Safety of Facilities and Operations in the Offshore Oil and Gas Energy Sector
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Outline
- Introduction
- Accident experiences
  - technical-physical causes
  - human and organizational causes
- Safety management
  Facilities
  - design criteria, with an emphasis on robustness criteria (ALS)
  - inspection/repair
  - structural reliability and risk analysis as decision tools
  - remarks on QA/QC of the engineering process
  Operations
- Future challenges
- Concluding remarks

ULS:
\[ R_C/\gamma_R > \gamma_D D_C + \gamma_L L_C + \gamma_E E_C \]

FLS:
\[ D = \sum n_i/N_i \leq D_{\text{allowable}} \]

Introduction

Offshore Energy Sector
- Oil and gas are the dominant energy sources
  - 70% of oil and 90% of gas still to be produced on Earth
- 20% of the hydrocarbon production (currently) takes place offshore
- 25% of remaining gas reserves in the arctic
- oil and gas production take place in
  - increasingly deeper water and
  - more harsh environmental conditions in view of hurricane experiences in the Gulf of Mexico and emerging arctic developments
- offshore floating facilities for production of
  - CNG or LNG for transport by ships
- wind-, wave- and tidal energy

Safety is the absence of accidents, that result in
- Fatalities, Environmental damage or Property damage associated with failure modes such as:
  - Capsizing/sinking
  - Structural or mooring system failure
  - Unavailability of Escapeways and Evacuation means (life boats….)
- Hazards
  - oil and gas represents energy with a large accident potential
  - offshore oil and gas industry operates in a demanding environment
Historical Notes on Safety Regulations

- 1834: The first Ship Rules by Register Society (later Lloyd's Register)
- 1960's: The first offshore design codes
- Early '70s: Environmental risk assessment
- Mid '70s: Reliability-based Code calibration
- 1978: Early applications of offshore risk assessment
- 1980: Alexander Kielland accident
- 1981: NPD Guidelines for Quantitative Risk Analysis
- 1984: NPD's Accidental Collapse Limit State (ALS)
- 1988: Piper Alpha accident
- 1991: NPD Regulations for risk analysis
- 2010: Deepwater Horizon accident

Trends in Safety Regulations in the Oil & Gas Sector...

North Sea (Norway/UK)
- Identify all hazards with the potential to cause a major accident; and
- Evaluate all major accident risks and take measures to control those risks
  - Reduce probability
  - Limit consequences

United States
- Production safety equipment used on the OCS must be designed, installed, used, maintained, and tested in a manner to assure the safety and protection of the human, marine, and coastal environments.

After 'Deepwater Horizon', even the USA is moving away from prescriptive rules to performance based regulation
- Design must be suitable to manage all foreseeable risks.
- That will mean gaining much more insight into role and function of the installations, not just the hardware
- Human factors, escape, evacuation, fire, explosion

Need to think through the consequences, not simply work to code.

Safety requirements

With respect to
- Fatalities
- Environmental damage
- Property damage

Regulatory requirements:
- Goal-setting (performance-based) viz. prescriptive
- Probabilistic viz. deterministic
- First principles viz. purely experiential

Regulatory issues:

Offshore oil and gas
- ISO
- National Regulatory bodies; partly building codes (MMS, HSE, PSA)
- Industry: API, NORSOK
- Class societies/IACS

Shipping
- IMO/ISO(CEN) IMO
- National Maritime Org.
- Class societies/IACS (ISO)

Other marine industries
- Broadly acceptable region
- ALARP region
- Negligible Risk
- Unacceptable region

- Aquaculture
- Offshore wind energy

- ISM
- National Regulatory bodies; partly building codes (MMS, HSE, PSA)
- Industry: API, NORSOK
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Safety: absence of accidents or failures

- **Technical-physical point of view**
  - Capsizing or total loss of structural integrity commonly develops in a sequence of events

- **Human and organizational point of view**
  - All decisions and actions made – or not made during the life cycle are the responsibility of individuals and organizations

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**Technical-physical causes:**
- Wave forces exceeded the structural resistance

**Human – organizational factors:**
- State of engineering practice (codes)
- Errors and omissions during the design (fabrication) phases
  - relating to assessment of
  - wave conditions or load calculation
  - strength formulation
  - safety factors

Should the platforms have been strengthened if improved state of the art knowledge became available later?

