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# Deepstar Study on Predicting FPSO Responses - Model Tests VS Numerical Analysis

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## 1. ABSTRACT

This paper presents the correlation study of FPSO model tests and numerical analyses sponsored by the DeepStar program. The numerical analysis results of FPSO responses provided by SBM-IMODCO, FMC SOFEC Floating Systems, Inc., MARIN and MARINTEK have been compared with the model test results compiled by MARIN. The study demonstrated that the FPSO global responses can be well captured by the current state of the art analysis tools developed by the offshore industry. However, there are areas where further studies would be required to explain the test and analysis discrepancies. Through a series of sensitivity analyses, the study also highlighted a number of key parameters that can considerably influence the FPSO responses.

## 2. INTRODUCTION

The DeepStar Program sponsored a series of tasks to evaluate the current industry capability in predicting the responses of deepwater theme structures, namely FPSO, TLP and SPAR. In its Phase IV program, engineering analyses of the theme structures were performed by the participating companies [Ref. 2] prior to the model tests conducted by MARIN [Refs. 3 & 5]. In the Phase V program, engineering companies and model test basins participated in a Post Model Test Study in conjunction with the development of Floater Design Guidelines. The study tasks include (i) evaluating correlation between the model tests and numerical predictions and (ii) conducting sensitivity analyses of key design parameters to support the Floater Design Guidelines development effort.

Under the joint coordination of OTRC and DNV, two FPSO designers, SBM-IMOODCO (SBMI) and FMC SOFEC Floating Systems, Inc. (FMC SOFEC), and two deepwater model test basins, MARIN and MARINTEK, participated in the study to evaluate the FPSO system responses. A series of engineering analyses and sensitivity studies have been conducted. The results represent the current state of the art of the industry capability in predicting the FPSO global responses through the means of model tests and numerical analysis.

This paper presents an overview of DeepStar’s post model test study on FPSOs and covers the following subject areas:

- Model test setup and test conditions
- The state-of-art analytical tools
- Evaluation approach, e.g. model the model
- Key results of comparisons – tests vs. analyses
- Sensitivities and uncertainties in predicting FPSO responses
- Assessment of current industry capabilities
- Recommended areas for future studies

## 3. STUDY DATA

**FPSO Model**
A 200,000 DWT tanker was selected for the purpose of model tests and engineering study. The model test scale is 1:87. The FPSO particulars (full scale) are presented in Table 3.1 and the lines plan is presented in Figure 3.1.

**Wind and Current Data**
In the tests, the tanker was provided with a relatively high bulwark and forecastle deck to prevent green water impact. Consequently, the FPSO wind area has been modified from the pre-test analysis. MARIN conducted wind load tests and provided the wind forces and moments data to be used in the study. The current loads were modeled using the OCIMF coefficients.

**Mooring and Riser System Data**
Four mooring systems have been developed for the study purpose. These are:

(i) 3,000 ft steel system
(ii) 6,000 ft steel system with mid-water buoys
(iii) 6,000 ft polyester system
(iv) 10,000 ft polyester system

The details of mooring line composition for the above four systems are summarized in Table 3.2. It is noted that the 3,000 ft steel system was model tested by MARIN and is the focus of the present study

The riser system consists of 4 production lines, 4 gas lines, 2 water injection lines, 2 gas injection lines and 1 gap export line. The riser system data are presented in Table 3.3 and hydrodynamic coefficients in Table 3.4.

**Environmental Conditions**
Two sets of environmental conditions, the hurricane condition and the loop current condition, have been considered. The wind, wave and current parameters are presented in Table 3.5.

## 4. FPSO MODEL TESTS

The FPSO model tests were carried out in the new deepwater offshore basin of MARIN, measuring 44,35m x 35,6 m with a maximum depth of 10,5 m [Ref. 10]. The basin is fitted with multiflap wave generators, 24 m width fans and capable of generating current across the full depth.

Since current can only be generated from one direction, two orientations of the test setups are necessary to model the hurricane and loop current conditions. The test orientation of the moorings and risers are illustrated in Figure 4.1 and 4.2. Because of basin dimension limit, 2 x 3 transverse lines have to be truncated by a small amount for the loop current condition.

The model tests conducted by MARIN consist of the following test components:

- Static load displacement tests
- Decay tests
- Hurricane wind only (mean wind – 0.5 hours)
- Hurricane current only (mean current – 0.5 hours)
- Hurricane wave only (3 seeds and repeat tests)
- Hurricane wind, wave and current (3 seeds and repeat tests)
- Loop current wind only (mean wind – 0.5 hours)
- Loop current current only (mean current – 0.5 hours)
- Loop current wind and current
- Loop current wind, wave and current (3 seeds and repeat tests)

The model test data are presented in both the time series and statistics formats.

## 5. ANALYSIS METHODOLOGIES

### 5.1 General
The general approach of predicting the FPSO responses can be categorized according to the frequency or time domain analysis method and the coupling between the FPSO and its mooring lines and risers.

The four participating companies as illustrated by the following chart have used different analysis methods:

| Company | Time or Freq. Domain | Coupled or non-coupled | Computer Program |
|---|---|---|---|
| SBMI | TD | Coupled | DYNFLOAT |
| SBMI | TD | NC | ARIANE |
| FMC SOFEC | FD | Coupled (*) | SEASOFT |
| MARIN | TD | Coupled | DYNFLOAT |
| MARINTEK | TD | Coupled | RIFLEX-C |

*(*) In the frequency domain analysis, the FPSO/mooring/riser coupling is modeled using average computed damping.*

The solution method statements of participating companies can be found in Table 5.1.

### 5.2 Coupling between FPSO and Moorings/Risers
For deepwater applications, the mooring lines and risers can significantly influence the responses of FPSOs and their contribution should be appropriately accounted for. The moorings and risers generate the horizontal restoring forces that govern the FPSO surge and sway natural frequencies as well as the damping to slow drift motions. The methods to model the mooring/riser contribution applying different levels of coupling with the FPSO are described below.

***(a) Non-Coupled or Statically Coupled***
This is the traditionally approach. The FPSO and the mooring/riser responses are analyzed separately. In analyzing the FPSO responses, the following mooring/riser effects can be included:

- Mooring and riser system stiffness
- Direct current loads (usually the relative velocity is not accounted for)
- Estimated slow drift damping

The FPSO static offset, the slow drift and wave frequency motions are solved first including the above mooring and riser contributions and, based on the derived FPSO responses, mooring line and riser responses are then predicted.

***(b) Coupled to Slow Drift Motions***
In this method, the mooring line and riser dynamics are fully modeled. Using the wind, current, wave drift load coefficients and FPSO dynamic coefficients, the FPSO responses are solved in the time domain taking into account the mooring line and riser dynamic loads. It is assumed that the FPSO wave frequency motions are not affected by the mooring lines and risers. In essence, at each time interval, the FPSO low frequency responses are computed taking into account fully the mooring/riser dynamic responses.

