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VOLUME 2

COMMITTEE V.2
FLOATING PRODUCTION SYSTEMS

COMMITTEE MANDATE

Concern for the design of floating production systems. Specific emphasis shall be given to semi-submersible, TLP and spar-type hulls and recent industry experience (e.g. Gulf of Mexico 2004 and 2005 hurricanes and model tests) that influences their design methodology. Consideration shall be given to identification of uncertainties in response prediction.

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KEYWORDS

FPSO, FPS, Floating Production, Offloading, Monohull, Semi-Submersible, Spar, Tension Leg Platform, Hull, Riser, Pipe in Pipe, Steel Tube Umbilical, Steel Catenary Riser, Mooring, Anchor, Tether, Offloading, LNG, GTL

CONTENTS

1. INTRODUCTION

The Special Committee V.2 "Floating Production Systems" has to cover a very wide field of interest. The report therefore risks to become superficial if it would give a comprehensive overview of the research related to FPS's. On the other hand, an in-depth discussion of certain topics would automatically mean that the report cannot be complete, due to the limited volume of the report. The Committee has made an attempt to "steer clear of these rocks", guided by the Mandate and the specialism of its members.

In accordance with the Mandate for Committee V.2, the current report addresses extensively the consequences of hurricanes in the Gulf of Mexico area. Both the description of the environmental conditions as well as the consequences for offshore facilities are being discussed.

The 2006 Report focussed on FPSO's. Guided by the Committee Mandate, this sequel report covers spars, semi-submersibles and TLP's as well. Nevertheless, the FPSO concept, primarily based on converted trading tankers, attracts substantial attention from the research community, because of the required further refined description of fatigue of FPSO's with a trading history. Moreover, the FPSO concept remains by far the most commonly used for floating production.

Another reason for interest in the fatigue life prediction of FPS's, including ship-shaped FPSO's, is the issue of life time extension of these units. Tie-in of nearby fields through sub-sea completions require the platforms to stay on station for a longer period than originally anticipated.

The offshore community is already for some time in anticipation of the introduction of the FPSO concept in the Gulf of Mexico. In this report no specific information is comprised about research on this subject. However, in view of the new information regarding environmental design conditions for the US Gulf, it will be interesting to see, in the upcoming reporting period, if these would affect the opinion about optimum mooring and riser concepts for this application.

LNG production on Floating Production Systems also has attracted the interest of researchers in previous reporting periods. The lack of actual projects comprising offshore LNG production may be the reason for relatively few new publications on this subject in the reporting period for this 2009 Report. Moreover, some of the research on this subject has a pre-competitive, confidential nature, and is therefore not available in the public domain. However, related subjects remain of interest, such as loads due to sloshing in partially filled storage tanks. They are being covered under CFD developments. It may be expected that the focus on LNG will be intensified as soon as real projects become imminent.

In this report relatively little reference is made to the influence of arctic conditions on the design of FPS structures. Only the paper of Nyseth and Holtsmark (2006) about the behaviour of plate structures under ice loading can be mentioned in this respect. However, the Committee is of the opinion that, in the near future the consequences of arctic design conditions may become an important research topic. This opinion is in line with the decision of the ISSC Standing Committee to propose a new Committee focussing on Arctic Technology for the reporting period to come.

2. ENVIRONMENT

2.1 Hurricane Conditions in Gulf of Mexico

2.1.1 Overview

Platforms in the Gulf of Mexico experienced three hurricanes exceeding the nominal "100-yr Storm" condition in the course of about one year: Hurricanes Ivan (2004), Katrina (2005) and Rita (2005). Figure 2.1 shows the tracks of these intense storms in 2005.

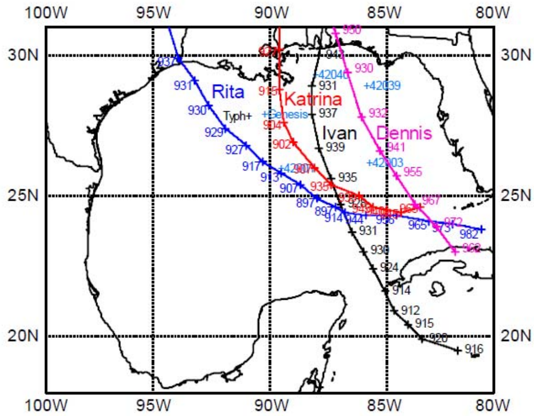

Figure 2.1: Tracks for Ivan, Dennis, Katrina and Rita (Cooper and Stear, 2006)

Hurricane Ivan generated the highest waves ever measured or hind cast in the Gulf of Mexico (Cooper *et al*., 2005). During the peak of Hurricane Ivan, the following conditions were measured at the Marlin TLP: H_s = 15.5 m, H_{max} = 26 m and Crest Elevation = 16 m. H_{max} of 26 m compares to the maximum wave height recommended by API RP 2A (2005a) of 21.5 m (70.5 ft). API RP2A does not specify a value for H_s.
These events caused a re-evaluation of the historical data and conclusions that had previously been used in recommending design waves in API RP2A. This re-evaluation resulted in three interim guidelines: Selection of Hurricane Parameters (API, 2007a),

Design of Offshore Structures (API, 2007b) and Assessment of Existing Structures (API, 2007c).

The main changes in the criteria focused on the central region of the Gulf of Mexico, between 89.5° W and 86.5° W (Figure 2.2). In particular, this region was found to be subjected to higher winds and wave heights (statistically) than other areas of the Gulf of Mexico (Berek *et al*., 2007).

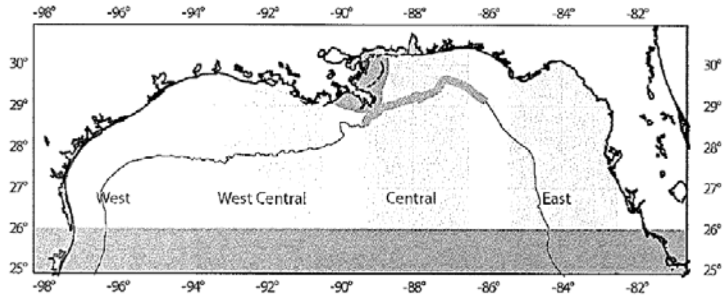

Figure 2.2: Gulf of Mexico regions for specifying hurricane wave conditions (API, 2007a)

New recommended criteria for four regions in the Gulf were proposed as opposed to the single criteria for the entire Gulf reflected in the 21st edition of RP 2A (API, 2005). A summary of these new criteria compared to the old criteria is given in Table 2.1.

A comparison between the proposed ISO criteria and RP 2A (API, 2005) is shown in Table 2.2.

Table 2.1
Parameters in API RP2A and DNV OS E301 compared to new parameters

	H_{max}	H_s	$A_{max\ crest}$	U_w, 1-hr	Uc, surface	Surge
	m	m	m	m/sec	m/sec	m
API RP-2A (2005)	21.5		14.8	41.1	1.1	1
DNV OS E301 (2004)		11.9		44.1		
Central	27.9	15.8	18.6	48.0	2.40	1.22
West Central	21.7	12.3	14.5	38.1	1.91	1.08
West	23.1	13.1	15.2	39.9	2.00	1.02
East	21.6	12.2	14.5	38.4	1.92	0.95

Table 2.2
Comparison of ISO and API criteria (Ghoneim and Colby, 2005)

GoM Design Criteria		
Wind (in mph)	10-min average	One-hour average
API RP 2A (2005)	101	92
ISO 19901-1 (2005)*	103	94
Waves	Hmax (in m)	Period (in s)
API RP 2A (2005)	21.5	13.0 (Tm)
ISO 19901-1 (2005)*	25.8	14.9 (Tp)
*Note: ISO includes IVAN		

The API Committee on Offshore Structures (SC2) recently decided to consolidate all environmental conditions related to the Gulf of Mexico (including waves, winds, surface and subsurface currents) into a single Recommended Practice (2MET) to which all other Recommended Practices will refer (Stear, 2008). Following the strategy of "align and merge" for reconciliation between API and ISO standards, the new RP 2MET is essentially a copy of ISO 19901-1 (International Standards Organization, 2005), with changes and updates made to various sections, in particular the ISO Gulf of Mexico Annex.

The work reported by Berek *et al* (2007), of which the environmental parameters are presented in summary in Table 2.1, will be used by API. More comprehensive data from this publication, applicable to the governing region "Central", is presented in Table 2.3.

Table 2.3
Extreme values for tropical cyclone winds, waves, currents and surge for central Gulf of Mexico (Berek *et al*., 2007)

Return Period (Years)	10	25	50	100	200	1000	2000	10000
Wind (10 m elevation)								
1 hour mean wind speed (m/s)	33.0	40.1	44.4	48.0	51.0	60.0	62.4	67.2
10 min mean wind speed (m/s)	36.5	44.9	50.1	54.5	58.2	69.5	72.5	78.7
1 min mean wind speed (m/s)	41.0	51.1	57.4	62.8	67.4	81.6	85.6	93.5
3 sec gust (m/s)	46.9	59.2	66.9	73.7	79.4	97.5	102.5	112.8
Waves, Water Depth ≥ 1000 m								
Significant Wave Height (m)	10.0	13.3	14.8	15.8	16.5	19.8	20.5	22.1
Maximum Wave Height (m)	17.7	23.5	26.1	27.9	29.1	34.9	36.3	39.1
Maximum Crest Elevation (m)	11.8	15.7	17.4	18.6	19.4	23.0	23.8	25.6
Peak Spectral Period (s)	13.0	14.4	15.0	15.4	15.7	17.2	17.5	18.2
Period of Maximum Wave (s)	11.7	13.0	13.5	13.9	14.1	15.5	15.8	16.4
Currents, Water Depth ≥ 150 m								
Surface Speed (m/s)	1.65	2.00	2.22	2.40	2.55	3.00	3.12	3.36
Speed at Mid-Depth (m/s)	1.24	1.50	1.67	1.80	1.91	2.25	2.34	2.52
0-Speed Depth (m)	69.3	84.2	93.2	100.8	107.1	126.0	131.0	141.1
Water Level, Water Depth ≥ 500 m								
Storm Surge (m)	0.32	0.52	0.66	0.80	0.93	1.13	1.22	1.41
Tidal Amplitude (m)	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42

2.1.2 Analysis of Gulf of Mexico Data

The hurricane seasons of 2004 and 2005 sparked a wave of re-analysis of hurricane hind cast information. This triggered a number of papers in the Offshore Technology Conference and it was featured as a main topic at the 10th International Wind and Wave Workshop in November 2007 (see e.g. Cardone *et al*., 2007, Westerink *et al*., 2007, and Dietrich *et al*., 2007).

Re-Analysis of Gulf of Mexico data (Cooper and Stear, 2006) indicated that there was not a single storm of sub-930 mb intensity prior to 1965. The authors considered four possible explanations for the apparently abnormal number and strength of hurricanes in the 2004-2005 seasons:

a) Global warming
b) Natural long-term climate variability
c) "Chance"
d) Bias in the data

Global Warming
Emanuel (2005a and 2005b) and Webster *et al*. (2005) have noted an increase in the number of intense storms in the past 40-odd years, and attempted to find a correlation with the increased sea surface temperature due to global warming. However, it was suggested that the data on this research is inconclusive (Klotzbach, 2006). The analysis by Cooper and Stear (2006) of Gulf of Mexico temperature rise failed to show any trends. Overall, Cooper and Stear (2006) could not find a strong case for the recent hurricanes being a result of increasing oceanic temperatures.

Natural Long-Term Climate Change
Cooper and Stear (2006) concluded that the effect of long term climate change on hurricane intensity cannot be correlated yet, because of the short time of reliable hurricane measurements.

Chance
Cooper and Stear (2006) examined a number of random events to see if the 2004-2005 hurricanes could simply be a result of "chance". They gave the probability of an intense hurricane in the Gulf of Mexico to be the result of the joint probability of four independent events:

a) A storm of sub-981mb intensity enters the Gulf of Mexico
b) Favourable atmospheric/shear condition
c) Presence of the Loop Current in the Storms track
d) Favourable steering flow

The authors also unveiled their ongoing work on establishing probability distributions for these variables and propose to apply Monte Carlo simulations for establishing the conclusion that the 2004-2005 seasons could be explained on the argument of "chance" alone (i.e. presumably whether the chance of this occurrence would be finite). The authors state that this work is ongoing.

Data Bias

Cooper and Stear's (2006) analysis indicated that a bias was introduced into the evaluation of hurricane data by including storms prior to 1950. From the work of Graham and Hudson (1960), Cooper and Stear observed that estimates of offshore intensity (central pressure index) of storms prior to 1950 relied heavily on extrapolation of coastal measurements to offshore locations as straight lines, i.e. no weakening near shore was assumed. Cooper and Stear found that when the pre-1950 storms are removed from the database, the 2004-2005 seasons do not look quite so unusual.

2.1.3 Hind casts

Current criteria for the Gulf of Mexico are based on the GOMOS USA (Gulf of Mexico Oceanographic Study) conducted in-house by Oceanweather, Inc. (Stiff *et al*., 2006). This is an update of three previous Joint Industry Projects, and is available for licensing from Oceanweather. GOMOS comprises three parts: tropical cyclone hind casts (all GoM storms 1900 – 2005), extra-tropical cyclone hind casts (70 winter storms), and a 13-year continuous hind cast (1990 – 2003) for operability studies. These hind casts were all made on a fine grid with spacing of 1/8th of a degree, as shown in Figure 2.3.

