CRANFIELD UNIVERSITY

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SMART OFFSHORE STRUCTURE FOR RELIABILITY PREDICTION PROCESS

OFFSHORE PROCESS AND ENERGY ENGINEERING
Offshore Structures

MSc
Academic Year: 2012 - 2013

Supervisor: Professor Feargal Brennan
September 2013

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ABSTRACT

A review of the developments within the field of structural reliability theory shows that some gaps still exist in the reliability prediction process and hence there is an urgent desire for improvements such that the estimated structural reliability will be capable of expressing a physical property of the given structure. The current reliability prediction process involves the continuous estimation and use of reliability index as a way of estimating the safety of any given structure. The reliability index β depends on the Probability Density Function (PDF) distribution for the wave force and the corresponding PDF of resistance from respective structural members of the given structure. The PDF for the applied wave force will depend on the PDF of water depth, wave angular velocity and wave direction hence the reliability index as currently practiced is a statistical way of managing uncertainties based on a general probabilistic model.

This research on Smart Offshore Structure for Reliability Prediction has proposed the design of a measurement based reliability prediction process as a way of closing the gap on structural reliability prediction process. Structural deflection and damping are some of the measurable properties of an offshore structure and this study aims at suggesting the use of these measurable properties for improvements in structural reliability prediction process. A design case study has shown that a typical offshore structure can deflect to a range of only a few fractions of a millimetre. This implies that if we have a way of monitoring this level of deflection, we could use the results from such measurement for the detection of a structural member failure. This advocated concept is based on the hypothesis that if the original dynamic characteristics of a structure is known, that measurement based modified dynamic properties can be used to determine the onset of failure or failure propagation of the given structure.

This technology could reveal the location and magnitude of internal cracks or corrosion effects on any given structure which currently is outside the current probability based approach. A simple economic analysis shows that the recommended process shows a positive net present value and that some $74mln is the Value of Information for any life extension technology that could reveal the possibility of extending the life of a given 10,000bopd production platform from 2025 to 2028.

Keywords:

Reliability, HUMS, Business controls, Risk, uncertainty, Offshore Structures, structural reliability, technology analogue, Smart process, real time data acquisition, dynamic reservoir simulation updating.

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List of Abbreviations and Acronyms

ALARP	As Low As reasonably Practicable
HSE	Health, Safety and Environment
LTIF	Lost Time Injury frequency
API	American Petroleum Institute
Bbl	Barrels
BHP	Bottom hole pressures
Boe	barrels of oil equivalent
Btu	British Thermal Unit
CEO	Chief Executive Officer
DOE	Design of Experiments
DRF	Dynamic Response Function
DTS	Distributed temperature surveys
E&P	Exploration and Production
FDP	Field Development plan
FEA	Finite Element Analysis
FEED	Front end Engineering design
FPSO	Floating Production Storage and Offloading
FRF	The Frequency Response Function
GDP	Gross Domestic Product
GOM	Gulf of Mexico
HEMP	Hazard and Effect management process
HSE	Health, Safety and Environment
HUMS	Health Usage and Monitoring Systems
ISO	International Standards Organisation
IWCF	International Well Control Forum
KPI	Key Performance Indicator
LTIF	Lost Time Injury Frequency
LTO	Licence To Operate
LTS	Long Term Scenario
MARS	Major Accident Reporting System
NGO	Non Governmental Organisation
NPV	Net present value
O&G	Oil and Gas
OPEC	Organisation of Petroleum Exporting Countries
OPEX	Operating Expenditure
PDF	Probability Density Function
PNG	Petroleum and Natural gas
POS	probability of success
SFM	Structural Failure Model
SHM	Strucural Health Monitoring
STOIIP	Stock Tank Oil Initially In Place

UNEP	United Nations Environmental Programme
US	United States (of America)
USA	United States of America
VOI	Value of Information

Contents

1 INTRODUCTION

Energy use and availability are important drivers for national development today and the per capita energy use is now gradually becoming accepted as a part of national development indices. In 2000, fossil fuels supplied 90% of global energy with crude oil accounting for 40% of the total, coal 25% and natural gas 25% [1]. Several studies have been done on future energy demand and supply and almost all studies reveal that there is going to be a significant gap between demand and supply from 2013 onwards. This view is supported by the Organization of Petroleum Exporting Countries (OPEC). According to its 2010 Long Term Scenario (LTS) document OPEC agrees that growing supply needs in emerging markets will continue to fuel development, especially as the axis of the global economy increasingly shifts towards developing Asia [2]. According to these studies, notwithstanding recent efforts on alternative energy sources, fossil fuels, with a growing contribution from nuclear energy is generally foreseen to be supplying the main share of the world’s energy supply hence the urgent need to develop safer and more efficient ways for oil and gas exploration and production.

Two of the key performance indicators (KPI) that determine the survival of operating companies in the Petroleum and Natural gas (PNG) extractive industry are cost and safety. There is some form of dependency between operating cost and safety performance. Some opex can be used for facility upgrade and hence improve on overall safety performance. On the other hand we can defer some maintenance program and operate with reduced safety margins or barriers while bearing in mind that the absence of necessary barriers could lead to accidents. Table 1 shows a listing of offshore platform accident statistics and related fatalities.

S/ No	**Rig Name / Well name**	**Date**	**Location**	**Fatalities**	**Incident**	**Comments**
1	Bombay High	7/27/2005	Indian Ocean	22	Fire	Boat impact
2	Cerveza	1983-00-00	-	0	Blowout	Abandon
3	Chevron	9/27/2005	GOM	0	Hurricane	Major damage
4	Cormorant A	4/18/1989	UK CS	3	Explosion	Gas leak
5	Ekofisk A	1975-00-00	Norwegian CS	6	Fire	-
6	Ekofisk B	4/22/1977	Norwegian CS	0	Blowout	Major release
7	Ekofisk P	1989-00-00	Norwegian CS	0	Fire	-
8	Enchova Central	8/16/1984	Enchova Field,	37	Blowout	Fire, lifeboat fell to sea
9	Enchova Central	4/24/1988	Enchova Field,	0	Blowout	Destroyed by fire
10	Fulmar A	1991-08-00	UK CS	0	Explosion	Shell
11	Funiwa Platform	1/17/1980	Nigeria	0	Blowout	Major release
12	Getty Platform A	5/13/1984	West Cameron,	1	Explosion	-
13	Hasbah Platform	10/2/1980	Persian Gulf	19	Blowout	Major release
14	Main Pass Block	2/10/1970	GOM	0	Fire	Burned for 2 months
15	Medusa Spar	9/15/2004	GOM	0	Hurricane	Damaged
16	Mississippi	11/4/1987	GOM	0	Blowout	Platform tilted
17	Mumbai High	7/27/2005	Indian Ocean	22	Fire	Boat impact
18	Nabors Rig269	7/17/1998	GOM	0	Collapse	-
19	NFX Platform A	9/9/1999	GOM	0	Blowout	Fire
20	Nowruz	1983-03-00	Persian Gulf	20	Fire	Major release
21	Oseberg B	1988-00-00	Norwegian CS	0	Collision	Sub collision - anchor
22	Petrobras P7	6/19/2001	Bicudo Field,	0	Blowout	Fire
23	Petrobras P36	3/20/2001	Campos Basin,	11	Sinking	Explosion
24	Petronius A	12/3/1998	GOM	0	Sinking	Lift failure, dropped
25	Piper Alpha	7/6/1988	UK CS	167	Fire	Explosion and loss after
26	Placid L10a	5/15/1983	SNS, NL	0	Blowout	Corrosion
27	Pride 1001E	4/1/1997	GOM	0	Blowout	Fire
28	Shell Mars	8/29/2005	GOM	0	Hurricane	Major damage
29	Ship Shoal 246b	3/9/1980	GOM	0	Blowout	Killed after 1 day
30	Sleipner A	8/23/1991	Norwegian CS	0	Sinking	-
31	Snorre A	11/28/2004	Norwegian CS	0	Blowout	Seabed gas blowout
32	South Timbalier	12/1/1970	GOM	4	Blowout	Platform lost
33	Steelhead	12/20/1987	Cook Inlet,	0	Blowout	Fire. Unocal, Penrod rig
34	Sundowner 15	1/24/1996	GOM	0	Blowout	Fire
35	Trinimar Marine	8/8/1973	Venezuela	0	Blowout	Major release
36	Ubit Platform	1996-00-00	Nigeria	18	Fire	Explosion
37	Union Oil	1/28/1969	Dos Cuadras F,	0	Blowout	Major release

Table 1 : Offshore accident statistics. Source : http//home.versatel.nl/the_sims/rig/losses.htm

Very expensive, high technology equipment is necessary for the acquisition and processing of high-resolution seismic images to the required level of certainty prior to commitment of investor funds for exploration or development well drilling. Also very expensive oil rigs, logging tools and high grade steel tubular are needed for well drilling and completion. The first attempt at accessing the hydrocarbon accumulations during exploration drilling operation is very risky, hence all the front end engineering design (FEED) work prior to initial well drilling is aimed at reducing known project risks. The FEED activities include seismic acquisition, interpretation and geological modeling, are used to develop plans for management of project risks. The risk and uncertainty management continues after appraisal well drilling through to development drilling, production operations, reservoir performance modeling and remedial field development up to field abandonment.

Accidents occur when risks are not properly evaluated and managed. The cost of accidents could be huge and are capable of having a significant effect on company’s bottom line: cost of impacted lives, damaged facilities, environmental remediation cost, and associated litigation cost, loss of revenue etc. Offshore accidents, especially those in offshore facilities with accommodation could additionally lead to multiple fatalities as was the case in the Piper alpha incident in 1988.

The PNG extractive industry has made significant steps on managing safety. Since the mandatory requirement for notification of major accidents in 1984, under the aegis of Major Accident Reporting System (MARS), the rate of major accidents has significantly and consistently decreased. By the end of the 1980s the average number of major oil spills each year dropped to one-third of that in the previous decade as documented by Kirchsteiger [3]. Also continuous improvement in accident statistics in the North Sea from 1960 to 2006 was recorded based on continuous improvements in legislation that follow any major accident review. Lindoe et al [4] showed that, from a LTIF level of almost 50 in 1976, the number of injuries per million working hours had a definite downward sloping trend and ends at about 10 in 2006. Also public awareness of major accidents via the media and in orchestra with issue champions, politicians, unions, public debates and decisions in parliament has also helped in enforcing HSE improvements [4].

Fig 1: A shallow water offshore structure prior to installation

Offshore structures as shown in figure 1 usually comprise of steel and are mainly deployed for oil and gas exploration or renewable energy extraction. These structures are safety critical structures and are designed, constructed and installed to create a platform for well drilling, hydrocarbon processing and accommodation for field operators. Such structures can be permanently fixed, or temporary anchored to the seabed. Some temporary anchored structures like tensioned leg offshore platforms can be towed out of location when necessary while others are capable of moving on their own. A self-propelled mobile structure like a floating Production Storage and Offloading (FPSO) structure can propel itself but it is not designed to move over long distances. The offshore structural installation site, especially for wellhead structures is determined by the location of the subsurface hydrocarbon accumulation that it plans to develop. This constraint is to ensure flow efficiency, flow assurance and efficient use of energy as there is a limit to the reach of a horizontal or deviated wells based on rig capability. The other constraint is tied to some additional requirement for subsurface gas or water injection energy efficient in support of sweep or pressure maintenance. The offshore installation surface location hence has to be close to the top of the subsurface hydrocarbon accumulation to maximize the injection energy efficiency.

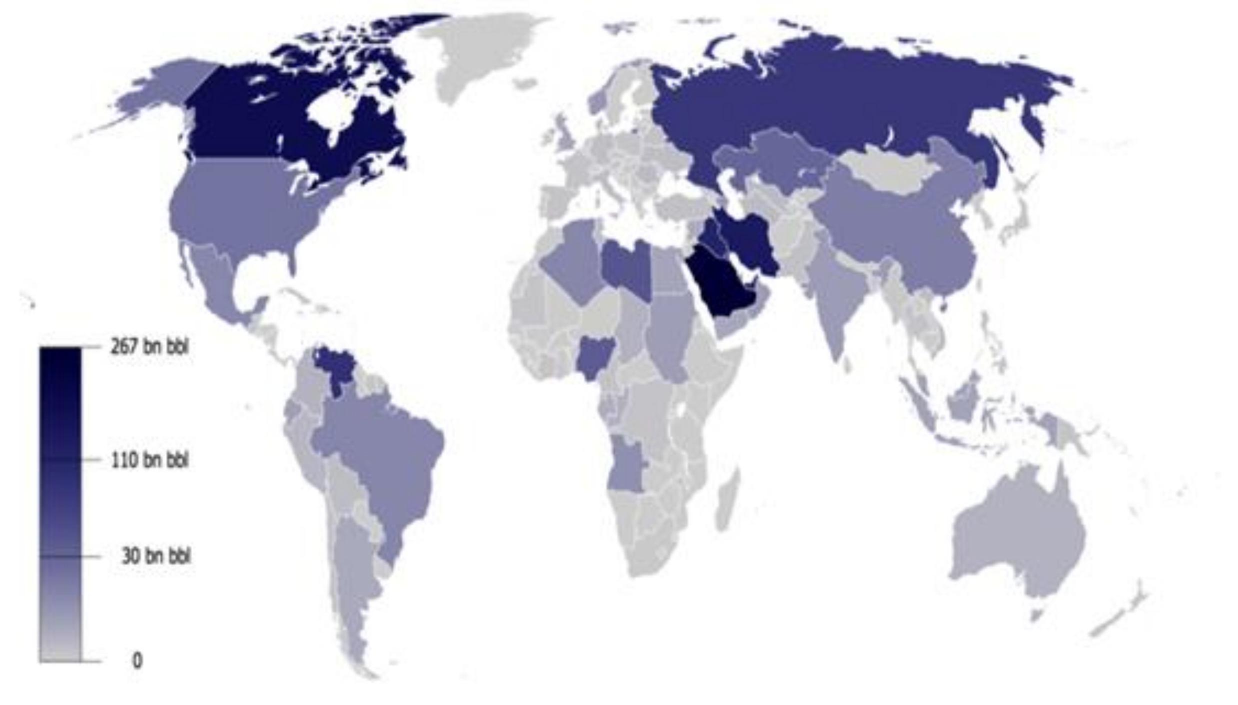


Fig 2 : world hydrocarbon distribution map. Source: Wikipedia http://en.wikipedia.org/wiki/File:Oil_Reserves.png

Figure 2 shows a graphical view of world hydrocarbon distribution map while the details for the top seventeen resource holder nations are shown in table 2. The USA GOM reserves is estimated at 4,886 x10^9 bbl [5] and the spread of associated GOM Offshore platform statistics by water depth is shown in table 3 [6] while a graphical representation of location of such structures is shown in figure 3.

Water depth (m)	Active platforms	Producing well	Producing well / Active platform
0–200	3489	3840	1.1
201–400	455	1873	4.1
401–800	49	285	5.8
801–1000	4	50	12.5
1000+	22	309	14

Table 3: GOM Offshore structures at various water depths

Table 2 Summary of Reserve Data as of 2011

Country	**Reserves 10^9 bbl**	**Reserves 10^9 m^3**	**Production 10^6 bbl/d**	**Production 10^3 m^3/d**	**Reserve life years**
Venezuela	296.5	47.14	2.1	330	391
Saudi Arabia	264.52	42.055	8.9	1,410	81
Canada	175	27.8	2.7	430	178
Iran	151.2	24.04	4.1	650	101
Iraq	143.1	22.75	2.4	380	163
Kuwait	101.5	16.14	2.3	370	121
United Arab Emirates	97.8	15.55	2.4	380	112
Russia	74.2	11.80	9.7	1,540	21
Libya	47	7.5	1.7	270	76
Nigeria	37	5.9	2.5	400	41
Kazakhstan	30	4.8	1.5	240	55
Qatar	25.41	4.040	1.1	170	63
China	20.35	3.235	4.1	650	14
United States	19.12	3.040	5.5	870	10
Angola	13.5	2.15	1.9	300	19
Algeria	13.42	2.134	1.7	270	22
Brazil	13.2	2.10	2.1	330	17
Total of top seventeen reserves	1,324	210.5	56.7	9,010	64

Source: http://en.wikipedia.org/wiki/Oil_reserves

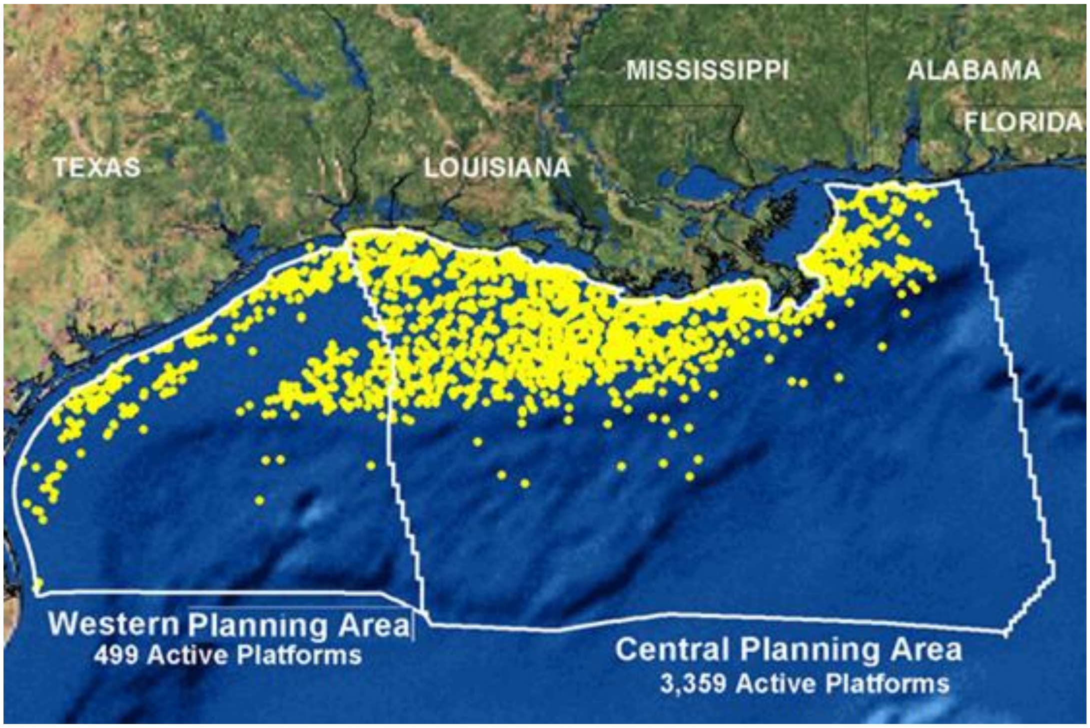


Fig 3 USA GOM offshore installations in; Source : http://en.wikipedia.org/wiki/File:Gulf_Coast_Platforms.jpg

Some 4000 offshore structures currently exist in the US GOM and many of these structures are approaching their design life. This USA GOM data analysis implies that, apart from the very deep water platforms, the productivity of existing GOM offshore wells is about 1.5 active wells per active platform. This implies that the 4,886 x10^9 bbl GOM reserves would also be at risk if many of these structures are found to be too risky to operate or too expensive to maintain. Additionally, these structures will have to be decommissioned when they are no longer operable and the cost of the decommissioning exercise is also huge. In 2012, 285 structures were decommissioned and 1,269 wells were abandoned in the GOM at a cost of about $2.1 billion [7].