Even though the mooring lines and risers are not coupled with FPSO's wave frequency motions, their contributions to such motions are often negligible since the FPSO's inertia properties are an order of magnitude higher than those of the mooring lines and risers.

### (c) *Fully Coupled Method*

In the so-called fully coupled method, the mooring line and riser dynamic responses are coupled to the whole range of FPSO responses, including the wave frequency responses. In this method, the complete system dynamic equations are solved in the time domain.

### 5.3 Methodologies and Computer Software Tools

SBMI, MARIN and MARINTEK used the time domain coupled analysis method to predict the FPSO responses. In particular, SBMI and MARIN used the coupled method (b) and MARINTEK used the fully coupled method (c) as discussed in the previous section. The time domain coupled analysis method is the most commonly adopted method for analyzing the turret moored FPSOs. FMC SOFEC used a non-linear frequency domain method.

SBMI also used the statically coupled time domain method via the ARIANE program as part of the sensitivity study.

### (a) *DYNFLOAT Program*

SBMI and MARIN both used the computer software tool, DYNFLOAT, to perform the present study. DYNFLOAT is developed by MARIN for the time domain coupled analysis of offshore mooring systems. The program is well suited for analyzing FPSO moorings since the turret mooring is a built-in feature and the coupling between the surface platform and the moorings/risers is to the second order slow drift motion level.

In the DYNFLOAT analysis, the following inputs are required:

- Wind and current coefficients
- FPSO hydrodynamic coefficients from the wave diffraction analysis (DIFFRAC or DUCHESS)
- Mooring and riser system details including drag and inertia coefficients

DIFFRAC and DUCHESS are linear 3D frequency radiation/diffraction programs developed by MARIN. DIFFRAC computes the hydrodynamic data for zero speed, while DUCHESS gives the data including the wave-current interaction. DIFFRAC was used for the loop-current condition, while DUCHESS was used for the hurricane condition.

In the DYNFLOAT analysis, the wind and current loads are computed using the force coefficients defined. Using the linear impulse response function based on the free floating wave frequency motion transfer functions and the input or generated wave trains based on the wave energy spectrum, the 6-degree of freedom wave frequency motions of the FPSO are computed. Using the quadratic impulse response function, the full matrix of wave drift force coefficients and the generated wave train, the wave drift loads are computed.

Before solving the dynamic response equation in the time domain, the wave frequency motions (6 DOF) and wave drift forces (3 DOF) are solved for each 5-degrees FPSO heading intervals and stored. During the simulation, the wave drift loads and wave frequency motions will be interpolated based on the instantaneous heading of the FPSO.

The mooring lines and risers are modeled using the lump-mass model (DYNFLX). Each time interval the complete dynamics of the mooring lines and risers due to the momentaneous displacement and velocities at their attachment point at the turret were carried out. The resulting forces were added to the equations of motion, so the dynamic response matrix is fully integrated with that of the FPSO. Based on the inputs of wind, current, wave drift loads and FPSO wave frequency motions, the integrated system dynamic equations are solved in the time domain.

The viscous roll damping can be added. The wave and current interaction and wave drift damping are modeled by Aranha’s approach.

### (b) *SeaSoft Program*

The computer programs utilized by FMC SOFEC for this study are components of a nonlinear analysis suite developed by SeaSoft Systems. Programs used in the DeepStar analysis include:

- **SPMsim®** - Stand-alone, turnkey simulation of a turret-moored vessel and its associated mooring structures.
- **Shipsim®** - Stand-alone six degree-of-freedom wave-frequency vessel motions module used by SPMsim.
- **Catsim®** - Comprehensive quasi-static analysis of multileg catenary mooring systems, for static offset analysis.
- **Slowsim®** - Stand-alone utility for evaluating mean wave, wind and current forces and moments on the FPSO.

SPMsim can be characterized as a nonlinear spectral analysis (or "nonlinear frequency domain") tool comprising a five-step simulation process:

- *Determine mean vessel position and orientation.* This step, along with a low-frequency (LF) motions evaluation described below, utilizes built-in or user-supplied coefficients describing mean and LF vessel response to mean and variable forces of wave reflection, wave dissipation, wind and current. Wave-current interaction effects form an integral part of the analytical model.

- *Evaluate wave-frequency (WF) vessel motions at the mean position and orientation.* This step assumes linear vessel response to the wave field, with standard nonlinear corrections for roll; it utilizes SeaSoft's WF vessel module (Shipsim).

- *Evaluate LF system damping*. Average damping contributions from significant mechanisms (wave reflection, wave dissipation, current, wind, WF line damping, etc.) are determined for the "step one" mean vessel orientation. Note that some damping mechanisms depend on the "step two" WF vessel motions; e.g., damping arising from hull-mediated wave dissipation and from WF line motions.

- *Evaluate modal low-frequency oscillation amplitudes.* The coefficients used in step one, in conjunction with a spectral representation of their associated environmental excitations, are used to compute generalized forcing functions that are then applied to the three LF normal modes of the system. (The three normal modes of a turret-moored vessel can be roughly characterized as a high-energy "surge" mode and two lower-energy coupled sway-yaw modes.) Important non-linearities in the mooring-riser restoration characteristic and in system hydrodynamic damping contributions from vessel and mooring structures are fully accommodated by direct analytical modeling of the nonlinear processes. In addition, non-Gaussian responses arising from the non-Gaussian nature of wave "drift" (i.e., reflection and dissipation) forces are fully integrated with the nonlinear modal analysis.

- *Re-evaluate WF motions at selected points within the LF configuration space.* Once LF motions are characterized, the boundary of an abstract three-dimensional configuration space (one dimension for each degree of freedom) enclosing the energetically achievable LF vessel location and orientation combinations is determined. Within this abstract 3-D volume, a collection of statistically meaningful points is chosen at which to re-evaluate vessel WF motions and the associated (nonlinear) mooring line and riser dynamics. Finally, overall system statistics and extremes are evaluated based on the selected subset of the vessel's LF/WF sample space.

It is worthwhile noting that SPMsim's default execution mode, which was used in the present analysis, provides no user control over system damping or excitation once the appropriate environmental forcing models (e.g., OCIMF for current, measured coefficients for wind, etc.) have been chosen.

### *(c) RIFLEX-C Program*

MARINTEK used the computer program system, RIFLEX-C, to do fully coupled analysis. The relative wave motion was analyzed by the WaveLand software.

In the RIFLEX-C analysis the floater load model is introduced as a nodal load component in the Finite Element Model of moorings and risers [Ref. 11]. Nonlinear time-domain analysis is used for the simultaneous computation of floater motions and dynamic responses of moorings and risers. Thus proper dynamic tensions are modeled directly.

Hydrodynamic forces on mooring lines and risers are modeled by use of Morison’s equation, taking into account the relative velocity in the drag term.

