Experiences with design and operation of fixed steel structures in the oil & gas sector

by

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Outline

- Introduction
- In-service experiences – with failures and accidents
- Safety management
  - life cycle approach, with an emphasis on design
  - risk and reliability analysis
- Developing and validating methods for
  - structural response and resistance assessment
- Concluding remarks
Oil and gas production plants

- fixed structures – by a civil engineering approach
  - Steel
  - Concrete
- floating structures – by a ”naval architecture” approach)

- Fixed steel platforms (jackets) are the dominant type of platform
- 5000 fixed steel platforms world wide

Development of deepwater jackets

Minimal platforms

45 000 tons
Facilities for wind vs oil and gas technology

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

Experiences

Background

- significance of the oil and gas industry to the world economy
- need for technology development for deeper water, challenging natural and industrial environment,…
- ageing facilities

Gathering of experiences – development of procedures/methods/data

- Failure - and accident data
- Safety management procedure
  - safety criteria, (limit states) – including accidental limit state
  - risk and reliability analysis of design, inspection/monitoring
- Methods (hydrodynamics, structural analysis)
- Data (strength data for tubular joints)
A Case of structural failure - due to ”natural hazards” ?

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

Human – organizational factors:
Design
- Inadequate wave conditions or load calculation or strength formulation or safety factors

Fabrication deficiencies
due to
- inadequate state of art in offshore engineering or,
- errors and omission during design or fabrication!

Severe damage caused by hurricane Lilli in the Gulf of Mexico
Accident experiences for mobile drilling and fixed production platforms

(Number of accidents per 1000 platform years)

(World wide in the period 1980-95, Source: WOAD 1996)
In-service experiences with cracks in fixed offshore platforms (See Vårdal, Moan et al, 1997...)

- Data basis
  - 30 North Sea platforms, with a service time of 5 to 25 years
  - 3411 inspections on jackets
  - 690 observations of cracks

- The predicted frequency of crack occurrence was found to be 3 times larger than the observed frequency; i.e. conservative prediction methods

On the other hand:
- Cracks which are not predicted, do occur.
  - Hence, 13 % of observed fatigue cracks occurred in joints with characteristic fatigue life exceeding 800 years; due to
  - abnormal fabrication defects (initial crack size ≥ 0.1 mm !)
  - inadequate inspection
Safety management (ISO 2394, ISO19900, etc)

- Measures to maintain acceptable risk
  - Life Cycle Approach design, fabrication and operational criteria
  - QA/QC of engineering design process
  - QA/QC of the as-fabricated structure
  - QA/QC during operation (structural inspection)
  - Event control of accidental events
  - Evacuation and Escape

ULS
FLS: \[ D = \sum \frac{n_i}{N_i} \leq D_{\text{allowable}} \]
ALS
### Safety criteria for design and reassessment
(with focus on structural failure modes) ISO

<table>
<thead>
<tr>
<th>Limit states</th>
<th>Physical appearance of failure mode</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td><strong>Ultimate</strong> (ULS)</td>
<td></td>
<td><strong>Component design check</strong></td>
</tr>
<tr>
<td>- Ultimate strength of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>structure, mooring or</td>
<td></td>
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<tr>
<td>possible foundation</td>
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<tr>
<td><img src="image" alt="Collapsed cylinder" /></td>
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</tr>
<tr>
<td><strong>Fatigue</strong> (FLS)</td>
<td></td>
<td><strong>Component design check</strong> depending on residual system strength and</td>
</tr>
<tr>
<td>- Failure of welded joints</td>
<td></td>
<td>access for inspection</td>
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<tr>
<td>due to repetitive loads</td>
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<tr>
<td><img src="image" alt="Fatigue crack" /></td>
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<tr>
<td><strong>Accidental collapse</strong> (ALS)</td>
<td></td>
<td></td>
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<tr>
<td>- Ultimate capacity(^1) of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>damaged structure with</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“credible” damage</td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Jack-up collapsed" /></td>
<td></td>
<td></td>
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</tbody>
</table>
Accidental Collapse Limit State for Structures (NPD, 1984)

- Estimate the damage due to *accidental loads* (A) at an annual exceedance probability of $10^{-4}$ and likely fabrication errors.

- Check survival of the structure with damage under functional (F) and environmental loads (E) at an annual exceedance probability of $10^{-2}$.

