RAVE RESEARCH AT ALPHA VENTUS

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

by

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NTNU Innovation and Creativity

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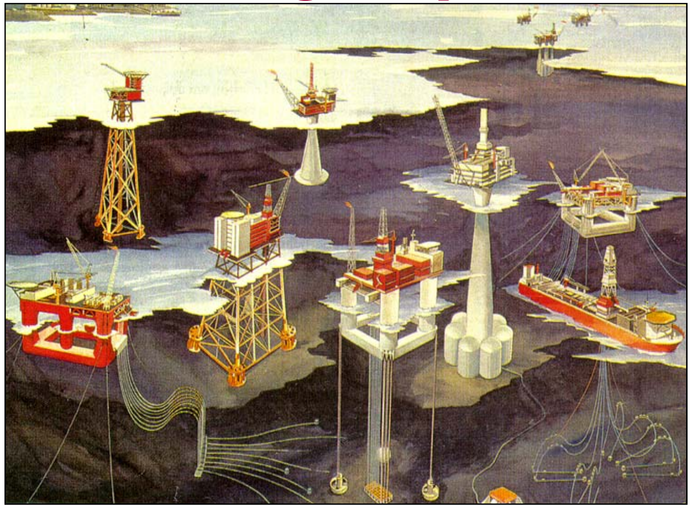
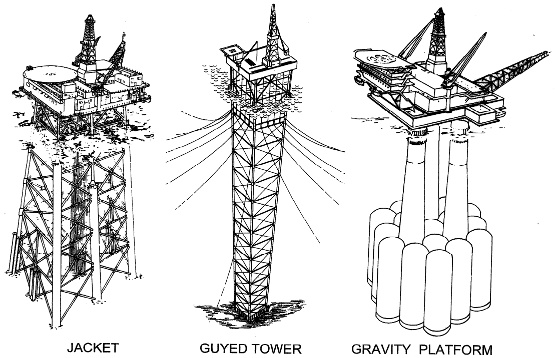
Outline

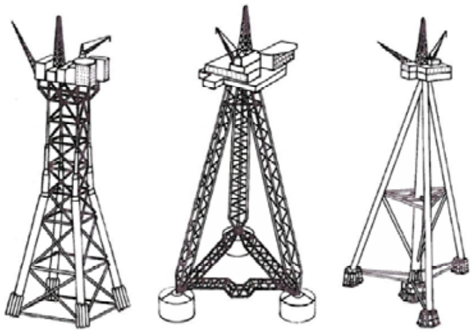
- Introduction
- In-service experiences – with failures and accidents
- Safety management
  - life cycle approach, with an emphasis on design
  - risk and reliability analysis
- Developing and validating methods for
  - structural response and resistance assessment
- Concluding remarks

Oil and gas production plants



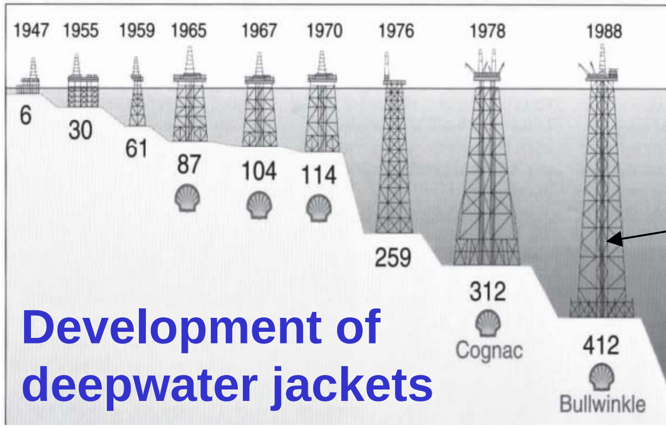
- *fixed structures* – by a civil engineering approach
  - Steel
  - Concrete
- *floating structures* – by a ”naval architecture” approach)