The FPSO’s hydrodynamic coefficients are derived by use of WAMIT, by which a linear vessel model was established. WAMIT is a 3D frequency-domain radiation-diffraction panel program developed by MIT. Coefficients for wave-frequency motions, as well as for slowly varying second-order drift forces, are obtained. Newman’s approximation was assumed. The added mass, potential damping and first order wave excitation are predicted from the linear analysis. The drift excitation is crucial for the horizontal modes (surge, sway and yaw) of a turret moored FPSO.

In the present coupled-analysis procedure, the first- and second-order wave excitation forces are calculated prior to the time-domain simulation. The frequency-dependent added mass and damping coefficients are transformed to retardation functions, introducing a memory-effect in the time-domain simulation.

For wave-current interaction correction, the wave drift force coefficients in the initial comparisons were modified according to Aranha’s method. In the final calibration, drift coefficients were checked against empirical coefficients obtained from cross-bi-spectral analysis, and coefficients in waves-only were increased by 10%.

The low-frequency vessel motion damping contributions from moorings/risers, which are significant especially due to the deep water, are modeled directly through the FEM.

In the final calibration, additional slow-drift surge damping was added in the model to tune the high damping observed in the measured motions. (In sea states with combined waves, wind and current the total relative damping levels were around 45%-50%).

Wind- and current loads were calculated by a set of direction-dependent quadratic coefficients, taken from OCIMF (current) and from the MARIN model tests (wind).

### *(d) ARIANE Program*

ARIANE is a mooring analysis package developed by Bureau Veritas. The program first solves the motion responses of the FPSO utilizing the RAOs, wave drift force coefficients and the user input damping of the mooring lines and risers. The mooring and riser system stiffness is fully accounted for in solving the FPSO offset and slow drift motions. Then based on the derived fairlead motions, the mooring line tensions are computed. The solution of the tensions does not involve the dynamic tension. Instead, the theoretical catenary formulation is used. The line dynamic tension can be predicted using a separate CABLE-3D module.

## 6. CORRELATION BETWEEN TESTS AND TIME DOMAIN ANALYSES

During the model test comparison, the static load extension curves were first compared and the results indicate clearly that the agreement is satisfactory (see Figure 6.1). In addition, the decay tests were reproduced using the dynamic transient motion analysis (see Figures 6.2 and 6.3). In this way, the damping to the slow drift motions is checked and the general conclusion is that the mooring line and riser induced damping is well captured by the present analysis methodologies. MARIN conducted a more detailed investigation of the damping as a load component, and advised that for the loop current condition, the riser VIV may be present and as the result, the drag force coefficients of the risers should be increased.

Screening of test case comparison has been carried out. It is noted that the wind, wave and current alone test results compared less well with analysis. Indeed, the FPSO seldom heads perfectly into the wind, wave and current directions during the wind, wave and current alone conditions. In order to match the test results, the environment directions have to be tuned. The comparison of test and analysis results presented in this paper focuses on the full wind, wave and current cases in both the hurricane and loop current conditions.

Detailed comparisons between the model tests and analyses have been conducted using the "Model the Model" techniques, i.e. the model test parameters were utilized exactly in the analysis to reproduce the FPSO responses. The "Model the Model" techniques were used by SBMI, MARIN and MARINTEK via the time domain analysis approach. The measured mooring line and riser properties and pretensions were modeled by the software tools, and the test measured wind speed and wave profile time series were directly input to the dynamic analysis program to simulate the system response time series. The derived response time series can then be directly compared with those recorded during the model tests. In this way, inconsistency of the system model and environmental conditions are supposed to be filtered out.

Figure 6.4 show the time trace comparisons between the model tested and analyzed vessel excursions and mooring line tensions for hurricane test seed 1. The general observation is that the predicted surge motion and windward mooring line tension correlates well with test results. However, correlation of the sway and yaw motions are less satisfactory.

Based the model test comparison results, the statistics of the analysis and test results were also compared. Figures 6.5 to 6.10 show the results of key parameters between the model tests and the different contractors for the hurricane environment. Similarly, the results are displayed for the loop current environment in Figures 6.11 to 6.16.
From the comparisons between conducted between the model tests and analysis, the following key observations can be made:

a) Correlation of the offsets in the predominant environment direction is very well. In the present case, the X offsets of the tests and analysis compare well. However, the Y offsets and yaw motions compare less satisfactory. There are a number of possible causes which include (i) the directionality of wind, waves and current generated by the basin and how they match the theoretical wind, wave and current headings; (ii) the coupling between the sway and yaw motions that may be difficult to replicate by the analysis.

b) For the DYNFLOAT analysis, the standard deviation of the roll motion is under-predicted by the analysis, even though the maximum roll motion between the tests and analyses correlate well. In particular, the tanker model is fitted with the bilge keels while no viscous damping has been applied in the SBMI and MARIN analysis. In theory, the analysis should have predicted larger roll motion standard deviation. This may be explained by the missing coupling between the FPSO wave frequency roll motion and mooring line and riser dynamics. Another possible explanation is that the waves generated by the basin are not completely long crest waves. It is noted that for the hurricane case, the FPSO heading almost towards the wave direction and any spread of wave energy can cause increase of roll motion. Also FMC SOFEC has not added viscous roll damping. On the other hand, however, MARINTEK has added a large amount of viscous roll damping to decrease the initially large computed roll angles. This is in contradiction with SBMI, MARIN and FMC SOFEC. The problems of the roll angle are not clear.

c) For the loop current condition, the mean yaw angle is under-predicted by 10 to 15 degrees analyses. The exact reason is unknown. Apart from that, the yaw motion standard deviation and angular range are well matched between the tests and analyses.

d) The maximum mooring line tensions between tests and analyses correlate very well. For both the loop current and hurricane conditions, the discrepancies of mooring line tensions of the most heavily loaded lines are within 10% for all four participating companies.

e) Comparison of the tension of slack mooring lines shows a much less satisfactory correlation. In general, analyses predicted higher leeward line tensions than those measured during the tests. There is no satisfactory explanation for this phenomenon.

f) Correlation between the turret loads, especially the turret moments are less satisfactory. The main reason is that the risers are pin-connected at the base of the turret while in the tests, they were connected at 8ft below the keel with bend stiffeners.

It must be noted that MARIN and SBMI have used the standard low frequency damping procedure for surge, sway and yaw direction as is present in the DYNFLOAT program. No additional tuned damping was used. For the standard procedures, see [Ref. 12]. MARINTEK made an observation that comparing the initially computed surge spectra to the measured ones indicates that the total slow-drift damping (which was quite high in the measurements: 45% - 50% relative damping) was under predicted. Thus additional damping is added in MARINTEK's analysis in the final calibrations to match the observations.

## 7. ADDITIONAL OBSERVATIONS FROM FREQUENCY DOMAIN ANALYSIS

In most respects, particularly in the prediction of individual line and riser loads, frequency-domain analysis results closely mirror those of the time-domain participants.