The evolution (time series) of winds, waves, surges and 2D currents were generated for each grid point. This database presents a rich source for further study. Stiff *et al*.(2006) used the database to demonstrate a methodology to determine if a jack-up rig (operating in shallow water) could be safely operated, and successfully abandoned, prior to the arrival of a damaging tropical event. The API and MODU Groups (Berek *et al*., 2007) used the GOMOS database to establish new criteria for the Gulf of Mexico as described in Section 2.1.1. Their methodology is a result of selecting five points in each region using the principles of grid point "pooling" introduced by Haring and Heideman (1978) and Heideman and Mitchell (2007). The pooling method assumes that the winds and waves experienced by J grid points in a homogeneous area over Y years is equivalent to the hind cast values that would be experienced by a single random point over a period of J x Y years. This requires that the data points used are affected by different storms (i.e. the same storm does not affect two points). Toro *et al*.(2004) compared this method with other methods for estimating extreme values and concluded that the pooling method works well for return periods of several hundred years or less.

The API group treated each of the regions shown in Figure 2.3 as "homogeneous" and negotiated for GOMOS hind cast data at five select points in each region. Their N-year results for the Central Gulf are shown in Table 2.3.

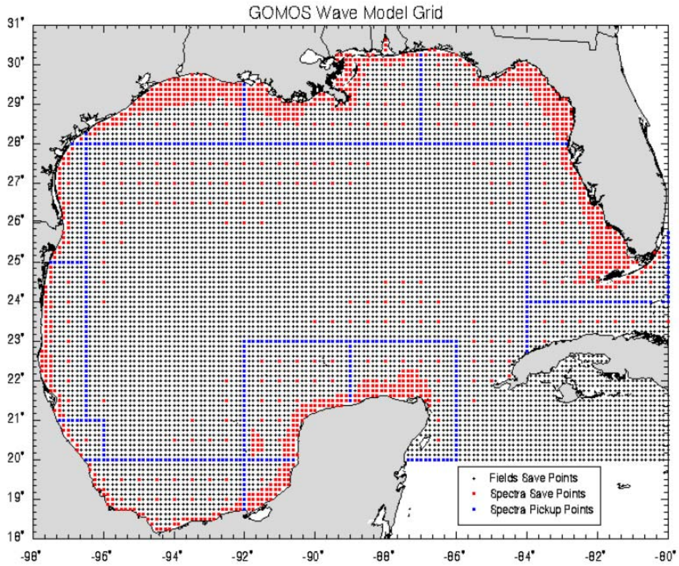

Figure 2.3: GOMOS hind cast grid (Stiff *et al*., 2006)

2.1.4 Wind Gusts and Spectra

Cooper *et al*. (2005) compared two one-hour segments of the wind record measured at the Marlin TLP during hurricane Ivan on September 15, 2004. They compared gust factors and wind spectra with used in API R2A. Their conclusions are that the NTS/API wind gust factors and spectra currently used in API RP2A are in reasonable agreement with the measurements.

2.2 Prediction of Large Waves

2.2.1 Introduction

Rogue waves are extreme events with potentially devastating effects on offshore structures and ships. A rogue wave, observed at the Draupner platform in the North Sea during a storm in January 1995, provides evidence that such waves can occur in the open ocean.

Research has focussed on the mathematical description of the sea surface and the preparation of stochastic models for the prediction of large waves, as well as on the spatial effect of wave grouping and multi-directional wave fields.

2.2.2 Stochastic models

When second-order nonlinearities are dominant, the sea surface displays sharper narrower crests and shallower more rounded troughs. As a result, the skewness of surface elevations is positive, and wave crests are distributed according to the Tayfun model (Tayfun, 2006) or the Forristall distribution (Forristall, 2000).

The Tayfun model originates from the second order narrow-band model of Stokes waves. Recently Fedele (2008), Tayfun and Fedele (2007), Fedele and Tayfun (2008) proved that the Tayfun model can also be applied to large second order waves, irrespective of the spectral bandwidth.

2.2.3 Spatial effects

The prediction of large waves is traditionally based on the statistical analysis of time series of the wave surface displacement retrieved from wave measurement devices at a stationary location.

The probability that such a stationary device picks up the largest crest height which could occur as the result of the dynamical effects of a group, or which could be caused by the interference between wave fields having various directions, is very limited. Therefore spatial effects have to be observed and analysed.

Fedele *et al*. (2008) and Gallego *et al*. (2008) proposed a video observational technology that is able to provide a multi-dimensional image of the oceanic state. Specifically, they proposed a novel ***W****ave* ***A****cquisition* ***S****tereo* ***S****ystem* (**WASS**) for the reconstruction of the water surface of oceanic sea states (Benetazzo, 2006). The rich informative content of the acquired three-dimensional video data measured by **WASS** was then exploited to compute reliable estimates of both the directional wave spectrum and the expected global maximum (largest crest height) over an area using the Euler Characteristic of random excursion sets (Adler, 1981; Adler and Taylor, 2007).

Other studies focussing on the prediction of height and probability of extreme waves were reported by Holliday *et al*. (2006), Guedes Soares *et al*. (2006), Dankert and Rosenthal (2004), Krogstad *et al*. (2004), Guedes Soares *et al*. (2003). Results obtained from the European Project MAXWAVE, which dealt with both theoretical aspects of extreme waves and new techniques to observe extreme waves using different remote sensing techniques, were described by Lehner and Rosenthal (2006).

The expected highest wave height over an area is of relevant significance in the offshore industry for a proper design of the air gap under the deck of offshore structures, with the aim to avoid localized damages. The expected highest wave height over an area can be obtained via application of Piterbarg’s results on global maxima of Gaussian fields (Piterbarg, 1995), or by the aforementioned Euler characteristics of excursion sets. Forristall (2006, 2007) applied Piterbarg's theorem to the air gap problem, and showed that this approach can explain observed damages during hurricanes.

2.3 Damage caused by extreme crest elevations

While the information in Section 2.2 suggests that crest elevations may be higher than previously predicted, recent studies on wave-in-deck forces clearly indicated that damage from extreme crests is localized, probably due to the short crested nature of confused seas (Qian and Marshall, 2007). This fact mitigates the global loads on the structure at the expense of higher local loads. Van Raaij and Gudmestad (2007) derived an empirical formula for predicting global wave-in-deck loads.

2.4 Update of DNV CN30.5

In an ongoing Joint Industry Project, DNV Classification Note 30.5: Environmental Conditions and Environmental Loads has been updated in accordance with the present state-of-the-art and corresponding industry needs and at the same time converted into a DNV Recommended Practice DNV-RP-C205 (Nestegård *et al*. 2006, DNV, 2007). The updates include topics on non-linear wave diffraction around large volume structures, higher order wave loading, slamming, run-up and wave in deck loads. The new RP also includes an improved description and statistical modelling of wind and ocean waves. Other new topics are shallow water waves and their load effects. New and updated guidance is provided on vortex induced vibrations in current and waves, and vortex induced motions of floaters.

2.5 European Storm Statistics

2.5.1 MARSTRUCT

The European Union network MARSTRUCT (www.mar.ist.utl.pt/marstruct/) is a 5-year programme for jointly executed research in the area of structural analysis of ships, the creation of research facilities and platforms and a continuous programme of dissemination and communication of research results. The main task of this project is to develop design environmental conditions for merchant vessels in Northern Europe (Guedes Soares and Pacheco, 2005; Pascoal *et al*., 2005).

It has long been a practice to extract wave spectra from buoy measurements, however the distribution of buoys is limited. To overcome this problem, one of the goals of the aforementioned research was the evaluation of procedures for extracting ocean wave spectra from ship motions. Pascoal *et al* (2005) evaluated parametric (based on a JONSWAP spectral shape) and non-parametric approaches to this problem, and found that the parametric representation is inherently smooth and easier to read than a non-parametric, but that this is probably the only advantage. The non-parametric representation converged in two minutes on average, for any type of generated spectra, while the parametric representation took three minutes for a single peak and failed to converge for poor search basins. In the parametric formulation, a genetic algorithm has shown a good candidate to provide the initial search basis for a gradient search algorithm.

Numerical comparisons were made using a simulated directional spectrum and theoretical transfer functions for an offshore supply boat. For the heading selected, Hs predictions were within 6% of the simulated Hs. The spectral shape was similar but had some extraneous peaks. Benchmarking of this procedure against actual sea states in wave tank or offshore, could not be located.

Bernardino *et al* (2008) proposed a new approach for storm statistics based on a Lagrangian model, i.e. incorporating the spatial distribution of storm parameters into the model. The classical Eulerian approach is capable to provide the storm frequency and statistics about storm duration and intensity as functions of different storm definition thresholds, but only for a given location.

Both approaches were applied to 10-year wave data and it was verified that information about intensity, duration and storm frequency is possible to obtain from both. However, these parameters have different meanings in the Eulerian and in the Lagrangian approach. Despite the different meaning of these parameters in both approaches, the relation between storm duration and storm intensity are similar in shape and the storm duration can be fitted by a two-parameter Weibull distribution. In the Lagrangian approach, more storm characteristics are possible to obtain, such as storm area, times of rise and decay, storm direction and even the coordinates of the storm path.

2.5.2 Hind cast of Dynamic Processes of Ocean and Coastal Areas of Europe

A 40-year wave hind cast for the Northeast Atlantic was provided by the project WASA (Günther *et al*., 1998). The WASA data set has proved to be very useful, but it did not provide a long term, fine scale homogeneous marine and atmospheric data set, including currents, specifically designed for coastal applications. As a result, the European Union funded project HIPOCAS—Hind cast of Dynamic Processes of the Ocean and Coastal Areas of Europe (Guedes Soares, 2008). HIPOCAS provided an improved quality of the wind fields close to the coast of Europe, by applying a technique to obtain small-scale analyses from the global re-analyses.

A special issue of the Journal of Coastal Engineering is being devoted to the results of HIPOCAS (see e.g. Musič and Nickovic 2008, Sotillo *et al*. 2008, Sebastião *et al*, 2008, Rusu *et al*. 2008, Ratsimandresy *et al*. 2008, Ponce de Leon and Guedes Soares 2008, Pilar *et al*. 2008, Cherneva *et al*. 2008).

2.6 Asian Environmental Conditions

There was little literature found on Asian environmental conditions (at least in English) compared to the Gulf of Mexico or Europe. Dong *et al*. (2008) analyzed 29 years of wind and wave data collected at the Weizhoudao Observation Station in the northern South China Sea. Simulations of the design base shears of a jacket platform were performed by using three distribution models. The results showed that the design base shears obtained from a bi-variable Pearson-III distribution model were considerably less than those resulting from the conditional distribution model, and significantly less than those derived from the independent distribution model. This suggests that in determining design loads of marine structures, it is important to consider the joint probabilities of extreme environmental conditions, since such a consideration would reasonably reduce the design load. The recommendation was made to apply the bi-variable Pearson-III distribution model (Pearson, 1895) to determine design environmental conditions for marine structures.

3. STRUCTURAL DESIGN ASPECTS OF FLOATING PLATFORMS

3.1 Factors Influencing Structural Design

Before entering into particular items for each of the different categories of floating production systems (i.e. FPSOs, semi-submersibles, spars and TLPs), factors of a general nature that influence the structural design procedures are addressed. The factors considered are:

- Hurricanes
- Extreme events, other than hurricanes (e.g. abnormal waves and squals)
- Application of model tests for design purposes

Hurricanes
In Section 2.1 publications have been cited, which deal with the description of hurricane conditions. Further knowledge is required to evaluate the effect of hurricanes on the design of FPS's.

An important path to reviewing technology is through failure investigation, which enables understanding of appropriate levels of safety and assurance of design criteria. Timerman *et al*. (2008) described the case of the TLP Typhoon. This TLP was found upside down after the passage of hurricane Rita. The paper addresses an investigative analysis carried out in order to establish the possible causes that resulted in the capsizing of the referred unit. The investigation focused on two major paths which were selected as being the most probable and also were feasible to be simulated: one that analyzes a possible lack of displacement due to the passage of a hurricane wave and the consequent loss of stability of the TLP and the other, concentrated on a dynamic analysis of the unit under the impact of the hurricane metocean conditions. This second analysis focused on obtaining the loads in the tethers, to establish if either they suffered excessive tension causing them to break or compression with possible associated buckling. Even though results need to be enhanced by more accurate models, the investigative analysis has revealed possible flaws, that could have led to the capsizing of the TLP.

Full-scale measurements were obtained from other platforms during the hurricanes, such as the Marco Polo Tension Leg Platform (Van Dijk *et al*. 2007, Mitchell *et al*.

2006), and the Horn Mountain Spar (Xu *et al*. 2007) for hurricane Ivan, and Tahar *et al*. (2006), Halkyard *et al*. (2004) and Tahar et. al. (2005) for hurricane Isodore.

The monitoring system installed on the Marco Polo Tension Leg Platform, was in operation during the passage of hurricanes Ivan, Katrina and Rita. Although Marco Polo was extremely close to the centre of these severe hurricanes, no significant damage was inflicted to the platform, even though wind speeds in excess of 62 m/s and maximum wave heights over 28 m were measured. However, very valuable data were collected on the wave, wind, current, as well as on the response of the TLP during the Hurricane conditions.

As part of a Joint Industry Project measurements on board of the Marco Polo TLP have been ongoing for nearly three years without interruptions. Although the motions of the platform have some effect on the measured wave elevation, in general these effects are small. For detailed analysis of extreme waves these factors can be taken into account. The three major hurricanes all passed Marco Polo at close distance. The measured extreme wave heights exceeded the expected extreme values. In hurricane Rita a maximum wave height of 26.9 m was observed (including the correction for platform motions) with an associated crest height of 17.4 m. Using the data of all three wave radars the wave spreading during the three hurricanes has been assessed. Significant differences in wave spreading have been observed between hurricanes Ivan and Katrina (with Marco Polo on left side of track) and Rita (with Marco Polo on right side of track). In some of the extreme waves that were observed on Marco Polo high frequency vibrations were observed on the topsides, which indicate impact loads of these extreme waves on the columns, although no structural damage was observed.

