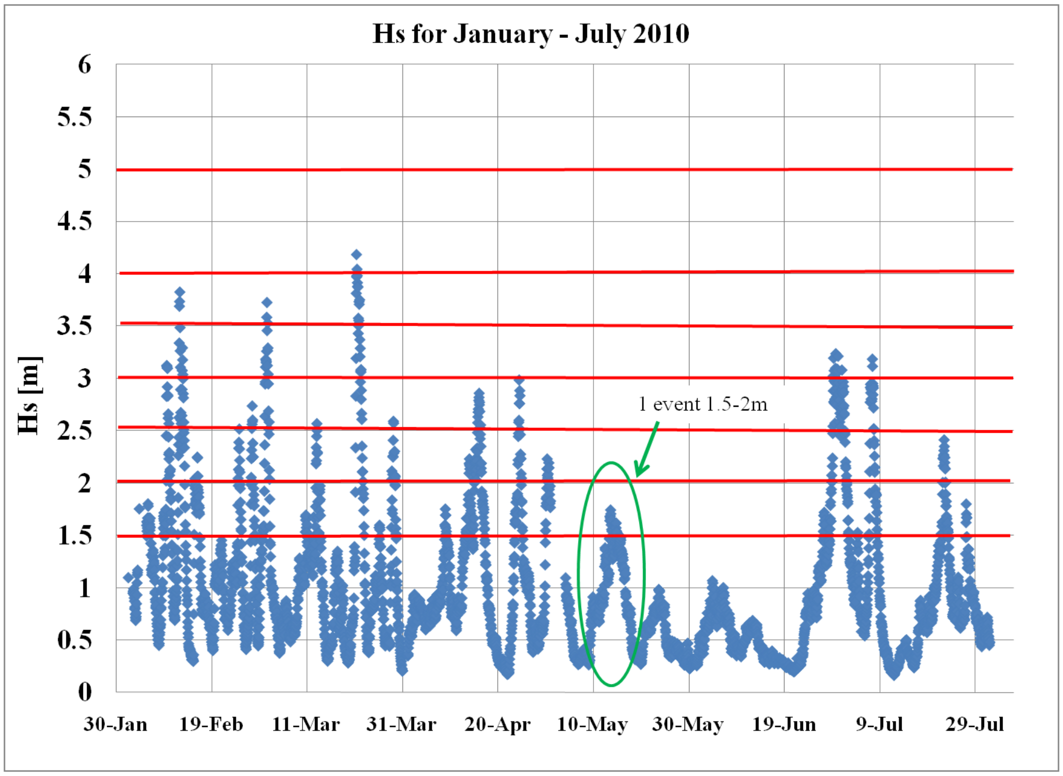

Figure 6 Hourly Hs from January to August 2010

Table 5 Tabulation of Hs Events for the Period

Hs (m)	2007	2008	2009	2010	Total	% of all events
12	-	1	-	-	1	1%
6	-	1	1	-	2	1%
4.0 to 5.0	-	6	1	1	8	6%
3.5 to 4.0	2	5	3	2	12	8%
3.0 to 3.5	1	2	5	3	11	8%
2.5 to 3.0	1	11	10	6	28	19%
2.0 to 2.5	2	9	13	3	27	19%
1.5 to 2.0	10	19	20	6	55	38%
Total	16	54	53	21	144	

Table 6 Occurrences of Specific Return Period Storms During the Period

Return Period (yr)	#
1	8
10	2
50	0
100	1
1000	0

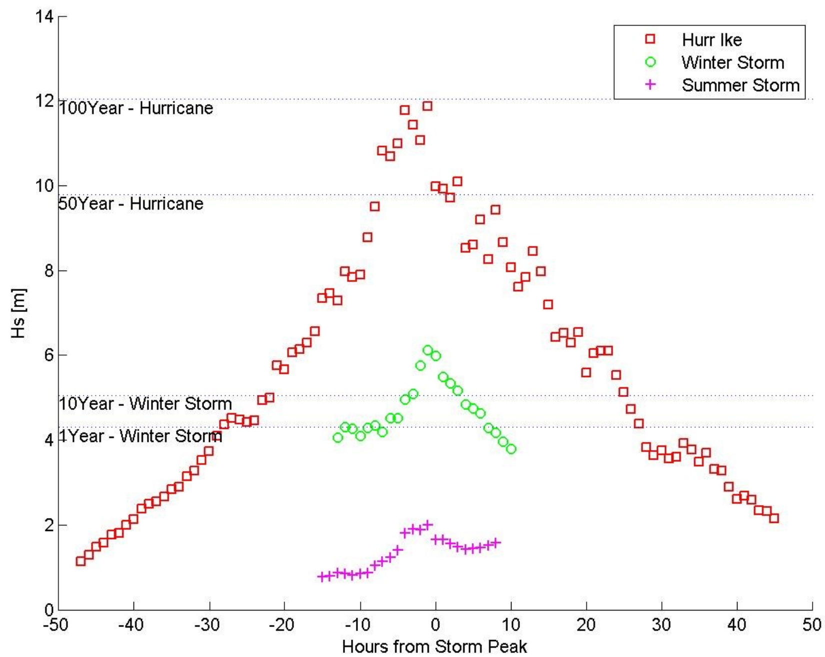

Figure 7 Significant Wave Height Comparison Between Storms for Study; 100yr and 50yr Hurricane and 10yr and 1yr Winter Storm Hs Values Shown for Comparison

The significant wave height was the primary criterion for determining the strength or category of extreme events. It is also interesting to determine how often wave heights occurred apart from specific events. Table 7 shows the tabulation of Hs in terms of hourly occurrence. The third column shows the number of hours that an Hs value was within the corresponding bin (column one), and column four shows the percentage of hours that Hs was within the corresponding bin during the study period. The fatigue damage index associated with a characteristic hour of the Hs bin was used to demonstrate a hypothetical platform damage life if the three years were assigned a loose representative of the distribution over the 20 year life of the platform.