With over a hundred years of oil and gas industry experience, a lot of improvement in technology, design codes, construction and operation processes has evolved around the world. Also the application of information technology improvement processes in the Petroleum and natural gas (PNG) exploitative industry led to some paradigm shift in decision cycle time relating to uncertainty management. These process improvements include the use of electronic monitoring devices for controlling processes or generating auto notifications on almost any design or process parameter anomaly. Some of these process parameters include temperature of electric motors, beam deflections and torques, fluid levels, pressures, and flow sensors. Process monitoring sensors are now routinely coupled together to process alarms and emergency shutdown systems for development of smart operations capabilities that can detect anomalies and send signals that are capable of preventing plant upsets and emergencies. Some of these smart technology capabilities are already used to aid subsurface hydrocarbon sweep monitoring. Fibre optic cables, distributed temperature gauges, electronic pressure and flow gauges for example are now used in standard hydrocarbon Well design and construction to aid real time data acquisition for dynamic reservoir simulation update. The results from these real time dynamic models are then used to predict more reliable performance forecast as well as plan future activities for improvement of asset value.

This thesis conducts a holistic safety assessment of offshore structural safety issues, examining not only the design aspects of offshore structures but also the operational safety issues, especially close to end of design life of such structures and their impact upon the overall structural reliability based on a design case study that underpinned the case for data driven reliability prediction process for offshore structures.

1.1 **Aims and Objectives**

1.1.1 Aim

The aim of this thesis is to reviews reports of past accidents along the developed HSE management systems and see through emerging themes if, through the use of technology, some process improvements can be recommended to improve on offshore reliability prediction process such that LTIF and fatalities can be reduced to ALARP.

1.1.2 Objectives

The objectives of the thesis are as follows:

- Identify emerging themes from recorded accident reports in offshore structures within the past three decades.
- Assess process or business improvement initiatives for addressing the root causes of reported accidents in fixed offshore structures.
- Conduct a computer simulation case study for an offshore structure for determination of magnitude of structural deflections and dynamic response function.
- Assess the usefulness of measurement based systems for predicting potential failure of offshore structures.

1.2 Thesis Structure

- Chapter 1 is an introduction to the thesis. It highlights the high demand for energy and how the gap between demand and supply would lead to energy supply pressures and hence the urgent need to develop safer and more efficient ways for energy exploration and production especially in offshore structural engineering.
- Chapter 2 describes the issues that could impact the LTIF in fixed offshore structures based on literature review. The review is based on the HSE management business controls of Policies, Plans and Strategic objective, Organisation, Hazard and Effect management process, Procedures and Standards, Implementation and Monitoring, and Review and Appraisal.
- Chapter 3 describes a design case study of a fixed offshore structure. It describes the process for structural modelling, highlights key issues and assumptions. The modelling results were used to calculate the DRF for the designed structure. This section ends with suggestions on how the failure of any given structure can be determined through the trending of the DRF of the designed structure.
- Chapter 4 describes uncertainty management in offshore structural engineering, the current structural reliability prediction process, a case for change in reliability prediction process and ends with a value of information economics for the proposed change in methodology. The proposed change is based on potential use of the DRF for structural failure determination.

- Chapter 5 presents research conclusions and recommendations for future research. It recommends the use of HUMS technology for continuous monitoring of the DRF of any structure such that deviation from the DRF trend based on structural response can be used to predict the failure of a structural member. It also recommends further research on HUMS technology selection for the advancement of recommended hypothesis on Smart Offshore Structure for Reliability Prediction Process.

2 ACCIDENTS STATISTICS AND INFLUENCING FACTORS

2.1 The cost of accidents

In 2010, offshore production regions represented nearly 650 billion barrels of oil equivalent (Gboe), or 20% of known remaining global oil reserves and 28% of remaining gas reserves [8]. The offshore is therefore a nonnegotiable imperative for oil companies, but one that presents multiple technological challenges as a result of the water depths and high reservoir pressures involved. It is estimated that offshore production involves some 17,000 operating platforms, with more than 400 new production facilities being constructed every year. The number of offshore construction projects has grown by an average of 15% per year since 2005 and it is expected that this growth in the overall number of construction projects will continue [9].

Offshore structural failures and accidents arise due to unanticipated service loads, earth movements, material defects, crack or propagation of cracks, loss of hydrocarbon containment, corrosion, explosion, fire, collision etc. The cost of such failures and accidents could be huge and capable of having a significant effect on any company’s bottom line: cost of impacted lives, facilities; remediation cost, cost of litigation and loss of revenue. Such accidents, especially those in offshore facilities with accommodation could have grave consequences as was the case in Piper Alpha incident in 1988. These accidents could additionally have damaging environmental consequences as seen in drilling failure that led to the sinking of an ocean rig in USA in 2010 [10]. Some 279 major energy accidents in the coal, oil, natural gas, hydroelectric, renewable, and nuclear sectors were reviewed over the last century and such disasters have been responsible for some $41 billion in damages and 182,156 deaths [11]. Accident is a product of risk potential and the likelihood of the risk happening. The risk itself is based on perception and is most times subjective. It is noted that although there have been accidents with major impact on human beings, it is the accidents with environmental impacts, such as oil spills, that are perceived as most risk relevant [3]. As a result of the perceived huge effect of offshore accidents several efforts have been made on continuous improvements on offshore HSE management since the commercial exploitation of oil and gas. These efforts include continuously developing Hazard and Effect Management process (HEMP) and the development of related HSE business controls. Good HSE operations management requires the installation of a fit for purpose physical, process, and regulatory barriers in order to prevent accidents. These barriers or business controls include Policies, Plans and Strategic objective, Organization, HEMP, Procedures and Standards, Implementation and Monitoring, and Review and Appraisal.

2.2 Factors influencing accident statistics

A review of offshore practices and related accidents along these well defined business controls shows that energy security, technology, organisational safety climate, legislation and regulation have direct effects or were used to improve on LTIF in offshore structures. These controls relate to Strategic planning, Processes, Organisation, Procedures, and Standards respectively as shown in table 3 below.

Identified Weakness	Related Business control
Energy security	Strategic Planning
Technology	Process and Procedures
Organisational safety climate	Organisation
Legislation	Implementation and Monitoring
Regulation	Review and Appraisal

Table 3: Mapping of Identified weakness to business control failure

2.2.1 Energy Security

Energy security and issues relating to uninterrupted energy supply at an affordable price are managed at country level through trade policies, common infrastructure development, bilateral or group treaties [8]. Energy security issues can sometimes lead to hostilities and in extreme cases wars where agreements break down. A jurisdiction can attempt to improve its energy security by targeting processes with policies that reduce energy consumption, replace insecure energy sources or processes with ones that are secure, and restrict demand to sources and processes that are secure [12].

Table 3 shows that the hydrocarbon resources are not equally distributed around the globe and this creates a form of energy insecurity among nations. Even within some developing nations the discovery of hydrocarbon creates its own peculiar tension. These natural resources, where they exist, bring with them great social and economic promise, providing financial growth for communities and energy services for local economies [11]. Notwithstanding the strife that comes with the discovery and production of hydrocarbons in multi-ethnic developing countries, the contributions of oil and gas industry to the development of such countries cannot be over emphasised. In most cases revenue from such oil and gas sector accounts for significant export earning that is required to finance major capital investment as well as add to the GDP of such countries. Additionally, such hydrocarbon extractive industries attract investors thereby creating employment and human capital development opportunities for the citizens of such nations.

In 2000, fossil fuels supplied 90% of global energy with crude oil accounting for 40% of the total, coal 25% and natural gas 25%. Nuclear energy contributed 7% and hydro-electricity 3%" [1]. Several studies have been done on future energy demand and supply and almost all studies reveal that there is going to be a significant gap between demand and supply from 2013 onwards. This view is supported by the Organization of Petroleum Exporting Countries (OPEC). In all their three planning scenarios for 2010, OPEC predicted a continued increase in world oil demand. According to its 2010 LTS document OPEC agrees that the growing supply needs in emerging markets will continue to fuel development, especially as the axis of the global economy increasingly shifts towards developing Asia [2]. The exact dimension of the energy gap may never be known due to huge uncertainty in the security situation of some of the key players in the world energy supply. This supply insecurity in developing nations is sometimes associated with tribal and religious conflicts, government instability, or inequity related to the use of revenue from the hydrocarbon resources. Other issues contributing to this energy insecurity at global level include wars and natural disasters.

Some of the efforts being made to address this energy insecurity include the development of new hydrocarbon heartlands in countries with stable economies and government, investment in combustion efficiency and energy efficient systems and cars, development of renewable wind and solar energy for electricity and the development of solar powered vehicles. According to the United Nations Environmental Programme (UNEP), the global investments in sustainable energy exceeded US$155 billion in 2008 and new investments in companies developing and scaling-up new technologies, including energy efficiency, increased to over US$23 billion in 2008 [12]. Notwithstanding all these efforts on alternative energy sources, fossil fuels, with a growing contribution from nuclear energy is generally foreseen to supply the main share of the world's future energy supply hence the urgent need to develop safer and more efficient ways for oil and gas exploration and production.

The push for energy independence sometime creates cost and desperation pressures and the likelihood of accidents are increased under such operating conditions. One attempt by the USA to address its energy security was to lift an offshore drilling moratorium in GOM in 2009. This led to aggressive drilling permit approvals and campaigns in 2010 which in turn led to a major accident in 2010 [13]. This state of energy insecurity pressures will continue to exist in foreseeable future hence the desire for improved HSE management of offshore E&P facilities.

2.2.2 Technology

Offshore structures are safety critical and are designed, constructed and installed to create a platform for well drilling, hydrocarbon processing and accommodation for field operators. Fig 1 shows a shallow water wellhead platform awaiting tow out for installation in the South China Sea. Depending on location and logistics, the cost of developing a 500 MMbbl reserves offshore field with 20 wells and a platform for the wells and hydrocarbon processing at a water depth of 30m can be in the range of $1bn.

The oil and gas E&P industry is a high skill, high capital, high risk and high technology industry. This requirement for high technology and huge investment is a part of the hydrocarbon process flow from seismic acquisition, interpretation, subsurface geological mapping, well drilling, production, hydrocarbon processing, transportation and use. Very expensive, high technology equipment is necessary for the acquisition and processing of high-resolution seismic images to the required level of certainty prior to commitment of investor funds for exploration or development well drilling. Some of the major risks that must be managed during drilling include presence of submarine salt domes, geological faults and fractures, and presence of shallow high-pressure gas accumulations. The first attempt to access the hydrocarbon accumulation during exploration drilling operation is a very risky one with huge uncertainties hence all the FEED work prior to initial well drilling is aimed at reducing the highlighted risks. The risk and uncertainty management through continuous data acquisition continues after appraisal well drilling. Such data acquisition during development drilling, production operations, reservoir performance modelling are aimed at refining the initial models that will be used for planning of remedial field development plan (FDP) activities.

The production and processing of hydrocarbons also has some inherent risk because it involves the production of hydrocarbons under high pressure and temperature from subsurface to surface, the processing of such hydrocarbon and transport for export or as feedstock to other process plants. The hydrocarbon itself is inflammable, hazardous, and sometimes contains high risk impurities like sand, hydrogen sulphide and carbon dioxide. Hydrogen sulphide is fatal if inhaled even at low concentrations. Both hydrogen sulphide and carbon dioxide can cause steel embrittlement and hence lead to loss of containment. Hydrocarbon conduit erosion due to sand production from sandstone reservoirs will also lead to loss containment. Any loss of containment could lead to fire, and explosion in the presence of an ignition source.

Carbon steel is the most common hydrocarbon conduit and processing materials but very expensive Chrome and Nikel steel alloys capable of handling impurities like Hydrogen sulphide, carbon dioxide and sand are sometimes used when operators are certain that such impurities are contained in the hydrocarbon reservoir being developed. Other hydrocarbon impurities like Hydrates, Scale, Wax and Asphaltenes are more of a hindrance to flow assurance rather than facility integrity hazards. Hydrates are managed by suitable chemical injection like methanol or glycol, reduction of process pressures, or increasing the process temperature. Scale is managed by continuous anti-scale chemical injection while wax is prevented through process insulation to ensure that the hydrocarbon cloud point is not realized. Asphaltenes prevention on the other hand can be avoided by preventing the mixing incompatible hydrocarbon streams.

A review of the developments within the field of structural reliability theory with particular attention to structural systems was undertaken [14]. The review appreciate that a measure of safety based on a general probabilistic model in general does not express a physical property of the structure in its operating environment. The review remarked that a safety measure should be a decision variable that embraces the applied knowledge about the strength properties of the structure in relation to the actions on the structure. Deflection and damping are some of the measurable strength properties of any offshore structure and hence some study was undertaken to see if these measurable properties could aid in getting structural reliability prediction closer to reality. Elshafey et al [15] investigated both theoretically and experimentally methods for structural damage detection using the free vibration response of the structure to validate the results of their finite element analysis. Other recent researchers on vibration based structural health reliability prediction include Basseville et al [16], Deraemaeker et al [17], and Straub et al [18]. These researchers agree that sensing technology could aid in predicting structural failure. It has also been shown by Li et al [19] that the cumulative fatigue damage of a bridge can be assessed if some structural health monitoring system is installed or retrofitted as part of the bridge.

This use of HUMS technology can also lead to a significant reduction in cycle decision time for reliability updating as obtained in the E&P reserves updating. Previously E&P operators have to wait for some significant oil volumes to be produced before a revision of the reservoir STOIIP is made but with the use of smart wells we now have the capabilities for real time data acquisition for dynamic reservoir simulation update. These smart technologies include pilots for controlling or generating auto notifications on almost any design or process parameters. These parameters include temperature of motors, deflections, torques, fluid level, pressure, flow sensors etc. These sensors are sometimes coupled together to several alarms and emergency shutdown systems for development of smart operations capabilities that are capable of early detection and preventing plant upset and emergencies. Fibre optic cables, distributed temperature gauges, electronic pressure and flow gauges are some of the sensors that can be used in standard hydrocarbon Well design to aid real time data acquisition for dynamic reservoir simulation update. The results from these real time dynamic models are then used to predict more reliable performance forecasts as well as plan future activities for improvement of asset value.

2.2.3 Organisational safety climate

The Organisation is a part of management control aimed at ensuring that business objectives, which also include safe operations, are met. The Organisational business control specifies the roles and responsibilities of persons and positions, required competences for respective roles, and required internal and external interfaces with relevant authorities among other things. The accountable E&P organisations for offshore energy exploitation include the energy exploitation and production companies that are licensed to explore and produce energy and their staff on one hand, and the supervising local authorities responsible for controlling the energy E&P companies on the other hand. Other stakeholders influencing the management of offshore structural risks include local communities, NGOs, and Politicians.

The HSE department in UK provides independent advice on the safety of people in the vicinity of major hazard establishments and this guidance enables hazardous substance authorities and local planning authorities to give due weight to safety concerns, balanced against other relevant planning considerations, when determining applications for hazardous substances consent and applications for planning permission in the vicinity of existing consented establishments [20]. The UK HSE and other similar bodies in other jurisdictions specify a guidance on safe distance around a major hazard establishment. Beyond this area the individual risk would be considered to be low enough that there would not generally be sufficient grounds to advice against any planning application.

The operating companies are required by law to promote a safe working environment and to continuously improve the work environment after any incident. About 80 to 90% of all types of offshore structural accident in the past three decades are traceable to human errors and these human errors could be due to lack of knowledge, unexpected operating environment, unanticipated event, unsafe conditions, external influence, and attitude to safety [21].

The organisational safety climate is made up of shared perceptions among stakeholders concerning the procedures, practices and kinds of behaviours that get rewarded and supported. This can be deciphered from organizational relative priorities; alignment between espousals and enactments, internal consistency of policies, procedures and practices and shared cognitions or social consensus [22]. E&P managers are aware of their roles and responsibilities as leaders and always attempt to demonstrate HSE leadership in all communication with staff and stakeholders. However research data shows that in most cases leaders are unable to promote safety by developing good quality participative and open relationships with subordinates [23]. As a result of this, good organizations regularly conduct internal reviews or sometimes engage external bodies to verify, on regular basis, how they rank on performance as well as on safety climate. The results from such surveys are used to create improvement plans, which among other things aim at improving the organizations safety culture. Also improvements in overall organisational safety can be achieved through training, coaching, networking, competence certification and continuous review of operating standards. The International Well Control Forum (IWCF) for example was established in 1992 to ensure the maintenance of common standards and the certification of all persons involved in well engineering critical roles during well drilling and workover activity.