Minimal platforms

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



45 000 tons

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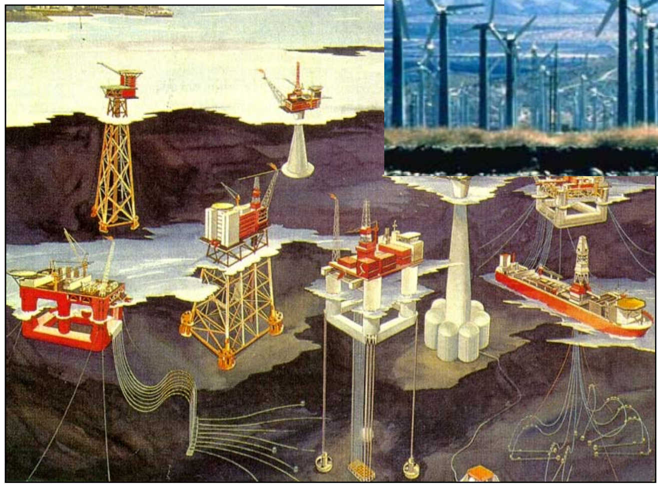
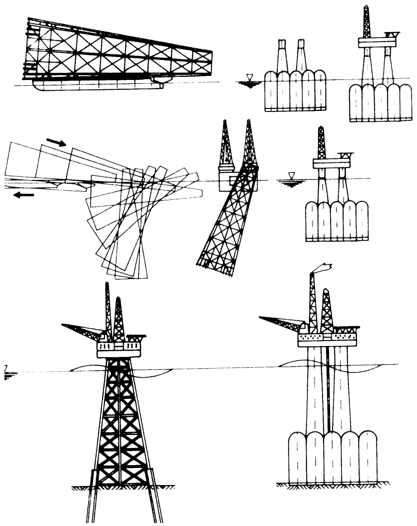
Facilities for wind vs oil and gas technology



Integrating knowledge

- **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)**



Wind turbines vs other marine structures

Experiences

Background

- significance of the oil and gas industry to the world econmy
- 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" ?