Table 7 Hs Hours Within Specific Hs Bin and Percentage of Occurrence Over Study Period

Hs Bin [m]	Hs Bin [ft]	# of Hours	%
0.0-0.76	0.0-2.5	10503	46.0%
0.76-1.22	2.5-4.0	5881	25.8%
1.22-1.83	4.0-6.0	4154	18.2%
1.83-4.30	6.0-14.0	2146	9.5%
4.30-6.10	14.0-20.0	54	0.3%
>6.1	>20.0	35	0.2%
Total		22738	100%

2.5 OrcaFlex

OrcaFlex is a time domain finite element program developed and distributed by Orcina Ltd (Orcina, 2010). This program specializes in the analysis of risers, moorings, installations and tows and the program deals exceptionally well with catenary line shape calculations. Lines are modeled as mass elements connected by a stiffness element; attributes such as axial stiffness, torsional stiffness and modulus of elasticity are assigned to the element. OrcaFlex was used in this study for modeling the tension in the mooring line when the motions at the fairlead are given. In our simulations all necessary line inputs to define the characteristics of the mooring line were available as well as the 6 degree of freedom motions of the platform. OrcaFlex allowed all nine mooring line fairleads to be moved based on the trace of the platform Center of Gravity (CG) time series input.

Orcina (Orcina, 2010) has evolved scripting integration of their software with MATLAB (MathWorks, 2010) and Python. This study would not have been feasible if it were not for the MATLAB scripting techniques available with OrcaFlex. Hundreds of tension cases had to be run and re-run to reach the objective of this study.

Furthermore, OrcaFlex has an application specifically designed for the fatigue index calculation of mooring lines. The user defines the parameters as set forth in API RP 2SK (2005)for defining cycles to failure of a certain tension range. OrcaFlex fatigue damage index is calculated on each range in the simulation defined by basic rainflow cycle counting principles. The fatigue damage index in regards to mooring lines is the accumulation of fatigue damages per each individual storm induced tension ranges through a particular event. Fatigue damage and fatigue damage index are described later in Section 3.3.

2.6 Wave Analysis for Fatigue and Oceanography (WAFO)

WAFO is a MATLAB toolbox designed and compiled primarily by members of Lund University Sweden and Trondheim University, Norway. The software suite provides the user a collection of routines designed for “extreme value and crossing analysis… and are specially designed for analysis of wave characteristics… from sea measurements or load sequences. Second, the toolbox contains a number of procedures of the prime importance for mechanical engineers working in the areas of random loads as well as damage and fatigue analysis " (Brodtkorb, 2000). Specific to this study, a rainflow counting algorithm was used to retrieve the tension ranges from each tension time series so that we could manually check the fatigue calculations from Orcaflex (see Figure 8), and later perform fatigue calculations on all hourly tension simulations for each line during the events.

Rainflow counting is a standard procedure for counting cyclic loads whether they be measured in stress, strain or tensions. The basis of rainflow counting is the distinguishing of a load loop- a maximum and minimum load over a specified window or criteria. Within a load loop there will exist additional lower amplitude local load cycles that are determined by further criteria. Both the large amplitude range that defines the load loop and the smaller amplitude loads within a load loop are recorded by the rainflow counter. Traditionally, when all the load loops and subsequent loads have been identified, then all the different load ranges are placed in bins. Each bin would then have an associated fatigue damage associated with it. The calculation of fatigue is discussed further in Section 3.3.

The damage calculations in OrcaFlex from the hurricane tension simulations were 50% greater than what was calculated by WAFO. The WAFO routines were used for all fatigue calculations as fatigue damage post- processing in WAFO is a less cumbersome task than using OrcaFlex. It should be noted that the fatigue calculations using WAFO are less conservative than the OrcaFlex calculations would have been.

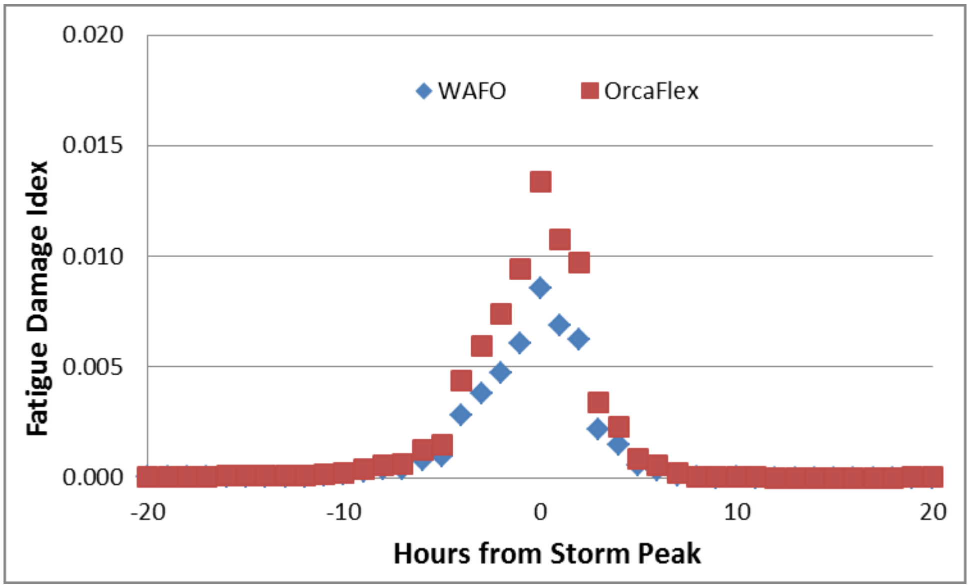

Figure 8 Comparison of Rainflow Algorithms For Hurricane Ike

3. METHODOLOGY

This study aims at estimating storm or a specific accrued fatigue damage of the platform mooring lines based upon a time series of tensions at the fairlead to gain knowledge of the magnitude of fatigue damage associated with actual storms experienced by the platform. Fatigue calculations and the hind-casting of platform response using field data are not new ideas. However, to our knowledge, the use of specific platform response to calculate fatigue damage index and moreover to compare the fatigue damage index accrued from one storm to another is unique. The methods used in this study relate to the three major components of the process.

1. Create a mooring model that minimizes the difference between measured and modeled mean tensions
2. Validate the tension calculations
3. Calculate the fatigue damage index from the simulated tension ranges

It is documented in Tahar et al. (2005) that fairlead friction can 'absorb' a significant amount of dynamic tension at the chainjack. Thus, for a loaded windward line the dynamic tension recorded at the chain-jack would be significantly less than that actually experienced at the fairlead. While the mean tension is of no consequence for the calculation of fatigue on stud-less chain, the magnitude of the dynamic tension plays a critical role in estimating the fatigue damage in mooring lines. It was, therefore, decided that hind-casting tension was necessary to better capture the dynamic tensions experienced at the fairlead and that the tension time series recorded at the chain-jack by the EPRMS were used only for the comparison.