The system layout for the Horn Mountain Spar is illustrated in Figs. 3.1, and 3.2. This spar experienced the full strength of Hurricane Ivan, a virtually 2500-yr wave and 600-yr wind in the Gulf of Mexico in 2004. The measured and hindcast sea state reached a 16 m significant wave height and 45 m/s wind speed (1-hr average at 10m elevation), which is significantly higher than the spar’s maximum design criteria of 12.7 m wave height and 40.2 m/s wind speed. Both the environment and spar responses in the hurricane were measured. However, 6 hours prior to the peak of the storm, the generator which powered the instrumentation stopped, preventing further measurements. In order to estimate the spar's actual responses at the peak of the storm and to evaluate the accuracy of the existing spar motion analysis tools, a blind analysis test was performed using the measured and hindcast environmental conditions as input. The analysis results were then compared to the last available measurements of the spar responses in the hurricane. Since the analysis from the design phase was known to be conservative, a fully coupled spar motion analysis model was used in this blind analysis test in order to achieve a higher level of accuracy. The environmental condition was also modelled to a higher level of detail than in the design phase, including wave spreading, dual-peak and wave spectrum. Some minor adjustments to the fully coupled model were necessary to achieve the desired accuracy.

Figure 3.1: Horn Mountain spar

Figure 3.2: Typical truss-spar Arrangement

From the blind test and the subsequent motion analysis for the peak of the storm, the following conclusions could be drawn: (1) The result from the fully coupled analysis model generally agrees very well with the measured spar motion responses early in the storm when measurements were still available and (2) The spar's pitch, roll and heave responses were estimated to be within the design limit even though the environment measured at a nearby platform significantly exceeded the maximum design condition at the peak of the storm

The calculated Line-6 tension was found to be significantly higher than the design criteria, even though the current velocity was smaller than the design value. The tensions at the wire rope top and anchor were also significantly higher than the design allowable. An underwater inspection of all mooring lines was performed in October 2004 and an underwater survey of all mooring line catenaries was performed in September 2006. Neither the inspection nor the survey revealed any damage to Line-6.

Halkyard *et al*. (2004) and Tahar *et al*. (2005) have compared measured spar responses such as motion and mooring line tensions with numerical predictions. In Halkyard *et al*. (2006), this work was extended based on comparison of the full scale data during hurricane Isidore. Results of time domain and frequency domain simulations were compared with field measurements. Particular attention was paid to the importance of the phase relationship between motion and excitation force. The time domain analysis showed better agreement with the field data than the frequency domain. Overall, however, the frequency domain method is still promising for a quick assessment of relevant statistics, and therefore suitable for a pre-design evaluation.

<u>Abnormal waves</u>

In Fonseca *et al*. (2007, 2006a, 2006b, 2005) and Guedes Soares *et al*. (2006a, 2006b) structural response to abnormal waves was considered. In the first of these papers, an advanced time domain method was applied to calculate the responses of an FPSO in deterministic wave traces comprising abnormal waves. The analysis focussed upon probability distributions of the vertical bending moments in an FPSO, induced by measured sea states with such abnormal waves. The simulations were carried out for storm durations of three hours. For examples of resulting vertical bending moments refer to Fig.3.3.

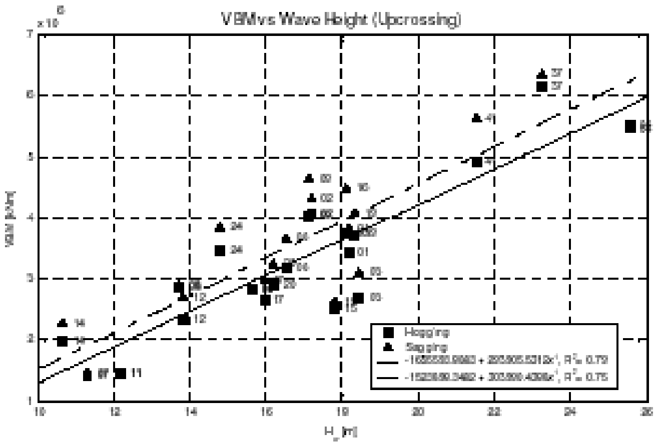

Figure 3.3: Correlation between hogging and sagging peaks and the height of abnormal waves

The authors concluded that the abnormal waves do not induce abnormal vertical bending moments, meaning that while the probability of occurrence of the abnormal waves is very low, the magnitude of the moments induced by these waves are not extreme to the same extent. Some of the largest measured abnormal waves were characterized by an extremely high crest compared to the trough. These type of waves appeared not critical in terms of global bending moments. The 3-hour simulations in the storms in which the abnormal waves were detected, comprised of several other wave sequences that induced moments larger than those due to the "abnormal wave events". These wave sequences were characterized by groups of 3 or 4 nearly regular waves with a period that maximizes the vertical bending moment response. A method based on the Hilbert Huang transform was tested. The objective was to correlate the amplification of the vertical bending moment responses with the dominant frequency content of the irregular wave encountering the platform, and this was found to be a satisfactory approach.

Clauss *et al*. (2007) and Jacobsen and Clauss (2006) presented a segmented FPSO model with amidships force transducers at two levels, which was investigated in various deterministic wave sequences to identify the vertical bending moment and its associated neutral axis, in combination with the simultaneous longitudinal forces. It was shown that the neutral axis of the vertical bending moment is far below the water line level, with the consequence that the highest cyclic loads would be expected at deck level. However, since the simultaneous longitudinal forces - even if significant – appear to generate a counteracting moment, this effect is largely compensated. Both, frequency- and time-domain results are presented. The frequency-domain analysis provided the basic data for the standard assessment of structures, concerning sea keeping behaviour, operational limitations and fatigue. The time-domain analyses in real rogue waves gave indispensable data on extremes, both for motions and structural forces. In the numerical simulations as well as in the sea keeping model tests, it was assessed that even loads due to freak waves are still covered by IACS-rules.

Squalls

Squalls have been present in the environmental specifications for floating units in West Africa for the last couple of years. It appears that such phenomena tend to be the designing factor for mooring systems of deepwater FPSO's (in spread or turret moored configuration) and offloading buoys, as highlighted by Legerstee *et al*. (2006). At the design stage, due to the lack of proper modelling/characterisation, squalls tend to be represented for design purposes by on-site recorded time series of varying wind velocity and associated relative headings applied from any direction. This leads to rapid changes in offsets and loads in the mooring lines induced by the transient response of the vessel to sudden load increase which is generated by such a representation of the squall (see Fig.3.4). Through diverse simplified example calculations, the paper illustrated the influence of the consideration of squalls in the design process. Present shortcomings in the modelling process, either in terms of extreme conditions, or in terms of operating conditions are addressed, knowing that such events are difficult to be forecasted. In addition the effect of tugs, and associated operational limitations were also discussed as well as areas needing further investigation. Dedicated instrumentation, sharing of collected data and statistical processing are listed as important issues.

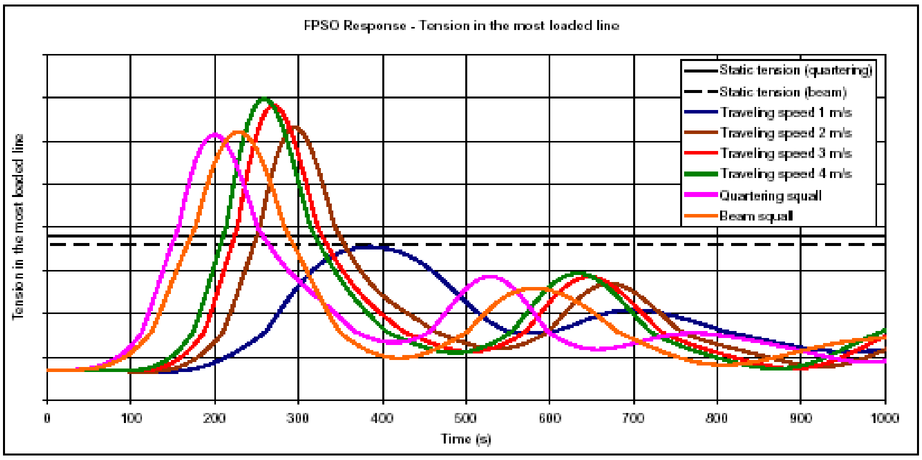

Figure 3.4: FPSO response to a forward travelling front

Application of model tests

Papers which address the application of model tests combined with numerical computations of platform response are considered next.

Spar production systems are subject to Vortex Induced Motions (VIM) which may impact mooring and riser design. Helical strakes are employed to mitigate VIM. Model tests are typically required to validate the performance of the strakes. Halkyard *et al*. (2005) and (2006), and Atluri *et al*. (2006) discussed the comparison of computational fluid dynamics (CFD) results with model tests, based on benchmarking studies that have been conducted over the past few years,. "best practices" for the use of CFD for these types of problems and issues related to turbulence modelling and meshing of problems at large Reynolds numbers.

These studies as well as other studies indicated that CFD may be used to successfully to predict the occurrence of VIM. In particular, the "hot spots" for a particular spar configurations are identified and the amplitudes are conservatively estimated. Evidence is provided that the amplitudes may be more accurately predicted when refining the mesh, particularly in the area of the boundary layer. Run times remain practical for engineering purposes. Consequently, in the early design stages, CFD seems practical for looking into sensitivities, such as the relative affect of strake height and pitch and the impact of appurtenances. There is still not enough benchmarking work done to recommend that CFD should replace experiments for obtaining final design values, but as more studies are performed it is believed that this is a reasonable goal.

Similar to SPAR platforms, it was also assumed that mono-column floaters (see Fig. 3.5), can exhibit VIM behaviour. Hence, an experimental investigation was started in a towing tank, which focused on VIM responses of small-scale mono-column floaters. Cueva *et al*. (2006) presented a set of preliminary results, considering environmental conditions for the Campos Basin and GoM. In accordance with other VIM studies, a strong effect of the heading on VIM was confirmed. The maximum cross flow amplitude varied from 0.8D to 1.2D, for different headings. The need of experiments in a wider range of headings was illustrated accordingly. An assessment is also given of the impact of VIM of mono-column floaters on the mooring line design and riser specification.

Figure 3.5: Mono-column floater

Application of model test data in global design of TLPs was addressed by Phadke *et al*. (2006). Rapid advances in computer technology have made it possible to employ sophisticated time-domain techniques as primary tools for the global performance analysis of TLP systems. However, response characteristics such as higher-order tendon response, wave runup and air gap can still not accurately be predicted using the available numerical tools. Wave basin model tests, therefore, are indispensable to designers for estimating responses that cannot be reliably predicted. At the same time, using model tests alone as an analysis tool is not practical due to large number of design cases typically defined in global performance analysis. It is necessary to verify and calibrate numerical tools using model test data prior to their application in global performance analysis. The paper described a methodology for calibrating and correlating predicted response from time-domain software tools against wave basin model tests. The application of correlation data in conjunction with predicted response to obtain various design quantities of interest was investigated. Discussion for determination of model test correlated design maximum/minimum tendon tension, higher-order tendon tension response, and incorporation of vortex induced motion was presented. A simple technique for incorporating VIM response, measured in model tests, into time-domain analysis tools was also described. These methodologies have been used in the design of deepwater TLP systems in GoM and elsewhere.

In anticipation of Floating Production Vessels for offshore LNG production, significant research is devoted to sloshing of LNG in partially filled storage tanks. The structural particulars of the storage tanks require an accurate evaluation of design pressures. Most of the research is based on numerical simulations using Computational fluid Dynamics (CFD). However, there is the need to validate results, using physical modelling in controlled conditions. Wemmenhove *et al* (2007) presented the progress made with a numerical simulation, using two-phase compressible flow. Their paper also reports of validation model tests at relatively large scale (1:10), executed for different types of motion of the sloshing tank and different filling ratios. Bunnik and Huijsmans (2007) provide further details of same verification model tests.

Baarholm *et al*. (2006), Fylling and Stansberg (2005) and Stansberg *et al*. (2002) addressed model tests for global design verification of floating production systems in depths beyond 1000m to 1500m, which cannot be made directly at reasonable scales. Truncation of mooring line and riser models, software calibration, as well as extrapolation and transformation to full depth and full scale are required. The paper discussed that the choice of proper procedures for the set-up and the interpretation of tests, and consistent and well documented methods, are essential. A case study with a deep-water semisubmersible was presented (see Fig. 3.6). In general, good agreement between results obtained from model tests and numerical calculations based on time-domain coupled analysis of the floater system responses was achieved.

Figure 3.6: Snapshot from irregular wave test

3.2 Spar

A sequence of truss spars have been successfully installed in deep water fields since late 2001. One of the aspects of a truss spar is that it exhibits both high-frequency and low-frequency motion responses. The high-frequency motions, or wave frequency motions, are peaked around the wave spectral energy, while the low-frequency motions correspond to the natural periods of the spar's rigid-body motions. Accurate structural design should include loads due to both wave and low frequency motions. Resource-demanding time domain analyses were previously employed for design of the truss and a combination of time and frequency domain analyses was applied to design the other structural components. The procedure proved to be time consuming and inefficient, requiring extensive engineering hours.

An enhanced hull design procedure was presented by Luo *et al*. (2007) and Wang *et al*. (2002). The procedure is based on developing an integrated structural analysis methodology. It was found that efficient use of personnel for the labour-intensive structural modelling tasks was achieved. Use of this methodology in two spar projects was found to be of benefit. The procedure is also applicable to a range of floating platforms such as Technip's extended draft platform (EDP) and other deep draft floating platforms. Key features of the integrated structural analysis methodology for both strength and fatigue analysis of the truss spar were discussed in the papers. Structural loads determined from the integrated methodology were compared with those from a complete time-domain analysis of the truss spar.