The regulatory government organizations have also continuously and diligently been using the Reviews and Appraisal process as well as related consequence management for noncompliance to improve HSE and organisational safety climate. The effect of regulatory organisations became more noticeable since the mandatory requirement for notification of major accidents in 1984, under the aegis of the Major Accident Reporting System (MARS) as the rate of major accidents has significantly and consistently decreased. By the end of the 1980s the average number of major oil spills each year dropped to one-third of that in the previous decade [3]. This view is supported in the work of O'Dea & Flin [23] when they remarked that over the past 10 years, a plethora of technological, engineering and design improvements have undoubtedly helped to reduce the accident rates offshore to their current plateau. This HSE data reporting has since the 1980s come to stay as a KPI for HSE performance measurement for most organisations. Such KPIs are used as vehicles for continuous HSE improvement and some HSE proactive organisations have even gone to adopt slogans like Zero Tolerance to Accidents.

2.2.4 Legislation and Regulation

The main goal of most enterprise is to make profit, although there is now some emphasis on social responsibilities. The investments on social responsibilities developed over the years and in most cases were actually imposed on such companies by the local governments, the regulating authorities, and pressures from NGOs. Some of the social responsibilities include improvements in safety culture through education, environmental upgrade of facilities, process modifications, adoption of environmental management systems e.g. ISO 14001, so as to attract the required staff loyalty and dedication. Through these investments in social responsibilities, corporations are known to get social licence to operate (LTO) from their host communities, local governments and even the media. The LTO benefits can be overwhelming and includes goodwill to corporation staff and facilities, favourable government considerations during future licence bids or renewals. It can therefore be said that a combination of self-effort and compliance to local laws has contributed to improvements in overall HSE performance in several jurisdictions around the world.

Public awareness of major accidents via the media and in orchestra with issue champions, politicians, unions, public debates and decisions in parliament, is another mechanism of enforcing HSE improvements [4]. The use of the media as a means of putting pressure on authorities has been useful regarding some recent fatal accidents. The effect of such pressure was overwhelming and had damaging effects on BP stock in April 2010 when BP stock fell by 40% in June 2010 after several attempt to shut off spurring oil well in the GOM that resulted from an offshore blowout from a drilling rig [64]. The media position has also contributed to shaping opinions and forcing governments and regulators to be more stringent on laws and punishment for non-compliance. The media, especially the USA media, mounted such pressure on the initial handling of the BP disaster in the USA that the US President had to cancel his trip to Indonesia to stay at home and demonstrate his commitment to resolving the crises [10]. Also the continuous improvement in accident statistics in the North Sea from 1960 to 2006 was recorded based on continuous improvements in legislation that follow any major accident review. Lindoe et al [4] showed that, from a level of almost 50 in 1976, the number of injuries per million working hours had a definite downward sloping trend levelling at about 10 in 2006.

But legislation and regulation are just one part of Implementation and Monitoring business control. The other parts are the planning, execution and monitoring of operating integrity needs. Currently offshore Inspection plans are made and executed in line with company operating procedures and applicable regulation. This approach can be improved upon if we can borrow some best practices from other industrial sectors.

One readily available option would be the adaptation some proven technologies from reservoir modelling and simulation process in the E&P business sector.

2.3 Chapter Conclusions

Nonrenewable energy like petroleum and natural gas are not equally distributed around the globe and this creates some form of energy insecurity among nations. Some of the several efforts being made to address this energy insecurity include development of new hydrocarbon heartlands in countries with stable economies and government, investment in combustion efficiency, energy efficient systems and cars, development of renewable wind and solar energy for electricity and the development of solar powered vehicles. Notwithstanding all these efforts, it is projected that fossil fuels is generally foreseen to be supplying the main share of the world's energy supply hence the urgent need to develop safer and more efficient ways of oil and gas exploration and production.

Offshore structures are vital in chasing the limited patches of petroleum around the world. Four hundred such structures were built in 2005 and studies have shown that the number of offshore construction projects has grown by an average of 15% per year since 2005. It is expected that this growth in the overall number of construction projects will continue hence the urgent need to develop safer and more efficient ways of managing structural safety in E&P operations.

A review of the development within the field of structural reliability theory with particular attention to structural systems shows that some gaps still exist in the reliability prediction process and hence there is a urgent desire for improvements such that the estimated reliability is capable of expressing a physical property of the structure rather than a measure of safety based on a general probabilistic model. One way of closing this gap is to design a measurement based system that measures some physical properties of any given structure. Deflection and damping are some of the measurable properties of an offshore structure and so a some study was undertaken to see if these measurable properties could aid in getting structural reliability prediction closer to reality. This suggested approach would eliminate reliance on people’s capability and hence eliminate human errors which were estimated as being responsible for 80 - 90% of all offshore structural accidents.

The feasibility of this recommendation will be tested using a design case study in chapter 3.

3 OFFSHORE STRUCTURAL DESIGN CASE STUDY

The required performance of offshore structures is ensured by designing them to comply with serviceability and safety requirements for a service life as specified by the owner, as well as carrying out load or response monitoring, or inspection and taking appropriate remedial actions. The safety requirements are imposed to avoid ultimate consequences such as fatalities and environmental or property damage.

Moan [24] documented that the current practice which is implemented in new offshore codes are characterized by:

- Design criteria formulated in terms of limit states.
- Semi-probabilistic methods for ultimate strength design which have been calibrated by reliability or risk analysis methodology.
- Fatigue design checks depending upon consequences of failure and access for inspection.
- Explicit accidental collapse design criteria to achieve damage-tolerance for the system.
- Considerations of loads that include payload; wave, current and wind loads, ice (for arctic structures), earthquake loads (for bottom supported structures), as well as accidental loads such as e.g. fires, explosions and ship impacts.

- Global and local structural analysis by finite element methods for ultimate strength and fatigue design checks.
- Nonlinear analyses to demonstrate damage tolerance in view of inspection planning and progressive failure due to accidental damage.

This research and the case modelling below aims at demonstrating a data based concept which could be added as a criteria in support of global and local structural analysis for ultimate strength and fatigue checks. This advocated methodology has the capacity to contribute to addressing the Long-term planning and Implementation of Safety Cases where the UK HSE plans to collaborate with the UK industry towards a unified approach to the safety management of ageing offshore infrastructure.

3.1 CASE MODELING

The shallow water oil and gas development is critical to ensuring energy security as they are simpler and involve cheaper drilling rigs and operations. Table 4 shows that 86% of the installed offshore structures in the GOM are below 200m of water and these are classified as shallow water installations. Figure 4 shows the Nigetria coastal area and continental shelf. The inner Nigerian continental shelf of 0 to 45m water depth areas extend from the shoreline to between 30 km inland to150km in the Niger Delta [25]. The water depths of the Niger delta creeks which have been heavily drilled are in also less than 30ft hence a 60m offshore structural design was selected as fit for purpose for this research which is in support of shallow offshore structural engineering development in Nigeria.

Table 4: GOM Offshore structures at various water depths

Water depth (m)	Active platforms	Producing well	Producing well / Active platform
0–200	3489	3840	1.1
201–400	455	1873	4.1
401–800	49	285	5.8
801–1000	4	50	12.5
1000+	22	309	14

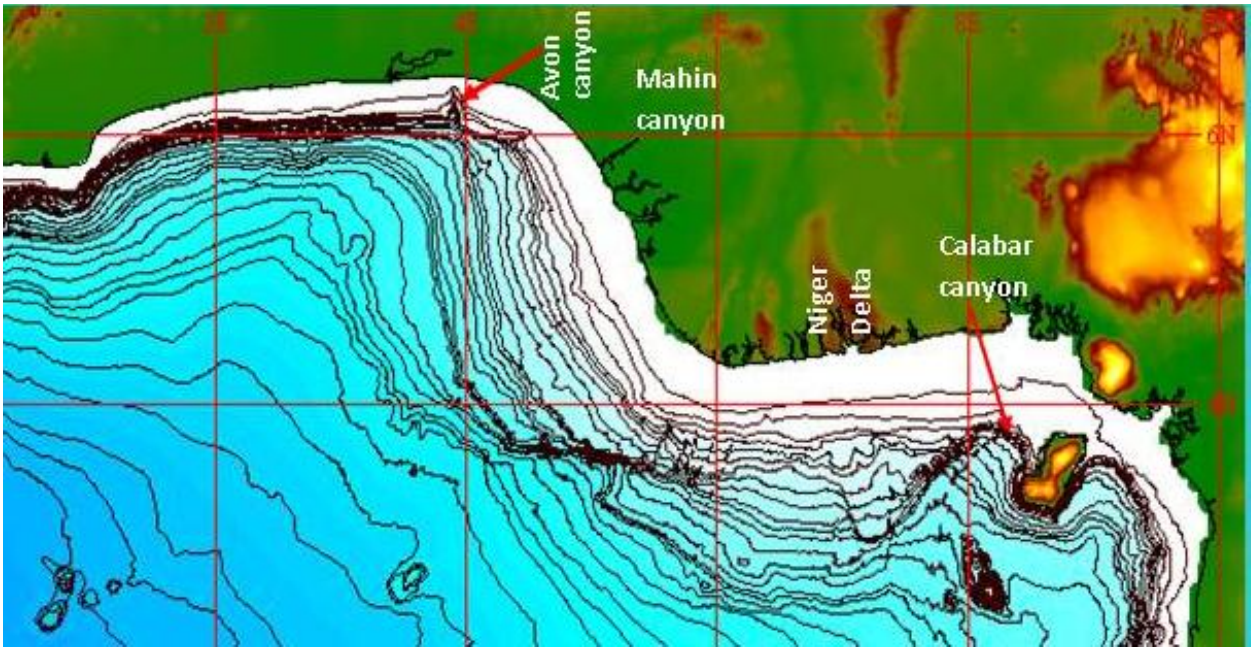


Figure 4 Bathymetric configuration of the Nigerian continental shelf [25].

A 60m shallow water offshore steel structure was therefore modelled and subjected to possible high case loads realizations in 30m water depth in other to estimate the magnitude of measurable data in support of the thesis on smart offshore structure for reliability prediction process. Having discussed the application of smart technology to the oil and gas industry in Chapter 2, an attempt is made to discuss the application of the smart operations technology process to offshore structural reliability prediction process.

The ABAQUS Unified FEA product suite from Dassault Systems USA was chosen for this modelling research based on availability. The deflection predictions from the ABAQUS model was calibrated with manual computations based on a simple 20 m, 0.75m diameter pipe with 0.0254m thickness, cantilever beam subjected to 1KN end load as shown in figure 5. The results from both methods are in very close agreement with a maximum error of 2.97% as shown in table 5 hence the justification for the use of ABAQUS FEA modelling tool.

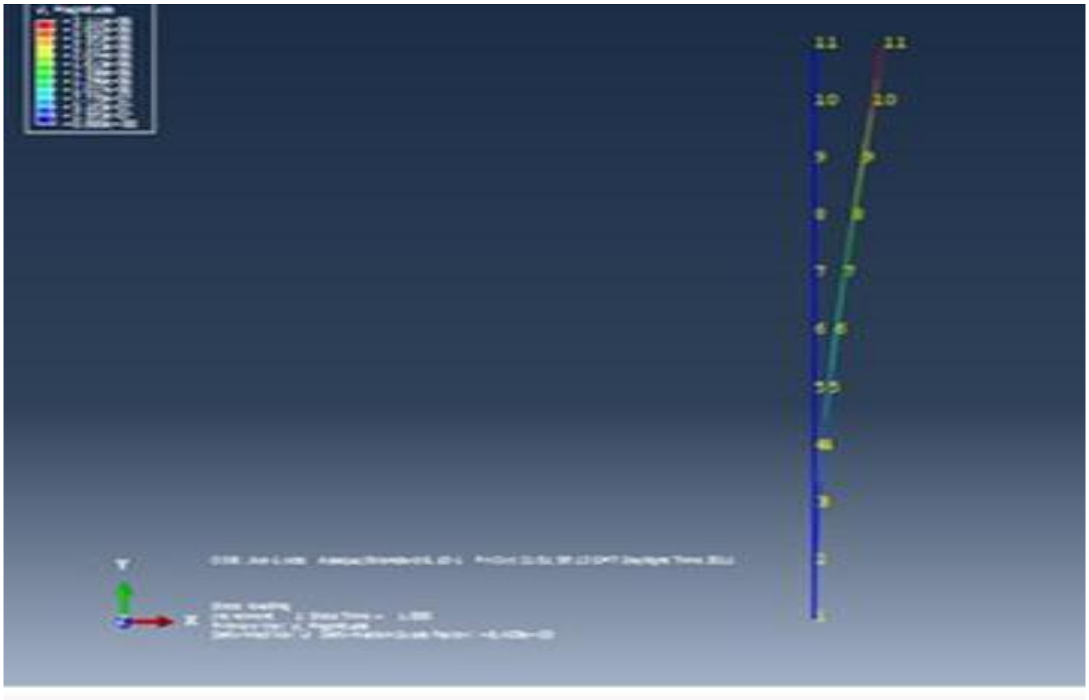


Figure 5 Cantilever bean design for ABAQUS calibration

Table 5: Abaqus model static deflection calibration

Manual Calculation			Calculations from ABAQUS Model				Error
Node	distance (x) m	$\delta = \frac{Px^2(3L-x)}{6EI}$ m	Deflection (m)	V.Mises Stress N/m2	Strain	Young Modulus N/m2	%
1	0	0	0	8.96E+01	4.27E-10	2.10E+11	0.00%
2	2	4.64919E-08	4.59E-08	1.79E+02	8.53E-10	2.10E+11	1.35%
3	4	1.79555E-07	1.75E-07	3.58E+02	1.71E-09	2.10E+11	2.26%
4	6	3.8957E-07	3.80E-07	5.38E+02	2.56E-09	2.10E+11	2.56%
5	8	6.66918E-07	6.49E-07	7.17E+02	3.41E-09	2.10E+11	2.71%
6	10	1.00198E-06	9.74E-07	8.96E+02	4.27E-09	2.10E+11	2.80%
7	12	1.38514E-06	1.35E-06	1.08E+03	5.12E-09	2.10E+11	2.86%
8	14	1.80677E-06	1.75E-06	1.25E+03	5.97E-09	2.10E+11	2.90%
9	16	2.25726E-06	2.19E-06	1.43E+03	6.83E-09	2.10E+11	2.93%
10	18	2.72699E-06	2.65E-06	1.61E+03	7.68E-09	2.10E+11	2.95%
11	20	3.20634E-06	3.11E-06	1.70E+03	8.11E-09	2.10E+11	2.97%

E =		2.10E+11
I =	$\frac{\pi}{64}(D^4 - d^4)$	0.003960409
6EI=		4990115475

The ABAQUS FEA suite was used to create a conceptual shallow water wellhead structure using the data shown in table 6 below:

DESIGN ENVIRONMENTAL DATA		STEEL MATERIAL SPECIFICATION
Water depth :	30m	• Base of structure is 20.00 x 20.00 m • Top of structure is 13.48 x 13.48 m • Height of Structure 60 meters divided into three equal parts of 20m. • Main beams : 0.76m pipe and 0.0254m thickness • Horizontal beams : 0.60m pipe and 0.0254m thickness • Braces: 0.308m pipe and thickness of 0.0127m
Lowest water level :	20m	
Highest water level	30 m	

Table 6: Design basis and specifications for offshore structures case

Wellhead structures do not support any deck load and hence no deck load was used in this design case study. Figure 6 shows the designed structure while figure 7 is a schematic of the said design that will be used for wave force estimation.