The mooring line payout changed infrequently and, in general, by less than 3m during the period, so the same model was used for all storm simulations during the period. The EPRMS data was given in the form of motions at the design platform center of gravity. Hence, the motion of the fairlead of each mooring line is calculated according to the 6DoF motion of the spar and the position of the fairlead with respect to the center of gravity of the platform. The shallow (15m) and deep (150m) current were utilized when available and the drag coefficients were supplied by APC. The mean hourly current was applied with its associated direction for the entirety of each hour simulation. These current average values came from BMT post-processing, and the profile of the current has been previously discussed.

3.1 Mooring Line Model

Five important design parameters of the central line of each mooring cluster of the mooring system (line 2, line 5, line 8) were given:

1. Water depth for the anchor position,
2. Horizontal excursion from the fairlead to the anchor position,
3. Platform chain length,
4. Wire rope length, and
5. Anchor chain length.

The mooring line segment lengths would have been the easiest attribute to perform quality control on during the fabrication process, so the polyester and anchor chain design lengths were used in the model. OrcaFlex allows the user to specify the water depths at different anchor points. Four different depths were used to define the model seabed: depth at platform “mean” position (1515m), depth at mooring line 2 anchor (1566m), depth at mooring line 5 anchor (1509m), depth at mooring line 8 anchor (1465m). We placed the anchors at the design locations and altered the platform chain to match the field tension.

The first method for determining the Constitution mooring system was to take data from time periods when the met-ocean condition was benign and the platform total offset was within five feet of the “design” position (the GPS datum of 0ft North 0ft East). As explained previously, the anchor depth, anchor position and segment lengths for anchor chain and wire rope were held constant. We then placed the center of the spar model at the location of the offset location and attitude given by the platform EPRMS and changed the platform chain length until the tension was matched.

This seemed like a straight forward approach, but the results turned out to be problematic. In some cases when trying to match the measured tensions, the platform chain length required to match the measured tension was less than the distance between the fairlead and the chainjack and in other cases more platform chain had to be let out than what was expected to be present on the platform. During this process we abandoned the use of mooring payout to match the field data. Also, there were several instances when the tension was matched for all lines at one benign position, but the system was checked at another benign location (only a short time later or before) the tensions would be 2-3 times greater than the field data.

The second approach for determining the mooring model was directed more at the storm events that would be simulated in the study. Again, the model was initially set-up with the anchor depth, anchor position, design anchor chain length and design wire rope length. However, for this attempt the mooring line system was examined with five cases of two summer storms (August 15, 2007 and June 29, 2007), two winter storms (December 11, 2008 and November 9, 2009) and for another case with a significant positive surge (March 3, 2008, the other cases had a negative average hourly surge). The mean offset locations of the platform for each of these storms are depicted in Figure 9. The goal of the examination was to use all five different storms and bring the error of the mean tension of each line at each position to within 10% for the same mooring model configuration.

For each storm, we surveyed the offset 12 hours before the peak Hs and 12 hours after the peak Hs. We looked at the offset of the platform over the storm period and chose three consecutive hours in which the platform offset changed the least. The average offset of the center hour was calculated. Then, from the 4Hz raw file we found the instance where the platform position most closely matched the hourly mean offset. The model was set at this location (all six degrees of freedom). With the position and attitude of the platform set, and the measured tensions known at that instant, we altered the line length of the platform chain in such a way that the overall error between the simulated tension and the measured tension was within 10% for all nine mooring lines Table 8 compares the hourly mean tension of each line at each test location between the measured and simulated hours. All but winter storm 1 was under or near 10% and those lines that had greater difference in tension were the least loaded during the event and therefore of lesser interest. Table 9 shows the design line lengths and calculated line lengths of the platform chain as well as the wire rope length (same lengths used in model and design) and anchor chain lengths (same lengths used in model and design).

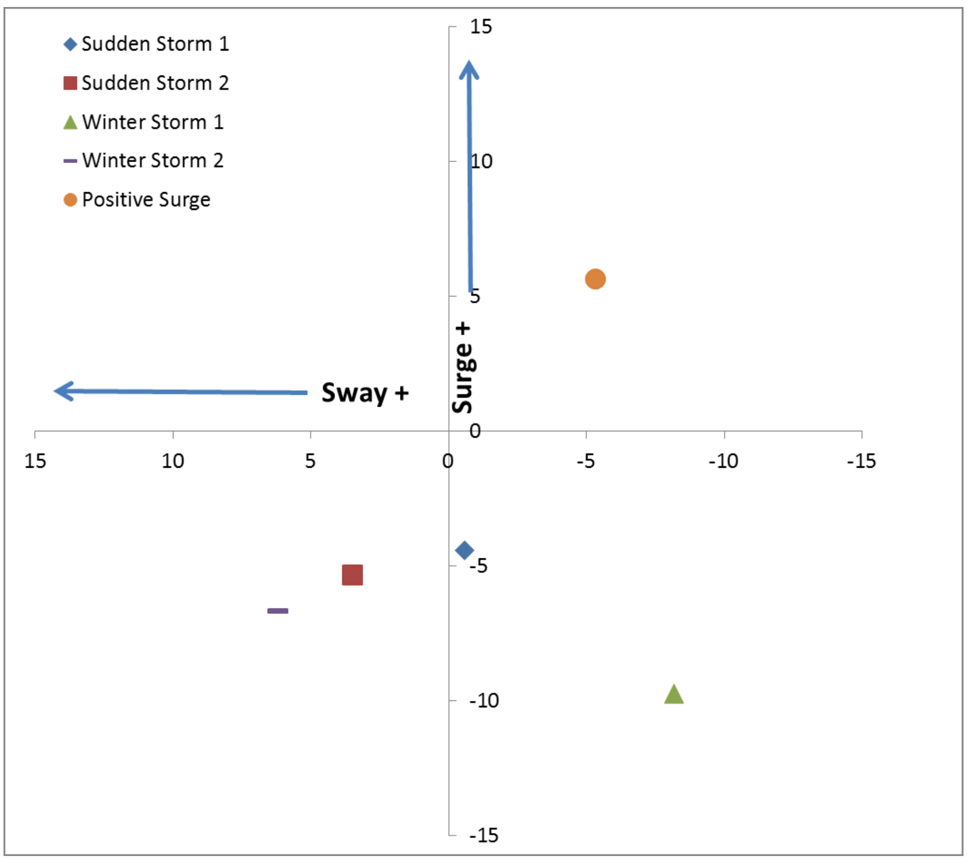

Figure 9 Preliminary Storm Checks at Different Offset Locations (m)