The collision mechanisms of spar platforms have not received so much attention as that for ships, and this type of collision accident has not been reported. However, this does not guarantee that such events will not occur in the future. Investigation of both the "external" mechanism and the "internal" mechanism for a ship colliding with a spar platform was performed by Hu *et al*. (2007). A model test was designed to study the external mechanism. The collision scenario corresponds to a ship striking a spar platform which is moored in 1500 meter water depth. It was found that the maximal displacements and the maximal pitch angles of the spar platform, and the maximal tension forces of mooring lines are basically all linearly proportional to the initial velocity of the striking ship. The internal mechanism of the ship colliding with the spar platform was simulated numerically by means of a non-linear finite element analysis. A Truss-Spar was considered with a double hull structural design for the part of the hard tank which is located near the water surface. The crashworthiness of the double hull design was verified for the particular striking ship considered by means of results from the numerical simulations. The maximal tension forces of the mooring lines are also less than their breaking strength.

3.3 FPSO

A comprehensive list of classification rules, standards and guidelines relevant for design of FPSOs were given by Cocodia (2008).

There appear to be two main design issues which are extensively addressed by recent research activities. These are:

- Efficient and accurate methods and procedures related to the ultimate limit state. This includes ensuring residual strength associated with damage, e.g. due to collision
- Fatigue capacity

In addition, the effect of corrosion on the hull strength was also addressed in a number of studies.

Full-scale measurements obtained from the Triton FPSO (a turret moored FPSO in the central North Sea) were reported in Lawford *et al*. (2008). It was considered that a full characterisation of the individual components of a sea-state is key to enable the response of an offshore structure to be accurately calculated. The partitioning of a time series of directional wave spectra into wind-sea and swell components with distinct frequency and direction characteristics was addressed

Huang *et al*. (2005) and (2006) presented the new probabilistic models for still-water loads and the combined still-water and wave load effects of FPSOs. A procedure for determining load combination factors, which is suitable for semi-probabilistic and probabilistic design of FPSOs, was established. The most relevant load combination factors in harsh and benign conditions were derived. In general, combination factors depend on the parent distribution, time variation and relative magnitude of individual loads.

It was shown that the extreme values of still-water and combined loads can be greatly overestimated if operational control is not accounted for. On the other hand, the control is unlikely to be perfect. Hence, the partially truncated model is recommended to account for control of the still-water bending moments. A truncation factor should be determined from actual operational data; however, available operational data for FPSOs are insufficient to reliably determine this truncation factor. Therefore, it is recommended to, conservatively, base it on the operational experience of trading vessels, such as tankers, and use a truncation factor of 0.5.

In the harsh condition of the North Sea, in which wave induced load is dominant, and for FPSOs mainly operating in sagging conditions, the relevant combination factors of the sagging still-water bending moment with a truncation factor of 0.5 are about 0.80, 0.75 and 0.70 for return periods of 1, 20 and 100 years, respectively. For FPSOs operating in hogging conditions, the respective relevant hogging combination factors are about 0.8, 0.65 and 0.60. In the benign conditions of West Africa, in which still-water load is dominant, based on a particular FPSO working mainly in hogging conditions, the relevant combination factors for the hogging wave-induced bending moment are about 0.85, 0.70 and 0.65 for return periods of 1, 20 and 100 years, respectively.

FPSOs have their own unique characteristics, including various operational requirements. In addition to that, the expectation of safety and economic aspects of FPSOs require an optimized structure to be designed. This calls for reliable structural assessment methodologies. One of the most important aspects of FPSO structural design and assessment is the hull girder ultimate strength. Comparison of different methods for ultimate hull girder strength was made by Wang *et al*. (2008). Numerical calculations of hull girder ultimate strength were presented based on six different FPSO designs by application of different methods. The methods applied were the incremental-iterative approach by Sun and Wang (2005), an in-house code HULLST developed by Yao and Nikolov (1992) based on Smith's method, and application of the idealized structural unit method (ISUM) by Fujikubo and Kaeding (2002). The results were analyzed in terms of their differences, and conclusions were made based upon reliable methodologies for hull girder ultimate strength assessment of FPSOs. All these three methods show good agreement in terms of hull girder ultimate strength calculation for the selected FPSOs. In general, the predicted hull girder ultimate strength from Yao's method and Fujikubo's method are almost identical for most of the cases, while Sun and Wang's method gives slightly conservative results in some cases. It was concluded that all three methods can be applied for hull girder ultimate strength calculation of FPSOs.

Risk assessment of ship-FPSO collision was considered by Wang and Pederson (2007), Wang *et al*. (2003) and Pedersen (2002). The following topics were addressed: existing criteria, FPSO collision accident, design scenarios for FPSO collision, mechanics of collision incidents, consequences and acceptance criteria. The research achievements in relation to ships' collision and grounding since the 1990s were summarized. Issues specific to ship-FPSO collisions that deserve further development were addressed. The content of the first mentioned paper (Wang and Pedersen, 2007) was mainly drawn from the ISSC 2006 Specialist Committee V.1 on Collision and Grounding.

The paper also listed the conclusions and recommendations of ISSC 2006 V.1 that are relevant to ship-FPSO collision risk assessment. The recommendations apply to five different areas. In relation to Structural Crashworthiness, the committee advocated more application and recommends refinement of analysis approaches. For assessment of Probability of Collisions, it was recommended that future research should focus on developing risk-based software. The calculated cost of risk reducing measures can then be compared with savings from calculated reductions in expenses. Regarding Risk assessment, the committee recommended focusing on integrating predictive calculation tools, including the development of streamlined software/programs. In connection with Rules and Regulations Development it was found that future rules and regulations need to address design incident/accident scenarios, responses (of ships, offshore installations, bridges, etc) to an incident/accident, consequences, and acceptance criteria. When it comes to Predictive calculation approaches it was recommended that topics that will further refine these methods include rupture strain and post-accident loads (both still-water and dynamic loads).

Reliability assessment of an FPSO considering the effects of both corrosion and collision was performed by Zhang *et al*. (2006). Since FPSO’s have long intervals of docking for thorough inspection and maintenance, and are exposed to collision risk at sea, the time-variant reliability of FPSO's becomes very important as for the risks of corrosion and collision. The corrosion defect was represented as an exponential function of time. The Idealized Structural Unit Method was proposed to predict ultimate strength of the hull girder. Still water and wave-induced bending moments were also combined into stochastic processes. Reliability of the intact hull during the service was calculated to serve as a reference for that of the damaged and corroded hulls. The focus was on damage due to collision, and the damage was modelled according to ABS guidelines. According to these guidelines, the section with highest bending moment should be considered. The reliability of damaged hulls throughout the service life was obtained, which could be applied as a reference for further inspection and maintenance plans. It was found that the intact hull would have sufficient reliability during 25 years in operation. For the damaged hull, the permitted time in operation was reduced to around 8 years for the sagging condition and around 14 years for the hogging condition. Based on the obtained reliability estimates, decision related to inspection and maintenance can be made to update the reliability when a target level is defined.

An extensive number of papers on fatigue assessment of FPSOs have been published during recent years. A brief summary is presented in the following.

Schmidt *et al*. (2008) evaluated the effect of random wave slamming for a stiffened panel which was located in the fairlead support structure of an FPSO, see Figs. 3.7 and 3.8. The fatigue lifespan was estimated in a complete stochastic analysis, considering all possible sea states during the lifetime of the offshore structure as well as each associated probability of occurrence.

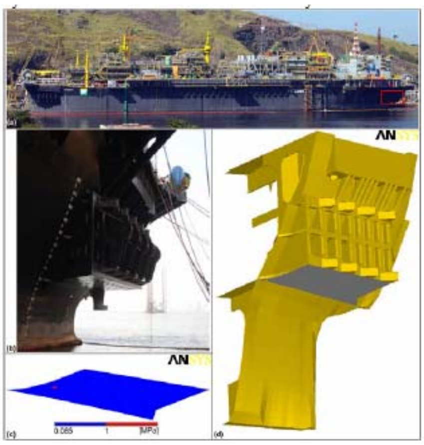

Figure 3.7: Fairlead support structure

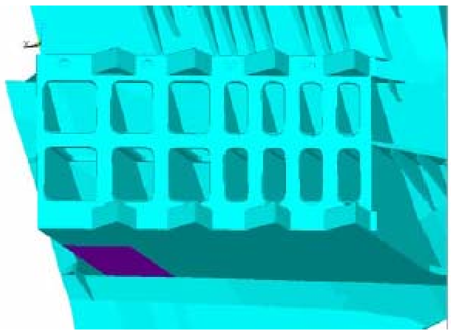

Figure 3.8: Location of sub model

For the particular case studied, the peak pressure for each discrete slam was assumed to generate one stress cycle and for each stress cycle the damage is estimate through the use of the S-N fatigue approach. The stresses on selected critical details are assumed to be linearly proportional to the peak pressure.

A summary of statistical models related to various parameters associated with calculation of fatigue damage was given in Wastberg (2007), which was based on the previous report from the ISSC Committee on Fatigue and Fracture.

Lotsberg (2006) reported on fatigue data related to fillet welds. The objective of that work was to develop a suitable methodology for the fatigue assessment of fillet welds relevant to FPSO details from the view point of the weld throat. In order to examine the validity of the recommendations and to supplement the fatigue test data base, a test matrix with 33 specimens was developed. This included 8 simple fillet welded cruciform joints that were subjected to axial loading and 25 fillet welded tubular specimens that were subjected to axial load and/or torsion for simulation of a combined stress condition in the fillet weld. The test data were presented and also compared with the design guidance from IIW (1996), Eurocode 3 (1993) and DNV-RP-C203 (2005). Based on this work, the following conclusions were drawn (I) There was no evidence from the fatigue test results to indicate that there is a thickness effect related to the size of the fillet weld or the main plate thickness. (II) The equation for the stress concentration factor at the roots of fillet welds in cruciform joints to allow for misalignment-induced bending developed by Andrews was found to be reasonable. (III) The test data with pure parallel shear in the fillet weld indicated that IIW and Eurocode are conservative by a factor of 10 on life for this loading condition. However, they were in reasonable agreement with the mean line of DNV-RP-C203. (IV) The mean S-N curve fitted to the results for pure parallel shear in the fillet weld had a slope in between those of the IIW/Eurocode and DNV-RP-C203 (IV) The R-ratio ($R = \sigma min/\sigma max$) with respect to parallel shear stress does not seem to have a significant effect on the fatigue life (V) Based on a comparison with the test results obtained for combined stresses in the fillet weld, the design procedure in IIW and Eurocode was found to be on the safe side, while the design procedure in DNV-RP-C203 appeared marginally on the safe side for the endurances considered. The approach in DNV-RP-C203 for combined stresses becomes more conservative relative to that of IIW and Eurocode with increasing number of fatigue cycles.

Lotsberg (2008) addressed the calculation of fatigue damage at weld toes based on S-N data when the principal stress direction is different from that of the normal direction to the weld toe, see Fig. 3.9. Different design criteria were presented together with recommendations on analysis procedure.

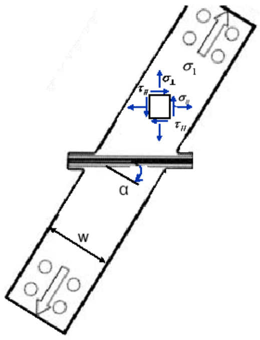

Figure 3.9: Example of weld with inclined principal stress direction

Fatigue of fillet-welds based on Structural Stresses was addressed by Fricke *et al*. (2006a, 2006b). The papers addressed practical approaches for typical problems encountered.

Maddox (2006) presented a critical review of current design methods, including their background and relevant experimental data, for assessing the fatigue performance of steel fillet welds with respect to failure in the weld throat. The main focus was on fillet or partial penetration welds in cruciform, T or lap joints under transverse loading failing by fatigue crack growth across the weld throat under normal stresses. Also considered were the cases of fillet welds failing in shear or combined normal and shear stresses.

Lotsberg et.al. (2006), Lotsberg (2005), Bergan and Lotsberg (2004), Bergan *et al*. (2002) presented the new DNV Recommended Practice for Fatigue Analysis of Offshore Ships (DNV-RP-C206). This document is intended for fatigue design of floating production, storage and offloading units.

Rodriguez-Sanchez *et al*. (2005, 2007) addressed the application of controlled weld toe profiles as an option to extend the fatigue life of welded connections when existing tankers are converted into offshore ships (FPSOs and FSOs). It will be difficult to implement such fatigue improvement when these vessels are in service, since a converted ship is designed to be inspected, maintained and repaired in situ and not in dry dock. Codes recognize fatigue life extension by means of a controlled weld toe profile. The papers document that application of a controlled weld toe profile during conversion, in selected areas previously identified by stress analysis of the hull structure, indeed can extend the fatigue life expectation of the converted vessel.

Comparisons between spectral fatigue analysis using both the surface extrapolation and Battelle structural stress methodologies, see Bureau Veritas (2007), were made by Healy (2004) and Rucho (2007). A side shell connection detail typical of a representative FPSO was considered. Fatigue damage at the toe along a number of weld lines was computed for a variety of surface extrapolation strategies and Battelle method options.

Application of the structural stress(SS) method developed by BATTELLE was further assessed by Kim *et al*. (2007) based on small or mid-size scale specimens. Fatigue lives based on class society rules and the SS method were compared. The simplified fatigue analysis methods by ABS and DNV were adopted to check the validity of the SS method.. From the computed results, it was concluded that the SS method gives reasonable fatigue lives when based on hot spot stress or notch stress. Several structural details were subsequently considered. When compared with results from the simplified fatigue analysis procedures of ABS, DNV and CSR, the computed fatigue lives according to the structural stress approach do not show to match results from conventional fatigue life calculations well. It was hence recommended that additional structural details and also actual damage should be considered.