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**Overview of accident experiences for offshore platforms worldwide**

![Overview of accident experiences for offshore platforms worldwide](image)

**Number of accidents per 1000 platform years**

- Technical-Physical: Fatality, Equipment, Construction failure, Explosion, Fire, Loss of containment, Offshore structure damage, Operational errors
- Human and organizational: Design or Fabrication errors

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**Lessons learnt from total losses**

- **a)** Alexander L. Kielland—fatigue failure, progressive failure and capsizing, North Sea, 1980
- **b)** Ocean Ranger, flooding and capsizing, New Foundland, 1982. (Model during survival testing)
- **c)** Piper Alpha fire and explosion, North Sea, 1988
- **d)** P - 36 explosion, flooding and capsizing, Brazil, 2001
- **e)** Deepwater Horizon undesirable build-up of pressure in drill pipe during replacement of drill fluid with sea water, "blow-out", explosion-fire, sinking, oil spill, GoM, USA, 2010
The Alexander Kielland Accident

- Fatigue/fraction in brace D-6
- Fracture in other 5 braces
- Loss of column D

- Listing
- Flooding
- Evacuation
- Escape
- Capsizing

The Alexander L. Kielland accident in 1980

**Technical cause**
- Fatigue failure of one brace initiated by a gross fabrication defect
- Ultimate failure of braces and loss of a column, listing, capsizing
- Inadequate evacuation and rescue operation

**Human and organizational factors**
- Fabrication defect due to bad welding inadequate inspection
- No fatigue design check carried out
- Codes did not require structural robustness nor buoyancy of the deck
- Evacuation not planned for an accident of this kind
- Lack of life boats, survival suits
- Long mobilizing time for rescue vessels

The Deepwater Horizon Accident

**Technical-physical causes**
- Loss of control of an exploratory well
- Gas leak, explosion/fire damage
- Oil spill
- Platform foundering

**Human-organizational factors**
- Multiple flawed decisions in the treatment of the well
- Lack of adequate safety culture/training
- Deficient quality of the BOP

Causes of structural failures and risk reduction measures

<table>
<thead>
<tr>
<th>Cause</th>
<th>Risk Reduction Measure</th>
<th>Quantitative method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than adequate safety margin to cover</td>
<td>- Increase characteristic load, safety factors or margins in ULS, FLS; - Improve inspection of the structure (FLS)</td>
<td>Structural reliability analysis</td>
</tr>
<tr>
<td>“normal” inherent uncertainties.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross error or omission during life cycle</td>
<td>- Improve skills, competence, self-checking (for life cycle phase: d, f, o) - QA/QC of engineering process (during d) - Direct ALS design (in d) - with adequate damage conditions arising in f, o (NOT d) - Inspection/repair of the structure (during f, o)</td>
<td>Quantitative risk analysis</td>
</tr>
<tr>
<td>phase: d, f, o</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unknown phenomena</td>
<td>- Research &amp; Development</td>
<td>None</td>
</tr>
</tbody>
</table>
Safety Management through the Life Cycle

**Design**
- serviceability & producability
- safety

**Fabrication**
- Fabrication plan - Inspection/repair

**Operation**
- Operation plan (restrictions)
- Inspection/monitoring/repair/maintenance

**Design QA/QC** of the design process

**QA/QC**
- of the structure and operations

**Reassessment**

Quantitative measures of risk (SRA and QRA)

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Design criteria for safety
(with focus on structural failure modes)

<table>
<thead>
<tr>
<th>Limit states</th>
<th>Physical appearance of failure mode</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultimate (ULS)</strong></td>
<td>- Overall &quot;rigid body&quot; stability - Ultimate strength of structure, mooring or possible foundation</td>
<td>Different for bottom – supported, or buoyant structures. Component design check</td>
</tr>
<tr>
<td><strong>Fatigue (FLS)</strong></td>
<td>- Failure of welded joints due to repetitive loads</td>
<td>Component design check depending on residual system strength and access for inspection</td>
</tr>
<tr>
<td><strong>Accidental collapse (ALS)</strong></td>
<td>- Ultimate capacity of damaged structure with &quot;credible&quot; damage</td>
<td>System design check</td>
</tr>
</tbody>
</table>