Table 8 Hourly Comparison Mean Hourly Tensions

		Mean Mooring Tension by Line kN								
		1	2	3	4	5	6	7	8	9
Summer Storm #1 8/15/2007 12:00	Simulated	2747	2685	2762	2635	2620	2626	2922	2934	2824
	Measured	2929	2678	2962	2606	2594	2843	2749	2751	2691
	Diff (kN)	-181	7	-200	29	26	-217	174	183	133
	Diff (%)	-6%	0%	-7%	1%	1%	-8%	6%	7%	5%
Summer Storm #2 6/29/2010 6:00	Simulated	2848	2770	2857	2611	2595	2598	2867	2885	2791
	Measured	3063	2771	2958	2690	2685	-207	2641	2713	2856
	Diff (kN)	-215	-1	-102	-79	-91	-	226	173	-65
	Diff (%)	-7%	0%	-3%	-3%	-3%	-	9%	6%	-2%
Winter Storm #1 12/11/2008 9:00	Simulated	2598	2549	2602	2615	2611	2624	3225	3229	3051
	Measured	3180	3011	3278	2669	2660	3074	3002	2887	2838
	Diff (kN)	-583	-463	-676	-53	-49	-449	222	342	214
	Diff (%)	-18%	-15%	-21%	-2%	-2%	-15%	7%	12%	8%
Winter Storm #2 11/9/2009 12:00	Simulated	2906	2813	2900	2581	2565	2567	2885	2911	2819
	Measured	3137	2821	3051	2527	2457	2703	2764	2601	2636
	Diff (kN)	-232	-8	-151	54	107	-136	120	310	183
	Diff (%)	-7%	0%	-5%	2%	4%	-5%	4%	12%	7%
Positive Surge 3/3/2008 5:00	Simulated	2704	2664	2753	2727	2709	2713	2780	2771	2678
	Measured	2878	2633	2931	2722	2731	2998	2758	2740	2624
	Diff (kN)	-173	31	-178	4	-22	-285	22	31	53
	Diff (%)	-6%	1%	-6%	0%	-1%	-9%	1%	1%	2%

Table 9: Platform Chain Values for Simulations

	Platform Chain [m]		Wire Rope [m]	Anchor Chain [m]	Depth [m]	Horizontal Excursion [m]
	Modeled	Design				
Line 1	84	91	1997	61	1566	1463
Line 2	89	91	1997	61	1566	1462
Line 3	89	91	1997	61	1566	1463
Line 4	146	137	1951	61	1509	1542
Line 5	146	137	1951	61	1509	1543
Line 6	145	137	1951	61	1509	1546
Line 7	76	91	1997	61	1465	1576
Line 8	73	91	1997	61	1465	1573
Line 9	76	91	1997	61	1465	1573

3.2 Tension Validation

The EPRMS data are housed as hourly files at 4 Hz while the mooring models were run one hour at a time with a maximum time step of 10Hz. The software, OrcaFlex, interpolates the time series data so that there are no erroneous snap loads between samples.

Overall, the measured tension recorded at the chain-jack agreed reasonably well with the simulated tension for most of the events. For winter storm 2 (November 9, 2009) the mean simulated tension (Figure 10) was within 7% of the measured data for all of the storm and the dynamic tension (see Figure 11) was within 70% at the peak of the storm. In the study by Tahar et al. (2005) on the impact of a Truss Spar by Hurricane Isidore (whose strength was similar to our winter storm) two cases were simulated and it was found that- 1) tensions simulated based on measured met-ocean conditions were twice as much as the measured tensions and 2) the simulated tensions based on measured fairlead motions were within roughly 10% of the measured tension. However, their results were post Coulomb friction corrections and there were no data for the simulated mooring tensions before the Coulomb friction was accounted for. Our simulated tensions were without Coulomb friction correction. The results of the summer storms and positive surge event matched equally well or better than the winter storm 2. The other storm, winter storm 1, did not match as well. For some of the leeward lines, the simulated tensions are less than measured tensions by nearly 20%, but for the most loaded lines there is about 10% difference between the simulated an measured tensions. These results are expected and similar to findings in Tahar et al. (2005).