Fatigue assessment was performed for the Agbami FPSO at OPL 216/217 offshore Nigeria by Hwang *et al*. (2007), see Figure 3.10. The FPSO is positioned with spread moorings at a water depth of about 1500 m for a service life of 20 years. As per the design requirement, the hull of FPSO was to be designed to meet ABS's SFA (Spectral Fatigue Analysis) notation and the seagoing condition. This Seagoing condition is an additional requirement assuming that the FPSO is equivalent to a typical tanker navigating in the North Atlantic. For the spectral fatigue analysis, a Jonswap spectrum was applied for wind wave and Gaussian spectra were applied for swells. The results from the analyses demonstrated that the seagoing condition leads to more critical fatigue damage for most of the hull components than the onsite condition would do, since this comprises of more moderate sea states.

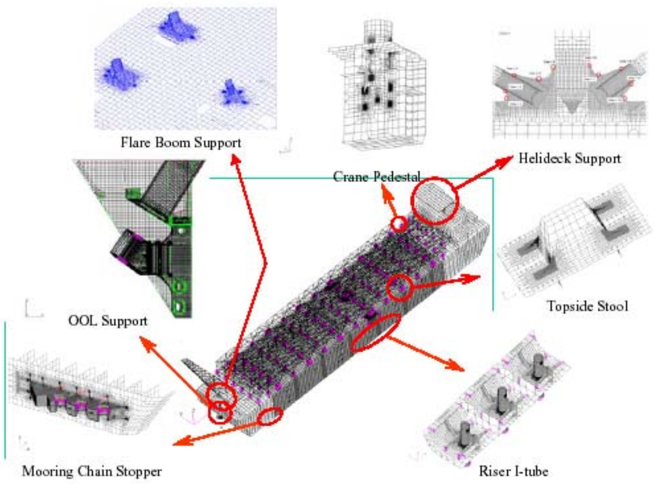

Figure 3.10: FE model of global FPSO and specific details

Zhang *et al*. (2006) addressed the effect of mean stress on the fatigue life of welded joints in FPSOs. Fatigue life decreases when tensile mean stresses increase, while the compressive mean stresses have a favourable effect on fatigue life. The paper compared different fatigue analysis procedures, i.e. JBP, JTP, DNV CN30.7 and IIW procedures, and a new procedure which explicitly considers the effect of mean stress, with the fatigue test data of different specimens representing various typical welded connections in ship-shaped hulls.

The effect of shake-down of residual stress was investigated by Li *et al*. (2007). Some typical welded connections in ship shaped structures were investigated with 3-D elastic-plastic finite element analysis. It was found that the combined effect of both applied stress and high initial residual stress may be assumed to cause shakedown of the residual stresses.

There seems to be renewed interest in the application of concrete for hull construction driven in part by steel construction prices, the sizeable order books of shipyards worldwide, the growing dimensions of newbuild FPSOs and in particular LNG FPSO concepts. The use of concrete materials for hull construction is not novel. In 1975 the Ardjuna LPG FPSO was installed offshore Indonesia, based on a concrete barge. In Lanquetin (2006) and Lanquetin *et al*. (2007) integrity management for the NKossa FPU is addressed, see Fig. 3.11. This facility is the largest prestressed concrete FPU that has been installed, and has now been in operation for 10 years. A tailor-made methodology to ascertain the structural integrity of floating units was developed in 2004. The approach is based on continuous monitoring and analysis of the condition of the units. For the NKossa FPU, the methodology makes use of a full non-linear Finite Element Model of the concrete hull. After 10 years in operation without significant maintenance the concrete FPU is found to remain in good shape.

In addition to materials, new floater shapes are explored. In the Far East a series of cylindrically shaped FPS hulls is being built, with an oil storage capacity of 300,000 bbls. Application is envisaged in Brazil and in the UK sector of the North Sea.

Figure 3.11: NKOSSA concrete FPU

Fig. 3.12: Hull structure of the new generation of floating platforms

3.4 Semisubmersible and TLP

Estefen *et al*. (2006) and (2007) focussed on the design of the new generation of semi-submersible platforms for oil and gas production offshore that is based on column square cross-sectional area, see Fig.3.12. The platform column is based on an arrangement of stiffened flat panels having their ultimate strength characterized by buckling under in-plane compressive loading. Distortions induced by fabrication have considerable influence on the buckling behaviour and were discussed in order to provide design recommendations. To analyze the failure behaviour of the stiffened panels, a segment of the column structural arrangement between robust transverse frames was studied. Numerical and experimental simulations were carried out for small scale isolated panels in order to perform a correlation study to adjust the numerical model for further use in more complex numerical simulations of the structural failure of the column arrangement.

The paper also studied the influence of different geometric imperfection distributions on the buckling behaviour of this column segment, based on nonlinear finite element analyses. The magnitude of the initial geometric imperfections was confirmed to be a factor determining the allowable axial buckling load. However, the greatest influence on the ultimate strength and on the failure sequence of the plates was found to be the initial imperfection mode. An initial distortion mode which coincides with the natural buckling mode of a particular plate generates a lower bound buckling load. On the other hand, some imperfection modes can counteract the buckling failure, hence generating upper bound values for the respective buckling loads. The rounded corners were the last regions to collapse in all analyzed models, except for the model with the geometric imperfection mode coincident with the natural buckling mode. For this model the curved plates were the first to collapse, which indicated the importance of these curved regions on the buckling initiation and the progressive failure of the column.

The same structural concept was also considered in relation to supply vessel collision and the associated residual strength by Estefen *et al*. (2006) and Amante *et al*. (2008). Normally, damage from such events is in the form of local dents. The ultimate buckling residual strength of a typical column after initiation of such a damage was evaluated. The buckling analysis was validated using a finite element model considering geometric and material nonlinearities. Residual strength results from the damaged column were compared with the ultimate strength of equivalent intact column to estimate the safety margin associated with the column structural capability after supply vessel collision.

For the structure and the collision under consideration, the residual strength appeared 9 % less than the intact buckling strength of the column. This reduction may be considered small, so that the platform studied exhibits a large safety margin for the in-plane compressive load.

However, the authors state that the result of such analysis of residual strength will depend on the collision scenario/energy and the structural arrangement of the column in the region prone to collision. More thorough analyses of possible structural failure after collision should therefore be performed in the design stage. The results can be used as an indicator of the severity of offshore collision and provide insight to lower bound safety factor to deal with such accidents, which are rather common. Moreover, the comparison of various structural arrangements for the column members close to the splash zone could contribute to the prevention of serious loss of structural integrity, in case of collision.

The structural redundancy of semi-submersible drilling vessels was considered in Chakrabarti et. al. (2007) in order to withstand the loss of a slender bracing member without overall collapse of the structure, similar to requirements for fixed structures. Unlike static 'pushover' type analysis used in a relatively dynamically insensitive fixed jacket structure, semi-submersibles require nonlinear dynamic redundancy analysis in the time domain to determine the safety against collapse due to environmental loading. A simple time domain nonlinear analysis procedure was suggested in the study to capture the realistic behaviour of the structure under wave loading. Dynamic loads were generated from hydrodynamic analysis of the floating body using a diffraction-radiation analysis program which assumes that the wave excitation is harmonic and so is the response. These loads are transferred to the structural analysis model. Each wave frequency is analyzed to produce a pair of loading conditions –'in-phase' and 'out of phase'. Combining these two components, a time history of the wave loading is created. In nonlinear structural analysis, first static loads are applied, and then a wave load time history is applied for a few wave cycles in small increments. Results show that nonlinear analysis for one single cycle or two can usually predict the safety against collapse. If the analysis continues for these cycles, the structure passes the redundancy test, otherwise the structure has a deficiency that needs to be addressed.

In Ren *et al*. (2008), fatigue damage for a semisubmersible platform was calculated based on a global finite element model. Three-dimensional source distribution theory in the frequency domain was used to calculate the loading due to regular waves. The hot spot stress in the welded knuckles was calculated on the basis of a local and detailed finite element model. The effect of ageing (in particular corrosion) was also taken into account.

The new strength guidance in API RP 2T recommends the axial tension-hydrostatic collapse interaction equation currently used by API RP 2A LRFD, coupled with a working stress design format with explicit tension and collapse safety factors. The latter factor controls the water depth applicability.

Rinehart and Buitrago (2006) addressed future TLP designs and the maximum depth in which tendons can be installed while still maintaining adequate and consistent reliability. To establish a basis for a hydrostatic collapse safety factor, an independent reliability study was performed in order to arrive at a safety factor consistent with the new interaction equation accuracy and current fabrication and design tendon practices. The paper presented the data gathering, analysis procedure, and interpretation of results leading to a safety factor that is consistent with standard practices. The analyses were conducted via Monte Carlo simulations for a number of design cases across a range of safety factors. Results indicate that a collapse safety factor of 1.67 (which seems to correspond to a reliability index of around 3.0 within the context of the analysis). This applies to the Category A operational load case that controls tendon design in deep water, and yields levels of reliability consistent with those historically sought by design codes such as AISC and API.

In Cicilia (2004) and Cicilia *et al*. (2006) a Load and Resistance Factor Design (LRFD) criterion was applied to the design of Tension Leg Platform (TLP) tendons in their intact condition. The design criterion considers the Ultimate Limit State (ULS) of any tendon section along its whole length taking into account both dynamic interactions of load effects and the statistics of its associated extreme response. The partial safety factors were calibrated through a long-term reliability-based methodology for the storm environmental conditions, like hurricanes and winter storms, in deep waters of the Campeche Bay, Mexico. In the reliability analysis, the uncertainties in the definition of load effects and analytic limit state models for calculation of tendon strength and randomness of material properties were included. It was found that the partial safety factors reflect both uncertainty content and the importance of the random variables in structural reliability analysis. When tendons are designed according to the developed LRFD criterion, a less scattered variation of reliability indexes is obtained for different tendon sections across a single or various TLP designs. (A target reliability index of 3.75 was applied, and a scatter of less than 2% was achieved). However, it was emphasized that the derived partial coefficients need to be adjusted taking into account a greater number of TLP models with variations in geometric and material characteristics, hull size, etc. Besides, updated environmental data and their joint probabilistic description need to be considered.

Jayalekshmi *et al*. (2007) considered the hull-tether coupled dynamics for TLP's in very deep water. This effect cannot be accurately studied through model tests due to depth limitations of the existing model testing facilities and possible scale effects (in the case of ultra-small scale models). An experimental methodology was presented for physically simulating such coupled behaviour for a single column TLP in a wave basin having dimensions 30m x 30m x 3m. The experimental results were presented for hull motions, tether displacements and dynamic tether tension. Combination of model tests and numerical analysis were carried out. Results revealed that significant dynamic amplification could occur as a result of hull-tether coupling, thus highlighting the importance of coupled dynamics for deepwater compliant platforms.

3.5 Hull shape optimization

In traditional hull designs, hull shapes are often generated by modifying existing parent design models. In contrast, the modern hull designs tap on optimization techniques to seek the optimal topology of hull shapes based on specified objective functions such as minimum down time due to heave motion and maximum fatigue life. Hull shape optimization for a semi-submersible structure was studied by Lee and Clauss (2007).

Birk and Clauss (2008) and Birk (2007) illustrated the application of constrained multi-objective optimization algorithm for spar hull (see Fig.3.13) and semi-submersible hull designs. Lee and Lim (2008) and Lee *et al*. (2007) presented optimal hull shapes of TLP based on coupled analysis.

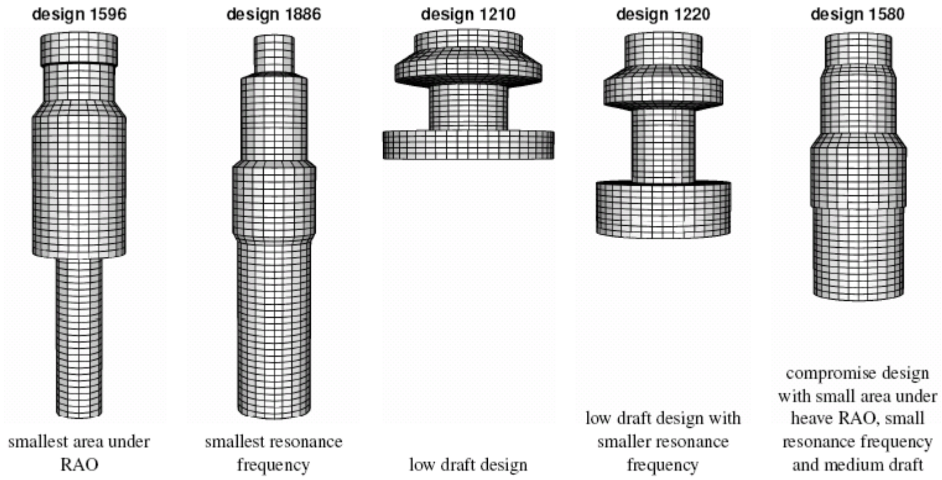

Fig.3.13: Example of spar hull optimization results, using various criteria (Birk and Clauss 2008).

Oliveira (2008) used the design optimization process for semi-submersible hull shapes, considering deck area requirements, deck weight, subsea systems interface, stability issues and motions in waves.

4. MOORING LINES AND RISERS

4.1 General

This section presents the recent developments on risers and mooring lines which are an inextricable part of Floating Production Systems. During the reporting period, riser systems appear to attract more attention than mooring systems from the global research and industrial communities. This is probably due to a focus on mooring, cable and anchoring systems over the preceding years. In addition, several problems related to risers arose and they are both of academic and practical interest. The latter include, but are not limited to, the compression loading when the dynamic tension exceeds the static tension, possible collision of riser systems, Vortex Induced Vibration (VIV) and VIV induced riser fatigue. With regard to the developments on mooring systems, there appears a particular interest in specific aspects related to the application of mooring systems, such as the proper evaluation of mooring line damping in conjunction with the use of mooring lines in Wave Energy Converters (WEC) and issues related to the optimum design of moorings.

4.2 Mooring lines

There are limited amount of research publications on coupled risers-moorings-hull operation. Examples of these studies are those by Low and Langley (2006a) and Low (2008), in which a coupled time and frequency domain analysis was applied for calculating the coupled vessel/riser/mooring system response. Their frequency domain approach yielded good predictions of the system when benchmarking against time domain analysis. Furthermore they applied their linearization scheme for estimating the contribution of the slow drift damping.