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"Exposure levels"
ISO 19900

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Consequences other than fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C1 High</td>
</tr>
<tr>
<td>S1</td>
<td>Manned nonevacuated</td>
<td>L1</td>
</tr>
<tr>
<td>S2</td>
<td>Manned evacuated</td>
<td>L1</td>
</tr>
<tr>
<td>S3</td>
<td>Un-manned</td>
<td>L1</td>
</tr>
</tbody>
</table>

Three safety levels (L1, L2, L3) of importance to
- Safety factors
- Extent of QA/QC

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Quantification of structural safety (ULS)
Structural reliability (prob. of failure):  \( P_f = P[R \leq S] \)

The uncertainty/variability in the resistance \( R \) and load effect \( S \) are modelled as random variables

**Mature, general methods**
- First/Second Order Reliability methods
- Monte Carlo (MC) methods

**Special case:** Random \( R \) and \( S \) with lognormal distribution

\[
P_f = P[R \leq S] = \Phi\left(-\frac{\ln(\frac{\mu_S}{\mu_R})}{\sqrt{\sigma_S^2 + \sigma_R^2}}\right) = \Phi(-\beta)
\]

- \( \mu \) - denotes mean value
- \( \sigma \) - denotes standard deviation
- \( V = \sigma/\mu \) - coefficient of variation
- \( \Phi(-\beta) \) - standard cumulative normal distribution

**Challenge:** Assessment of uncertainty
Uncertainty in environmental conditions -

Macroscale phenomena (Climatological)
- wind-waves and swell
- squalls are short-lived but intense thunderstorms and may cause lightning strikes
- current vortices

Hurricanes in the GoM
- crest heights; wave-in-deck

Microscale phenomena
- individual waves
- current turbulence

Implication on safety level?
- Known vs unknown source of uncertainty

Draugen wave record

Abnormal ("Freak wave") or "simply" rare?

Uncertainties of Hydrodynamic Loading

Model uncertainty = \frac{F_{predicted(i)}}{F_{measured(i)}}
Mean = 1.06
COV = 25%

Hydrodynamic loads with significant uncertainty

Challenges relating to environmental loads

<table>
<thead>
<tr>
<th>Region</th>
<th>Climate</th>
<th>Annual</th>
<th>100 yrs</th>
<th>1000 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulf of Mexico</td>
<td>Hurricane area</td>
<td>0.3</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>North Sea</td>
<td>Extratropical</td>
<td>0.8</td>
<td>1.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>

- How can we achieve a failure probability less than $10^{-4}$?

Normalised Wave Load level

$\gamma S_{100}$ 

"Bad-behaved" loading

Wave in deck

Design based on 100 year loading: Well-behaved loading

Hazard curves for seismic, wave and ice actions

- seismic (in red),
- wave (in black: AUS - Australia, GoM - Gulf of Mexico, NNS/CNS/SNS - Northern, Central and Southern North Sea) and
- sea ice (in blue) actions

<table>
<thead>
<tr>
<th>Seismic10,000</th>
<th>Seismic100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 1.0 1.4</td>
<td></td>
</tr>
<tr>
<td>0.8 1.0 1.25</td>
<td></td>
</tr>
</tbody>
</table>

Wave10,000 = 1.4 – 1.9

Ice10,000 = 1.4 – 1.5

Relative wave height

Return Period in years

Normalised Load $L/E_{100}$
Safety implications of ULS criteria based upon SRA interpretation

- Failure probability implied by current ULS offshore code requirements: annual $P_f \approx 10^{-3} - 10^{-5}$ based on "normal" uncertainties
- The actual failure probability is much higher than that calculated by SRA due to error-induced accidental loads and abnormal resistance

NOTE: Structural Reliability Analysis provides a means to:
- Achieve consistent ULS design criteria

Reliability-based Calibration of ULS requirements

Goal: Implied $P_f \approx P_f$

Load ratio, $E_c/(L_c+E_c)$

<table>
<thead>
<tr>
<th>Fatigue</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall configuration differ</td>
<td></td>
</tr>
<tr>
<td>- global hydrodynamic loads and response</td>
<td></td>
</tr>
<tr>
<td>- number of potential crack locations</td>
<td></td>
</tr>
<tr>
<td>- consequence of fatigue failure</td>
<td></td>
</tr>
<tr>
<td>Local geometry differ</td>
<td></td>
</tr>
<tr>
<td>- FPSO and semi-sub: monocoque plated structures jackets, jack-ups: members/tubular joints</td>
<td></td>
</tr>
</tbody>
</table>