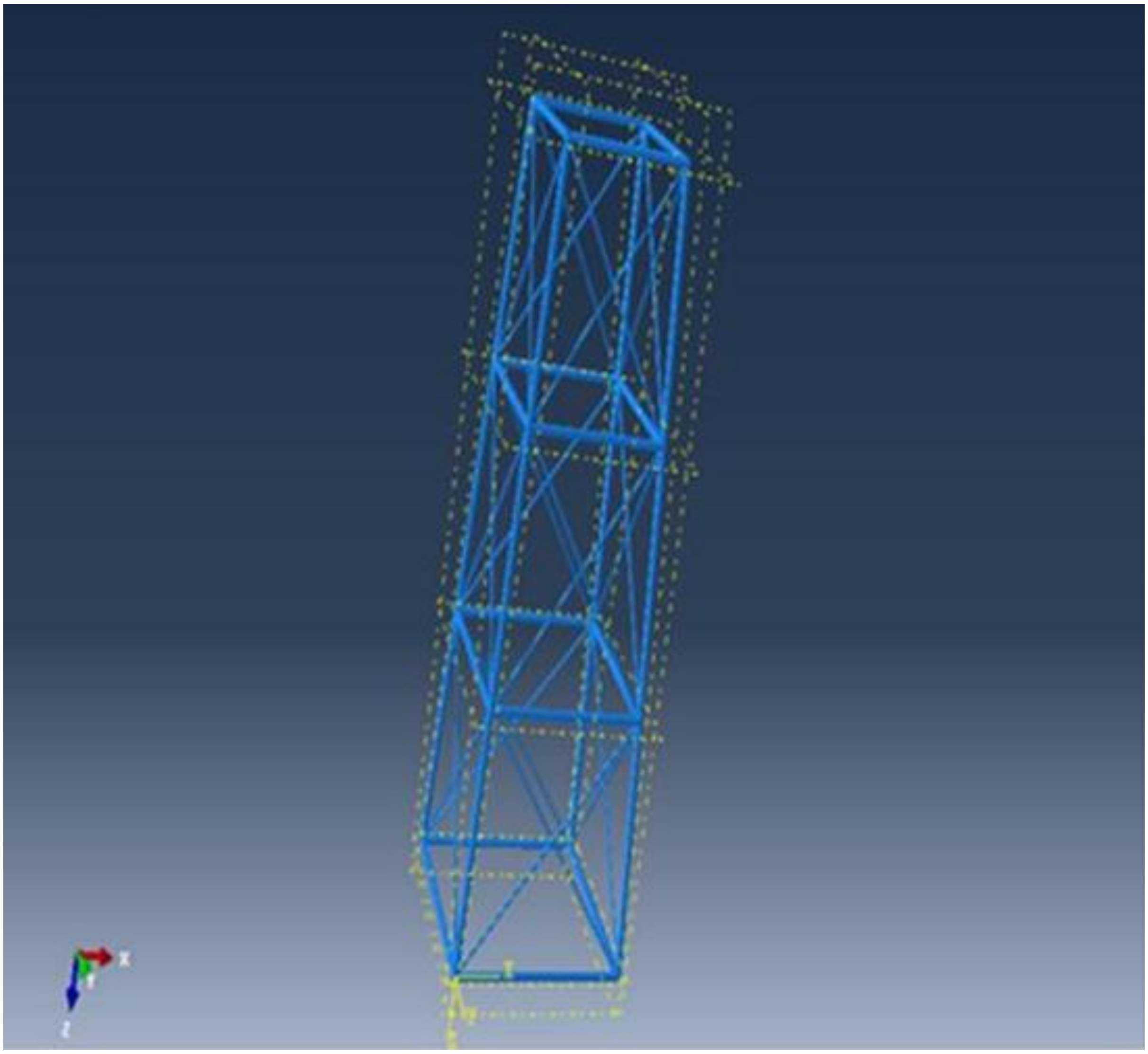


Fig 6: ABAQUS Model Simulation

3.2 WAVE FORCE ON DESIGNED STRUCTURE

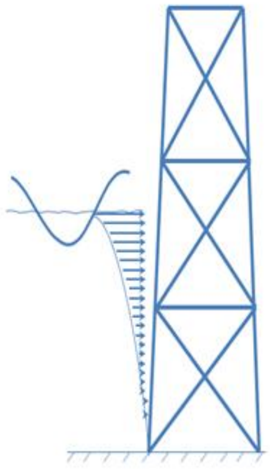


Fig 7: Model Simulation schematics

WAVE FORCE ESTIMATION

The details of the design data for the modelled structure are shown in table 6.

Wave amplitude of 2m and frequency of 0.6286rad/sec on a 30m water depth was used to estimate the wave force on the designed structure as shown below.

$\mathbf{F} = \boldsymbol{C_D \rho \frac{D}{2} |u| u + C_{AM} \rho \pi \frac{D^2}{4} \dot{u}}$ **(Morison's equation)**

It can be shown that $C_D = 1 + C_{AM}$

Velocity potential $\Phi = -\frac{a\omega}{k} e^{ky} \cos(kx - \omega t)$

The Morison's equation can be written as ***dF(t)***$= \boldsymbol{(1 + C_{AM})\rho \dot{U}_n dV} + \boldsymbol{\frac{1}{2} C_D \rho |U_n| U_n dS}$

$\boldsymbol{U_n = \frac{\partial \Phi}{\partial x} = \frac{a\omega}{k} e^{ky} k \sin(kx - \omega t) = a\omega^2 e^{ky} \sin(kx - \omega t)}$

$\boldsymbol{\dot{U}_n = \frac{\partial U_n}{\partial t} = -a\omega^2 e^{ky} \cos(kx - \omega t)}$

For the designed structure the total horizontal wave force on the body (x=0 at the FWL of the body) :

$F(t) = \int_{-d}^{0} dF(t) dy$

$= \int_{-d}^{0} \left[(1 + C_{AM}) \rho dV \left(\boldsymbol{-a\omega^2 e^{ky} \cos(-\omega t)} \right) + \frac{1}{2} \boldsymbol{C_D \rho dS \left| a\omega e^{ky} \sin(-\omega t) \right| a\omega e^{ky} \sin(-\omega t)} \right] dy$

$= -(1 + C_{AM}) \rho a\, \boldsymbol{\omega^2 \cos(-\omega t)}\, dV \int_{-d}^{0} \boldsymbol{e^{ky}}\, dy + \frac{1}{2} \boldsymbol{C_D} \rho \boldsymbol{a^2\, \omega^2 |\sin(-\omega t)|\, sin(-\omega t)} dS \int_{-d}^{0} \boldsymbol{e^{2ky}}\, dy$

D = 0.76m
Volume per unit length dV=$\pi \left(\frac{0.76}{2} \right)^2$ *= 0.454 m*^{3}*/m*

Surface per unit length dS= 0.76/2 = 0.38m^2*/m*

Amplitude a = Hw/2 = 4m/2 = 2m

Frequency ω=2π/T= 2π/10 = 0.6286rad/sec

Wave number k=2π/λ=4π^2*/(gT*^{2}*) = 0.0365rad/m*

d=30m

$\int_{-d}^{0} \boldsymbol{e^{ky}}\, dy = \frac{1}{k} e^{ky} \Big|_{-d}^{0} = \frac{1}{k}(1 - e^{-kd})$ *= 18.23m*

$\int_{-d}^{0} \boldsymbol{e^{2ky}}\, dy = \frac{1}{2k} e^{ky} \Big|_{-d}^{0} = \frac{1}{2k}(1 - e^{-2kd})$ *= 12.16m*

Substituting
$F(t) = \int_{-d}^{0} dF(t) dy$

$= -(1 + 1) * 1025 kg/m3 * 2m * (0.628 \frac{rad}{s})^2 \boldsymbol{\cos(-\omega t)} * \boldsymbol{0.454 \frac{m3}{m}} * 18.23m + \frac{1}{2} * \boldsymbol{0.7} * \frac{1025kg}{m3} * 4\boldsymbol{m^2} * (0.628 \frac{rad}{s})^2 \boldsymbol{|\sin(-\omega t)|\, sin(-\omega t)} * \boldsymbol{\frac{0.38m2}{m}} * 12.16m$

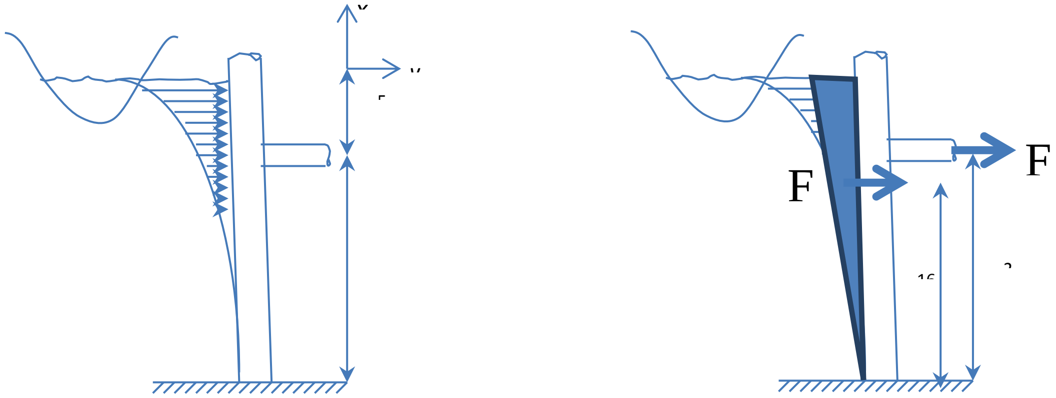
$= -13382.8N * cos(\boldsymbol{-\omega t}) + \boldsymbol{2615 |\sin(-\omega t)|\, sin(-\omega t)}$

For the given frequency of ω of 0.6286rad/sec the wave force due to the wave loading can be calculated as a function of time (t) as shown in table 7

Time (Sec)	Force (N)	Time (Sec)	Force (N)	Time (Sec)	Force (N)
0	-13383	18	-7362	36	4285
1	-9082	19	-13290	37	-9160
2	3407	20	-7641	38	-13011
3	13197	21	5500	39	-5998
4	10245	22	13382	40	7474
5	-1392	23	9003	41	13279
6	-12646	24	-3532	42	7550
7	-11218	25	-13219	43	-5620
8	-612	26	-10178	44	-13382
9	11749	27	1518	45	-8924
10	12003	28	12690	46	3657
11	2556	29	11163	47	13240
12	-10540	30	488	48	10110
13	-12606	31	-11815	49	-1644
14	-4396	32	-11959	50	-12734
15	9061	33	-2437	51	-11107
16	13033	34	10624	52	-364
17	6099	35	12573	53	11879

Table 7: Dynamic wave force on designed structure

Table 7 shows that the force on the designed structure as a sine wave and varies from a low of about 0.48 KN to a maximum of 13.2 kN. This force is calculated at a FWL of 30m. This free water level varies from 20m to 30m. To generate another load realisation the calculated force of 13KN was evaluated at an average free water level of 25m. Figure 8a shows a representation of the wave on the designed offshore structure based on the realisation of max force of 13.3kN acting at an average FWL of 25m. By replacing the exponential wave force with a uniformly varying triangular force, the equivalent wave force acting on the node of the designed structure at average FWL of 25m can be calculated. The calculation was made by calculating bending moments around the seabed where the structural leg is fixed. By assuming that the calculated 13KN act acts through the centroid of the triangular force shown in fig 8b an equivalent nodal force of 11kN is estimated. This 11KN wave force was then used for structural analysis of the designed structure. The uncertainties related to wave force estimation and how they impact on the estimated structural reliability will be discussed in chapter 4.



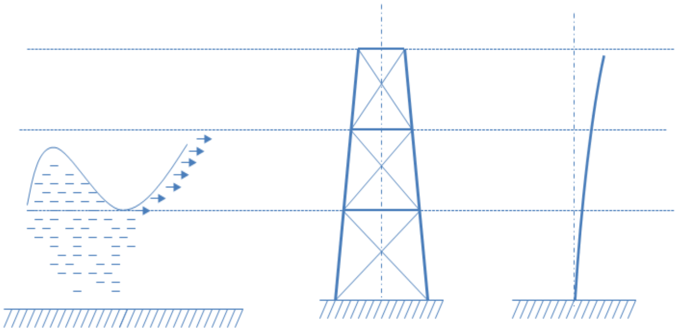
Fig

Fig

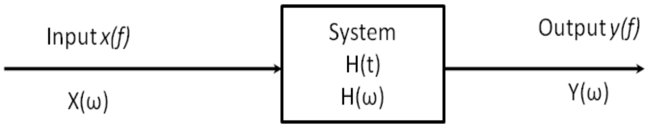
Fig 8: Equivalent Force estimation due to wave action.

3.3 DYNAMIC RESPONSE FUNCTION OF DESIGNED STRUCTURE

The elasticity property of steel has been documented as Hooke’s law. The Frequency Response Function (FRF) or Dynamic Response Function (DRF) is a measure of the ratio of the output to the input signal for any given system and can be used for the identification of system characteristics in engineering. In its basic form the DRF of a system response, at any load, can be described by the ratio of amplitude of output to input function [26]. The Wave forces to which the offshore structures are subjected are cyclic. The structural resistance is also cyclic and the cyclic load - resistance effect can be modelled through the use of dynamic response as represented in figure 9 [27].



Action and reaction forces on an offshore structure



Block diagram of a linear system

Fig 9: Dynamic response function illustration block diagram

For the block diagram in fig 9 the DRF

$$H_{\omega} = \frac{Y_{\omega}}{X_{\omega}} = \frac{\delta_{dynamic}}{\delta_{static}} = \frac{\sigma_{dynamic}}{\sigma_{static}}$$

Where $\delta_{dynamic}$ and δ_{static} are the dynamic and load static deflections respectively. Figure 10 shows a harmonic response of the designed structure at different time intervals. It should be noted that dynamic force has to have enough acceleration in comparison to the structure's natural frequency otherwise the structure will not vibrate as shown in figure 10. Only the first nodes of the harmonics of the designed structure for each wave frequency was used in the calculation of the DRF as documented in this section.

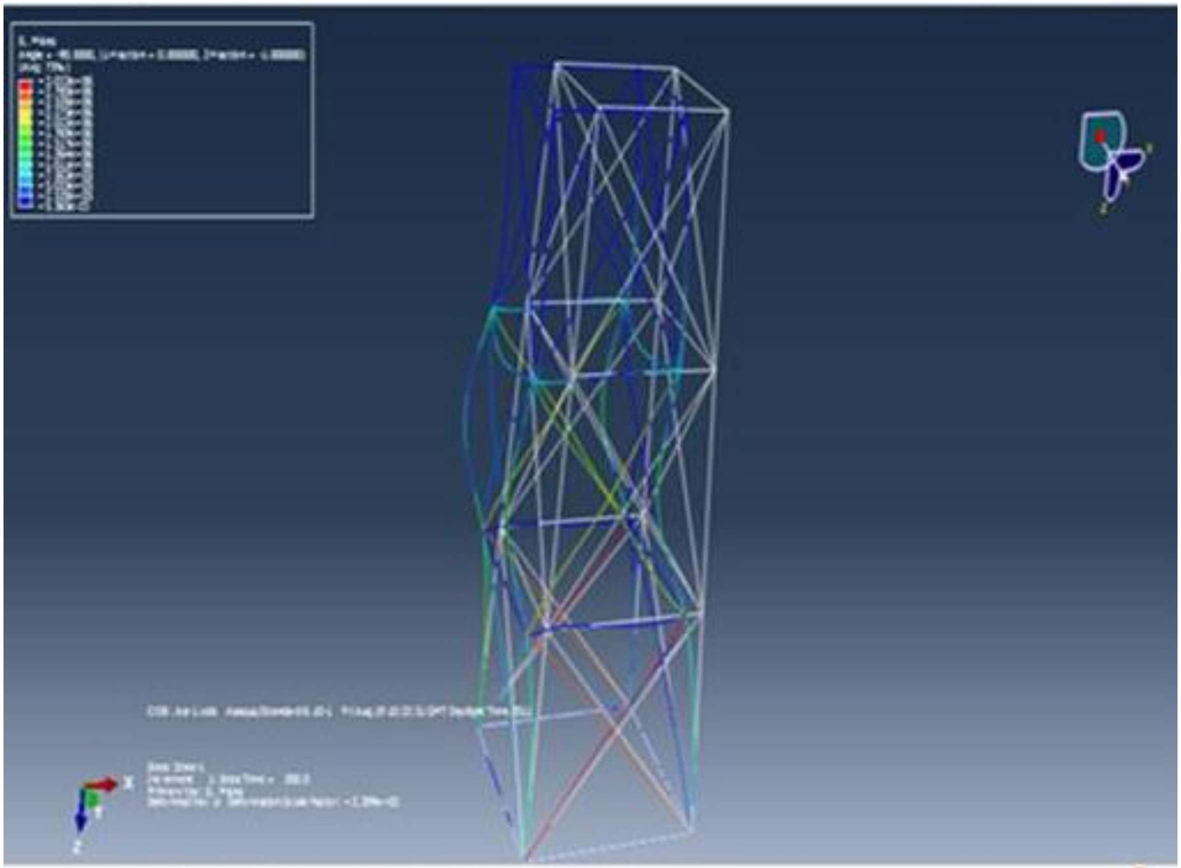


Fig 10: ABAQUS Structural response to Wave load

The dynamic response function is analogous to the tuning fork sound damping experiment and, like any given tuning fork, any given offshore steel structure will vibrate at a given frequency when subjected to a particular dynamic load. These dynamic characteristics of the structure will change due to failure of one or more structural members of the given structure.

This change in the dynamic properties of a modified structure can be determined by experimental testing or numerical simulation, both of which are complex, expensive, and time-consuming. The modified dynamic properties can also be determined numerically without solving the equations of motion of the fully modified structure and this is the focus of this case study.

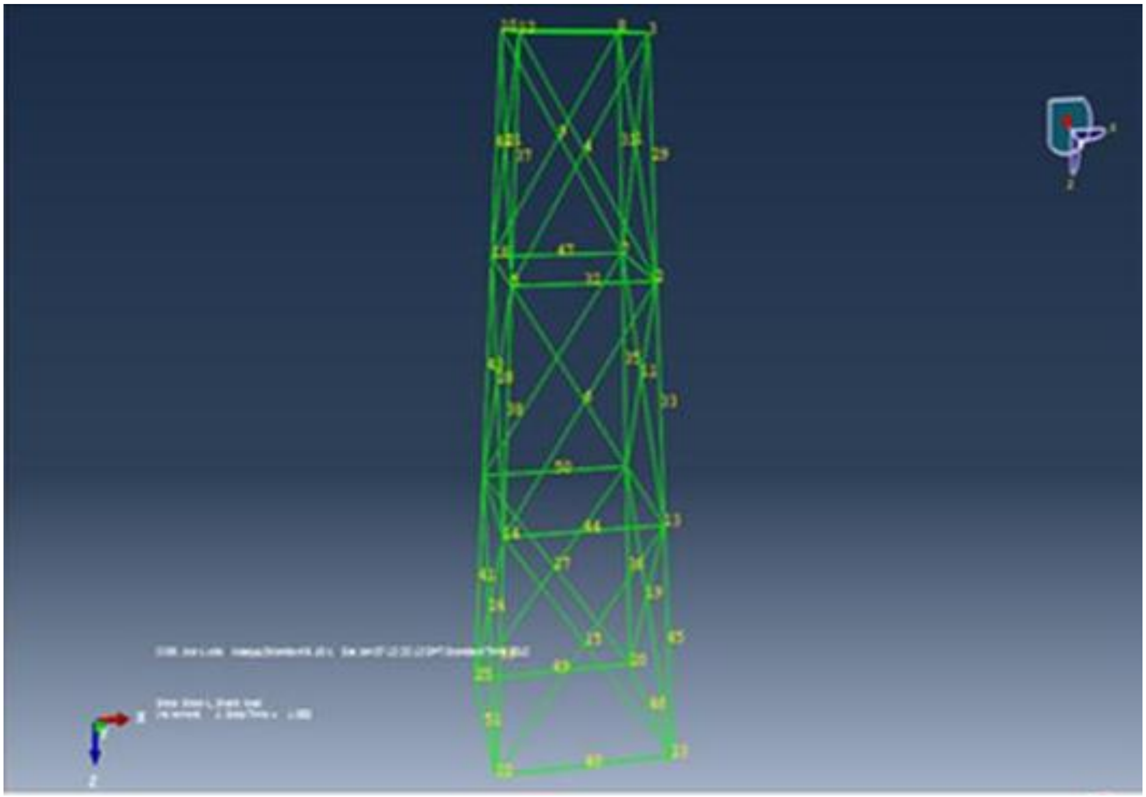


Fig 11: ABAQUS model for structural response investigation of members

Labels were assigned to structural members in the structural case as shown in figure 11 for monitoring of respective stress response for each dynamic loading simulation run. The 11kN equivalent nodal load was used to generate the static deflection in ABAQUS. Using the same 11kN equivalent nodal load and several frequencies the max dynamic deflection for each frequency for the respective members were recorded after each simulation run.