There are also examples of studies that try to advance the existing analysis techniques in order to improve the efficacy of the numerical solver. Possible causes of instabilities are still important for researchers. Chakrabarti (2008) investigated the instability of an upright tower subjected to surface waves. He considered the Duffing's equation and Mathieu type instability in the analysis of moored floating structures. In the paper, it was concluded that the frequency domain analysis applicable for upright articulated towers, is generally not applicable for Single Leg Inclined Moorings (SLIM). Matulea *et al*. (2008) introduced a mathematical model and a matching numerical method based on the finite difference approach, in order to predict the static configuration of mooring or towing compound cables. The model was also applied to analyze a lazy-S riser application.

Mooring of a Wave Energy Converter (WEC)

The Huse model, proposed back in the 1980s, was admittedly the first attempt to quantify the so-called mooring induced damping phenomenon. Since then relatively few publications have been made of further research into this subject. The recent application of mooring systems to provide restraining characteristics to floating WECs has enhanced the interest in mooring line induced damping. The determination of the associated energy dissipated per cycle and the quantitative description of damping through linearized damping coefficients have been studied both numerically and experimentally during the reporting period. In this context, Lie *et al*. (2007) developed a simplified dynamic model of mooring line tension to estimate the corresponding mooring line damping. Short-term time domain simulations of dynamic line tension were carried out to verify the accuracy of the simplified frequency domain approach. When the results of the simplified model were compared with the full time domain simulation, the simplified method appeared to underpredict the damping coefficient of individual mooring lines by maximum 30 % and the damping of the whole mooring system by maximum 20 %.

Johanning *et al*. (2006) and (2007a) investigated the design and operational aspects of a chain mooring for a WEC by conducting experimental measurements of the mooring line damping at a scale of 1:10. The measurements were conducted on a single mooring line for surge motions and include the study of axial stretching and high top-end dynamics. According to the authors, the experimental findings for WEC devices support the conclusion that dynamic mooring line motion is an important variable, and needs to be considered carefully in the design. Johanning *et al*. (2007b) performed large scale experiments with an 82t vessel moored on a 22mm single chain at a mean water depth of 24m at Scapa Flow (Orkney) to study mooring conditions for the installation of WECs. The study included also a numerical model of the experiments by applying line properties, installation conditions and the displacement measurements to the simulation and calculating the resulting tensions. The experimental problems that needed to be overcome in order to obtain meaningful results from large scale experiments under real sea conditions were explained and the importance of mooring line dynamics for WECs was discussed.

Finally, Fitzgerald and Bergdahl (2008) developed a method to include the influence of mooring cables in the frequency domain analysis of WECs. Their method can be described as follows: through the application of a non-linear time domain simulation for each individual mooring line, for the average position of the top connection to the WEC and for representative top motions, the amplitude and the phase of the resulting line tension is recorded. Considering the attachment point and orientation of the mooring cables in a suitable equilibrium condition of the device, the linearized contribution of each mooring cable is resolved to the global co-ordinates of the device and added to the frequency domain equation of motion.

Design of mooring systems for FPSO's

The optimum design of a mooring system is a very essential factor for the safe and efficient operation of FPSO systems. Because of this importance several researchers studied aspects pertaining to the optimal design of mooring systems. Vazquez-Hernandez *et al*. (2006) presented the results of a reliability-based calibration study for partial safety factors, to be applied in an LRFD approach to mooring line design. The calibration exercise was applied to three FPSOs, considering North Sea environmental conditions and different water depths. Both mooring systems composed of chains and polyester ropes were considered. The authors concluded that a design procedure based on long-term response presents least scattered reliability indices around the target level.

Shafieefar and Rezvani (2007) presented a procedure for the optimization of the mooring design of floating platforms, in which an automatic design sequence is also established. Regarding the optimization philosophy, they dealt with the following aspects: (i) The optimization of the platform heading and its mooring pattern, taking into account the directionality of the environmental conditions and (ii) the optimum line length or line tension for each mooring line, associated with the optimization of the mooring line materials and sizes.

Nakamura *et al*. (2007) designed an automatic mooring system for a ship in order to reduce the labour load of standby operations in domestic shipping. They built a simulator to calculate the mooring tensions and ship motions . They also performed model experiments to validate the numerical predictions. Finally, Guarize *et al*. (2007) presented a hybrid Artificial Neural Network (ANN)–Finite Element Method (FEM) to perform a nonlinear mapping of the current and past system excitations (inputs) to produce subsequent system response (output) for the random dynamic analysis of mooring lines and risers. Their method first generates a short FEM-based time-domain response simulation. Next, an ANN is used to predict the remaining structural response time-history simulation. The authors claim that the hybrid ANN–FEM approach can be very efficient for predicting long time-histories.

4.3 Risers

The dynamics of risers are admittedly, more complex than the dynamics of mooring lines. This is caused by the stiffness characteristics of risers, with their own associated dynamics, which are not present with mooring lines. As a consequence, analysis tools capable to analyse the dynamic behaviour of risers can also be applied to mooring lines, but not vice versa. In addition, there are several phenomena pertaining to riser dynamics that are not yet fully understood. Research issues keep surfacing from the installation of risers in deep waters. Nowadays, there are several respected numerical codes for the analysis and design of riser systems, which are used broadly within the industry as well as academic and research institutions. Relevant examples are the commercially available computer codes, such as Deeplines (Principia web: www.principia.fr), Flexcom (MCS web: www.mcs.com), Riflex (Sintef web: www.sintef.no) and OrcaFlex (Orcina web: www.orcina.com), which are all based on the FE approximation. Nevertheless, the literature survey in the reporting period shows that the global research community still devotes significant effort to fully understand the details of the dynamics of risers. Amongst these riser studies, analyses of steel catenary risers (SCRs) have a prominent place. Their low cost makes this kind of risers very attractive. Relevant issues include, amongst others, the development of new methods for riser modal analysis, which is also important for predicting possible VIV phenomena, the dynamics close to the touch down region, compression loading in the same area, effects that resemble buckling in straight bars, and the stimulation of instabilities. It is also broadly acknowledged that VIV is a very interesting and relevant topic related to riser dynamics, because of relative motions between risers, apparent current drag, and most of all, fatigue related design particulars.. Therefore, a separate section is provided on this topic.

The proper modal analysis is very important for predicting the details of riser dynamics, without actually solving the complete dynamic problem. It is also the base for developing alternative solution methodologies, such as semi-analytical formulations, which can be used for complicated geometries like catenary configurations. In this context, Sanches *et al*. (2007) applied a modal analysis to structural dynamics of a marine riser by focusing on the evaluation of non-linear normal modes. The method was applied to both vertical and free-hanging catenary risers. Chatjigeorgiou (2006) and (2008a) treated the problem of the eigenfrequencies and the natural modes of vertical riser type slender structures by applying a perturbation technique and solving the associated boundary layer problems at the riser's ends to obtain the asymptotic approximations to the shape of the vibrating riser-type structure. Xiros and Chatjigeorgiou (2007) calculated the modes of motion of a vertical riser by employing a Galerkin-type semi-analytical formulation. The time histories of the response are then used by a Volterra expansion technique to systematically determine the dominant modes of motion. The resulting models provided by the authors constitute an explicit input-output relationship between the imposed motions and the modes of the structure. Finally, Chatjigeorgiou (2008b) used the so-called WKB (Wentzel-Kramers-Brillouin) approximation to provide analytical forms for the calculation of the eigenfrequencies and the mode shapes of catenary risers. The mathematical formulation of riser dynamics, for which the WKB method was applied, included the variation of tension, the angle and the curvature along the static configuration of the riser. The author considered both in-plane and out-of-plane vibrations and validated his results with those obtained by numerical methods.

The details of the dynamic behaviour of a SCR close to the touch down zone have been established to be a very important topic, mainly because of the risk for compressive loading caused by the axial component of the excitation. The static tension reaches its maximum very close to the point of the limiting lift. Apparently, this value is amplified during the dynamic response and the dynamic amplification becomes very important when the structure is subjected to negative total tension, the so-called compression loading. It is evident that such conditions are critical for fatigue. The compression loading, including matters pertaining to riser soil interaction have been addressed by several researchers in the last few years. Examples are found in the work of Clukey *et al*. (2007), Cheng *et al*. (2007), Chatjigeorgiou *et al*. (2007), Passano and Larsen (2006) and (2007). More specifically, Clukey *et al*. (2007) examined in detail the impact of soil stiffness modelling, trench depth and soil non-linearity on the overall SCR response. They identified an important aspect in the touch down point response following from the degradation of the soil stiffness due to cyclic loading of the soil. Cheng *et al*. (2007) dealt with the problem of compression loading at the touch down zone of steel catenary risers. They investigated the compression that could be experienced by deepwater SCRs, including methodology, failure modes considered, acceptance criteria, computer modelling, and described the steps necessary for assessing the compression forces. Chatjigeorgiou *et al*. (2007) analysed the extreme bending moments, which are developed at the touch down area of steel catenary risers mainly due to heave excitation. The authors applied numerical (FD and FE) as well as semi-analytical methods, based on the WKB approximation, for calculating the eigenfrequencies and the corresponding mode shapes. Finally, Passano and Larsen (2006) and (2007) focussed on understanding the riser behaviour in extreme, low-tension response. They tried to establish suitable strategies to concentrate nonlinear simulations to circumstances where they are most useful.

Other publications on riser dynamics can be mentioned, which address a variety of subjects. Vidic-Perunovic and Nielsen (2007) dealt with the problem of high frequency riser motions inducing riser fatigue. They analyzed the hydrodynamic behaviour of a flexible riser, excited at the top by springing high frequency motions of the host vessel and they calculated the responses to different environmental conditions and various water depths. Chatjigeorgiou (2008c) presented a new methodology for the solution of the catenary riser dynamic problem. The method applied an efficient finite difference numerical scheme, known as the Keller Box approximation. Both the linear and the nonlinear riser dynamics were considered and the comparisons between the two techniques highlighted the impact of the geometrical nonlinearities. The method was validated against the numerical code Riflex, in which both the effect of extreme heaving motions applied at the top and the effect of the compression loading near the touch down region were included. Low and Langley (2006b) investigated the dynamics of flexible risers in the time and frequency domains using lumped mass discretization, where tension and bending were modelled with extensional and rotational springs respectively. For the time domain analysis, the integration was carried out using the Wilsontheta implicit scheme, which according to the authors allows the use of relatively large time steps without compromising stability.

Also, Santilan *et al*. (2007) modelled flexible risers and pipelines as slender elastic structures. Their theoretical formulation led to a type of nonlinear boundary value problem, that can be solved numerically given appropriate boundary conditions. The offsetting effects of gravity and buoyancy were included in the analysis. The authors focus on the fact that the gravity and buoyancy forces can provide considerable axial loading (as can thermal changes) and hence stability (buckling) is a major concern. Tanaka and Martins (2007) used an optimization technique through Generic Algorithms for the design of a steel riser, with the maximum dynamic stress amplitude along the riser span as objective function. The authors applied the optimization tool they developed, to study the feasibility of using a steel riser in an FPSO turret, subjected to a 100-year wave condition. Roitman *et al*. (2006) conducted a structural damping test on a representative model of steel riser in air with a damper mechanism application. This was done in an attempt to quantify and evaluate the damping coefficients. The researchers performed 100 tests, which showed that damping coefficients can be 16 times higher than assumed. Smith *et al*. (2007) described the background of hysteresis in relation to non-bonded flexible pipes and outlined the methodology of riser motions software that incorporates bending stiffness with hysteresis. Finally, Fernandes *et al*. (2008) performed experiments for investigating the clashing of flexible jumpers caused by the wake interference. They presented a comparison of experimental results with a numerical code that applies automatically the Huse's formula for the drag coefficients, in order to provide guidance on the required minimum distance between the jumpers.

4.4 Vortex Induced Vibration (VIV)

VIV effects on risers will continue to attract the attention of researchers for many years to come, since the current computational capabilities to test dense grids in deep water applications, to include elasticity in the existing numerical models, and in particular to apply high Reynolds numbers, are rather limited. An alternative procedure for understanding the particulars of VIV behaviour of risers is to perform experiments. Several researchers in the field propose semi-empirical models for predicting the VIV effects on risers. Usually these models are based on huge data bases of experimental measurements.

The work published in the reporting period, can be categorized either of numerical or experimental nature. Some of the papers presenting numerical work, address VIV from a purely theoretical viewpoint. The publications referenced in this report focus more on practical applications like riser installations.

At first, experimental studies into VIV effects on risers are discussed. Lubbad *et al.* (2007) tried to verify the efficiency of round-sectioned helical strakes in suppressing VIV. To this end, they performed experiments with 28 configurations of round-sectioned helical strakes, aiming to find an optimal strake configuration. In comparison with the behaviour of a smooth cylinder, their optimum configuration of strakes reduced the amplitude of riser oscillation by 95.6 % in the cross-flow direction, and by 96.9 % in the inline direction. Iranpour *et al.* (2008) conducted a series of experimental tests for the fatigue life estimation of risers. They also investigated the influence of load interaction effects. The authors concluded from the measurements that higher harmonics cause significant fatigue damage and cannot be ignored. The work of Jaiswal and Vandiver (2007) aimed at describing the VIV response of long cylinders equipped with strakes. They also provided damping measurements from Gulf Stream experiments. The measured response showed the characteristic of travelling waves. Finally, Xu *et al.* (2008) presented measurements of the wake field behind three riser models obtained by using a Digital Particle Image Velocimetry (DPIV). The range of tested Reynolds numbers was from 3×10^4 to 2.5×10^5 based on the diameter of the cylinder. The measurement results showed that the transverse vibration amplitudes for both the faired and straked cylinder were far less than those for the bare cylinder.