Severe damage caused by hurricane Lilli in the Gulf of Mexico

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**

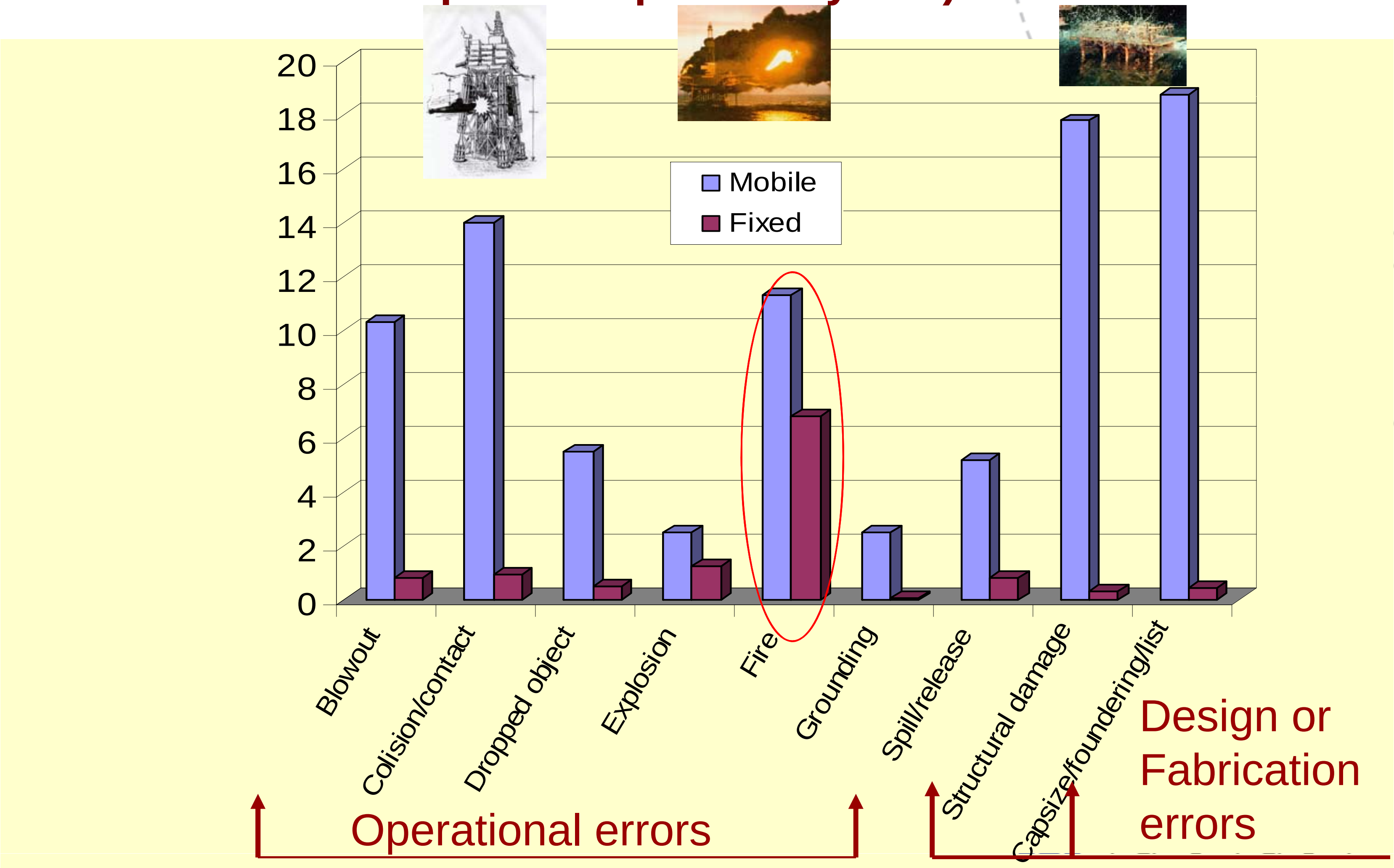
Fabrication deficiencies

due to

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

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)

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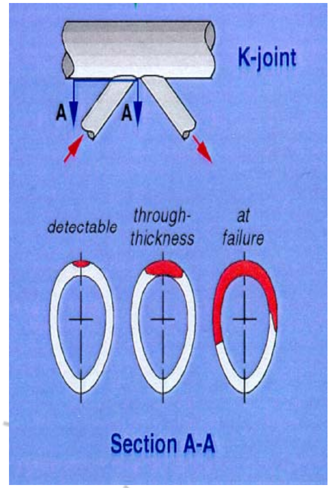
In-service experiences with cracks in fixed offshore platforms (See Vårdal, Moan et al, 1997...)

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

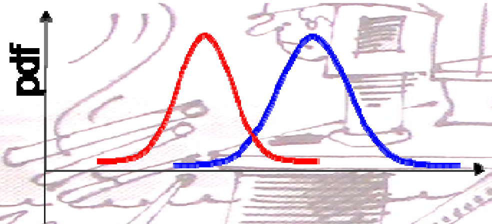
- The predicted frequency of crack occurrence was found to be 3 times larger than the observed frequency; i.e. **conservative prediction methods**



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)

ULS
FLS: $D = \Sigma n_i / N_i \leq D_{allowable}$
ALS



- **Measures to maintain acceptable risk**

- Life Cycle Approach
design, fabrication and operational criteria

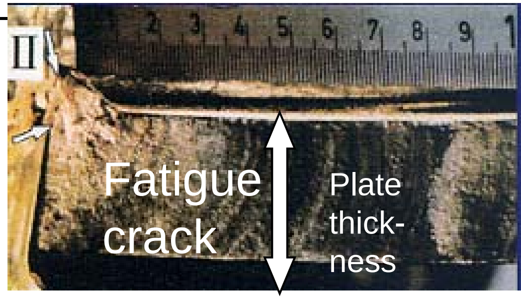
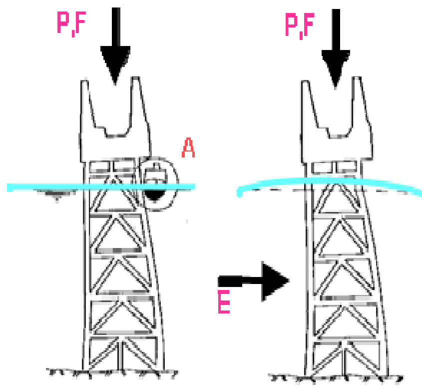
- QA/QC of engineering design process
- QA/QC of the as-fabricated structure
- QA/QC during operation
(structural inspection)