That said, any state-of-the-art mooring line or riser load simulation that properly accounts for the nonlinear dynamics and hydrodynamics of these structures will give similar results in a specified wave environment, provided only that the mean and low-frequency vessel offset estimates governing quasi-static line and riser profiles are similar. Since participating time-domain and frequency-domain analyses exhibited similar mean and variable surge, sway and yaw offset estimates in all tests, it is not surprising that mooring line and riser load predictions between the two approaches would be similar.

A closer look at the tests and analyses reveals a few interesting differences that are as yet unexplained and require additional scrutiny.

- *Fluctuating Current Modeling.* SPMsim incorporated current fluctuations on an equal footing with wind and wave variability. The model tests exhibited substantial current fluctuations, which in a tribute to the experimental excellence surrounding the test program, were carefully quantified. The analysis, utilizing MARIN's measured current spectra, indicates that in the loop current tests the significant part of low-frequency excitation in surge, sway and yaw arose as a result of current fluctuations.
- *Loop Mean Yaw Estimates.* In the loop current tests, the mean yaw angle measurement was satisfactorily reproduced in the frequency-domain analysis. The predicted mean yaw angle discrepancy between time-domain and frequency-domain analyses requires further investigation.
- *Loop Mean Offsets: Role of Riser VIV.* In the frequency-domain analysis a nominal riser drag coefficient of 1.0 was found to be sufficient to reproduce the observed mean loop current offsets. The exact role of VIV in the loop current condition requires further quantification.
- *Lateral Motion and Load Estimates*. In both loop current and hurricane tests, the mean and variable lateral motions (sway and yaw) and lateral turret loads were satisfactorily reproduced in the frequency-domain analysis.
- *Tests Without Waves.* It was determined that in all tests lacking waves, turret loads and vessel offsets could be satisfactorily explained using only OCIMF current coefficients, measured wind coefficients and, for winds-active cases, an expected shallow surface current arising from sustained action of wind stress on the water surface.

## 8. SENSITIVITY ANALYSIS

SBMI and FMC SOFEC have conducted sensitivity analysis of key FPSO design parameters. The following observations are made when the response statistics are compared for the different parameters:

a) The wave peak energy period (Tp) is an important design parameter that can have significant influence on FPSO responses. The natural periods of roll, pitch and heave motions are usually close to the period of design waves and the motions can be substantially affected by the wave period variation. More importantly, the wave drift force coefficients are highly period dependent and in general, the wave drift force and the associated slow drift motion increase with reducing wave periods.

b) The drag force on the mooring lines and risers add to the mean static load in current as well as damping to low frequency motions. The increase of mooring and riser drag force coefficients tend to increase the mean offset but reduce the slow drift offset. Depending on the contributions of these two components, the overall impact can be case dependent.

c) The environmental alignment variation, i.e. the directionality of wind, waves and current combinations, has a more profound impact on the turret load than on the turret total offset.

d) A study of simulation duration and its effect on low frequency motions has been conducted. It was found that the 3-hours simulation period is shown to be adequate in capturing the FPSO low frequency response magnitude. The possible explanation is that the mooring stiffness is near linear in deep water and thus the input loads to the near resonant slow drift motion has been filtered out to produce a near sinusoidal motion response.

e) The water depth is an important parameter. Indeed, as water depth increases, the mooring system often has to be modified to meet similar design criteria and the conventional steel mooring system may fail to perform. As a result, the mooring system configurations and line materials have to be modified. The following has been observed from the sensitivity analysis conducted with respect to water depth and line materials:
   - For the same mooring configurations, the FPSO offset and overall mooring loads increase with water depth. However, the offset as percentage of water depth actually reduces. The mean mooring line tension increases with water depth, while the dynamic tension decreases. The overall line tension may not be significantly affected.
   - As the mooring system changes over to the polyester configuration, there is a change of mooring leg configuration from the catenary shape in the steel mooring case to the taut leg shape in the polyester case. By effectively utilizing the taut leg configuration, the offset can be drastically reduced.
   - The associated penalties of taut leg configuration are higher mooring line tensions and turret load. If the polyester system is designed to be more compliant, the maximum line tensions and turret loads can be significantly reduced.
   - The polyester line has greater strength to weight ratio and therefore is more attractive for deepwater mooring applications.

   f) A brief study was conducted by truncating the bottom chain segment. The same mooring line stiffness characteristics have been maintained while the drag and initial forces were removed. The truncation affects both the mooring leg damping and natural period properties. It can have considerable effect on the

FPSO responses. Further studies in this area would be required to fully explore the truncation impact.

g) Sensitivity to the following parameters was also analyzed: wave drift damping, roll viscous damping, and JONSWAP peakedness factor. The FPSO responses were found to be less sensitive to variation in these parameters. It is noted that this conclusion may only apply to deep water FPSOs, as in shallow waters, the wave drift damping contribution is more significant.

## 9. DISCUSSION

Answer is often sought as to whether the industry has the capability to predict the FPSO global responses in deepwater without doing model tests. The answer is a conditioned yes. The industry has installed about a dozen FPSOs in deep waters and has accumulated valuable experience. The assessment of correlation between model tests and analytical analyses concludes that the current state-of-the-art analytical tools are capable of predicting the extreme responses, which are important for designing the mooring system. More scatter is observed when comparing the low frequency horizontal responses, and in particular the sway-yaw coupling. Generally, a good agreement with the model test measurements was found among the participating companies, when comparing the spectral contents and response statistics of the key design parameters. In addition, the current correlation analysis between the tests and analyses show that even without any tuning of the analysis, the FPSO responses can be reasonably well predicted. To illustrate the point, an exercise was undertaken by SBMI by simulating the FPSO responses 10 times (using different random seeds) using DYNFLOAT and comparing the average responses of the 10 simulations with those of the 3 tests. The results of the comparison are presented in Table 8.1. It can be seen that the extreme offset and mooring line tensions are all well predicted.

Does this lead to the conclusion that the offshore industry has a total understanding of all FPSO responses and load interactions? The answer would more likely to be no. Even though the extreme responses can be well predicted for design purpose, there are many detailed load interactions which are less well understood. The key areas of discrepancies are highlighted in the following discussion.

a) When the time series of FPSO responses were compared between tests and analysis, it is consistently observed from all the cases compared, that the surge motion and line tension compare well, while the sway and yaw motions do not match in phase.

b) For all cases, the leeward line tensions are over-predicted by analysis by a significant margin. This fact has been observed from engineering analyses conducted by a number of companies.

c) The roll motion was computed including only potential roll damping, except for MARINTEK. If additional viscous damping would have been used in the simulations, the analysis would under-predict the roll motion. MARINTEK, however, had to add additional viscous damping to obtain reasonable roll angles.

d) When the low frequency and high frequency components of the test and analysis results are compared, the correlation is less satisfactory.

Furthermore, there are still a few unexplained phenomena in model tests and analyses. Our ability to predict VIV occurrence is just one of them.