3.4 DYNAMIC LOADING OF DESIGNED STRUCTURE

The static displacement calibration for Abaqus modelling has been documented in section 3.3. The same model used for static deflection calibration was also used for the calibration of ABAQUS result with that for manual calculation. The objective of this calibration is to verify that the dynamic load deflection results from Abaqus modelling compares very well with manual computation. The manual computation derives from some form of approximation to solution to the differential equation for estimation of displacement as discussed below. The analogue for the cantilever deflection figure 12a would be the spring deflection as shown in figure 12b.

The deflection of a spring system due to load M can be expressed as:

$M\ddot{x} + Kx = 0$ or $\ddot{x} + p^2x = 0$ where $p = \sqrt{k/M}$

Cheng [28] has shown that the solution to the dynamic displacement (x) of the structure in figure 12 below can be given as

$$x = x_{to}\cos p\,(t - t_0) + \frac{\dot{x}_{t0}}{p}\sin p(t - t_0)$$

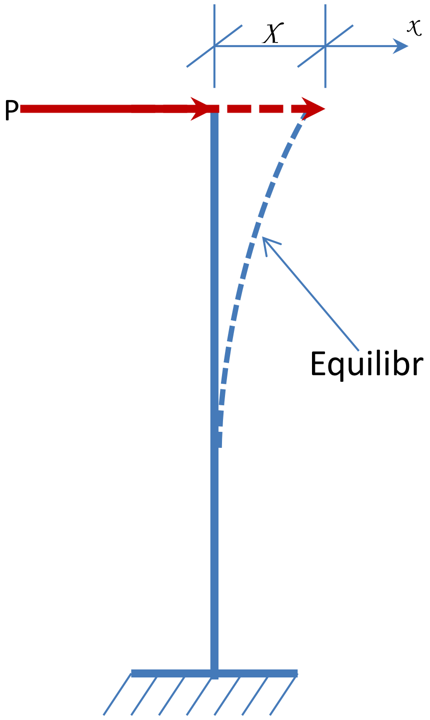


Fig 12a

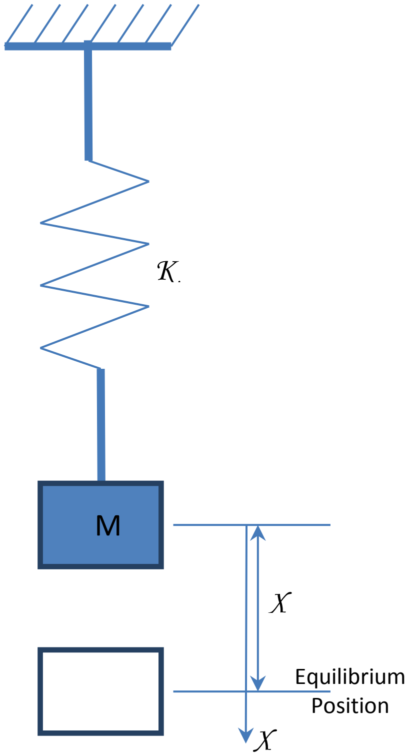


Fig 12b

Where $p = \frac{2\pi}{T}$=$2\pi f$ (angular frequency, rad/s)

$f = \frac{1}{T} = \frac{p}{2\pi}$ (natural frequency , cycles/s)

$T = \frac{1}{f} = \frac{2\pi}{p}$ (natural period , s)

This implies that the displacement profile is a form of sine wave when the applied force is a sine wave.

By evaluating the displacement at high angular frequencies the contribution of $\frac{\dot{x}_{t0}}{p}\sin p(t-t_0)$ can be ignored.

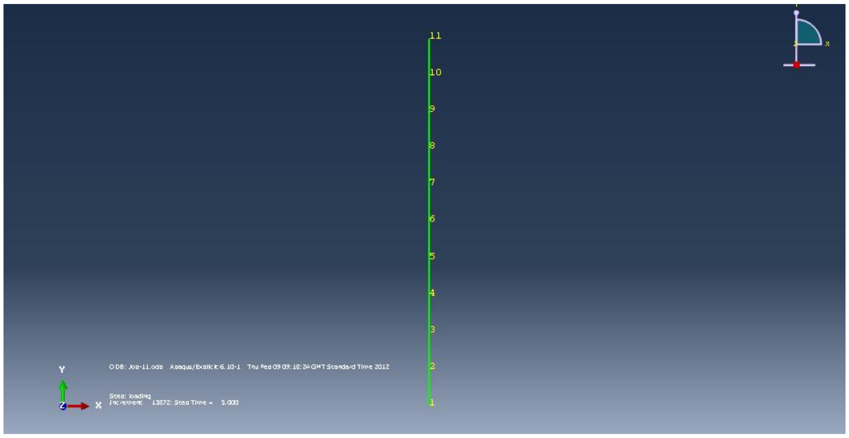


Figure 13 ABAQUS cantilever beam model for dynamic response calibration

The ABAQUS cantilever beam model for dynamic load calibration is as shown in figure 13. Node 1 is fixed while a 5kN static load in the x direction was applied at node 11. The resulting static deflection at node 11 from ABAQUS model was 5.31958E-03m. For the same 5kN force at node 11 and a frequency of 40 cycles/s (p= 2*π*40=251.327 rad/s), the deflection from manual calculation at any point can be approximated to

$$x = (5.31958\mathrm{E} - 03) * \cos p\,(251.327 * t)$$

The dynamic deflection due to wave load at the respective nodes from ABACUS model simulation were generated. The manual estimate of the dynamic deflection based on the approximate equation above was also made for the respective nodes. The comparison of this approximate manual calculation with Abaqus model result at different time intervals, for the respective nodes are shown in table 8 below.

	STATIC	Dynamic Deflection (m) after		
Node	Deflection (m)	t=1sec	t=300sec	t=450sec
1	-2.60294E-03	-2.60709E-03	-2.60309E-03	-2.60298E-03
2	-1.81072E-03	-1.81361E-03	-1.81082E-03	-1.81075E-03
3	-1.01850E-03	-1.02012E-03	-1.01856E-03	-1.01852E-03
4	-2.26276E-04	-2.26632E-04	-2.26288E-04	-2.26278E-04
5	5.65954E-04	5.66863E-04	5.65985E-04	5.65962E-04
6	1.35819E-03	1.36036E-03	1.35827E-03	1.35822E-03
7	2.15044E-03	2.15387E-03	2.15056E-03	2.15047E-03
8	2.94271E-03	2.94740E-03	2.94286E-03	2.94275E-03
9	3.73498E-03	3.74093E-03	3.73518E-03	3.73504E-03
10	4.52728E-03	4.53447E-03	4.52752E-03	4.52734E-03
11	5.31958E-03	5.32803E-03	5.31985E-03	5.31964E-03

Table 8: Abaqus model dynamic deflection calibration

A comparison of Abaqus modelling simulation results and approximate solution at maximum deflection point (node 11) is presented in table 9. The results show very good comparison and hence reinforced the used of Abaqus FEA simulator for the analysis of dynamic analysis of the designed offshore structure.

Elapsed	Max (Node 11) Dynamic Deflection (m) after		
t (sec)	Manual calculation	From Abaqus	Percentage error
1	5.31958E-03	5.32803E-03	0.15860%
300	5.27894E-03	5.31985E-03	0.76898%
450	5.22829E-03	5.31964E-03	1.71723%

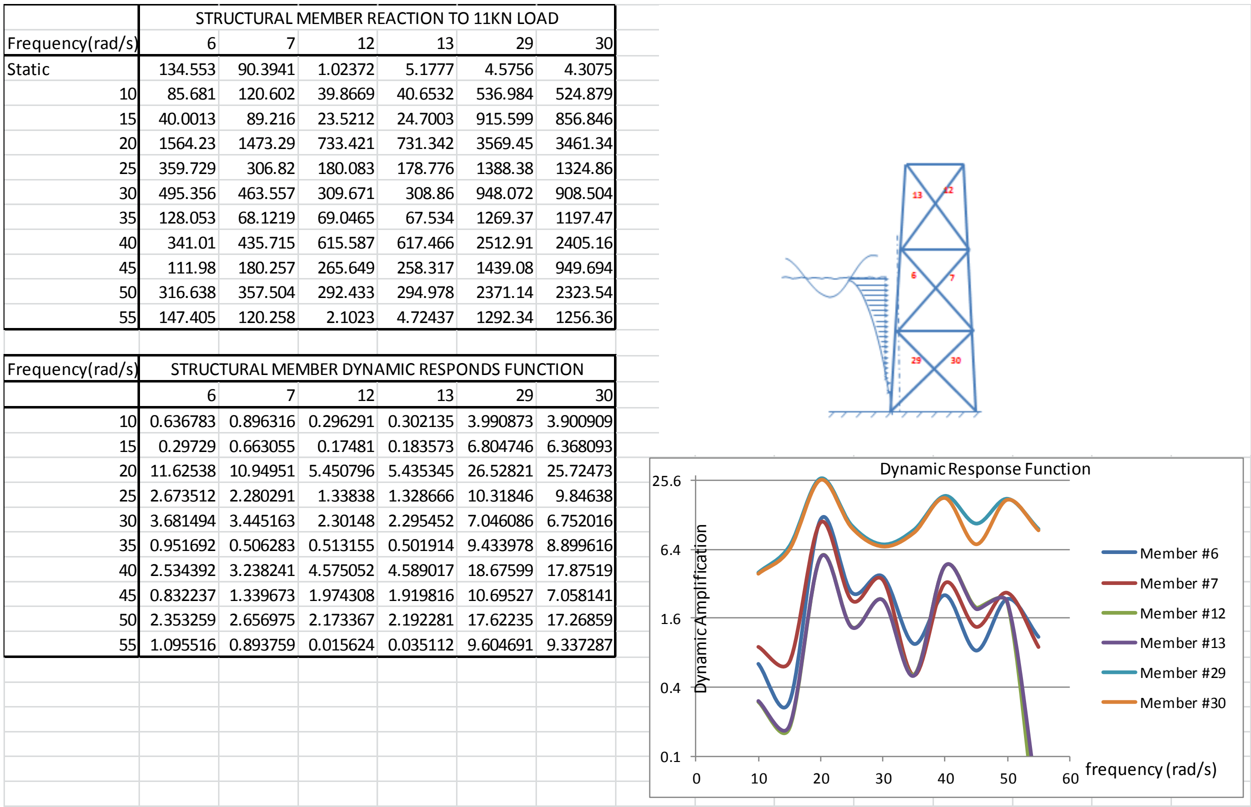
Table 9: Dynamic deflection calibration error propagation with time

Having obtained a very good match between manual computation and ABAQUS simulation, the case model created in section 3.3 was then used to calculate the Dynamic response of the designed structure based on the 11kN approximate equivalent wave load.

3.5 STRUCTURAL DYNAMIC RESPONSE FUNCTION

Abaqus simulation runs was made for several wave frequencies and the dynamic response (load) for each member was generated. A wave amplitude of 2m and frequency of 0.6286rad/sec was the Basis for Design for the case study described in this thesis. This level of wave dimension are typical of benign shallow water offshore environments and present very little dynamic response on any offshore structure. As a result much higher wave frequencies are used in the estimation of the dynamic response function presented below in other to simulate a typical hostile offshore environment.

The ratio between this dynamic response and static load response was used to calculate the DRF for respective structural members. The calculated DRF for selected members of the designed structure for various frequencies is as shown in figure 14.

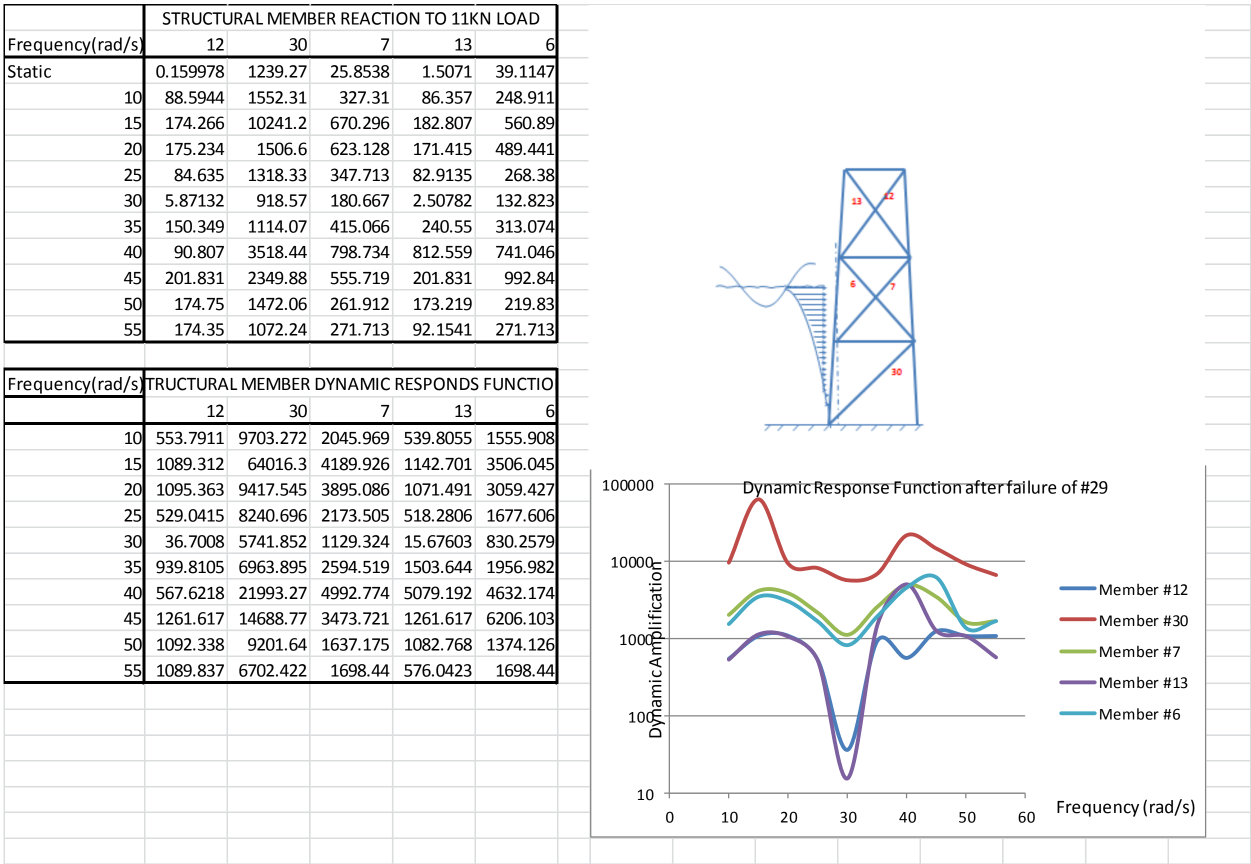


	STRUCTURAL MEMBER REACTION TO 11KN LOAD					
Frequency(rad/s)	6	7	12	13	29	30
Static	134.553	90.3941	1.02372	5.1777	4.5756	4.3075
10	85.681	120.602	39.8669	40.6532	536.984	524.879
15	40.0013	89.216	23.5212	24.7003	915.599	856.846
20	1564.23	1473.29	733.421	731.342	3569.45	3461.34
25	359.729	306.82	180.083	178.776	1388.38	1324.86
30	495.356	463.557	309.671	308.86	948.072	908.504
35	128.053	68.1219	69.0465	67.534	1269.37	1197.47
40	341.01	435.715	615.587	617.466	2512.91	2405.16
45	111.98	180.257	265.649	258.317	1439.08	949.694
50	316.638	357.504	292.433	294.978	2371.14	2323.54
55	147.405	120.258	2.1023	4.72437	1292.34	1256.36

Frequency(rad/s)	STRUCTURAL MEMBER DYNAMIC RESPONDS FUNCTION					
	6	7	12	13	29	30
10	0.636783	0.896316	0.296291	0.302135	3.990873	3.900909
15	0.29729	0.663055	0.17481	0.183573	6.804746	6.368093
20	11.62538	10.94951	5.450796	5.435345	26.52821	25.72473
25	2.673512	2.280291	1.33838	1.328666	10.31846	9.84638
30	3.681494	3.445163	2.30148	2.295452	7.046086	6.752016
35	0.951692	0.506283	0.513155	0.501914	9.433978	8.899616
40	2.534392	3.238241	4.575052	4.589017	18.67599	17.87519
45	0.832237	1.339673	1.974308	1.919816	10.69527	7.058141
50	2.353259	2.656975	2.173367	2.192281	17.62235	17.26859
55	1.095516	0.893759	0.015624	0.035112	9.604691	9.337287

Figure 14: Data and DRF of members of interest

This FEA results show that the bottom braces support the bulk of the unidirectional wave load force with member 29 being slightly more stressed than member 30. Two structural members were removed from the bottom of the 60ft modelled structure in other to simulate a failed structural. The failed structure was then subjected to the same 11kN wave. The resistance from this damaged structure was then evaluated. Figure15 shows the DRF after the failure of brace 29 and its corresponding pair on opposite plane. It highlights the stress redistribution with the failure of member 29 (and its corresponding member on the opposite plane shows) in the form of increased DRF responses on the middle and top braces.