- Event control of accidental events

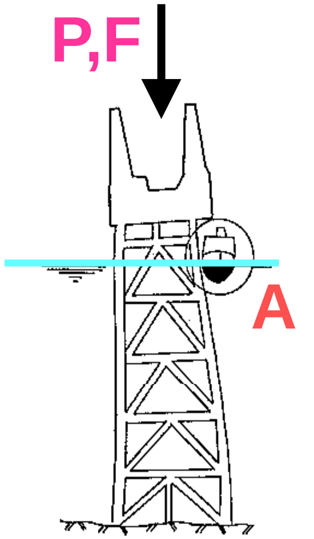
- Evacuation and Escape

Safety criteria for design and reassessment

(with focus on structural failure modes) ISO

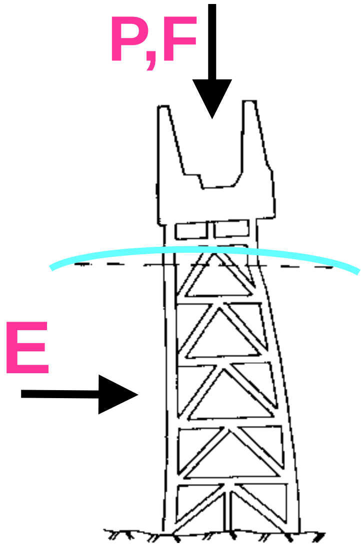
Limit states	Physical appearance of failure mode	Remarks
Ultimate (ULS) - Ultimate strength of structure, mooring or possible foundation		Component design check
Fatigue (FLS) - Failure of welded joints due to repetitive loads		Component design check depending on residual system strength and access for inspection
Accidental collapse (ALS) - Ultimate capacity[1)] of damaged structure with "credible" damage 		

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

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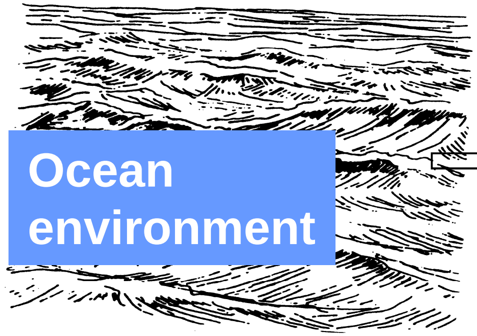
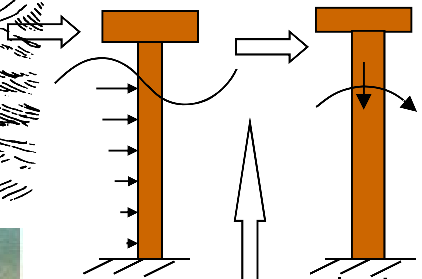
Analysis for demonstrating compliance with design criteria

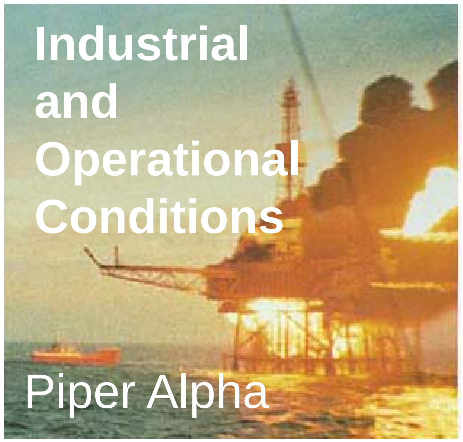
Functional loads
- dead loads
- -pay loads



Ocean environment

Sea loads



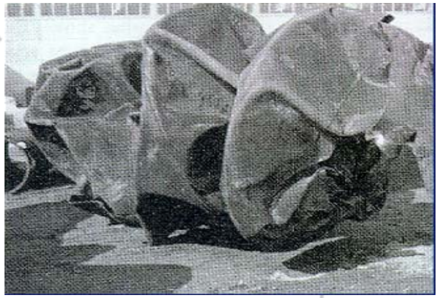


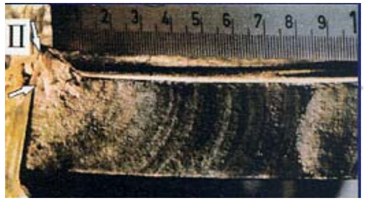
Accidental loads

Analysis of damage

Response analysis
- dynamic v.s. quasi-static/ quasi-dynamic

Load effects		Design criteria
Extreme moment (M) and axial force (N)	⇔	**ULS:** Collapse resistance
Local stress range history	⇔	**FLS:** SN-curve/ fracture mechanics
Damaged structure Extreme global force	⇔	**ALS:** Ultimate global resistance





Design check

Defined probability level

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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

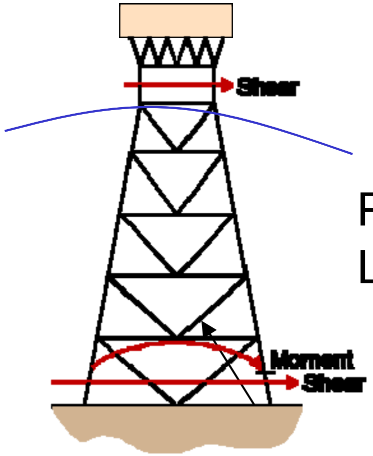
- **Risk:**
  Expected loss (probability times consequences)
- **Reliability:**
  Probability of a component/system to perform a required function