Crack size, $a$

- Through thickness crack
- Plated joint
- Tubular joint

Time (No. of cycles)

Experiences with fatigue cracks

Cracks have occurred, especially in North Sea structures, due to:
- lack of fatigue design check,
- inadequate design check,
- abnormal fabrication defects (initial crack size) $\geq 0.1 - 0.5$ mm!
- inadequate inspection

Mobile semi-submersibles

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Year</th>
<th>Dpl. (%)</th>
<th>F.U.</th>
<th>No. offälle</th>
<th>Crack trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYFORD DOLPHIN</td>
<td>1974</td>
<td></td>
<td>23.3%</td>
<td>0.80</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>DEEPSEA DYNEM</td>
<td>1976</td>
<td></td>
<td>22.5%</td>
<td>0.98</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>TANACOON VICTORY</td>
<td>1977</td>
<td></td>
<td>24.0%</td>
<td>0.20</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>AEGIRLAND DOLPHIN</td>
<td>1977</td>
<td></td>
<td>43.9%</td>
<td>0.68</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>DEEPSEA SEATTA</td>
<td>1981</td>
<td></td>
<td>0.0%</td>
<td>0.99</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>WEST VANGUARD</td>
<td>1982</td>
<td></td>
<td>6.8%</td>
<td>0.81</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>

Mainly at brace joints
Crack control in mobile semi-submersibles
• Implication of FLS criterion: \( D = \sum \frac{n_i}{N_i} \leq 1 / \text{FDF} \)

\( P_f \approx 10^{-1} \) and \( 10^{-4} \) in the service life; for FDF = 1 and 10
based on normal uncertainty/variability,
• Causes of fatigue failure and safety measure

<table>
<thead>
<tr>
<th>Cause</th>
<th>Safety measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of fatigue design</td>
<td>Accomplish proper design</td>
</tr>
<tr>
<td>Inadequate fatigue design</td>
<td>QA/QC of design process</td>
</tr>
<tr>
<td>Abnormal fabrication defects</td>
<td>Fatigue design check (FDF), QA/QC</td>
</tr>
<tr>
<td></td>
<td>(Inspection as-fab., during operation), ALS design(^1)</td>
</tr>
<tr>
<td>Inadequate inspection</td>
<td>Fatigue design check (FDF), LBB-</td>
</tr>
<tr>
<td></td>
<td>monitoring, NDE inspection, ALS</td>
</tr>
<tr>
<td></td>
<td>design(^1)</td>
</tr>
</tbody>
</table>

\(^1\) ALS: - residual life time after trough thickness crack,
- residual strength after failure of a member

Frequent crack occurrences have made it possible to compare
predictions and observations using state of the art methods
- conservative prediction for tubular joints in jackets (Vårdal et al, 1997)

Cracks which are not predicted, do occur
- 2-3% of the inspections resulted in crack observations

- reasonable predictions for steel-plated joints in semi-submersibles and FPSOs
Compare experiences with trading vessels (Moan, 2004)

Relevance as a function of design criterion and uncertainty level

\[ n_{\text{inD1}} / F_{\text{DN}} = \sum \leq \frac{1}{\text{FDF}} \]

Reliability probability by account of inspection

\[ P_{F,\text{up}}(t) = P[F(t) \mid I] \]

- Failure event, \( F(t) \):
  - \( a_c - a(t) \leq 0 \): \( a_c \) = critical crack size
  - \( a_D - a(t) \geq 0 \): \( a_D \) = detectable crack size

- Inspection events, \( I \):
  - No detection: \( a_D - a(t) \geq 0 \)
  - Diver inspection
  - Leak
  - Probability of crack detection (POD)

Inspection with uncertain outcomes, assessed at the design stage
Updating of reliability based upon data at design stage viz. in-service inspection

Some issues on updating:
- If no crack found, only last inspection could commonly be considered in updating, i.e., disregard previous inspection history.
- Larger effect of updating as the structure ages.