For numerical analysis of riser dynamics, the CFD RANS (Computational Fluid Dynamics - Reynolds Average Navier-Stokes) method appears most commonly adopted by researchers. With regard to the wake-oscillator model, the van der Pol oscillator is the prevailing model. In line with these observations, Pinto *et al.* (2006) aimed to optimise and calibrate a numerical code providing reliable results within a reasonable analysis timeframe and without, or with very limited, need of experimental verification. They used the aforementioned unsteady RANS code to solve a typical riser VIV problem and compute the three-dimensional riser-fluid dynamics interaction. Constantinides *et al.* (2006) used CFD to model a full scale truss spar with vertical risers. They found that the presence of the spar hard tank causes flow speed increase in the array below the spar of about 30%. They also noticed that the truss members create a significant wake field causing channelling and speedup the flow and also affected the hydrodynamics of the tubes. Wanderley *et al.* (2008) conducted a two-dimensional numerical investigation in an effort to predict correct amplitudes of the VIV oscillations. They used the Roe–Sweby scheme to solve the slightly compressible RANS equations, written in general curvilinear coordinates. Silveira *et al.* (2007) investigated the effect of vertical motion of the floating unit (or equivalently the effect of variable tension) on the vortex-induced vibrations of vertical risers. The authors used a numerical procedure, based on modelling assumptions, which, though simple, succeeded in describing some expected dynamic behaviours. The model simulated the riser dynamics using a finite element model coupled to a wake-oscillator model, of the van der Pol type, used to emulate the fluid dynamics.

More publications on methods of VIV analysis of risers, or the reduction of fatigue of risers, can be reported. For example, Riveros *et al*. (2007) presented a response prediction model for oscillating flexible risers. The model was based on the Finite Element Method (FEM) and a harmonic model for the prediction of the cross-flow forces due to VIV phenomena. An increased mean drag coefficient model and amplitude-dependent lift coefficients were considered. Trarieux *et al*. (2006) studied a method to correlate varying wave heights, current speeds and directions with the VIV response of flexible risers and umbilicals. The authors showed results from spectral analysis in several combinations of wave, vessel motions and current. Jung *et al*. (2006) outlined a general methodology and simulation results for risers coupled with a floating vessel. They found that the internal content flow makes the riser stiffer and reduce the riser curvature. In the VIV analysis, the VIV excitation zone of the riser was obtained based on the eigenfrequencies of the structure and the maximum response was evaluated from the corresponding mode shapes in the VIV region.

Fortaleza *et al*. (2008) presented a first control strategy to reduce the VIV of risers. According to the authors the advantage of their strategy is the small external force which is required to reduce VIV and the fact that no structural change is required along the structure's submerged part. Lie *et al*. (2008) presented the preliminaries of a new model for prediction of fatigue damage from VIV in risers. The paper presented the background of the model, the basic assumption of the new model and a comparison between results obtained from a preliminary code and model test results. The cases included both 2D uniform current conditions and 3D (non-uniform) current conditions. Finally, Violette *et al*. (2007) considered the dynamics of flexible slender systems undergoing VIV. The wake dynamics were represented using a distributed wake oscillator coupled to the dynamics of the slender structure, such as a cable or a tensioned beam. Based on comparative calculations, the authors claim that the proposed method can be used as a simple computational tool in the prediction of relevant aspects of VIV of long flexible structures.

4.5 Anchoring Points for Mooring Lines

Randolph *et al*. (2005) presented recent developments on fixed point for mooring lines in anchoring system of floating units for production and exploration in deep waters. At the same time, research studies to define precise soil data and calculation methodology have been performed to validate the anchor solutions. Design guidelines have been developed by API and ISO. Validations of new design by regulatory bodies, ABS, DNV and Lloyds Register have been supported by research findings and helpings.

Nowadays, there are several options of fixed points to anchor floating units, such suction anchors, drag embedment vertically load anchor (VLA), suction embedment plate anchor and, the newest ones, torpedoes piles. Figure 4.1. shows some different anchor or pile types.

Torpedo pile VLA Suction anchor

Fig. 4.1: Some alternative anchor points

Related to design soil parameters (refer to Table 4.1), the great challenge is to define the undrained shear strength, which is the main information relevant for anchor design. The piezocone penetrometer test (PCPT) is the most commonly used in situ test to define point and friction resistance and pore-pressure measured along the soil depth. The problem is to calibrate the undrained shear strength for design. Laboratory tests are necessary to obtain the resistance data, using soil samples acquired in situ.

Table 4.1
Basic Soil parameters required

Basic Soil Parameters Required	
Clay	Sand
Grain size	Grain Size
Atterberg(plastic/liquid) limits	Relative Density
Water content	Max / Min Density
Total unit weight	Total Unit Weight
Undrained shear strength	Friction Angle
Remoulded Shear Strength	
Elastic modulus	Elastic modulus

Soil samples can be taken either from some depth below the seabed (downhole mode) or from the seabed (seabed mode). Boreholes (downhole mode) will normally be drilled from a dedicated geotechnical drilling vessel, using heave-compensated rotary techniques. Sampling and in-situ testing will be performed by means of downhole tools, operating through an open drilling bit. The "primary" methods of acquiring shallow seabed soil data for marine projects have traditionally involved relatively simple coring and sampling equipment such as (a) vibrocorer, (b) gravity corer, (c) grab sampler and in-situ testing by means of the (d) cone, or piezocone, penetration test (CPT/PCPT or CPTU). As disturbances from drilling may affect soil properties up to 40 to 80 cm below the drill base, PCPT results have to be discarded. Although the seabed coring mode is more limited in depth, sample quality is better to ensure good results from resistance laboratory tests.

The very high cost of vessels suitable for carrying out soil investigations, both for mobilization and in daily rates, is a key point for the geotechnical investigation. Site investigations are generally delayed until the project is fully approved, so that much of the early concept development studies have to be undertaken with little or no detailed knowledge of soil conditions. Anticipation of researches about soil data with simpler methods to define soil parameters for design has to be carried out. Thus, another challenge for future years is the development of suitable methods to speed up site investigations and to foresee soil resistances in early design stage of floating units.

Subsea arrangement congestion and geological problems, such, steep slopes, in general lead to small anchorage radius and the requirement of fixed point with large load capacity. This problem can be worsened when associated with poor soil resistances. Thus, fixed points with very high capacities are the most recent challenge in ultra-deep waters, mainly regarding installation procedures and cost.

In the case of torpedo pile or another anchor device, for which the connection point to the mooring line exceeds 10 meters inside the marine soil, reliable approaches to define the effective load acting on the connection point with the anchor shall be developed. Nowadays, the extreme value of the mooring line tension is used to design the torpedo pile or the anchor, without any consideration of soil damping, due to lack of reliable data and knowledge of actual behavior of the interaction of soil and embedded mooring lines.

Bhattacharya *et al* (2006) presented a methodology to design anchor piles, when subjected to cyclic loading. Since cyclic loading in storm conditions tends to progressively degrade the load carrying capacity of the soil, such conditions generally govern the design.

Complex 3D finite element models (FEM), to represent the soil/anchor interaction, are used to determine the holding capacity of the foundation and verify the distribution of tension in the structure. In these cases, it is very difficult to determine the soil rupture. Tests with soil models and in situ tests with prototype anchor point models have to be used to develop new methodologies and simpler calculations.

Aguiar *et al*. (2008) presented an example of complex three-dimensional finite element modeling for, the analysis of the anchor alternative torpedo (long cylinder with four equidistant fins and a conical point of steel, filled with lead or iron ballast). The analysis of a torpedo anchor typically evolves the evaluation of its load capacity and the stress distribution along the anchor due to the imposed load This FE-model employs isoparametric solid elements to represent both the soil and the anchor. These elements are capable of representing the physical non-linear behavior of the soil and, eventually, of the anchor. Large deformations may also be accounted for. Soil-anchor interaction is ensured by surface to surface contact elements placed on the external surface of the anchor and the surrounding soil. This approach has been successfully used to design torpedo piles for a floating production unit in Brazilian deepwater.

5. CONSTRUCTION, ASSEMBLY AND INSTALLATION

5.1 General

The growing numbers of Floating Production Systems (FPS's) and their increased complexity and harsher working environment, have pushed oil companies, exploration companies, fabricators and all related industry players to refine their construction and assembly methods and to improve their installation techniques.

This section focuses on some of the developments and advancements reported in relation to the construction and installation technologies. The construction methodology for the above deck equipment on a modern drill ship and the installation of production modules on various types of FPS substructures, as reported by several contractors, are highlighted.

5.2 Construction and Assembly

5.2.1 Improved Construction Method for Modern Drill Ships

With the increasing demand for energy, explorations and drilling in deeper water and harsher environment have been intensified. Owing to this, and coupled with the advancement in drilling technology, operators and owners are requesting more sophisticated equipment to be installed on their vessels.

You *et al*. (2008) presented improved construction methods for modern drill ships. The paper describes the adoption of zone wise mapping for modular construction of the Dual Hoisting Tower (DHT) and Drill floor of the drill ship, modular erection of the drill floor, dimension control for the construction of drill floor and the DHT. It describes the benefits, in terms of time saving, of the improved installation sequence of the DHT (see Fig. 5.1), the improved construction method of the Sub Sea module and the Hydraracker.

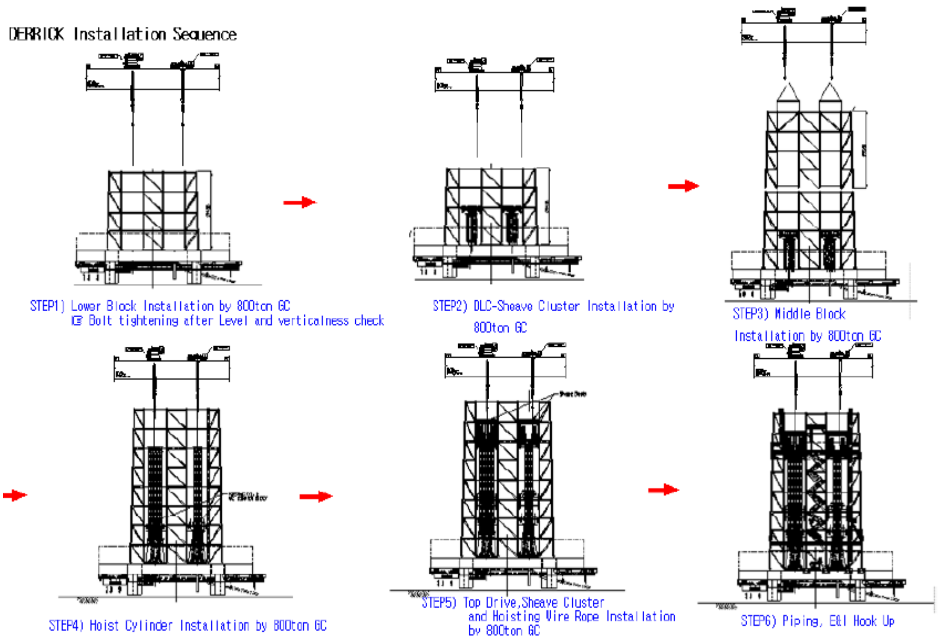

Figure 5.1: Dual Hosting Tower Installation Sequence

The paper also addresses the major challenges during construction, namely, in the design phase, interfacing process, erection and the integration and hookup phase of a drill ship project. Areas of further improvement are also mentioned, focusing on the delivery of the equipment, mechanical completion and punch control and commissioning system.

5.2.2 Jack-Deck for FPSO Module Installation

The assembly of FPSO systems, comprises the integration of oil production modules on the deck of either converted tankers or specific new build hull structures. The size of the individual modules is limited by available lifting capacity in the yard, where the assembly is taking place.

By recognizing the difficulties and challenges faced in construction schedule and commissioning due to traditional construction methods for an FPSO, Tcherniguin and Cholley (2008) have introduced an installation method called the "Jack Deck" installation concept. This "Jack-Deck" method (see Fig. 5.2) consists of fabricating the FPSO topsides in only 1 or 2 large "Integrated Modules", loading onto a transportation barge and transporting them to the integration site where they are jacked-up by the 8 legs "Jack Legs" system. This paper also describes the load-out calculation, the elevated condition calculation, load transfer on the FPSO calculation and provides a detail description of the "Jack Legs". With this new installation concept, the topside contractors will not only be endowed with the flexibility to choose their preferred construction method according to their capabilities, but will also considerably reduce the time associated with the integration, pre-commissioning and commissioning work at the yard.

Figure 5.2: "Jack-Deck" Installation Concept

5.3 Offshore Float-over and Lift installations

5.3.1 Float-Over of Integrated Deck on Jacket structure

The installation phase for an integrated production deck (topside) has always been one of the most challenging and critical parts of an offshore installation project. Understanding the limited availability of heavy lift vessels, and the significant costs related to the mobilization of such vessels, many projects have been based on float-over installation as a commercially viable solution compared to lifting.

Concerning this subject , Kocaman and Kim (2008) presented a paper on the float-over for Arthit PP Deck (see Fig. 5.3) offshore Thailand. The paper explained the various steps of the installation process. The float-over procedures cover from load-out using strand jacks of 900 tons of pull, transportation using their Intermac 650 barge, to the mooring and loose slot method. The paper also contains explanation on the computer modeling carried out for the floatover, and the model testing done with the weather data and workability information gathered.

Figure 5.3: Arthit Deck – as the barge enters the jacket slot

In order to facilitate the float-over installation of Arthit PP topside in December of 2007 in Gulf of Thailand, 3 types of hardware components were designed and fabricated (see Tan *et al*. 2008). They are the Deck Support Units (DSU), the Leg Mating Unit (LMU) and the Receptor/ Sandcans (see Fig. 5.4). Their design criteria and issues were also given.