	STRUCTURAL MEMBER REACTION TO 11KN LOAD				
Frequency(rad/s)	12	30	7	13	6
Static	0.159978	1239.27	25.8538	1.5071	39.1147
10	88.5944	1552.31	327.31	86.357	248.911
15	174.266	10241.2	670.296	182.807	560.89
20	175.234	1506.6	623.128	171.415	489.441
25	84.635	1318.33	347.713	82.9135	268.38
30	5.87132	918.57	180.667	2.50782	132.823
35	150.349	1114.07	415.066	240.55	313.074
40	90.807	3518.44	798.734	812.559	741.046
45	201.831	2349.88	555.719	201.831	992.84
50	174.75	1472.06	261.912	173.219	219.83
55	174.35	1072.24	271.713	92.1541	271.713

Frequency(rad/s)	TRUCTURAL MEMBER DYNAMIC RESPONDS FUNCTIO				
	12	30	7	13	6
10	553.7911	9703.272	2045.969	539.8055	1555.908
15	1089.312	64016.3	4189.926	1142.701	3506.045
20	1095.363	9417.545	3895.086	1071.491	3059.427
25	529.0415	8240.696	2173.505	518.2806	1677.606
30	36.7008	5741.852	1129.324	15.67603	830.2579
35	939.8105	6963.895	2594.519	1503.644	1956.982
40	567.6218	21993.27	4992.774	5079.192	4632.174
45	1261.617	14688.77	3473.721	1261.617	6206.103
50	1092.338	9201.64	1637.175	1082.768	1374.126
55	1089.837	6702.422	1698.44	576.0423	1698.44

Figure 15: Data and DRF of members of interest after initial failure of two members

3.6 Dynamic Modelling result analysis

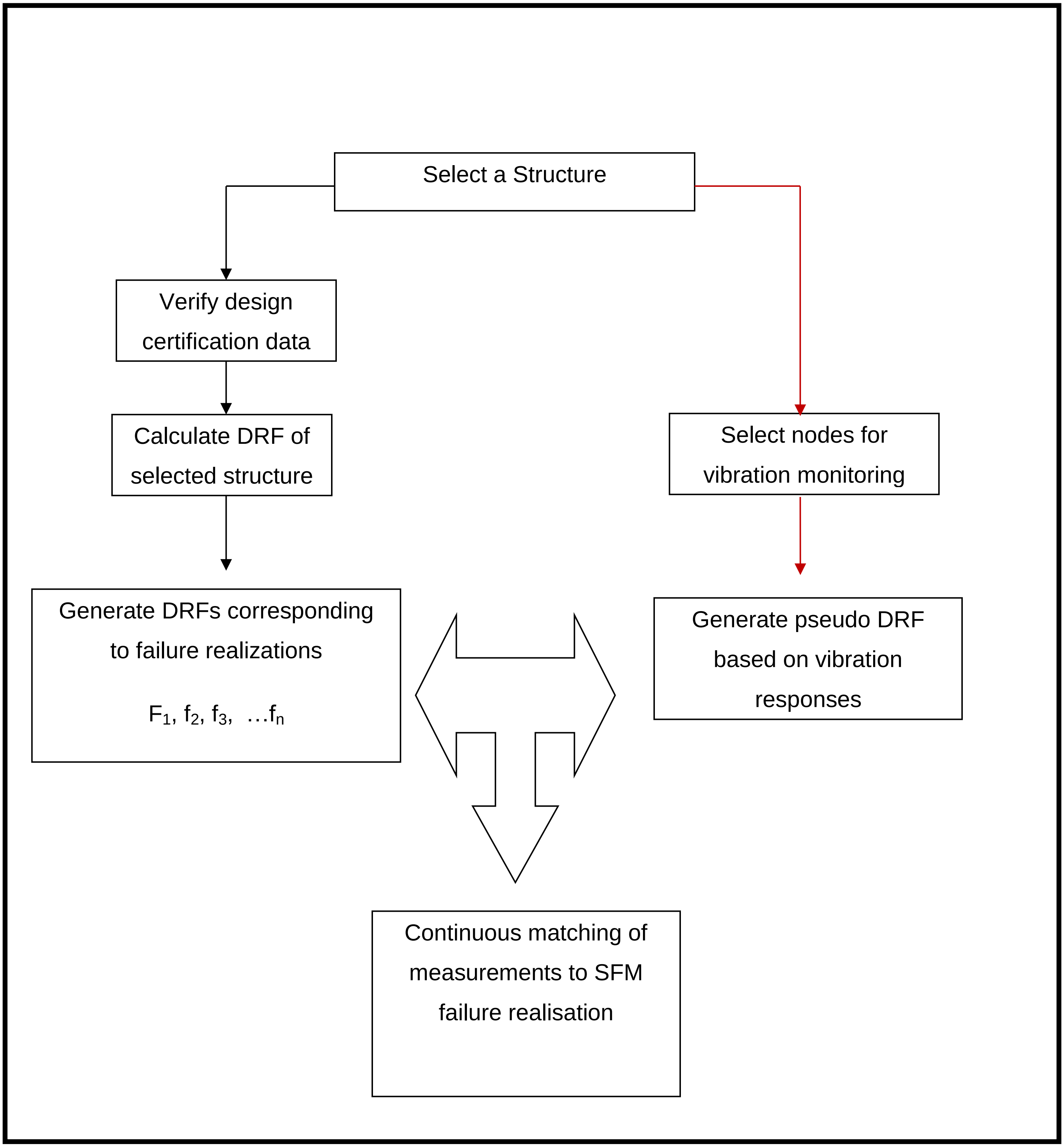
The DRF analysis of the case model have shown that the bottom braces of the designed offshore structure bear most of the dynamic load. In the case described above the bottom braces yields a maximum load amplification of 25 due to the applied wave force equivalent to 11KN nodal force. These bottom members are much more difficult to access and repair, implying that a lot of front end engineering design (FEED) work is necessary for structural robustness of these members. This also implies that, in addition to ensuring that the cathodic protection for the structure is functional, the bottom brace materials, as well as structural legs that will be submerged in water have to be made much thicker and with stronger steel grades. The corrosion risk on these main load bearing members can also be managed by applying stricter fabrication methods and standards. This is especially critical considering that these members also have to support the hydrostatic load which is not felt by other members that are not submerged. With the failure of two bottom brace, the dynamic load amplification of all other structural members increased as shown in the figure15. The finding of this FEA result is in line with assertion by Lee & Shin [29] when they documented that the existence of structural damages within a structure leads to the changes in dynamic characteristics of the structure such as the vibration responses, natural frequencies, mode shapes, and the modal damping.

The foregoing therefore means that by designing a smart system that records the changes in dynamic characteristics of a structure we can detect structural damages within such structure. This is the basis for the advocated smart structure for reliability updating process documented and explained below.

3.7 SMART OFFSHORE STRUCTURE FOR RELIABILITY PREDICTION

The fact that structural failure can be detected by designing a smart measurement system that records the changes in dynamic characteristics of a structure has been demonstrated in section 3.8. Though recommended for new structures, retrofitting the advocated process improvement to existing structures will not be difficult since higher deflections will always occur around the top of the designed structure and higher magnifications will also be noticed around the top and middle braces of the respective structures when any of the bottom braces fail. Also, since the DRF is a ratio of output to input forces, this process could eliminate the requirement for precision in the determination of anticipated maximum design load. The deployment challenge would however be the limit to vibration sensors that could detect the very slight deflections noticeable in fixed offshore structures. This detail of the advocated smart structure for reliability updating process is documented in figure 16 and explained below.

Fig. 16 : SMART OFFSHORE STRUCTURAL RELIABILITY PREDICTION PROCESS



The shortcomings of the current reliability process are explained in section 4.3. This recommended process, aimed at addressing some of shortcomings of the current reliability process, involves the generation of failure realisations F_{x_1,y_1,z_1}, F_{x_2,y_2,z_2}... F_{x_n,y_n,z_n}, generation of pseudo DRFs F'_{x_1,y_1,z_1}, F'_{x_2,y_2,z_2}... F'_{x_n,y_n,z_n} based on measurements and designing an electronic system for continous matching of F_{x_1,y_1,z_1} , F_{x_2,y_2,z_2}... F_{x_n,y_n,z_n} to respective F'_{x_1,y_1,z_1} , F'_{x_2,y_2,z_2}... F'_{x_n,y_n,z_n}.

F_{x_1,y_1,z_1} is the DRF realisation in x,y,z direction based on dynamic loading of a particular member and F'_{x_1,y_1,z_1} is a Pseudo DRF realisation in x,y,z direction based dynamic loading of the corresponding member. The calculation of the DRF has been discussed in section 3.5 through 3.7. The process for the generation of pseudo based dynamic response function involves the use of sensors on any given offshore structure for gauging water level, measuring wave angular velocity and the corresponding structural deflections. An algorithm can then be developed for estimating the real-time wave force based on measured data and using these real time data to determine both the DRF and the Pseudo dynamic response function. By continuous trending of the calculated DRF and Pseudo DRF any onset of trending anomaly can be used to identify the onset of failure and by comparing the DRF at failure with defined failure realisation data an estimate of the failed member can be made.

The selection of measurement systems requires further research and this proposed technology improvement can contribute to savings in steel usage by using suitable HUMS technology to justify the use of fit for purpose design factors for middle and top brace members of the designed offshore structure. The intent for the use of the HUMS monitoring for these members would be to determine the onset of failure of the submerged members and hence determine when to reinforce the upper members or when to plan the repairs of failed bottom members.

This recommended approach is suitable for detecting all failure causes as the structural failure will be detected irrespective of failure cause if a suitable sensing technology is applied an integral part of the given offshore steel structure. Whether the failure is as a result of earthquake, corrosion, frequent boat landing, accidental impacts or even explosion it will be detected. It is also possible that real time online data from these sensors can be designed and transmitted via satellite to an operational base where the data will be used for real time updating of the offshore reliability data.

The approach described above for a single member failure can be used to generate several DRFs for several single or multiple member failures. The DRF so created can be stored in a database as Structural Failure Models. Measurement systems can then be created for the designed structure and used together with real time data response to determine when a particular structural member has failed based on a matched SFM.

3.8 CHAPTER CONCLUSSION

The case study has shown that if we have a way of monitoring deflections in the fractional millimetre range, we could use the results from such measurement for the detection of member failures through the monitoring of DRF in offshore structural members. The DRF is a ratio of output to input signals hence the suggested measurement approach will eliminate the requirement for exactness in the determination of the anticipated maximum design load in an offshore structure.

The selection of measurement systems requires further research and where such sensors are available, they can be made part of the offshore structural design for monitoring of vibration trends. This measurement based reliability updating technique could lead to some cost savings especially in marginal offshore field development where the hydrocarbon accumulation cannot pay for the deployment of huge offshore structures.

4 UNCERTAINTY MANAGEMENT AND STRUCTURAL RELIABILITY ISSUES

4.1 UNCERTAINTY MANAGEMENT

Every project has an associated risk which is a representation of what we do not know. These risks can be Technical, Economic, Commercial, Operational or Political. The offshore Technical risks have been discussed in chapter 2. Uncertainty management involves processes for managing risks while risk management is what you can achieve if you manage well despite conditions of uncertainty.

One uncertainty management technique involves the use of probabilistic forecasts about the future and calculating summary statistics from those distributions as risk. A more recent way of managing uncertainties include the use of Design of Experiments (DOE) which aims at using statistical models to address data paucity. This technique involve the use of independent variables to create possible realizations that could be used to manage project uncertainties. The cyclic wave force acting on an offshore structure, for example, depends on wave force direction, water level, wave height, angular velocity etc. A set of possible combination of all realizations of these variables can be used to generate a PDF of the forces on individual structural members and this can be used as a design basis for the structure. This is a probability based design and in a similar way the reliability estimate for such structure can be based on probability.

Inspection and monitoring is routinely used for managing uncertainties for offshore structures. The techniques and tools to conduct such inspections vary widely from country to country. In some instances periodic inspection is required by law while in other instances there is no such requirement once a structure has been installed. The total cost of underwater inspection to the operator is also high, especially if production interruption is required, and will get higher as the water depth and structural complexity increases.

A detailed review of issues relating to underwater inspection has been documented [30]. Traditionally the diver has been, and still is, the primary inspector for offshore structural defects and visual inspection, photographic and video documentation have been his primary tools. The review reveals that until 1953 the only requirements for inspection of such structures were those which the platform operator/owner elected to impose upon themselves. In the U.S. this situation still prevails although the U.S. Geological Survey in 1953 and the Occupational Safety and Health Administration in 1970 obtained statutory permission to conduct and/or require inspection of structures in U.S. waters. In England five classifying societies are authorized to set standards for underwater inspection: Lloyds Register of Shipping, Germanischer Lloyds, Bureau Veritas, Det Norske Veritas (DNV) and the American Bureau of Shipping [30].

There is also no strong financial incentives for structural health monitoring as a way of managing the reliability of offshore structures. This is partly because there is no regulatory requirement for such in all locations. From the operator’s point of view, the structure is just an enabler rather than the “actual” asset. Once there is enough hydrocarbon reserves, the required structure will be built and the given structure will be abandoned once the reserves are recovered. The cost of inspection and production interruptions are fully captured in the project economics and companies can afford to accommodate inspection and maintenance costs which sometimes are huge if there are enough hydrocarbon reserves to be exploited.

The use of measurement techniques for uncertainty management is much more recent and have demonstrated huge capacity in uncertainty management. This approach addresses the uniqueness of any given facility and can be used, through elimination process, to point to the exact model failure realization. This continuous data acquisition process for uncertainty reduction has gradually developed into health Usage and monitoring systems (HUMS) technology. Continuous data acquisition has been applied in subsurface hydrocarbon development as a way of managing uncertainties. This involves regular Bottom hole pressures (BHP) surveys for monitoring of reservoir pressure depletion, reservoir saturation logs for monitoring of hydrocarbon contact movement etc. With this approach the uncertainties with respect to hydrocarbon reserves are continuously updated and used for redevelopment planning. More recently, the introduction of Smart-well technologies has further reduced the requirement production interruption for data acquisition and hence accelerated remedial activity planning response time. Pressure gauges, Distributed temperature surveys DTS, flow meters are now part of the Smart well completion such that real time uncertainty management are possible through the integration of the data from these Smart wells for regular update of the reservoir models.

4.2 STRUCTURAL RELIABILITY

One way of managing the offshore structural design uncertainties involves the use of generous design safety factors. However the increasing demand for steel and the associated long lead times between order and delivery makes the use of very generous design factors very unpopular.

Structural reliability index (β) was introduced in offshore structural engineering as a statistical concept for estimating failure probability of any given structure. It is associated with the notion of dependability and survival of offshore installations in the face of structural integrity threats [31]. It is determined using quantitative measures of failure and is based on the priority of regulators to develop internal guidance on the appropriate use of reliability techniques which is used to determine if the structure as a whole survives by assessing various combinations of members and their associated load effects.

Once a decision to construct a facility has been made, the uncertainties affecting the Reliability index (β) for the designed structure can be grouped in terms of modelling and measurement capabilities as shown in table 10 below:

Uncertainty	Uncertainty Class (Risk)	Impact ***(cost, & schedule overrun)***	Uncertainty management
• Metallurgy. • Manufacturing methods. • Welding.	Low	Medium	Design standards (e.g. API, Eurocodes etc).
• Modelling	Low	Medium	Research and process improvements.
• Service loads (cyclic loads and thermal loads) in familiar environment.	Low	Low	History and design Reviews.
• Corrosion, & Cathodic protection effectiveness.	Low	Medium	Modelling / measurements
• Service loads (Cyclic loads and Thermal loads) in new frontlines	High	High	Use of analogues
• Shocks and explosion. • Boat landing & deck mating impact. • Unpredicted Sea environment • Earth movements	High	High	Measurement of shock effects on designed models

Table 10 Offshore structural design Uncertainty classification

With over 100 years of improvements in offshore facilities construction, a lot of process improvements have been made in metallurgy and fabrications methods such that the uncertainties due to these issues are classified as low and well controlled. Also with developments in super fast computers and research on experimental testing the uncertainties with respect to the representation of physical, mechanical and processes with mathematical algorithms is so enhanced that the uncertainties with respect to these issues are well controlled and managed. Marine corrosion and the anticipated load on very benign marine environment are also known and managed. Unfortunately the service load in new frontiers as well as shocks, explosions, boat landing and deck mating impacts, unpredicted sea environment, earth movements carry a lot of uncertainties. The HSE management business control discussed in chapter 2 requires that the management of high risk, high impact activities must be governed by detailed standards and stricter design codes.

A review of the current design limits and standards for offshore structures concluded that external factors such as load, model accuracy, failure prediction accuracy, model updating process demands a detailed consideration as they all have a direct effect on the confidence of the predicted reliability [32]. Also selecting the reliability targets for structural engineering purposes is difficult because of the unique nature of the facility in question, limited data, and small limit state probabilities of relevance [33]. The US Navy Argus Island Tower in Bermuda failed within ten years of operations in 1969 as a result of storm generated wave height of 21m which was also the wave weight upon which the tower design was based [34]. The structural failure for this structure was assessed as being too costly to repair and maintain and hence the tower was demolished. Also the effect of hurricane Rita and Katrina are constant reminders that not much is known about the character of most tsunamis or hurricanes. Hurricane Ivan, Katrina, and Rita that passed through the GOM during 2004 and 2005 are some examples of high risk, high Impact events. The total remaining reserves from the set of destroyed structures destroyed by those hurricanes range in value between $1.3 and $4.5 billion [6].