Event tree analysis:

1. Basic case, No inspection
2. Upt, full inspection history
3. Upt, ONLY last inspection
4. Inspection during operation with No crack detection

Effect of Inspection predicted at design stage:

- $10^{-3}$
- $3\times10^{-3}$
- $3.5\times10^{-2}$

$P_f$

Reliability-based calibration of FLS requirements

Design criterion:

$D = \sum \frac{P_i}{N_i} \leq \frac{1}{F_{DF}}$

- $F_{DF}$ - depends upon:
  - consequence of failure
  - inspection quality

Reliability-based calibration for tubular joints in jackets, due to:
- the effect of inspection predicted at the design stage
- consequence of system failure

$$P_{P(SYS(i))} \leq P\left[F_{SYS(U)}|F_i\right] \cdot P[F_i|I_i] \leq P_{f(i)}$$

Fatigue cracks have initiated total losses

Ranger I, 1979
Alexander Kielland, 1980

Safety management w.r.t. Accidental and Abnormal Actions – the Accidental Collapse Limit State (ALS)

- Motivation
- History
- NPD criterion for structural integrity (1984)
  - NORSOK
  - ISO

a) Capsizing/sinking due to (progressive) flooding
b) Structural failure e.g. due to impact damage,...
c) Failure of mooring system due to "premature" failure
Framework for Risk-based Design against Accidental actions

\[
P_{FSYS}(i) = \sum_{j,k} P[F_{SYS} | D] \cdot P[D | A_{jk}^{(i)}] \cdot P[A_{jk}^{(i)}]
\]

- Probability of damaged system failure under relevant F&E actions
- Probability of accidental action at location (j) and intensity (k)
- For each type of accidental action:
  - Collisions
  - Fires/explosions

\[P[A_{jk}^{(i)}]\]
is determined by risk analysis while the other probabilities are determined by structural reliability analysis.

\[P[F_{SYS} | D]\]
is determined by due consideration of relevant action and their correlation with the hazard causing the damage.

Accidental Collapse Limit State with respect to structural strength (NPD, 1984)

- Estimate the damage due to accidental loads (A) at an annual probability of \(P[A_{jk}^{(i)}] = 10^{-4}\)
- Apply risk analysis to establish design accidental loads

Survival check of the damaged structure as a whole, considering P, F, and environmental loads (E) at a probability of \(10^{-2}\)

Target annual probability of total loss:
\[P_{FSYS}(i) \leq 10^{-5}\] for each type (i) of hazard

Risk indicators for large scale accidents - monitoring of incidents (near-misses)

- Blow-out related incidents
  - Uncontrolled hydrocarbon leaks
  - Lack of well control
- Structure related incidents
  - Structural damage, leak, collisions, loss of mooring line...
  - Ships on collision path, etc.
- Nonfunctioning barriers against large scale accidents
  - E.g. lack of detection, deluge

Relevant Accidental Loads and their Measure of Magnitude

1. Explosion loads (pressure, duration - impulse)
   - Scenarios
   - Explosion mechanics
   - Probabilistic issues
   ⇒ Characteristic loads for design
2. Fire loads (thermal action, duration, size)
3. Ship impact loads (impact energy, -geometry)
4. Dropped objects
5. Accidental ballast
6. Unintended pressure
7. Abnormal Environmental loads
8. Environmental loads on platform in abnormal floating position
Prediction of Explosions & Fire Events

- Explosion is a process where combustion of premixed gas cloud is causing rapid increase of pressure
- Fires is a slower combustion process

Release of Gas and/or Liquid

- Immediate Ignition
- Formation of combustible fuel-air cloud (Pre-mixed)
- Ignition (delayed)

Implication of simultaneous occurrence of explosion and fire:
Explosion can occur first and damage the fire protection before the fire occurs

Calculation of gas explosion loads

- FLACS
- PROBLAST

Dispersal Analysis
- Gas leak location and direction
- Gas leak rate
- Environmental conditions

Explosion Analysis
- Ignition location
- Gas cloud location and size

Monte Carlo Simulation
- Probabilistic scenario definition
- Overpressure definition

Overpressure Exceedance Data

- Including model uncertainty

From goal-setting (risk-based case-by-case) to a prescriptive approach:
“Generic” Design Explosion Loads

Significant experiences form the basis for prescriptive Explosion Loads for design for commonly occurring cases