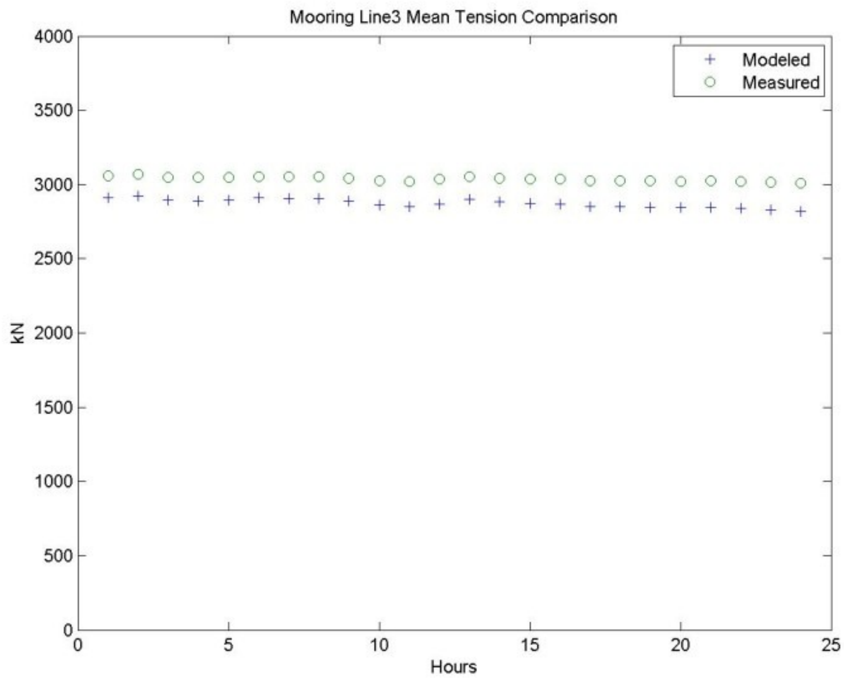

Figure 10 Mean Tension Comparison for Winter Storm 2

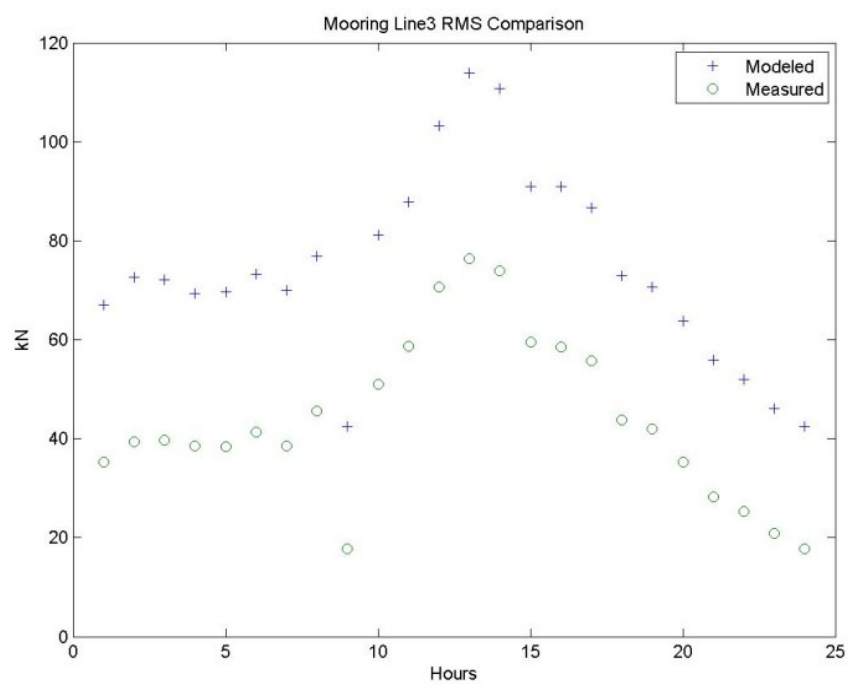

Figure 11 RMS Tension Comparison for Winter Storm 2

Figure 12 and Figure 13 show the mean tension and RMS tension comparisons respectively, for Hurricane Ike. During the storm, the simulated mean hourly tensions stayed within 15% of the measured tension except 4 hours before the peak tension and 3 hours after the peak tension. During the peak tension hour of the storm, the tension is over predicted by almost 50%. This should be compared to the numerical simulation of 10% over-prediction after the Coulomb friction calculation by Tahar et al (2005). The simulated dynamic tensions were within 20% of the measured data except for 7 hours before the storm peak and 6 hours after. At the peak the dynamic RMS tension was nearly 1.5 times the measured tensions. This in not necessarily alarming as Tahar et al. (2005) found that during Hurricane Isidore, which was a storm of only 6.4m Hs, the simulated dynamic tension accounted for about 8% of the tension. In the case of Hurricane Ike, its wave height is about twice as that of Isidore, the measured dynamic tensions were over 12% of the mean tension, and the simulated dynamic tension were about 20%. Thus, the discrepancies associated with the dynamic tension calculations were expected to increase as the environment intensity increased. Again, it should be recalled that error comparisons made with results from the Isidore study were after Coulomb friction corrections. The comparison is made between the 'measured' values from the EPRMS and the 'modeled' values for Line 3, the most loaded line during the event.

These simulations were driven solely by a platform trace; no wave kinematics were present in the simulation. Some error could be also attributed to the inertial forces that are most certainly distorted by not having a sea that moves with the platform.

However, the data does agree relatively well for most points during the study except for the very peak of Hurricane Ike, so it is interesting to accept them at minimum as plausible values and are regarded as such.

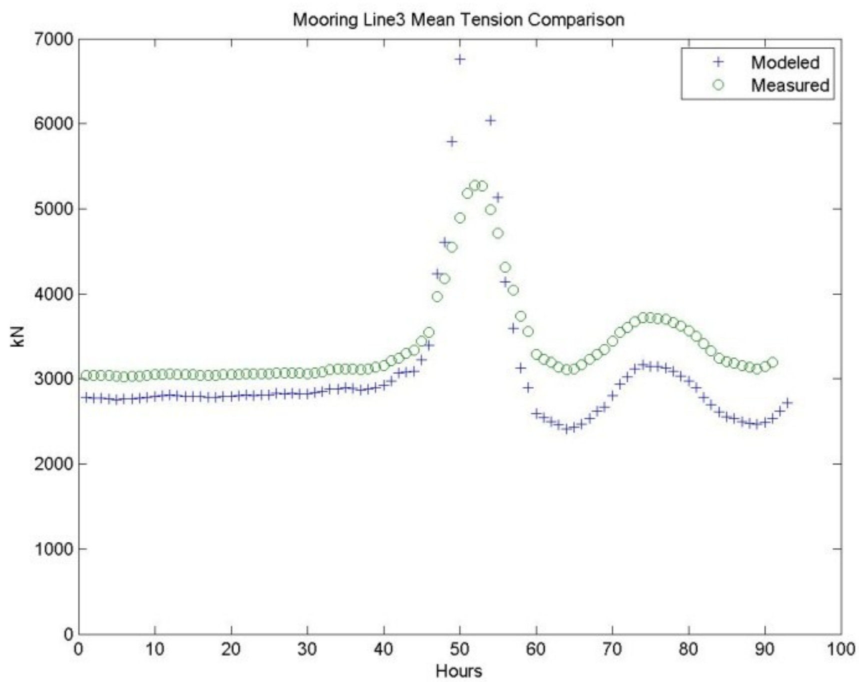

Figure 12 Mean Tension Comparison for Hurricane Ike

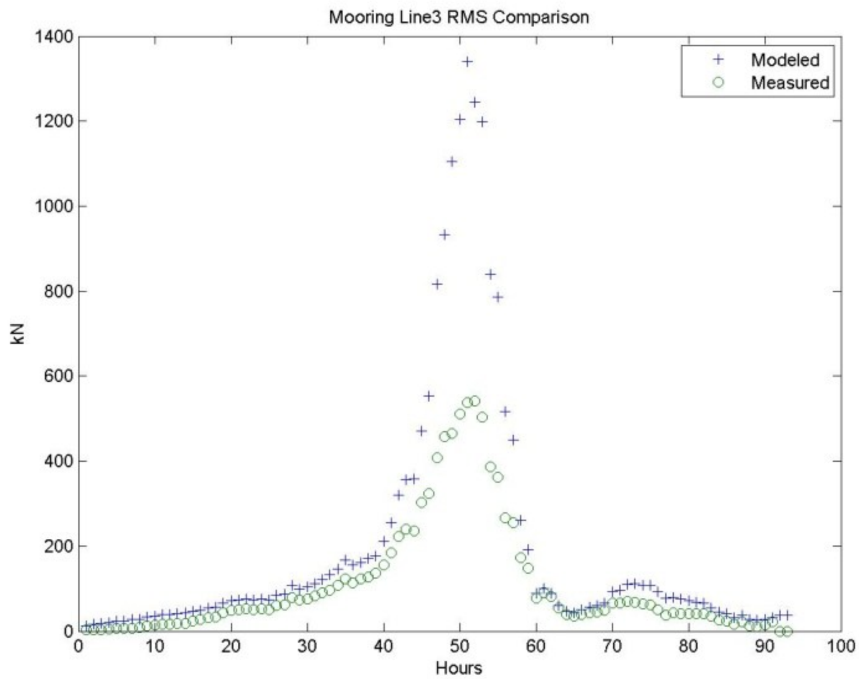

Figure 13 Dynamic Tension Comparison for Hurricane Ike

3.3 Fatigue Calculations

In this study, fatigue is calculated based upon the tension simulations through the use of rainflow counting. The number of cycles at dynamic cycle range R normalized by related breaking strength follows guidelines set forth in API RP 2SK (2005).