It is often difficult to plan repair after a high impact event like Tsunami. This is primarily because of the uncertainty involved in damage assessment and remedial cost estimation. Mark Kaise et al [6] highlighted that some of the questions raised following the Katrina and Rita hurricanes include whether current design standards are adequate, whether current monitoring systems are sufficient, whether pipe laying in mudslide areas is appropriate and whether all pipe work should be buried. The costs of the resulting repairs after major platform damage are usually weighed against the potential revenue generating capability from the given structure. The revenue generation potential is expressed through the remaining reserves, expected production levels, and future hydrocarbon prices. If the anticipated benefits exceed costs, redevelopment may be approved while deferral or decommissioning will be recommended if repair costs exceed potential benefits. Even in cases where no visible damage is evident on the impacted offshore structure, some form of reliability re-assessment is needed prior to production start-up. Such reassessment exercise could involve some expensive and time consuming inspection scenario planning. The scenario planning depends on the experience of the assessment team and hence still carries some uncertainties. Most times an initial data modelling planning approach had to be followed by a physical inspection before decisions can be made for production start-up. As a result of the foregoing, some step out process for monitoring the effects of these high risk, high impact events on the designed structure is therefore recommended for the management of these uncertainties.

4.3 CURRENT STRUCTURAL RELIABILITY PROCESS

The Reliability Analysis for Linear Safety Margins has been discussed and documented [35]. The analysis will be presented here for analysis of uncertainty management and how the concept for recommended smart offshore structure for reliability prediction process was scoped.

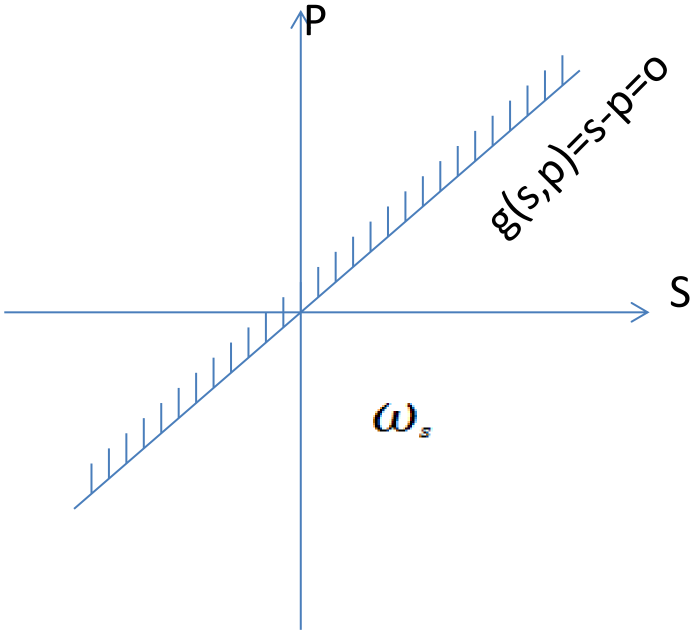


Figure 17 Failure function

A safety margin, which is linear in basic variables, can be written

$M = a_o + a_1 x_1 + \ldots + a_n x_n$

where a_o , $a_1, \ldots, a_n$ are constants. The expected value μ_M and the standard deviation σ_M are:

$\mu_M = a_o + a_1 \mu_{x1} + \ldots + a_{n1} \mu_{xn} = a^{\mathrm{T}} \mu_x$

$\sigma_M = \sqrt{a^{\mathrm{T}} C_a}$

If the basic variables are independent then

$\sigma_M = \sqrt{a_1^2 \sigma_{x_1}^2 + \cdots + a_n^2 \sigma_{x_n}^2}$

As a measure of the reliability of a component with the linear safety margin the reliability index β can be used:

$$\beta = \frac{\mu_M}{\sigma_M}$$

If the basic variables are normally distributed and the safety margin is linear then *M* becomes normally distributed. The probability of failure is, see figure 18:

$$p_f = P(M \leq 0) = P(\mu_M + U\sigma_M \leq 0) = P\left(\mu_M \leq -\frac{\mu_M}{\sigma_M}\right) = \varphi(-\beta)$$

where Φ is the standard normal distribution function and *U* is a standard normally distributed variable with expected value zero and unit standard deviation ($\mu_U = 0$, $\sigma_U = 1$).

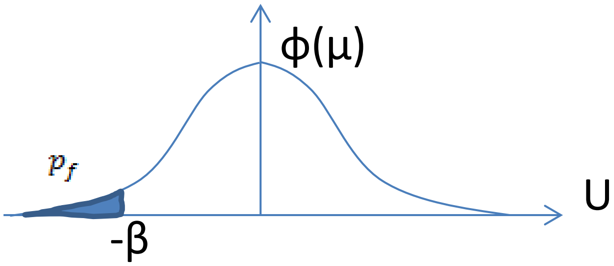


Figure 18 Reliability index and probability of failure.

If the stochastic variables *P* and *S* are independent then the reliability index becomes:

$$\beta = \frac{\mu_M}{\sigma_M} = \frac{\mu_S - \mu_P}{\sqrt{\sigma_S^2 + \sigma_P^2}}$$

from the above equation the reliability index β depends on the PDF distribution of the applied force and hence the PDF resistance for the respective structural members. The PDF for the applied force will depend on the PDF of water depth, wave angular velocity and wave direction. Therefore the reliability index as currently practiced is a generally accepted way of managing these uncertainties. Several researchers have reviewed the process for reliability prediction and refined the process for managing uncertainties with respect to statistical reliability prediction. Notwithstanding these past efforts, selecting the reliability targets for structural engineering purposes is still difficult because of the unique nature of each facility, limited data, and small limit state probabilities of relevance [33]. Also the calculated Structural Reliability for any given structure, by definition, changes with the amount and quality of the information on basis of which it is calculated.

4.4 DATA DRIVEN UNCERTAINTY MANAGEMENT

It would then be desirable to have a structural design model that enables fast and reliable decisions based on some dependable data during the operate phase of such facility. These data will help in reliability assessment post emergency situations like earthquake or major accidents. This would be analogous to the role played by flight data recorders post flight emergencies in the aviation industry. This aspiration was supported Cruz and Krausmann [36] when they noted that there was little coordination and guidance in efforts to carry out post-storm assessments after Katrina and Rita and hence recommended that industry needs to work on improved pre-storm preparation and planning through post-storm response and recovery.

So how can we ensure that the residual uncertainties on the predicted reliability for any offshore structure can be verified as being ALARP or what else can we do to improve on the management of structural reliability uncertainties during emergencies.

To achieve ALARP requires a cost effective, efficient and reliable system. The question then is whether there are workable systems in other engineering sectors that can be copied and adapted to the offshore reliability prediction process. The SMART Wells operations in subsurface hydrocarbon development looks like a suitable analogue. Table 11 compares the components of the smart well operations concepts to equivalent components in offshore structural engineering. It should be noted that while the smart well was designed to manage reserve uncertainties, the smart offshore reliability prediction process can be designed to manage the remaining life of any given structure. The detailed comparison of the selected technology analogue is shown below:

	Technology Analogue	**Offshore Structural equivalent**
Asset	Subsurface trap (STOIIP)	Offshore Structure
Managed Uncertainty	Reserves	Remaining life
Monitoring points	Wells draining the reserves	Nodes within the offshore structure
Desired measurements	Production, Fluid contacts	Deflections, vibrations and DRF
Results	Remaining field life. Asset value	Remaining facility life. Asset value

Table 10 Smart Offshore structural Reliability technology analogue

Having identified an analogue technology application in Smart Well operations, an attempt is made to build a case for a change to Smart Offshore Reliability prediction Process.

4.5 CASE FOR CHANGE IN METHODOLOGY

A detailed review of methods for structural system reliability was undertaken and some of the findings and conclusions of the review by Ditlevsen and Bjerager [14], which tend to support an urgent design for further process improvements, include:

- That the mathematical methods of structural systems reliability analysis beyond the event of first element failure requires quite restrictive mechanical idealizations either of the failure performance of the structure or of the load history.
- That except for very simple structures or for model structures defined to have ideal elastic-plastic performance, meaningful statements about the structural system reliability can at present only be given for proportionally increasing loading i.e. for essentially a deterministic load history.
- That only upper and lower probability bounds can be calculated, and these bounds may for larger structural systems be quite wide.
- That without an explicit definition of the load history it easily becomes impossible to judge under which conditions some advocated engineering approach really gives a valid estimate of the system reliability.

Also the construction and installation method for offshore structures introduces some huge uncertainties on the Limit State analysis. The computing ability to accurately model the effect of welded joints to great accuracies is yet to be achieved. We also do not we have real calibrations on joint failures other than those determined through laboratory experiments. Also loading the offshore structures in even fairly advanced models are still based on assumptions, and the coupling of corrosion modeling experimental results is still an area of further research.

It has been demonstrated in chapter 3 that the frequency response analysis can be used for the identification of the system characteristics of any given offshore steel structure. If the frequency response functions (FRFs) of the modified structure can be computed then it is possible that through some form of measurement, the delta change in measured dynamic data can be used to determine when the structural stiffness is modified through crack, crack propagation or a member failure. We know the uncertainties on predicted structural reliability reduce with the amount and quality of the information on basis of which it is calculated. We also know that measurement systems can be designed based on the technology analogue presented in section 4.4. We also know that the frequency response function (FRF) does not necessarily have to be calculated based on model simulation but can also be calculated based on measurements from the given.

However the reality is that some gaps still exist between our measurements based reliability prediction process aspiration and the current reality. The gap relate to the limit of available sensing technology. Some advances have been made on the use of very sensitive accelerometers to detect and monitor vibration in the past but before delving deep into further research on sensing techniques there is need to evaluate, even though notionally, the potential gains derivable from this measurement based reliability prediction effort.

4.6 VALUE OF INFORMATION ECONOMICS

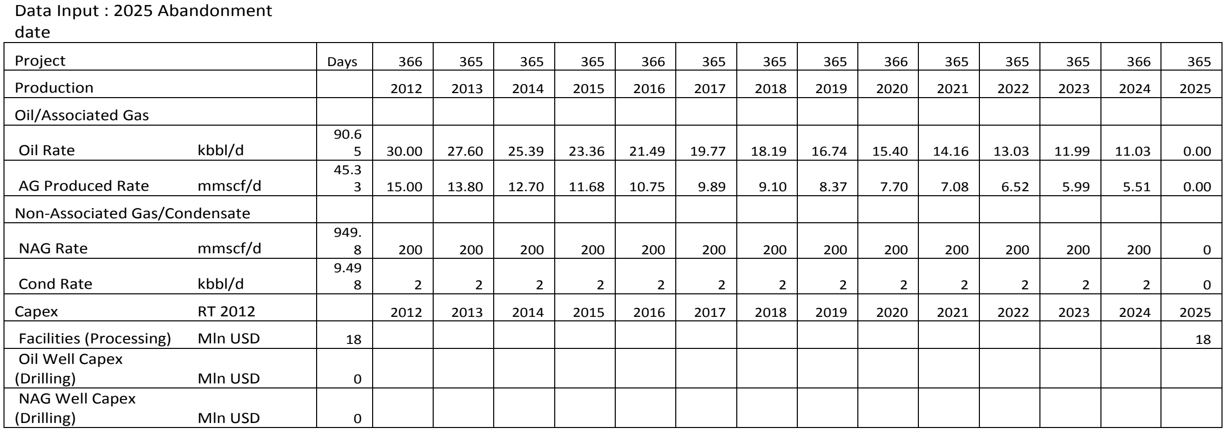
A necessary condition for an offshore field development project to be economic requires that the future precedes from discovered subsurface hydrocarbon accumulation pays for the field development project (FDP) capital expenditure (Capex) and Operating expenditure (Opex). The FDP activities include well costs for drilling, crude processing and transportation, facility construction and deployment as well as all abandonment expenditures.

A value of information case modelling was undertaken to quantify some data driven economic results (gains or losses) that could arise as a result of optimal maintenance programme that is underpinned by data from the structure under consideration. This VOI economics is based on a 30 year facility design life that will be abandoned in 2025. The planned decommissioning is based on economics and platform reliability. This value of information case relates to the cost of capital that is available for data acquisition and analysis to determine if any life extension possibility exists after 2025 for safe operation of the given facility to produce some of the remaining reserves. The premise for this economic analysis are:

Oil prize :	\$60/bbl
Condensate prize :	\$60/bbl
Gas prize :	\$1.7 / mmbtu
Cost sensitivity	100%
Production :	100%
Royalty rate :	85%
Other Tax rate :	30%

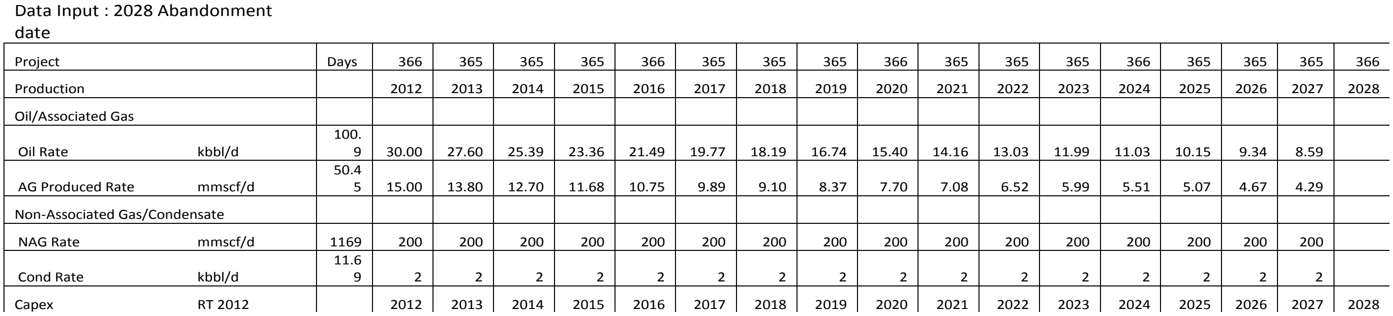
Discount rate : 10%

Other input data are shown in table 11 below:



Data Input : 2025 Abandonment date

Project		Days	366	365	365	365	366	365	365	365	366	365	365	365	366	365
Production			2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Oil/Associated Gas																
Oil Rate	kbbl/d	90.65	30.00	27.60	25.39	23.36	21.49	19.77	18.19	16.74	15.40	14.16	13.03	11.99	11.03	0.00
AG Produced Rate	mmscf/d	45.33	15.00	13.80	12.70	11.68	10.75	9.89	9.10	8.37	7.70	7.08	6.52	5.99	5.51	0.00
Non-Associated Gas/Condensate																
NAG Rate	mmscf/d	949.8	200	200	200	200	200	200	200	200	200	200	200	200	200	0
Cond Rate	kbbl/d	9.498	2	2	2	2	2	2	2	2	2	2	2	2	2	0
Capex	RT 2012		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Facilities (Processing)	Mln USD	18														18
Oil Well Capex (Drilling)	Mln USD	0														
NAG Well Capex (Drilling)	Mln USD	0														



Data Input : 2028 Abandonment date

Project		Days	366	365	365	365	366	365	365	365	366	365	365	365	366	365	365	365	366
Production			2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Oil/Associated Gas																			
Oil Rate	kbbl/d	100.9	30.00	27.60	25.39	23.36	21.49	19.77	18.19	16.74	15.40	14.16	13.03	11.99	11.03	10.15	9.34	8.59	
AG Produced Rate	mmscf/d	50.45	15.00	13.80	12.70	11.68	10.75	9.89	9.10	8.37	7.70	7.08	6.52	5.99	5.51	5.07	4.67	4.29	
Non-Associated Gas/Condensate																			
NAG Rate	mmscf/d	1169	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	
Cond Rate	kbbl/d	11.69	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
Capex	RT 2012		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028

Table 11 VOI economics input data

The governing equations for the Net present value economics is

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{\mathrm{C}_t}{(1+r)^t} + \mathrm{C}_0$$

C_t= net cash inflow during planning period

C_0= initial (unrecovered) investment

r = discount rate

t = number of time periods

T = end of field life

For the case study above the NPV is generated from the sale of Oil, gas and condensate as shown in table 11. Royalty and tax rates are calculated by applying the applicable royalty and tax rates on the generated gasflow from salses of hydrocarbons.

Therefore $\text{NPV} = \text{NPV}_{oil}$+$\text{NPV}_{gas}$-Royalty-Technical cost-Taxes

Economics analysis and sensitivities were executed to compare the NPV of the given field if the offshore structure will be abandoned in year 2025 as planned or if the planned abandonment can be rescheduled to 2028. The decommissioning cost of $18mln is spent in 2025 and 2028 for the respective scenarios. The economic analysis shows that the field NPV increased from $909mln to $983mln if any information can reveal that the platform life can be extended by three years from the originally planned abandonment year of 2025 to 2028. Figure 19 and 20 shows the respective economic runs for field abandonment date of 2025 and 2028. The calculated NPV is sensitive to hydrocarbon production and operating cost as shown in the respective tornado charts for the respective abandonment dates. Production sensitivity of 60% and 125% of base production was used while the cost performance of 70% and 145% was used for the calculation of tornado chart.