<table>
<thead>
<tr>
<th>Explosion scenario</th>
<th>Structural component</th>
<th>Overpressure (barg)</th>
<th>Duration</th>
<th>Impulse (kPa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process area</td>
<td>Deck girder (30%)</td>
<td>0.3-0.5</td>
<td>0.1</td>
<td>&lt;1.4-2.0</td>
</tr>
<tr>
<td></td>
<td>Process roof</td>
<td>0.2</td>
<td>0.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Export riser area</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wellbay area</td>
<td>Central blast wall</td>
<td>0.3-0.7</td>
<td>0.2-0.4</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td></td>
<td>Upper deck</td>
<td>0.2</td>
<td>0.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Note: Overpressure is controlled by ventilation
Pressure in a completely enclosed compartment: 4 barg

Analysis of Initial Accidental Damage and Global Ultimate Strength of Damaged Structure

- Simple, “analytical” methods
- FE analysis methods
  - Non-linear dynamic analysis to assess the time-dependent response, i.e. the dynamic response/
  - Non-linear static analysis to assess static resistance and the static failure modes.

Challenges:
- (local buckling, fracture, rupture ...)
- Geometrical imperfections, residual stresses
- Nonlinear geometry
- Fracture criteria
"Survival" analysis of platform deck structure suffering explosion damage (Amdahl, 2003)

Ship collisions

Types and scenarios
- external ships (merchant, fishing..)
- offshore site related ships (supply vessels, offshore tankers, …)
- floating structures (storage vessels, drilling units, crane barges..)

Probability of ship impacts – the $10^{-4}$ event?

The pessimist view
Supply vessels
Collisions have been frequent.
Based on experiences:
Minimum impact energy for supply vessel
- head-on: 11 MNm
- sideways: 14 MNm

The optimist view
Trading vessels and other scenarios – site specific
by use of risk analysis models

Risk assessment of merchant ship collisions

$P_C = \sum_{i=1}^{n} \sum_{j=1}^{5} \sum_{k=1}^{4} P_{CC,i,j,k} \cdot P_{FR,i,j,k}$

$P_C$ – annual impact frequency for a given platform in a given location
$N_{ij}$ – annual number of vessels with a size ($j$) in route ($i$)
$P_{CC,i,j,k}$ – probability that vessel of size ($i$) in navigation group ($k$) in route ($i$) is on collision course
$P_{FR,i,j,k}$ – probability that a vessel with a size ($j$) in navigation group ($k$) does not succeed in avoiding the platform
Special scenario: Shuttle tanker impact on FPSO stern

For typical vessels:
- Penetration of machine room would occur by an energy of 38 MJ
- Strengthen FPSO stern to make the shuttle bow absorb the energy

Potential consequence
- Oil spill, Production loss
- Damage to flare tower – fire
- Possible flooding in machine room

Hazardous condition: Operational error in connection with large relative motion

(Amdahl and Moan, 2002)

Abnormal strength (damage) for ALS check
- Directly specified, not calculated via accidental loads
- Generic values for specific types of structures based on consideration of the vulnerability of the structural components.

Examples:
1) Slender braces in mobile drilling platforms (semi-submersibles) due to their vulnerability to ship impacts and fatigue.
2) Catenary mooring line
3) Tether in tension-leg platforms

Abnormal degradation due to fatigue or corrosion

Quality assurance and control
- of design process
- Offshore structural engineering today
  - Partly mature (many aspects of fixed platform technology)
  - Partly innovative technology emerging (e.g., in relating to floating platforms, risers, offloading of gas)
- QA/QC of novel concepts represent particular challenges
  - Requires robust control, i.e., independent reviews
  - Innovation depends upon R&D

Recent examples:
- Combined wind – and swell wave condition
- Flexible riser "corrosion" fatigue
- Tether springing

Safety of Marine Operations
- Hardware
- Software
- "Humanware"

Simulators
**Safety of Offloading operations**
- Shuttle tanker-FPSO collisions

- **Potential consequence**
  - Oil spill, Production loss
  - Damage to flare tower – fire
  - Possible flooding in machine room

- **Initiated by:**
  - DP failure
  - Position reference error
  - Main engine/propeller
  - DP operators