- Load & resistance factors equal to 1.0
Analysis for demonstrating compliance with design criteria

**Functional loads**
- dead loads
- -pay loads

**Load effects**
- Extreme moment (M) and axial force (N)

**Design criteria**
- ULS: Collapse resistance
- FLS: SN-curve/fracture mechanics
- ALS: Ultimate global resistance

**Sea loads**
- Local stress range history

**Accidental loads**
- Extreme global force

**Industrial and Operational Conditions**
- Response analysis - dynamic v.s. quasi-static/quasi-dynamic

**Damage structure**
- Analysis of damage

Piper Alpha

Defined probability level
Risk and reliability assessment

- Rational mechanics methods for design of structures, foundations
- Loads and resistances are subjected to uncertainties
  - Normal variability and uncertainty; gross errors
- Design is decision under uncertainty:
  - Rational treatment of uncertainty (range, mean + st. dev. etc)
  - Implying probabilistic methods
- Especially in connection with new technology, no standards

Definition

- Risk:
  Expected loss (probability times consequences)
- Reliability:
  Probability of a component/system to perform a required function

Recognised in the oil and gas industry

- Calibration of LFRD design approaches (1970s, 1980s)
- RBI (Risk/Reliability Based Inspection)
  (methods in 1980s-; industry adoption in 1990s-)

ALARP principle
Explicit safety measures by structural reliability analysis

Semi-probabilistic design code:
\[ \frac{R}{\gamma_R} \geq \gamma_S S_c \]
- \( R_c \); \( S_c \) - characteristic resistance and load effect
- \( \gamma_R \); \( \gamma_S \) - partial safety factors

Reliability analysis:
R and S modelled as random variables; e.g. by lognormal distributions

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

\[ \ldots = \Phi\left(-\frac{\ln\left(B_R \gamma_R \gamma_S / B_S\right)}{\sqrt{V_R^2 + V_S^2}}\right) = \Phi\left(-\beta\right) \approx 10^{1.2-1.4\beta} \]

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

Goal: Implied \( P_f \equiv P_{ft} \)
Reliability - based ULS requirements

Design equation

\[ \frac{R}{\gamma_R} > \gamma_D D_C + \gamma_L L_C + \gamma_E E_C \]

\( R \) — resistance
\( D, L, E \) — load effects due to
- permanent
- live
- environmental

Goal: The Implied

\[ P_f = P(R>D+L+E) \cong P_{ft} \]

\( P_f \) depends upon the systematic and random uncertainties in
\( R; D, L, \) and \( E \)

Reliability-based code calibrations:
- NPD/DNV; API/LRFD;
- Conoco studies of TLPs;

\[ \beta \]

\[ \beta_T \]

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

WSD

LRFD
Safety against fatigue or other degradation failure is achieved by design, inspection and repair.

- **Design criteria: FLS**
  
  \[ D = \sum \frac{n_i}{N_i} \leq D_{\text{allowable}} \]
  
  \[ \text{...} = 0.1 - 1.0 \]

- **Initial and modified inspection/monitoring plan**
  - method, frequency

- **NDE diver inspection or LBB**

- **Repair** (grinding, welding, steel...)
Reliability based inspection planning w.r.t. fatigue

- Failure probability
  \[ P_f(t) = P[a_c - a(t) \leq 0] \]
  \( a_c \) = critical crack size

- Updating of failure probability based on inspection (Madsen, Moan, Skjong, Sørensen, ...):
  \[ P_f \]

Example: no crack is detected:

\[ P_{f, up}(t) = P[a_c - a(t) \leq 0 | a_D - a(t) \geq 0] \]
\[ = P[F | IE] = P[F \cap IE] / P[IE] \]

\( a_c \) = critical crack size
\( a_D \) = detectable crack size
where \( F_{AD}(a) = POD(a) \)

- Known outcomes in-service vs uncertain outcomes at the design stage
- Updating late in the service life has larger influence
In-service scheduling of inspections to maintain a target reliability level

Inspection scheduling for a welded joint based upon no detection of crack during inspection

\[ P_f = \Phi(-\beta) \approx 10^{1.2-1.4\beta} \]
\[ \beta \approx 0.85 - 0.7 \log P_f \]

Extension of method:
- consideration of other inspection events;
- effect of corrosion etc
- many welded joints, i.e. system of joints
Target safety level

- The acceptable safety (failure probability) should depend on the consequences (ISO 19900):

<table>
<thead>
<tr>
<th>Fatality consequences</th>
<th>Consequences – other than fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Manned, non-evacuated</td>
<td>PSL 1</td>
</tr>
<tr>
<td>Manned, evacuated</td>
<td>PSL 1</td>
</tr>
<tr>
<td>Un-manned</td>
<td>PSL 1</td>
</tr>
</tbody>
</table>

- and should affect design criteria, QA&QC approaches etc

- if the fatality or spill risk is negligible, design could be based on minimization of costs

- Acceptable probability of failure of individual member or joint failure, depends on the consequences (reserve capacity)
Developing and validating methods

- Response analysis of nominal wave- and wind-induced load effects validated by
  - in-service experiences
    (Mandatory in the initial development of the Norwegian oil and gas industry)
  - laboratory test data

- Response analysis of hot spot stresses validated by laboratory testing

- Resistance (laboratory testing)