The number of cycles, N, to failure:

$$N = KR^{-m} \tag{3}$$

where:

K=316 (for stud-less chain)

R=Tension Range (per Cycle)/T_{max}

T_{max} = Reference Breaking Strength, 13,812 kN (for R3 grade stud-less chain) m=3

Damage Index DI:

$$DI = \sum \frac{n_i}{N_i} \qquad (4)$$

where:

n_i = number of cycles at the dynamic tension range R_i during the storm

N_i = number of cycles to failure at dynamic tension range R_i, given by Eq. (3)

The platform mooring chain on Constitution is R4 grade. During the fatigue assessment the maximum tension (T_{max}) used was 13,812 kN, which is the maximum breaking strength for the diameter equivalent of an R3 stud-less chain. This was also the approach taken by the designer in the original fatigue assessment.

4. RESULTS OF FATIGUE DAMAGE ACCUMULATION DURING VARIOUS STORMS

The results in this section describe the relative fatigue damage indices associated with the simulated tension values of the hurricane, winter storms and summer storms. We also formulate a 20 year approximation of damage based on hourly Hs distribution for the study period.

4.1 Hurricane Ike

The peak of Hurricane Ike at Constitution was on September 11, 2008 at 23:00 hours. Figure 14 shows the fatigue damage index accumulated each hour of Hurricane Ike as well as the related hourly average Hs during the storm. The plot is centered around the storm peak as defined by the peak Hs. This storm was not considered a particularly strong storm when compared to Hurricane Katrina, Rita or Ivan, but its path was very close to the platform and thus the platform experienced strong impacts from the storm. The significant wave height at the peak of the storm was 11.9 m which is close to the 100 yr design condition wave, 12.1 m Hs. The platform experienced at least a 50 yr hurricane environment (Hs 9.8 m) for nearly 12 hours. The highest 1-hour fatigue damage accumulation during the storm was 8.56×10^{-3} on Line 3, and Line 3 also had the highest damage accumulation of 4.76×10^{-2} for the whole storm. This means that nearly 20% of the damage accumulated during the 93 simulated storm hours can be attributed to the peak damage hour. A significant amount of the total damage occurred in 9 hours around the peak damage hour. This window (5 hours previous and 4 hours past peak damage hour) accounts for $4.37x10^{-2}$ or 92% of the total damage accumulation. A storm of this magnitude occurred only once during the three year period. If the damage index of $4.76x10^{-2}$ associated with the storm occurs 1 time in 100 years, then the associated fatigue damage index of the mooring line is roughly 1% during the 20-year life span of the platform.

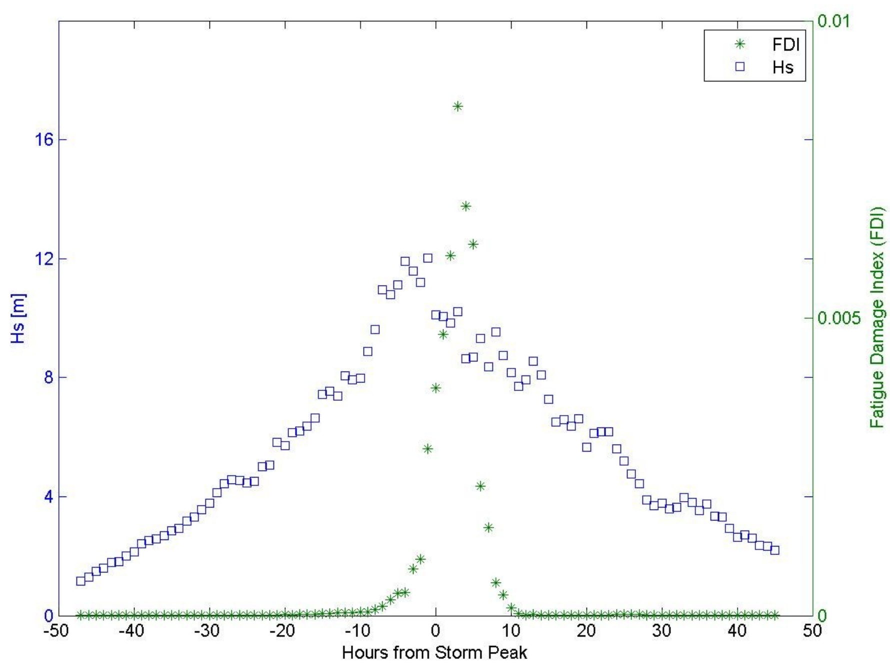

Figure 14 Hurricane Ike Damage Index on Line 3 with Hs

4.2 Winter Storm

The platform experienced a particularly strong winter storm on November 9, 2009. Figure 15 shows the hourly fatigue damage accumulation and associated significant wave height. The figure shows that the significant wave height at the peak of the storm was 6.1 m which put this storm between 50 yr hurricane (Hs 9.8 m) and a 10 yr winter storm (5.1 m). The highest 1-hour damage accumulation during the storm was 2.050×10^{-5} on Line 3. Line 1 had the highest total damage accumulation of 1.93×10^{-4} and its highest hour accumulation was 1.88×10^{-5} which is 10% of the total damage accumulation during this storm. This storm was similar in strength (Hs) to Hurricane Gustav (~6.4m) whose path did not come close to the platform.