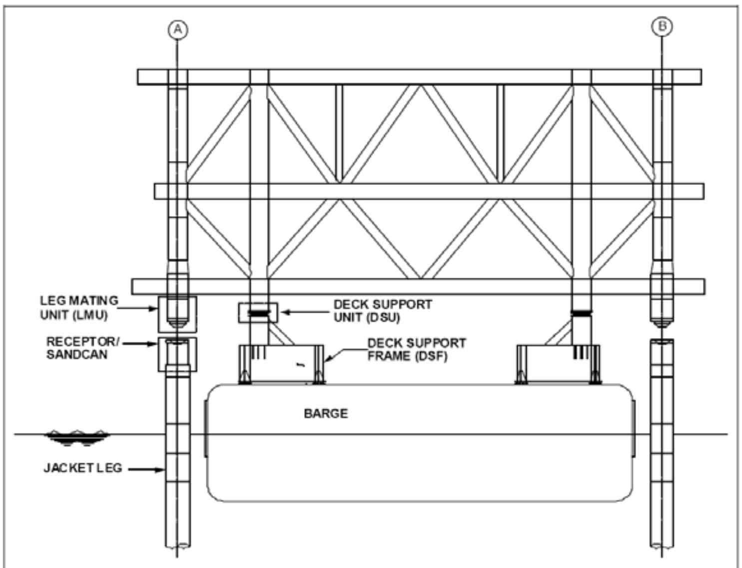

Figure 5.4: Location of Float-over Hardware Components

The paper described the necessary parameters, such as axial stroke, axial loads, relative motion at the sliding surface, rotation requirement - gimbal, and uplift during tow, that govern the design of the DSU . Other considerations like potential uplift during tow, safety, and fabrication of the DSU's were also highlighted. Furthermore the design parameters for the LMUs and Receptor/ Sandcan, including axial stroke, axial loads, lateral loads, lateral leg tip motions (surge/sway) and clearance between topsides leg tip and pile top evaluation were addressed in the paper.

Recognizing the various advantages of floatover installation for Production platform topsides, the industry has acknowledged that floatover is the preferred installation technique.

Hamilton *et al*. (2008) stressed the necessity for a thorough understanding of the system dynamics and environmental site data to allow the assessment of reliable loads for deck on jacket float-overs. The paper also describes the structural flexibility and the size of the gap between the barge and jacket. Jacket flexibility modeling was included in a finite element (FE) model for the dynamic simulation and was demonstrated to be relevant by means of eigenmodes analysis. Based on significant shorter natural periods of the topside, topside flexibility is modeled purely as an additional component in the vertical connection spring, used to model the dynamic motion response. In addition, modeling of jacket/ barge interaction and the importance of small fender gaps to prevent significant kinetic energy built-up in the barge's inertia was covered. The paper also presented the study of the characteristics of the deck mating receptacle, the pullout block system, the floatover analyses and the use of weather windows.

5.3.2 Mating of Topsides onto the Lower Hull - P52 Semi-Submersible

In their paper, Emery *et al*. (2008) presented the overall process and operation of the mating of topside onto the lower hull of P52 semi-submersible, using Technip's UNIDECK installation technique. The paper described the activities carried out in the detailed engineering stage of the mating operation, i.e. the calculation of expected deflections during the de-ballasting sequences to control the applied loads during weight transfer (see Figs. 5.5 and 5.6).

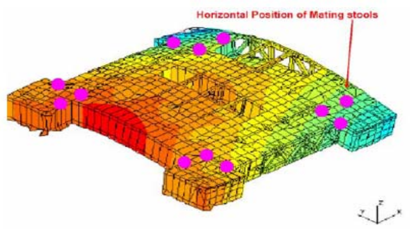

Figure 5.5: Deck box hogging when resting on barge

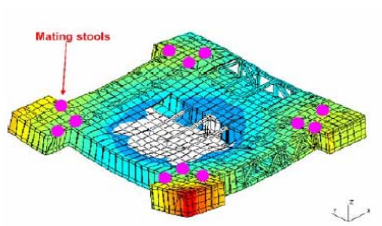

Figure 5.6: Deck box sagging when resting on mating stools

Preparation for the lower hull, the barge for sail-away, procedures for the lower hull mooring and ballasting to mating draft and the complete mating operation are also presented in the paper.

5.3.3 Kikeh Development: Spar Topside Floatover Installation

Also for the spar FPS concept, the integrated deck installation method of float-over is applied. Edelson *et al*. (2008) presented an overall description of the floatover operation for the Kikeh Spar, the first spar deck installation outside the Gulf of Mexico, covering all aspects including topside load out and transportation using a single barge, transfer from the transportation barge to the catamaran barge configuration, catamaran open water tow and floatover to the Spar at the Kikeh location (see Fig. 5.7).

Figure 5.7: Catamaran Tow Kikeh Deck from Labuan Harbor

This paper also clearly described the various issues considered when making the decision of using float-over installation rather than heavy lift operation for the Kikeh topside and the description of the Kikeh Spar and topside installation in terms of the approach, field layout, spar outfitting, topside outfitting, transportation barge selection and outfitting, and other important parts of the operation.

Structural design and analyses to support the floatover and mating operation, such as the design of the fender system, design of stabbing pin and shock cell, impact load calculation between barges and fenders on the spar hull and impact load on shock cell, legs and grillages were also covered by the paper.

5.3.4 Vessel Concept for Multiple Installation and Decommissioning

While the installation procedures described sofar have been developed as specific, one-off , installations, research has also been presented associated with the development of several different concepts for the execution of multiple integrated deck installation and/or decommissioning (i.e. reverse installation) operations.

Cholley *et al*. (2008) presented a new design of a linked catamaran shaped vessel with dimensions that permit it to go around the floater hull or jacket so that the deck can be lowered and stabbed. Additionally the vessel is designed for the removal of existing decks from platforms at the end of their operational life, hence the designation as a "Deck Salvage and Installation Vessel" (DSIV) (see Fig. 5.8). The paper describes the installation method adopted by the vessel. The paper also presents the system description of the vessel, its load-out operation (see Figs. 5.9 and 5.10), its transport and installation capabilities, its impact analysis and the basin test performed for the vessel.

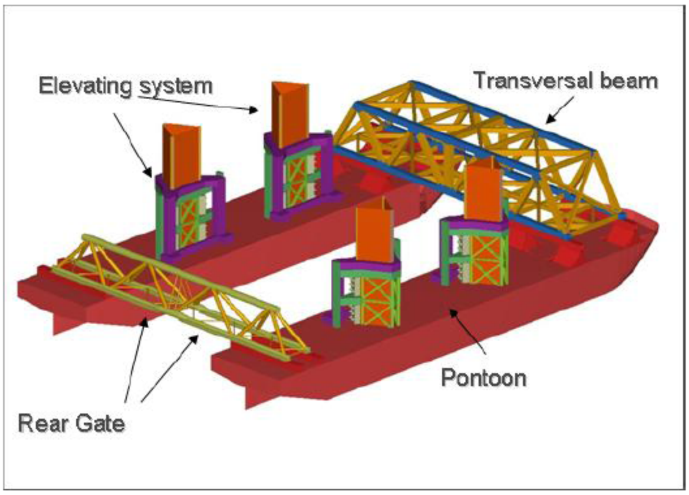

Figure 5.8: Main Structural Parts of the DSIVSystem

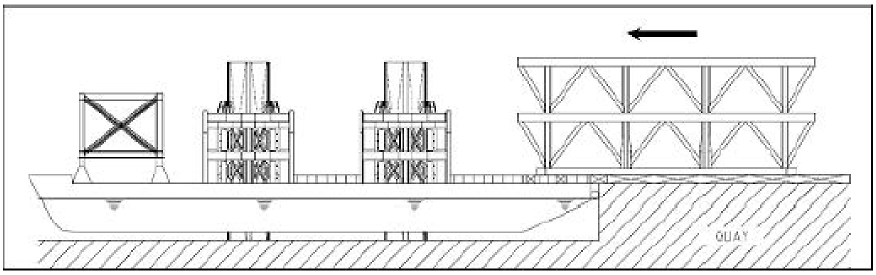

Figure 5.9: Topside load out from quay onto DSIV

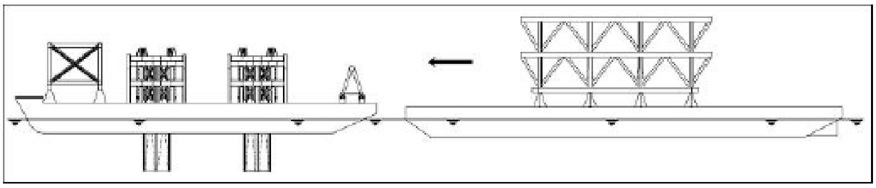

Figure.5.10: Topside load out from barge onto DSIV

5.3.5 Heavy lift Gas Module Installation Njord FPU

Two gas modules have been installed at the Njord FPU by Saipem's semi-submersible crane vessel S7000. Weight of the modules was 100 and 200 tonnes. Before the actual installation was performed, a study was carried out to simulate the operation so as to ensure a smooth and safe installation of the modules. The actual results of the operation were then used as a reference on how to monitor the accuracy of the model tests results. In their paper, Van der Wal *et al*. (2008) described the model tests performed by using an existing model of S7000, which was provided by owner Saipem UK to the test facilities of MARIN. Further preparation of the model and the provision of data acquisition and measuring equipment was by MARIN.

The design environmental conditions for the operation were modelled in the test basin. The model of the crane vessel was kept on station by a functional real time DP system. The paper also describes how the hoisting arrangements are simulated. The mooring system and risers of the FPUare simulated by means of four mooring chains. As the most complex part of the model test, the guiding system was represented by an accurate modeling of the stiffness and deformations of the guiding system.

Time domain and frequency domain computer simulations and diffraction-radiation calculation were carried out and the results of the comparison are described in the paper. The computer simulations and model tests were demonstrated in the paper to be a powerful approach for the analysis of the Njord FPU topside installation.

5.4 Heavy- Lift Transport Ships

With the strong demand for heavy-lift transport ships due to the boom of the oil and gas market and after a relative long period of status quo, the heavy lift transport vessel fleet is undergoing a significant expansion phase (see Fig. 5.11 for an example of a jumboised vessel).

Figure 5.11: Jumboised Blue Marlin transporting the 59,500 t heavy Thunder Horse PDG platform

Van Hoorn (2008) gave a brief history of heavy-lift vessels and some of results of the mergers and acquisition of heavy-lift companies, which resulted in the expansion of their fleet of heavy-lift vessels As the marine heavy-lift industry is going through the expansion phase, the current vessels are also upgraded in terms of crane lifting capacity and DP capabilities. As a whole, this paper gives an overview of the heavy-lift industry and a useful overview of the existing heavy-lift fleet and its future developments.

6. RECOMMENDATIONS

This section suggests technical subjects for which future research would be beneficial in reducing uncertainty in the design, construction, installation and operation of floating production systems.

The Committee has observed substantial research has been reported in the field of description of hurricane conditions, and other extreme environmental conditions. The occurrence of several severe hurricanes in the Gulf of Mexico has stimulated this research. The work as reported, has gained importance by the fact that traditional environmental design criteria appeared to underpredict the conditions as they were actually observed in the hurricanes. Based on the knowledge gathered, more design work is anticipated to adapt FPS configurations to meet the updated criteria for extreme environmental conditions.

The knowledge about fatigue behaviour of steel hull structures needs continuous attention, because of their relevance for the safe operation of offshore structures. Offshore structure tend to be of use for a longer duration than their original design life. This makes a proper understanding of fatigue, and a better quality of fatigue life predictions, even more important.

As a related topic, Reliability Centred Maintenance (RCM) was already included as a recommended area for further research in the 2006 Report. The committee has not found any substantial publications on this subject, so that the recommendation is still worthwhile.

Offshore operations in Arctic environment is expected to be more intensive. Focus shall be both on structures suitable for the environment of ice infested waters, as well as on the details of the loading imposed by ice. Also operational consequences of the cold climate, and special requirements to materials (if any) need to be addressed.

Deep water circumstances pose difficulties to properly represent the configuration to scale in a model test basin. Truncation of mooring and more specifically riser systems to enable testing in very deep waters needs further study.

Riser systems for very large water depths, including validation of flexible risers at larger diameters, will need to acquire continuous interest.

Although the description of VIV behaviour of individual risers, complete riser systems and spar type structures attracts continuous interest of the research community, further research remains valuable, to support the control of fatigue and vibration problems of these slender structures.

Computer aided optimization of hull shapes for various column stabilized units is an interesting development, which deserves further support.

Research shall be improved to define reliable soil mechanic parameters, such as soil elastic module, α factors, dilatance angle and thixotropy strength, for application in numerical analyses, which are required to support further developments of anchor points

Construction of large and complex FPS systems has led to construction of several elements at different locations. Mating of the elements to one integrated structure requires further attention, and mechanical compensation systems to reduce contact pressures during mating, should be further investigated.

Offshore production of LNG from a floating platform is coming closer to reality. Associated topics like motion reduction of the platform, sloshing in storage tanks and transfer of cryogenic fluids from the production facility into transport ships requires further research. Ship shaped LNG production units, carrying topsides for the LNG production and liquefaction, require an integrated design of hull and topsides support structures.

Finally, it can be stated that our offshore industry still bears on the traditional 'storm-level' based design methods, applying the working stress design (WSD) approach for the verification of structural integrity. In previous reports of the ISSC FPS committee, development of response-based design methods have been encouraged. Here the objective is to obtain a target level of reliability, operability and availability. In conjunction with such an approach, the use of the LRFD (Load and Resistance Factor Design) methodology to verify structural integrity, becomes more logical. Classification rules and guidelines have been developed for application of the LRFD method, but as yet, industry is hesitant to use these. Research which provides some benchmarking results of one methodology against the other, for realistic design cases, may accelerate the introduction of response based design and the LRFD approach, which are believed to have high potential.

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