- In-service damages (due to design, fabrication and operational error)
Estimate of uncertainty in the global wave load on jackets – base shear force of the Magnus and Tern jackets:

Model uncertainty = \( \frac{F_{\text{measured(i)}}}{F_{\text{predicted(i)}}} \)

Mean = 1.06

COV = \( \frac{\sigma}{\mu} \) \( \equiv \) 25%

The Magnus platform

ISO 19900 load analysis procedure
Stochastic analysis of wave load effects for ULS and FLS checks in a long term perspective

- long term analysis
  (all sea states)

- extreme response based on some sea states
  - 3 hour irregular wave sequence
    (by contour line method)
  - wave episode (of random waves)
  - regular (design) wave
Wave loading on slender members

Morison formula: 

\[ q = q_D + q_I \]

where the drag force: 

\[ q_D = \frac{1}{2} C_D \rho D v_x |v_x| \]

Additional components if the wave load is combined with a current, or if the load is integrated over the wetted surface of the cylinder.

**Wave force**

\[ q = q_D + q_I \]

**Drag force**

\[ q_D = \frac{1}{2} C_D \rho D v_x |v_x| \]

**Drag force pr. unit length**

\[ v_x = \sin(\omega t) \]

\[ q_D \propto v_x |v_x| = \sin(\omega t) |\sin(\omega t)| = 0.85 \sin(\omega t) - 0.17 \sin(3 \omega t) - 0.02 \sin(5 \omega t) + \ldots \]

\[ \rho \] - density of water

\[ C_D \] - drag coefficient

**Slamming loads**

www.ntnu.no
Dynamic analysis

- Stochastic wave loads
- Natural periods (2.5 s, 3.5 s)
  - excitation by $2\omega$, $3\omega$, ... where $\omega$ is the wave frequency

Response analysis methods of different refinement

A | SPECTRAL, NON-LINEAR, DYNAMIC
B | DETERMINISTIC, NON-LINEAR, DYNAMIC
C | SPECTRAL, LINEAR, DYNAMIC
D | DETERMINISTIC, NON-LINEAR, STATIC
E | SPECTRAL, LINEAR, STATIC
F | DETERMINISTIC, LINEAR, STATIC
Ringing in platforms (the Draugen platform)

Features
- Ringing occurs in:
  - high, steep waves
  - platforms with large volume and natural periods below 8s
- Load calculation is reasonably accurate for single columns
In general: loads need to be determined by lab. tests
- Transient dynamic response due to a sudden change of load
- The new phenomenon was discovered (while the Draugen platform was being built) and remedied
- What about monopiles?
Design against accidental actions according to e.g. NORSOK

- Fires, Explosions,
- Abnormal waves and earthquakes
- Dropped objects

Ship collisions,

Step 1
Damage due to accidental actions and abnormal env. loads, return period 10000 years - nonlinear structural behavior accepted

Step 2
Resistance of damaged structure to design environmental loads, return period 100 years Partial safety factors = 1,0
Ship collision risk (PSA/NORSOK approach)

- reduce risk by reducing the probability (traffic control) and the consequences of collision
- Design for collision events
  - Min collision: Supply vessel 5000 tons displacement and a speed of 2 m/s; i.e. 11, 14 MJ
  - events identified by risk analysis

- Collision at Ekofisk field in the North Sea in June 2009 – with a kinetic energy of 60 MJ
- Submarine U27 hitting the Oseberg B
Ultimate global collapse analysis of platforms

- Non-linear analysis to assess the resistance of
  - intact and damaged structures
    by accounting for
  - geometrical imperfection, residual stresses
  - local buckling, fracture, rupture in joints
  - nonlinear geometrical and material effects

Nonlinear FEM
- General purpose (ABAQUS….)
- Special purpose (USFOS….)
Residual global ultimate strength after damage (due to collision, dropped objects, "fatigue failure")

Residual strength of damaged North Sea jacket. Linear pile-soil model

<table>
<thead>
<tr>
<th>Ultimate strength</th>
<th>Broad side loading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brace 261</td>
</tr>
<tr>
<td>Ultimate strength $F_{ult} / F_{H100}$</td>
<td>2.73</td>
</tr>
<tr>
<td>Residual strength $F_{ult(d)} / F_{ult}$</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Concluding remarks

Experiences regarding
- failures and accidents and
- life cycle safety management
for oil and gas installations can serve as a basis for structures in other offshore industries, notably wind turbines,
- when the differences between
  the oil and gas and the other industries are recognised

In particular
- normal uncertainty and variability in structural performance as well as possible “gross errors” in fabrication and operation should be properly considered in the decision process

Thank you!
Selected references – which include more complete reference lists

Design codes: ISO 2394 (Reliability of structures); ISO 19900- (Offshore structures)