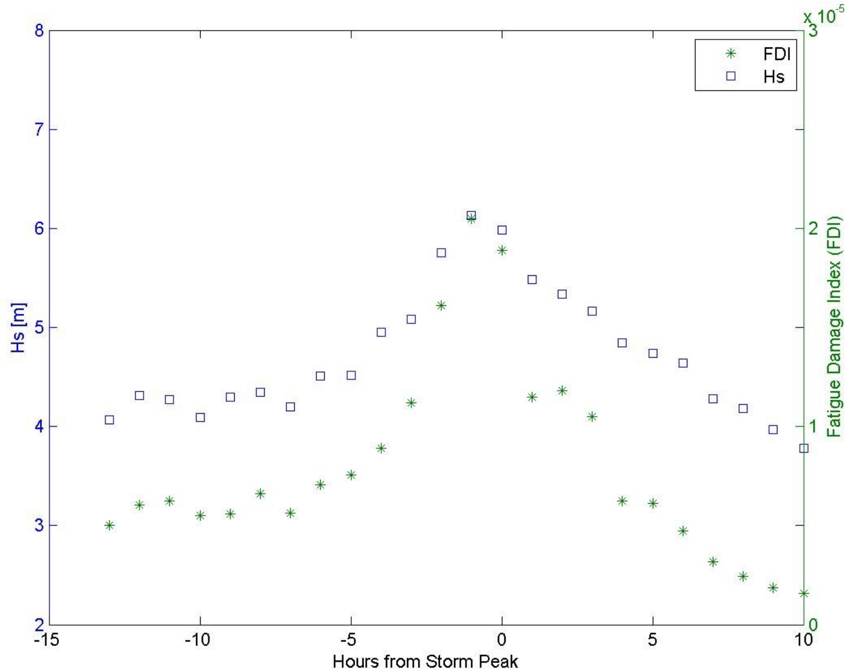

Figure 15 Winter Storm 2 Damage Index on Line 1 with Hs

4.3 Summer Storm

The summer storm analyzed by this study occurred on August 15, 2007 (see Figure 16). The term summer storm has no metocean or statistical association; it is a weak storm that occurred in the summer. The significant wave height at the peak of this storm was 2 m. This is a relatively weak storm, but interesting because a storm of such magnitude (1.5 - 2.5m) occurred roughly 82 times during the period. During the storm, Line 8 had the highest hour damage accumulation of 8.98×10^{-7} as well as the highest accumulation for the storm, 5.73×10^{-6}. The peak hour of the storm holds over 16% of the total damage accumulated in this storm.

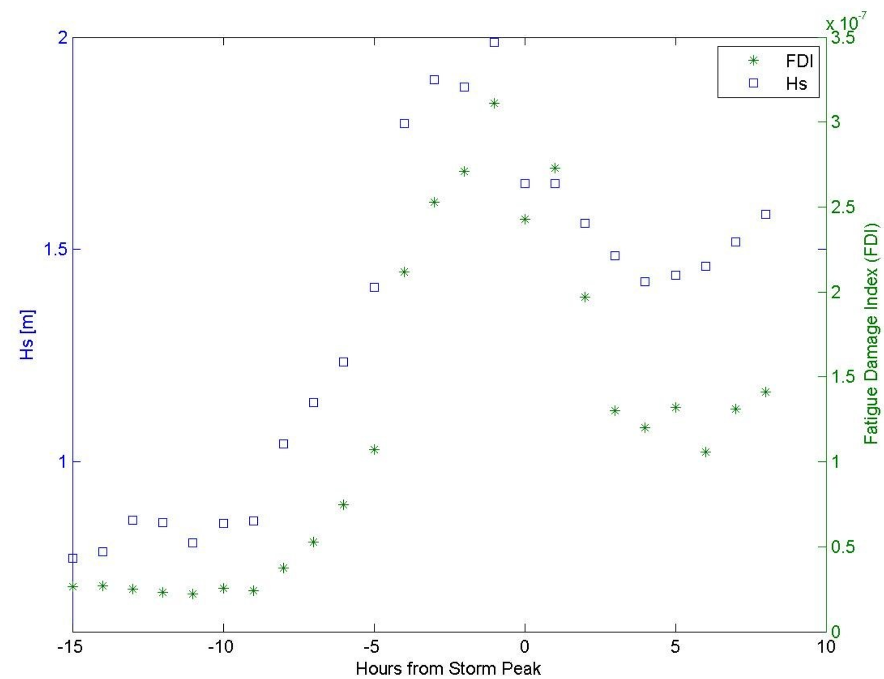

Figure 16 Summer Storm Damage Index on Line 8 with Hs

4.4 Storm Comparisons

It was demonstrated in the previous discussions that a significant amount of the total fatigue damage accumulation occurred during the peak hour of the related storm. This attribute and the total damage index are useful in comparing the fatigue damage associated with different storms. Table 10 shows the total damage, peak damage and peak damage as a percent of the total damage occurred during the different storms.

Table 10 Comparison of Storm Peak and Total Fatigue Damage Index

	Ike	Winter	Summer
Total Damage	$4.76E^{-02}$	$1.91E^{-04}$	$5.73E^{-06}$
Peak Hour	$8.56E^{-03}$	$2.05E^{-05}$	$8.98E^{-07}$
Peak (% of Total)	18.00%	10.73%	15.67%
Total (% of Ike Total)	-	0.40%	0.01%
Peak (% of Ike Peak)	-	0.24%	0.01%

The wave height of the winter storm was between the significant wave height of a 50yr hurricane and a 10yr winter storm with a maximum significant wave height of over 6.1m. However, Table 10 show that the fatigue damage index accumulated during Hurricane Ike was about 250 times greater than that which was caused by the winter storm. Furthermore, Ike inflicted 10,000 times the damage of the summer storm. An even more striking aspect is as stated previously, 93% of the damage inflicted by Ike occurred in a 9 hour period around the peak damage hour.

These observations place extreme importance in the fatigue damage index associated with extreme storms such as Hurricane Ike. Following is an argument that utilizes a non-statistical based scenario to further show the importance of the fatigue damage index associated with an extreme storm.

The metocean event tabulations in Section 2.4 shows that there were 82 storms with a maximum hourly Hs between 1.5m and 2.5m during the three year study period (average 27 events per year). Conservatively one could assign 50 such storm events per year or 1000 events in a 20 year period. In terms of the larger storm, winter storm 2, Section 2.4 showed that two storms occurred during the three year study period that had maximum hourly Hs greater than 6m. Conservatively one could assign a storm of this magnitude to every year in a 20 year scenario, or 20 events in a 20 year period.