For deepwater FPSO, the coupled analysis method is preferred since it captures the direct environment loads and damping/inertia forces due to the mooring lines and risers. However, study has shown that provided that the mooring line and riser contribution to FPSO low frequency motion can be accurately predicted, the non-coupled analysis should also be able to accurately predict the FPSO responses. SBMI has conducted a comparative analysis using the non-coupled computer software tool, ARIANE. By integrating the energy dissipation due to the mooring line and riser movement predicted by the coupled analysis, the equivalent mooring and riser damping was computed and then input into the ARIANE program. In this way, it is found that the FPSO extreme responses can be well predicted as for the coupled analysis approach (see Table 8.1).

## 10. CONCLUSIONS

A comprehensive study of correlation between FPSO model tests and computer simulation results has been conducted. It should be noted that the computer simulations were carried out as post model test analysis, and therefore not as “blind” simulations. However, the study leads to the conclusion that the FPSO global responses can generally be well predicted by the state-of-art analytical tools. Still, there are areas where further investigations are required.

The sensitivity study conducted has identified a number of key parameters that deserve special attention in the design stage. These include the wave period, water depth variation, and mooring configuration and line materials. The analysis also indicates that the truncation of mooring lines during basin tests can affect the mooring line tensions.

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10) Wichers, J and Devlin P – "The Benchmark Model Tests On The DeepStar Theme Structures FPSO, SPAR and TLP", OTC 15346, OTC 2003.

11) Ormberg, H., Larsen, K.: "Coupled Analysis of Floater Motions and Mooring Dynamics for a Turret-Moored Ship", Applied Ocean Research, Vol. **20**, 1998, pp. 55-67.

12) Wichers, J.E.W.: "A simulation model for a single point moored tanker", PhD, Delft University of Technology, 1988


**TABLE 3.1: MAIN PARTICULARS OF TURRET-MOORED FPSO**

| | | | |
|---|---|---|---|
| Vessel size | | kDWT | 200 |
| Length between perpendiculars | Lpp | ft | 1017 |
| Breadth | B | ft | 154.8 |
| Depth | H | ft | 92 |
| Draft | T | ft | 62 |
| Displacement | | ton | 240,869 |
| Block coefficient | Cb | | 0.85 |
| Center of gravity above base | KG | ft | 43.7 |
| Metacentric height transverse | GMt | ft | 18.96 |
| Metacentric height longitudinal | GMl | ft | 1324.9 |
| Transverse radius of gyration in air | Kxx | ft | 48.46 |
| Longitudinal radius of gyration in air | Kyy | ft | 254.17 |
| Yaw radius of gyration in air | $K\psi\psi$ | ft | 260.17 |
| Wind area frontal | Af | ft2 | 10,890 |
| Wind area side | Ab | ft2 | 40,600 |
| Turret behind Fpp (20.5% Lpp) | | ft | 208.5 |
| Turret elevation below tanker base | | ft | 5 |
| Turret diameter | | ft | 52 |

**TABLE 3.2 MOORING LEG COMNPOSITIONS**

| Designation | Unit | | | | |
|---|---|---|---|---|---|
| Water depth | Ft | 3000 | 6000 | 6000 | 10000 |
| Pre-tension | Kips | 270 | 320 | 320 | 380 |
| Number of lines | | 4*3 | 4*3 | 4*3 | 4*3 |
| Degrees between the 3 lines | Degrees | 5 | 5 | 5 | 5 |
| Length of mooring line | Ft | 6850 | 8700 | 11150 | 14000 |
| Radius of location of chain stoppers on turn table | Ft | 23 | 23 | 23 | 23 |
| **Segment 1 (ground section): Chain** | | **K4 studless** | **K4 studless** | **K4 studless** | **K4 studless** |
| Length at anchor point | Ft | 3000 | 400 | 850 | 400 |
| Diameter | Inch | 3.50 | 3.75 | 3.75 | 4 |
| Dry weight | Lb/ft | 110.78 | 127.17 | 127.17 | 144.69 |
| Weight in water | Lb/ft | 96.38 | 110.64 | 110.64 | 125.88 |
| Stiffness AE | Kips | 178616 | 205044 | 205044 | 233300 |
| Mean breaking load ( MBL) | Kips | 1464 | 1698 | 1698 | 1949 |
| **Segment2: wire** | | Jacketed spiral Strand | Polyester | Jacketed spiral Strand | Polyester |
| Length | Ft | 3700 | 8000 | 9500 | 13300 |
| Diameter | Inch | 3.50 | 6.3 | 3.75 | 7.09 |
| Dry weight | Lb/ft | 28.24 | 11.56 | 32.41 | 14.588 |
| Weight in water | Lb/ft | 23.96 | 3.02 | 27.5 | 3.81 |
| Stiffness AE | Kips | 155094 | 42000 | 178000 | 54000 |
| Mean breaking load (MBL) | Kips | 1443 | 1670 | 1850 | 2152 |
| **In-Line Buoy (spherical)** | | | | | |
| Net buoyancy | Kips | | | 165 | |
| Dry weight | Kips | | | 14 | |
| Segment 3: Pendant Wire | | | | | |
| Length | Ft | | | 200 | |
| Size | | | | Same as Seg #2 | |
| **Segment 4: chain** | | **K4 studless** | **K4 studless** | **K4 studless** | **K4 studless** |
| Length | Ft | 150 | 300 | 600 | 300 |
| Diameter | Inch | 3.50 | 3.75 | 3.875 | 4.00 |
| Dry weight | Lb/ft | 110.78 | 127.17 | 135.79 | 144.69 |
| Weight in water | Lb/ft | 96.38 | 110.64 | 118.13 | 125.88 |
| Stiffness AE-average | Kips | 178616 | 205044 | 162670 | 233300 |
| Mean breaking load (MBL) | Kips | 1464 | 1698 | 1820 | 1949 |

**TABLE 3.3 RISER PARTICULARS MODELED**

| | No. | Top tension | OD | AE | EI | W (dry/wet) | Cdn |
|---|---|---|---|---|---|---|---|
| | | Kips | inch | Kips | Kips/ft | lbs/ft | |
| Liquid production risers | 4 | 250 | 17.5 | 4.12E+06 | 667 | 132/71 | 1 |
| Gas production risers | 4 | 137 | 15.2 | 2.43E+06 | 274 | 117/36 | 1 |
| Water injection risers | 2 | 454 | 20.9 | 4.18E+06 | 542 | 192/130 | 1.414 |
| Gas injection risers | 2 | 304 | 11.3 | 7.06E+05 | 155 | 124/80 | 1.414 |
| Gas export riser | 1 | 102 | 13.5 | 1.94E+06 | 172 | 93/29 | 1 |
| Total length of risers | | 6000 ft | | | | | |

**TABLE 3.4 HYDRODYNAMIC COEFFICIENTS FOR CHAINS, ROPE AND WIRE**

| | | Chain | Rope/Wire | Riser |
|---|---|---|---|---|
| Drag normal | Cdn | 2.45 | 1.2 | 1.0/1.4 |
| Drag tangential | Cdt | 0.65 | 0.3 | 0.4 |
| Added inertia coefficient normal | Cin | 2.0 | 1.15 | 1.0 |
| Added inertia coefficient tangential | Cit | 0.5 | 0.2 | 0.2 |
| Coulomb friction over seabed | F | 1 | 0.6 | 0.6 |