- **High Frequncy:**
  1 drive-off in every 50-200 tandem offloadings

- **P(drive-off) × P(failure of recovery|drive-off) = P (collision)**

**Safety of heavy transports**
- reliability of seafastening
- capsizing risk

- **Uncertainties inherent in the operation:**
  - the environmental conditions
  - wave heading
  - forecast of environmental conditions

- **Uncertainty in the forecasted significant wave height:**
  - method to calculate motions (especially roll) and structural responses
  - method to calculate resistance

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**Bourbon Dolphin anchor handling vessel capsizing**

- **Failure mode:** instability/capsizing of vessel
  - stabilizing moment : hydrostatics
  - overturning moment : wind, current, line tension

- **Information needed:**
  - current and wind forces on the vessel, wave induced motions
  - vessel manoeuvering of vessel (human factors)
  - geometrical configuration of lines
  - line tensions

- **Provide information for:**
  - Design,
  - Operations planning,
  - Simulator training of the crew

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**Some future challenges**

- Oil and gas activities in the arctic
- Underwater operations in deep water or under the ice
- Renewable offshore energy
Safe and sustainable arctic oil and gas operations

- Concepts
- Operations: Health and personnel safety
  - demanding working conditions
    (temperature down to – 50º C and wind-chill factor – darkness, icing ...)
  - difficult to inspect/repair
  - challenging escape and evacuation due to a long distance to other facilities
- Environmental restrictions
  - The Arctic is vulnerable to any activity
  - Pollution will take a long time to go away

Strategies to handle severe ice conditions in the design of facilities

- Design system to avoid the ice
  - use subsea system and pipelines (in sufficiently large water depths)
- Ice management
  - Terra Nova iceberg management by moving icebergs out of the critical path
- Shut down and disconnect during the most severe winter
  - SALM offshore Sakhalin
    Production ~180 days/year
    Winter: repair, modifications
  - jack-up in Caspian Sea
- Design against ice loading
  - so far mainly caisson type installations

Ice loads for structural design

- Ice conditions
  - Level (mutual exclusive to wave loads)
    - Rafted
    - Ridge
    - Rubble
    - Iceberg (and bergy bits)

106 icebergs were observed in May 2003 in the Stockman region (Zubakinet al., 2005)
Mass of largest iceberg is estimated to be
~3 700 000 t (250 x 250 x 60 m)

Pressure on vertical cylinder due to level ice
("crushing" of level ice and other ice failure mechanisms)

API (1995)
Pressure (mean + 2 st.dev.):
\[ p = \frac{8.1}{A^{0.5}} \]
Facilities for wind vs oil and gas technology

- Number of units – one of a kind versus mass production.
- Safety issues: No hydrocarbons and people on board wind turbines
- The wind energy sector is a “marginal business”
- Return are more sensitive to IMMR (O&M) costs (access)

Wind turbines vs other marine structures

Wind turbine failure rates and down times

- Availability - 96 - 98% on land
- 80% for early wind farms offshore
- Need for robust design, (reliable and few components) & smart maintenance, but also improved accessibility
- Larger turbine size? (> 5 – 20 MW)
- Predict, monitor and measure degradation

Reliability analysis of drivetrain in FWT vs. WT

- Decoupled analysis to determine Tooth contact forces, Bearing forces, Gear deflections.
  - Global aero-hydro-servo-elastic simulation
  - Drivetrain multi-body simulation based on main shaft loading and nacelle motions

Example: response analysis under faults during power production of a spar wind turbine

- IEC code requires checking of nearly 40 cases with environmental loads for a system which is intact or fault. Example:

  Time history of tower bottom bending moment of a spar-type wind turbine under different fault conditions. Mean wind speed: 25m/s, Turbulence Intensity: 0.15, Hs=5.9m, Tp=11.3s

(Jiang et al, to appear)
Concluding remarks

- **Safety management**
  - Design criteria, especially structural robustness expressed by Accidental Collapse Limit State
  - QA/QC of design process w.r.t to novel phenomena
  - Inspection (QA) of structure (CVI, NDE and Leak before Break)

- **Facilities**
  - Structural Reliability Analysis is used to establish consistent ultimate resistance and fatigue criteria (The implied failure probability by current criteria, however, is small)
  - Quantitative Risk Analysis serve as basis for ALS criteria

- **Operations**
  - System design for man-machine interaction
  - Training

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Thank you!