Table 11 describes this scenario of 1000 summer storms and 20 winter storms. The fatigue damages associated with the summer storms and the winter storms are from the fatigue calculations performed specifically on summer storm #1 and winter storm #2. The scenario shows that even with an overly conservative scenario, the accumulated fatigue damage in the hypothetical 20 yr scenario is only 20% of the damage associated with Hurricane Ike.

Table 11 Hypothetical 20 Year Life Based on Storm Distribution

	Fatigue Damage Index	# per Year	Total	Total Damage	% of Ike
Winter Storm #2	$1.91E^{-04}$	1	20	$3.82E^{-03}$	8.03%
Summer Storm #1	$5.73E^{-06}$	50	1000	$5.73E^{-03}$	12.04%
Total				$9.55E^{-03}$	20.06%

4.5 Fatigue Approximation by Hour

Our primary study investigated the fatigue damage index accrued by specific storm events. As a corollary study, we decided to divide every hour of the study time period into the bins of significant wave height (shown in row one of Table 12), count the number of hours during the period associated with each bin (row four shows number of occurrences and row five shows percentage of total hours during the period), and calculate the fatigue damage index (row six) associated with 3 hour simulation of a representative Hs (row three shows the Hs of the 3 hours used in the simulation). The damage for 20 years based on the 3 hour damage simulations are in row 6. Figure 17 shows the number of hours associated with each bin and the projected 20 year accumulated fatigue damage index associated with each Hs (column 2 of Table 12). While the Hs of 3.95 m only represented 9.5% of the hours over the period it accounted for 85% of the damage.

Table 12 Hypothetical Platform Life Based on Hourly Distribution

Hs Bin [m]	Hs Bin [ft]	Hs [m]	# of Hours	%	3-Hour DI	20 Year
0.0-0.76	0.0-2.5	0.64	10503	46.0%	7.7E-08	2.1E-03
0.76-1.22	2.5-4.0	1.16	5881	25.8%	1.1E-07	1.7E-03
1.22-1.83	4.0-6.0	1.77	4154	18.2%	1.8E-06	1.9E-02
1.83-4.30	6.0-14.0	3.95	2146	9.5%	3.0E-05	1.7E-01
4.30-6.10	14.0-20.0	5.80	54	0.3%	5.0E-05	8.8E-03
Total		-	22738	100%	-	0.1999

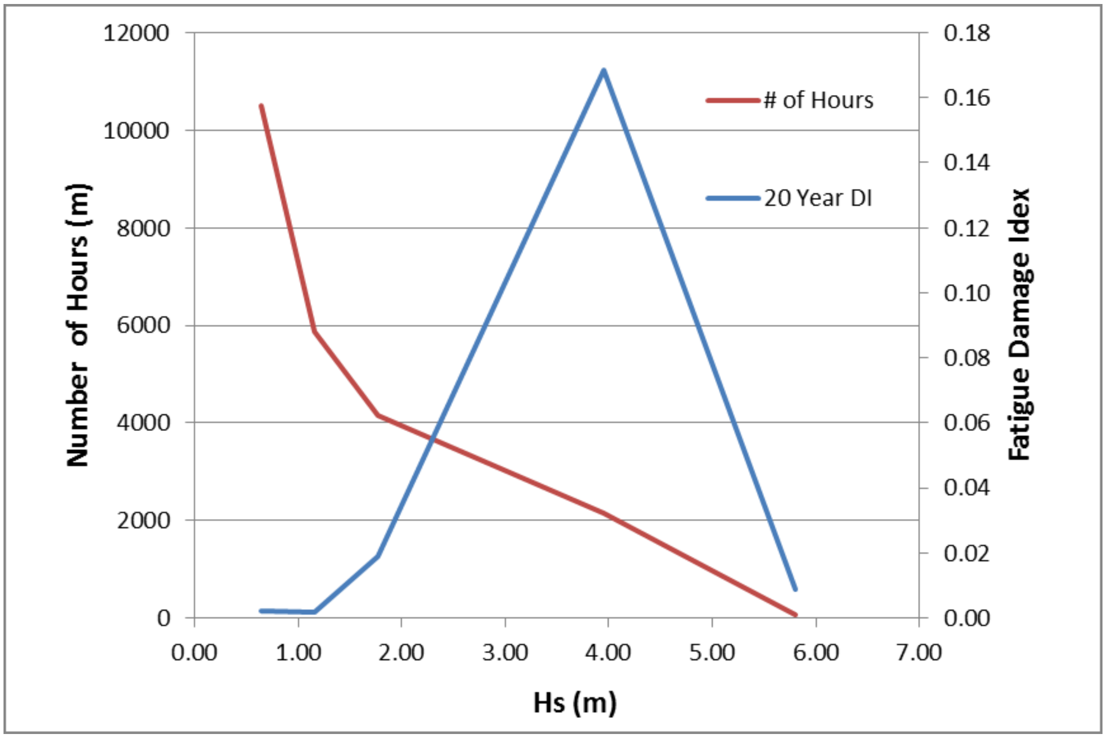

Figure 17 Hs and Associated Fatigue Damage Index by Hour

5. CONCLUSION

This study demonstrates that extreme events such as a 100 yr hurricane excites large dynamic tension ranges at low-cyclic frequencies that result in a large fatigue damage index. The tension simulations of Hurricane Ike showed a fatigue damage index of $4.76E^{-02}$, and that 92% of that damage occurred in just 10 hours at the peak of the storm. A scenario was discussed in which over a 20 year period the platform experienced 20 winter storms and 1000 Summer Storms. This scenario only amounted to 20% of the fatigue damage caused by Hurricane Ike. It is, therefore, recommended that additional sensitivity studies be explored for the fatigue damage accumulated by mooring lines during storms of extreme severity.

According to APC (Tule, 2010), the calculated fatigue damage index of the mooring lines was 3.16×10^{-2} and includes the fatigue damage associated with VIV over 20 years, 20 yr Wind/Wave and 100 yr loop current. The associated expected life with damage index was 631 years. If the damage index of 4.76×10^{-2} (5%) associated with the storm Ike is expected to occur ~1 time in 100 years, then the associated life of the mooring line is over 2000 years (statistically, a 100yr storm has an 88% chance of occurring in 20 years). If the 100 year storm occurred 1 time in 20 years then the associated life of the mooring line is still over 420 years. It is therefore believed that there is no drastic change to the fatigue life of The Platform mooring chain.

Further work on this subject could include the use of Coulomb friction algorithms to better predict the tensions and remove some of the error associated with the dynamic tension calculations. Improvement on the mooring line tension data collection would provide more accurate studies of the loads and associated fatigue damages that occur in the mooring line below the fairlead.

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