*Note: Chain added inertia coefficients based on nominal diameter (for chains diameter of the links)*

**TABLE 3.5 METOCEAN CONDITIONS**

| Description | Hurricane | Loop current |
|---|---|---|
| **Waves**: | | |
| Hs in m | 12.19 | 6.1 |
| Tp in sec | 14 | 11 |
| Wave spectrum type | JONSWAP($\gamma$=2.5) | JONSWAP($\gamma$=2.0) |
| Wave direction | 210° (to West) | 270° (to North) |
| **Wind:** | | |
| Wind speed | | |
| 1 hour mean speed | 41.12 m/s | 25.74 m/s |
| Wind spectrum type | API | API |
| Wind direction | 240° | 270° |
| **Current**: | | |
| Current direction: | 180° | 180° |
| 0 m-surface | 1.07 m/s | 2.13 m/s |

**TABLE 5.1 METHODOLOGY STATEMENTS OF PATICIPATING COMPANIES**

| Company | SBMI | | SOFEC | MARIN | MARINTEK |
|---|---|---|---|---|---|
| Type of Analysis | Time domain coupled analysis | Time domain non-coupled analysis | Frequency domain | Time domain | Time domain |
| Mooring System Model | Complete model from anchor to fairlead | Complete model from anchor to fairlead | Complete model from anchor to fairlead. | Complete model from anchor to fairlead | Complete model from anchor to fairlead |
| Riser System Model | Pinned connection at chaintable. Same types lumped together. | Pinned connection at chaintable. Same types lumped together. | Pinned connection at chaintable. All risers modeled. | Pinned connection at chaintable. Same types lumped together. | Pinned connection at chaintable. Same types lumped together |
| Wind Coefficients | MARIN Measurement | MARIN Measurement | MARIN Measurement | MARIN Measurement | MARIN Measurement |
| Current Coefficients | OCIMF | OCIMF | OCIMF | OCIMF | OCIMF |
| Wind Model | Wind speed time series | API wind spectrum | API wind spectrum | Wind speed time series | Wind speed time series |
| Response Coupling | FPSO/mooring/ riser coupled analysis | FPSO/mooring/riser non-coupled analysis | FPSO/mooring/ riser coupled analysis | FPSO/mooring/ riser coupled analysis | FPSO/mooring/ riser coupled analysis |
| Wave QTFs | Newman’s approximation | Newman’s approximation | Newman’s approximation | Newman’s approximation | Newman’s approximation |
| Wave drift damping | Computed at each time step | Averaged | Computed | Computed at each time step | User Input |
| Drag force on hull | OCIMF | OCIMF | OCIMF | OCIMF | OCIMF |
| Drag force on moorings and risers | Project defined. | Project defined. | Computed | Project defined. | Project defined. |
| Wave kinematics on mooring line dynamics | Included | Not Included | Included | Included | Included |
| Simulation time | 3 hours | 3 hours | 3 hours | 3 hours | 3 hours |
| Yaw angle | TD solution yaw motion equation | TD solution yaw motion equation | Coupled sway-yaw normal mode analysis | TD solution yaw motion equation | TD solution of yaw motion equation |
| Current load on moorings and risers | Included based on relative motion with surrounding fluid | Included as mean load | Included based on relative motion with surrounding fluid | Included based on relative motion with surrounding fluid | Included based on relative motion with surrounding fluid |
| Drag damping | Nonlinear | Linearized | Nonlinear | Nonlinear | Nonlinear |

**TABLE 8.1 COUPLED VS NON-COUPLED ANALYSIS**

| **Items** | **MARIN Tests** | **SBMI Coupled Analysis (*)** | **SBMI Non-Coupled Analysis** |
|---|---|---|---|
| X Offset (m) | 82.2 | 91.5 | 100.8 |
| Y Offset (m) | 40.0 | 23.6 | 46.3 |
| Z Offset (m) | 7.26 | 8.2 | 7.8 |
| Max Line Tension (KN) | 3145 | 3162 | 3247 |