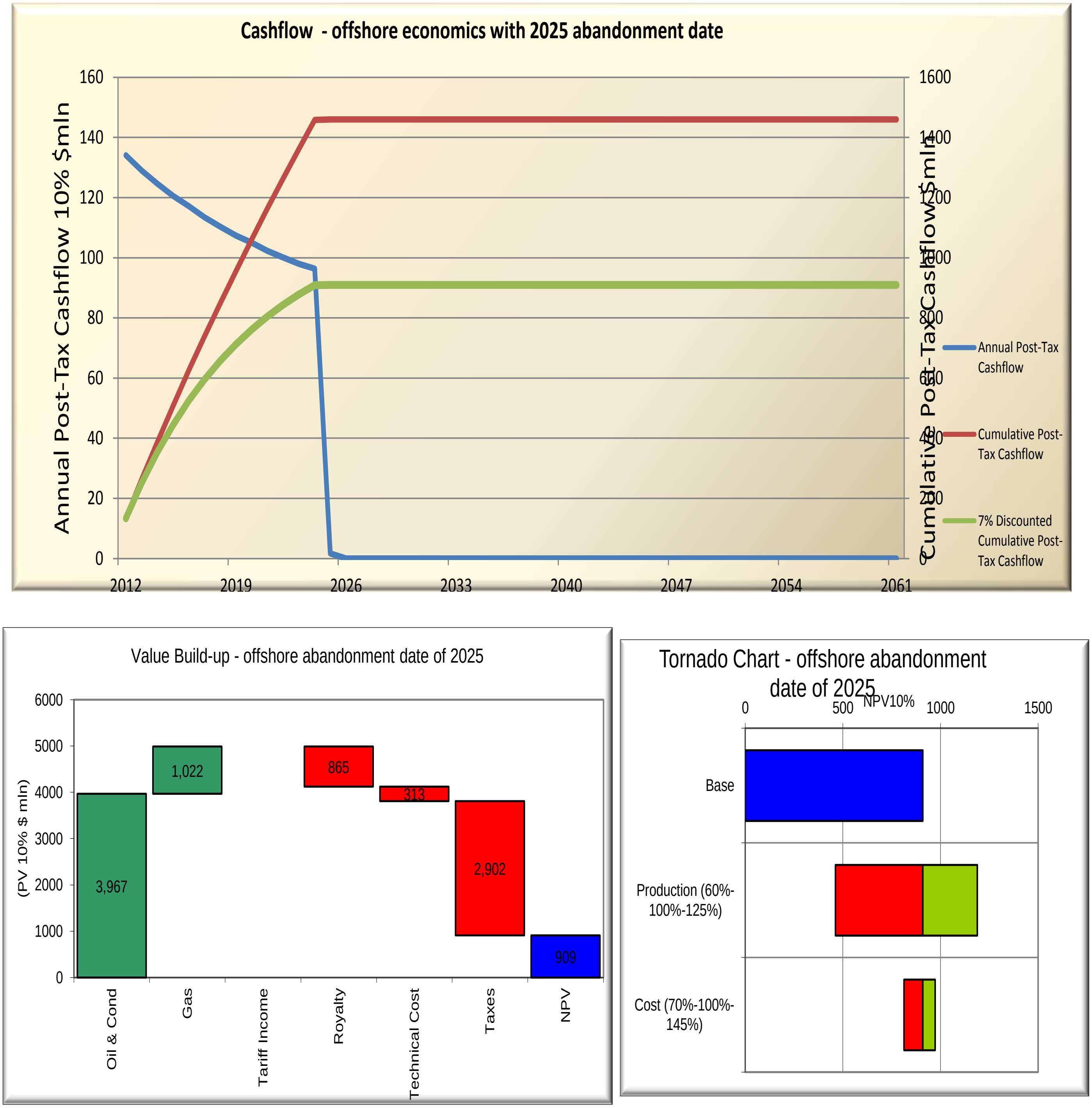


Figure 19 VOI ECONOMICS ANALYSIS WITH 2025 ABANDONMENT DATE

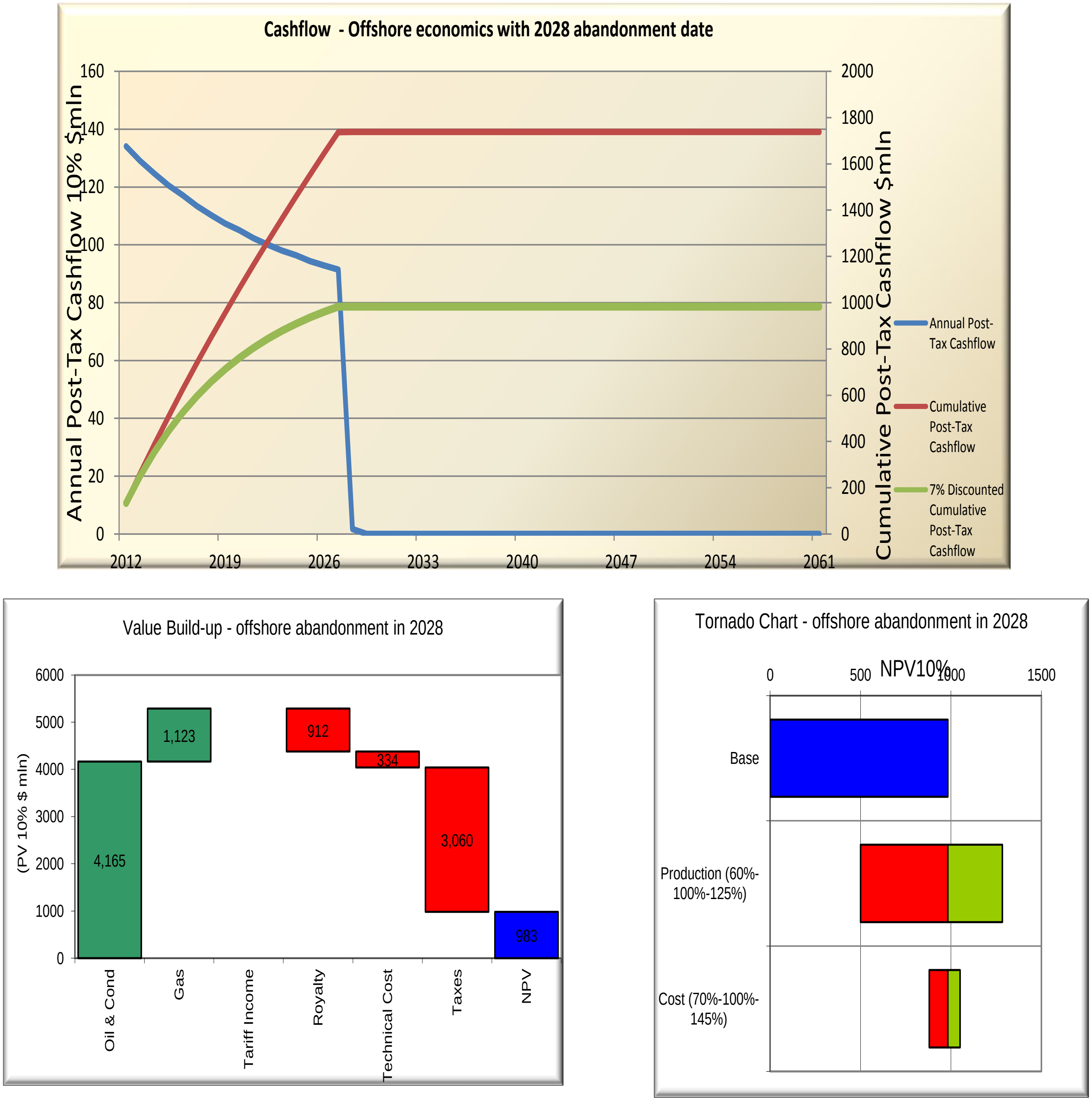


Figure 20 VOI ECONOMICS ANALYSIS WITH 2028 ABANDONMENT DATE

This economic analysis shows that $74mln is the VOI for any life extension technology that could reveal the possibility of extending the life of the given platform from 2025 to 2028 as the net present value (NPV) of the overall project would have increased from

$983mln to $983mln. On the other hand if the same data reveals the need to abandon earlier than 2025 then some critical HSE decisions could be made to safeguard the staff and the environment from serious impacts.

If some $74mln NPV can be gained by extending the life of a medium sized 30Mbopd offshore platform by three years then there could be huge potentials for some 17000 Oil and gas platforms by researching on technologies that could more accurately predict offshore structural reliability and yield potential life extension of these structures. Several sensitivities on this result still show some huge potential on this research into this proposed new approach to data driven reliability prediction process even at a quarter probability of success (POS).

4.7 CHAPTER CONCLUSIONS

One way of managing uncertainties for offshore structures include the requirements for underwater inspection of these structures. The techniques and tools to conduct such inspections vary widely from country-to-country. In some instances periodic inspection is required by law while in other instances there is no requirement whatever once a structure has been installed. The instruments to conduct underwater inspections also vary; their effectiveness is sometimes questionable, and the total cost of underwater inspection to the operator is high and will get higher as the water depth and complexity of the structure increases.

There is also no strong financial incentives for structural health monitoring as a way of managing the reliability of offshore structures. The offshore maintenance inspection objective is to locate defects and based on the size and location of such cracks or defects a detailed cause and effect analysis is then used for recommendation of immediate repairs or otherwise. The lowlight to this approach is that most times only the external corrosion and cracks are seen and so the effect of internal corrosion and defects are not properly represented nor assessed. Do we really have a case for improvement in operational excellence in reliability engineering or should we continue with routine inspection and monitoring programme ? One of the major hindrances for the improvement in functional excellence is lack of research cooperation and funding. Most organisations are also not able to share their maintenance programme. The case study result shows that for a small production platform some $74mln opportunity could exist if some data driven reliability prediction process can be made through measurement based reliability updating process.

Apart from the increasing demand for use of offshore structures in oil and gas development, there is also an increasing demand in renewable energy as documented in chapter 2. Climate change, the soaring global electricity demand, the scarcity of fossil fuels, and consequently, their rising costs, make renewable energy gain importance. Wind power and solar energy are promising alternative energy sources and can help countries lacking natural resources gain greater independence from fossil fuels and secure their own climate-friendly energy supply. It is projected that renewable energy will account for 17% of world energy demand in 2030 [37]. The offshore wind renewable energy source are also based on steel structures and whatever reliability prediction processes used for offshore structures also apply. However, unlike the inspection of offshore structures which involve diving for shallow water inspection, inspection of a wind turbine towers are cost prohibition. The additional cost and safety issues for erecting the required scaffold for wind turbine structures is much more than that required for diving in offshore structures and sometimes can be prohibitive.

In 2012 four hundred and seventeen (417) offshore structures were constructed for wind turbine [38]. Similar number of structures were constructed for hydrocarbon exploration and production and it is projected that this level of offshore deployment will continue up to 2030 in support of world energy demand. This implies that the value of the proposed smart structure for reliability updating process could be huge. This cost analysis could be a subject of further research but are indicative of value upside considering that a $74mln opportunity exists in medium sized shallow water offshore Oil and gas exploration and production through a three year life extension decision.

Based on the forgoing, a further investment in research is therefore recommended to test the feasibility of piloting a data driven reliability improvement process. This would help determine if we can live with defects based on actual data or determine the optimal life of a facility based on data.

5 RESEARCH CONCLUSSION

5.1 RESERACH CONCLUSSIONS

The goal of forecasting is not to predict the future but to tell you what you what you need to know to take action in the present [39]. Similarly the objective of reliability engineering in offshore structures should be to find what we need to know in other to predict the current safety performance of any given structure. The desire for a proactive safety culture in offshore structural engineering could not have come at a better time than now due to increased demand for energy as a catalyst for development on one hand and the general global economic stagnation that calls for cost cutting measures on the other hand. Other drivers for this improved HSE performance include projected increase in the number of new offshore structures in support of oil and gas exploration and renewable energy extraction.

Notwithstanding every effort aimed at guaranteeing energy supply and security, it is projected that fossil fuels will continue to supply the main share of the world’s energy supply in the foreseeable future. Offshore structures are very vital in chasing the limited patches of offshore petroleum and natural gas around the world as well as offshore renewable energy. The increasing demand for renewable energy is driven by climate change, soaring global electricity demand and the scarcity of fossil fuels among other things. The wind power and solar energy are the most competitive of the renewable energy sources and are helping countries lacking natural resources gain greater independence from fossil fuels and secure their own climate friendly energy supply. It is projected that renewable energy will account for 17% of world energy demand in 2030. In 2012 four hundred and seventeen (417) offshore structures were constructed for wind turbine. Similar numbers of structures were constructed for hydrocarbon exploration and production and it is expected that this growth in the overall number of construction projects will continue. Unlike the maintenance inspection of offshore structures which involve diving for shallow water inspection, inspection of offshore wind turbine towers are cost prohibitive. The additional cost and safety issues for erecting the required scaffold is much more than that required for diving in offshore structures hence the application of the recommendations of this research can also be applicable in monitoring of the reliability of offshore wind turbine structures.

A review of the developments within the field of structural reliability theory with particular attention to structural systems shows that some gap still exist in the reliability prediction process. This is partly because the estimated reliability indices do not express a physical property of the structure but a measure of safety based on a general probabilistic model. It has also been shown that the calculated structural reliability for any given structure, by definition, changes with the amount and quality of the information on the basis of which it is calculated hence reinforcing the need for designing a smart structure for reliability prediction process such that continuous data from the structure will continuously be used to update the reliability of that structure at any given time.

Another setback to the current practice is based on the fact that selecting the reliability targets for structural engineering purposes is difficult because of the unique nature of each facility, limited data, and small limit state probabilities of relevance. One way of closing this gap is to design a monitoring system that measures some physical properties of any given structure. Structural deflection and damping are some of the measurable physical properties of any given offshore structure hence a case study was undertaken to evaluate the magnitude of these measurable properties. This research has therefore recommended the use of these measurable properties to design an improvement process such that the data from the structure will be used to estimate the remaining life of the structure.

This thesis has propounded that if we have a way of monitoring deflection in an offshore structures, we could use the results from such measurement for the detection of member failures by monitoring the load redistribution in the form of increased DRF in other structural members. The applicability of this process improvement has been documented in this research. Though recommended for new structures, retrofitting the advocated process improvement to existing structures will not be difficult since higher deflections will always occur around the top of the designed structure and higher magnifications will also be noticed around the top and middle braces of the respective structures when any of the bottom braces fail.

5.2 RESERACH IMPLEMENTATION SETBACK

The deployment challenge to this propounded thesis would be the sensitivity of current strain or vibration sensors. Other issues militating against the non implementation of the thesis recommendations include lack of financial incentives for the use of Structural health monitoring devices. The operators views the structure as an enabler rather than the “actual” asset. Once there is enough hydrocarbon reserves, the required offshore structure will be built for the required wellhead and production platforms and will be abandoned once the reserves are recovered.

There is also no universal regulatory requirement mandating the implementation of regular inspection of offshore steel structures in accordance to any particular standard in any given location. The cost of inspection is also relatively cheap in shallow offshore structures. The inspection objective is to locate defects and based on the size and location of such defects a detailed cause and effect analysis is then used for recommendation of remediation plans. The lowlight to this inspection based approach is that most times only the external corrosion and cracks are seen and so the effect of internal corrosion and defects are neither properly represented nor assessed. Also most organizations are not willing to share their structural design, performance, and maintenance data hence making it difficult for the industry to undertake performance improvement research on the use of HUMS technology in offshore reliability prediction process.

5.3 Recent developments in measurement based reliability research

Hillis & Courtney [40] studied and documented structural health monitoring of fixed offshore structures using the bicoherence function of ambient vibration measurements to provide automatic early detection of damage in an offshore structure. This experimental research demonstrated that very small changes in stiffness of individual structural members are detectable from measurements of global structural motion.

Kopsaftopoulos & Fassois [41] undertook a comparative experimental assessment of vibration based statistical time series for Structural Health Monitoring (SHM) and their application to damage diagnosis in a lightweight aluminium truss structure. Their experiment assessment concludes, among other things, that statistical time series methods for SHM achieve damage detection and identification based on vibration response signals.

Also the damage detection in offshore structures using neural networks was studied by Ahmed et al [42]. Their experimental research showed that the random decrement technique can be used to extract the free decay of the structure from its online response while the structure is in service and can be used routinely to discover any changes in the shape of the damage index.

5.4 New knowledge contribution from this research

The most recent research works in the Smart Offshore Structural area were highlighted in section 5.3. All of these researchers agree that early detection of an offshore structural failure is possible through some measurement systems. These research conclusions are based on laboratory experiments but the recommendation from this research is slightly different based on the following:

1. It is based on generation of failure realisations from Dynamic Response Functions and trending of measurement based DRF to determine the onset of failure in an offshore structure. As a result, the proposed Smart Offshore

structure for reliability prediction process can form part of the basis for future prediction of offshore structural reliability prediction process.

2. It provides a better way of managing uncertainties and eliminates the need for detailed estimation of the wave load in any given environment. Only an idea of the uncertainty range is needed.
3. It could be used to pin point the exact structural member that failed by trending the DRF for the given structure and comparing that with several failure realizations for any given structure.
4. It can yield failures due to internal corrosion which is not revealed from Inspection based reliability updating process.
5. It can be used to re-evaluate old and aging structures.

The recommended Health monitoring systems are readily available and widely used in automotive engineering and the oil and gas industry. The recommended Smart Offshore structure for reliability prediction process will help and provide a more holistic view of the facility’s health by integrating asset performance and health monitoring data with maintenance data.

5.5 JUSTIFICATION FOR FURTHER RESEARCH

The case for the deployment of Smart Offshore Structure for Reliability Prediction Process has been made. A notional economic case study also shows that for a 30,000bopd production platform projected to be producing about 11,000bopd by 2025 abandonment date, some $74mln opportunity exist if some data driven reliability prediction recommendation can be made through measurement that could defer the abandonment to 2028. This cost analysis could be a subject of further research but are indicative of huge value upside. This research is worth undertaken as a reasonale value of $37mln would be realiosed at 50% probability of success. A major driver to this performance improvement research is the quantity of offshore structures being used for hydrocarbon and wind energy extraction. Based on the forgoing, a further investment in research is recommended to test the feasibility of piloting a data driven Smart Offshore Structure for Reliability Prediction Process. This would help improve decisions on maintenance planning and hence cost optimization.

The recomended further research could involve a case study for potential retrofitting of suitable HUMS equipment to an existing structure for piloting of advocated technology improvement process. This advocated methodology will contribute to addressing the Long-term planning and Implementation of Safety Cases where the UK HSE plans to collaborate with the UK industry towards a unified approach to the safety management of all ageing offshore infrastructure.

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