*(*) Pre-test values, average of 10 runs without any tuning*

**FIGURE 3.1 FPSO MEASUREMENTS AND LINES PLAN**

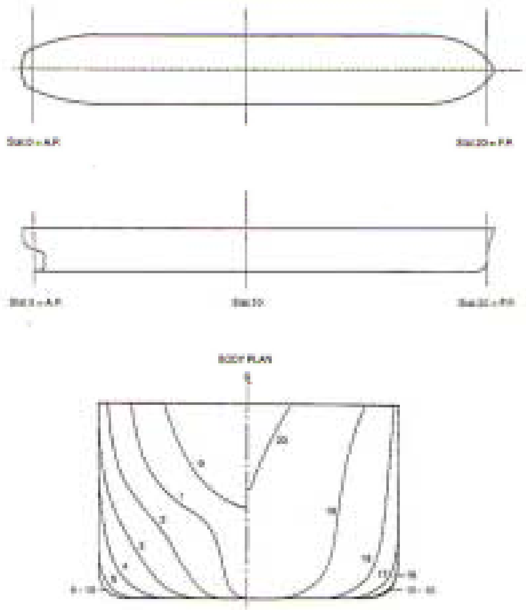

**Figure 4.1 Hurricane Test Setup**

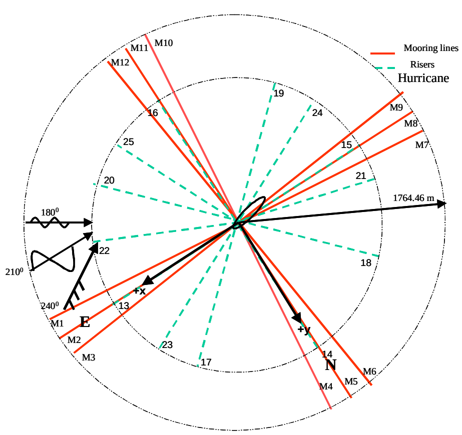


**Figure 4.2 Loop Current Test Setup**

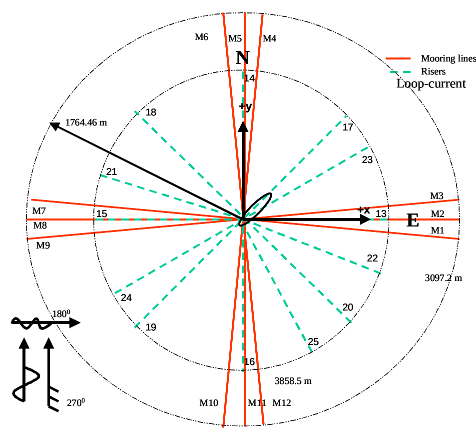


**Figure 6.1 Load Extension Calibration**

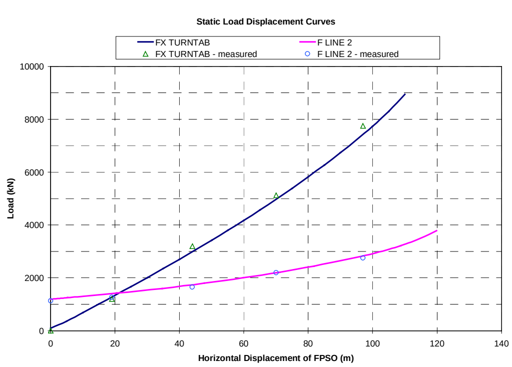


**Figure 6.2 – Surge Decay Calibration**

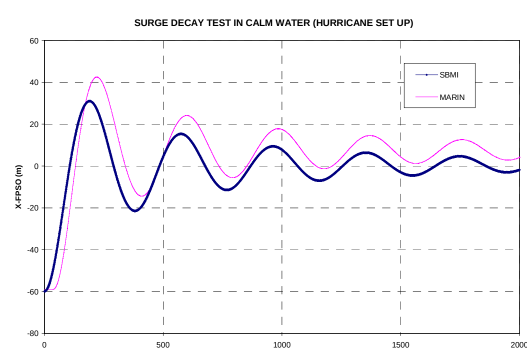

**Figure 6.3 – Roll Decay Calibration**

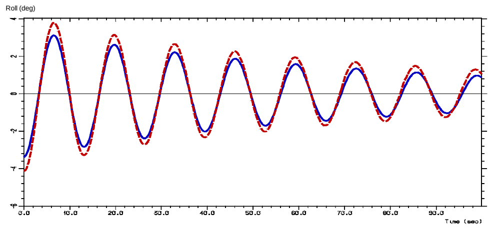


**Figure 6.4 Model the Model Comparison**

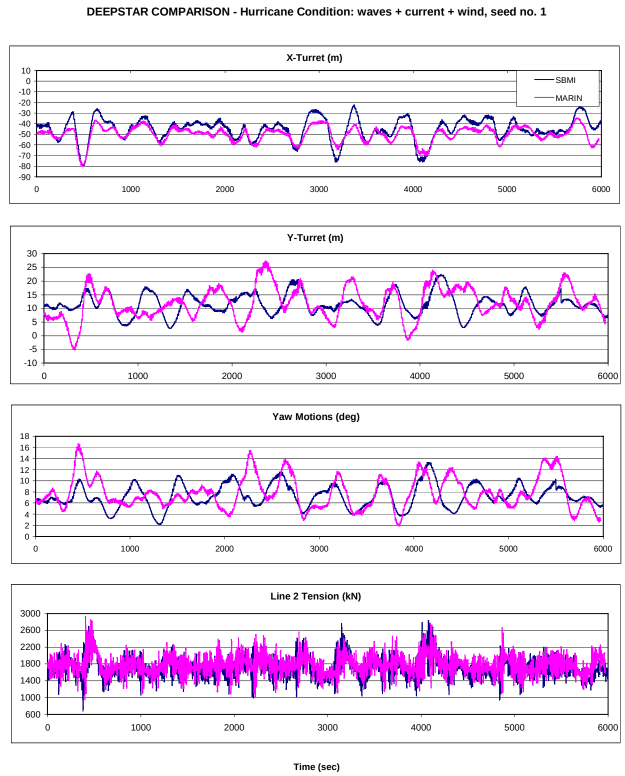

**Figure 6.5 – Hurricane condition: X-Offset**

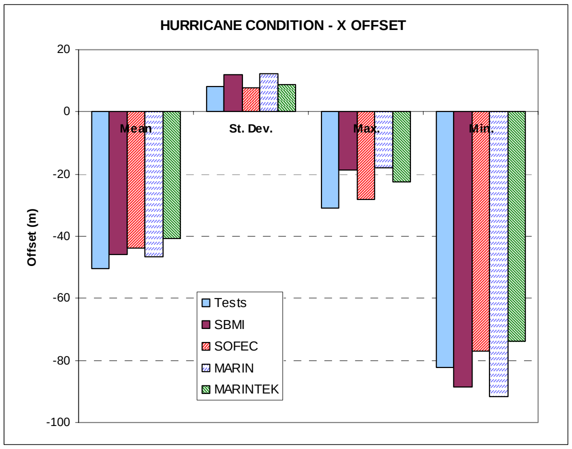


**Figure 6.6 – Hurricane Condition: Y-Offset**

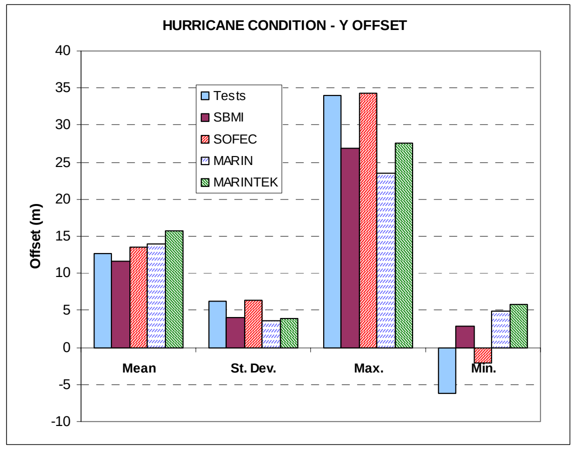


**Figure 6.7 – Hurricane Condition: Roll Motion**

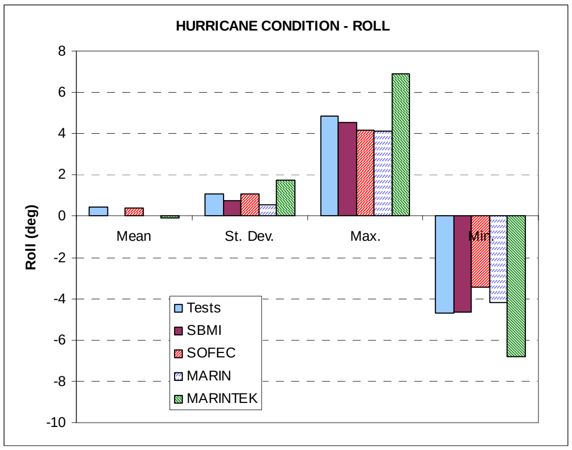


**Figure 6.8 – Hurricane condition: Yaw motion**

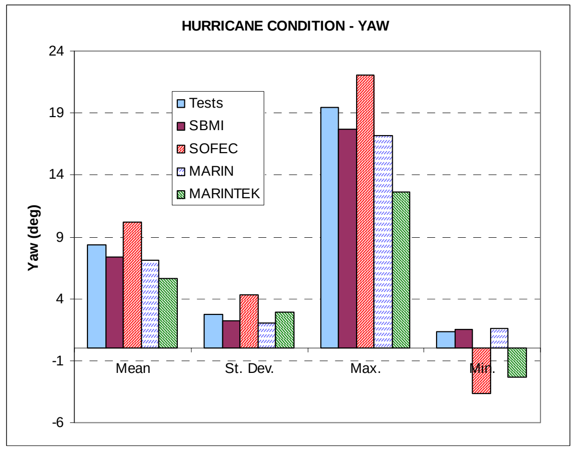


**Figure 6.9 – Hurricane Windward Tension**

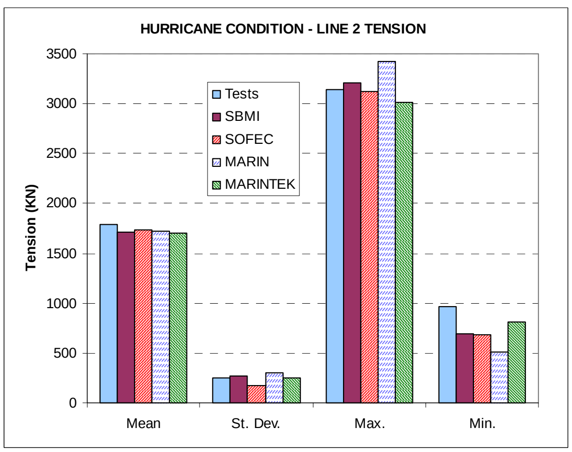


**Figure 6.10 – Hurricane Leeward Tension**

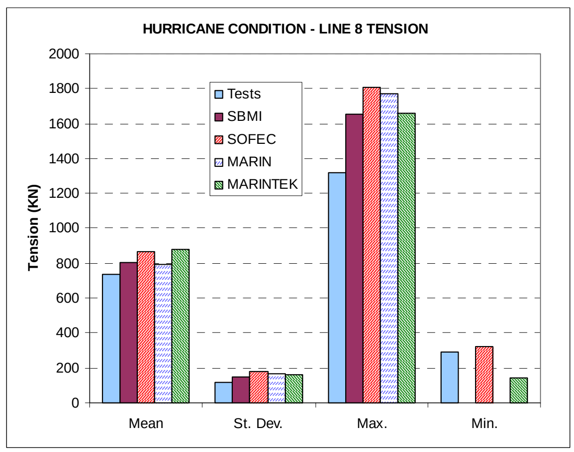

**Figure 6.11 – Loop Current condition: X-Offset**

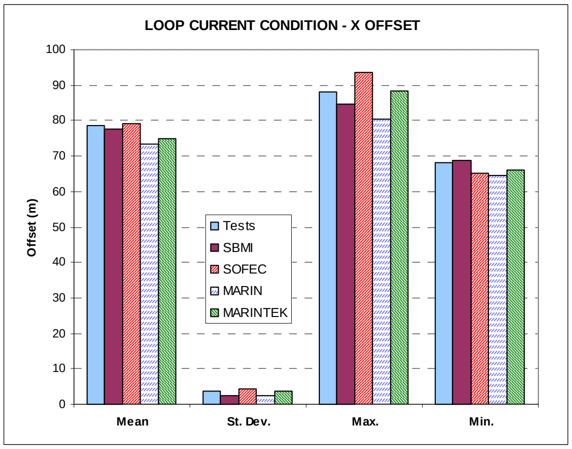


**Figure 6.12 – Loop Current Condition: Y-Offset**

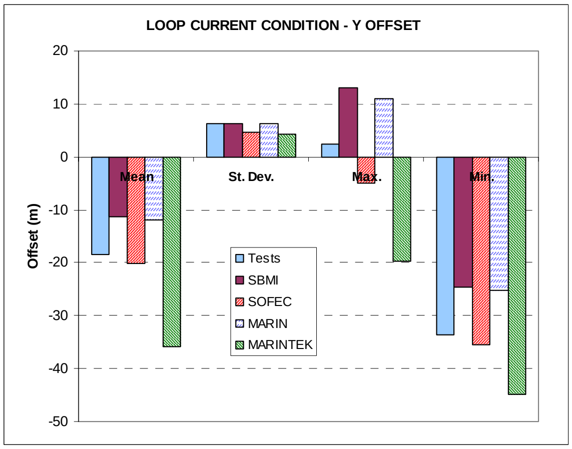


**Figure 6.13 – Loop Current Condition: Roll**

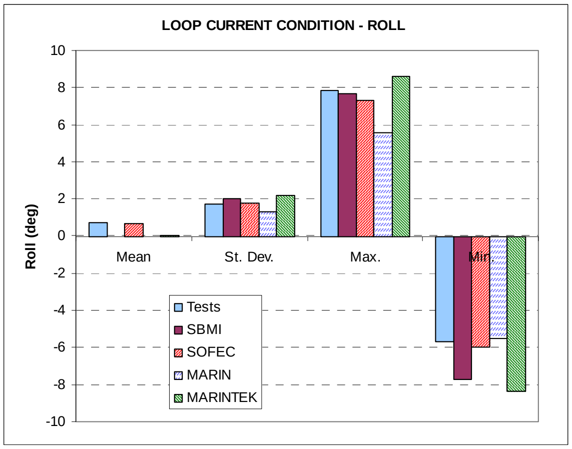


**Figure 6.14 – Loop Current condition: Yaw**

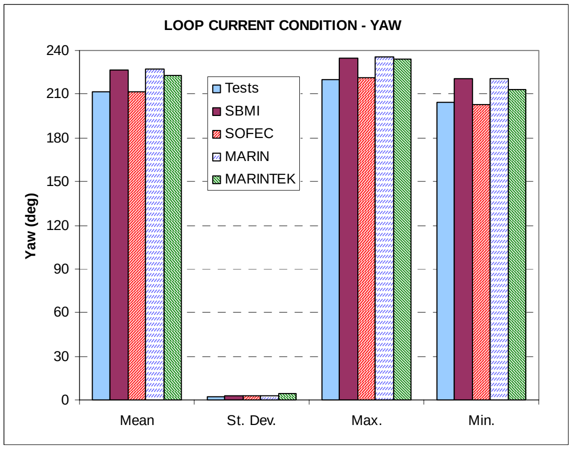


**Figure 6.15 – Loop Current Windward Tension**

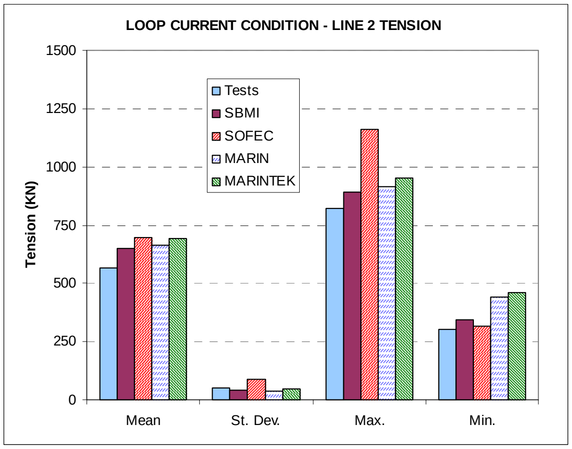


**Figure 6.16 – Loop Current Leeward Tension**