Recognised in the oil and gas industry

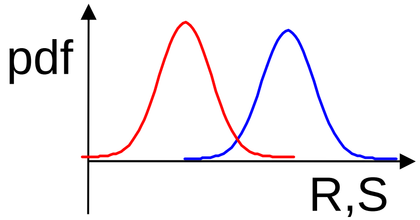
- calibration of LFRD design approaches (1970s, 1980s)
- RBI (Risk/Reliability Based Inspection)
  (methods in 1980s-; industry adoption in 1990s-)

ALARP principle

Explicit safety measures by structural reliability analysis



Resistance R
Load effect S



$$(\mu_R, V_R); (\mu_S, V_S)$$

$$\boxed{\mu_R = B_R R_C \qquad \mu_S = B_S S_C}$$

$$B_R \geq \mathbf{1}; B_S < \mathbf{1}$$

Goal: Implied $P_f \cong P_{ft}$

Semi-probabilistic design code:

$$R_c/\gamma_R \geq \gamma_S S_c$$

- R_c ; S_c - characteristic resistance and load effect

- γ_R ; γ_S - partial safety factors

Reliability analysis:

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

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

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

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

Reliability - based ULS requirements

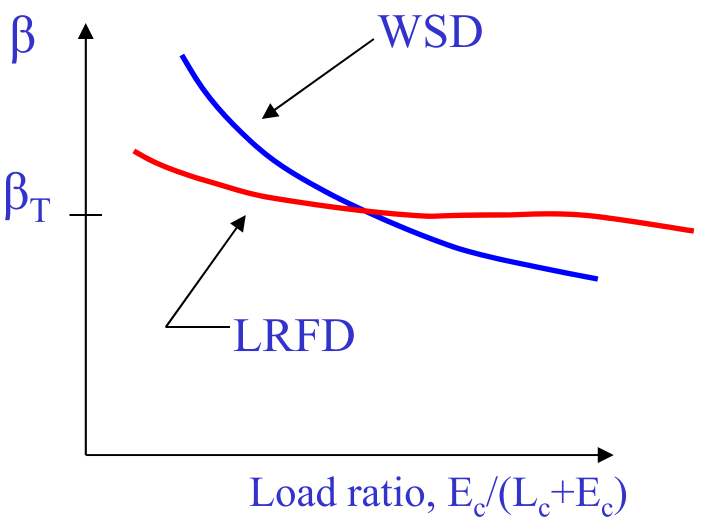
Design equation

$R_C/\gamma_R > \gamma_D D_C + \gamma_L L_C + \gamma_E E_C$

R — resistance

D, L, E — load effects due to

$\left.\begin{array}{l}\text{• permanent} \\ \text{• live} \\ \text{• environmental}\end{array}\right\}$ load effects



Goal: The Implied

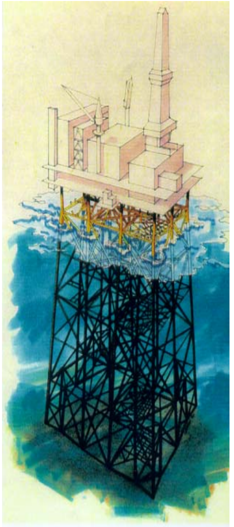
$$P_f = P(R>D+L+E) \cong P_{ft}$$

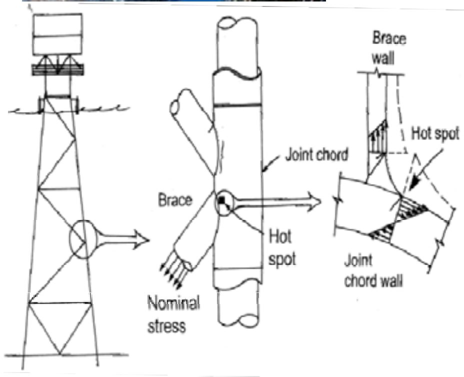
P_f depends upon the systematic and random uncertainties in R; D, L, and E

Reliability-based code calibrations:

- NPD/DNV; API/LRFD;
- Conoco studies of TLPs ;

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





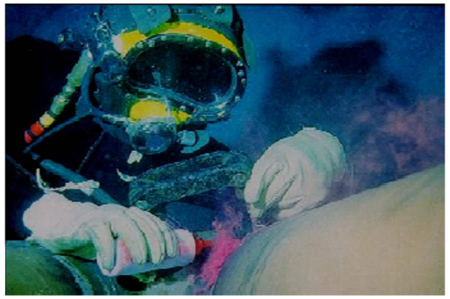
- **Design criteria: FLS**

$$D = \sum \frac{n_i}{N_i} \leq D_{allowable}$$

$$.... = 0.1 - 1.0$$

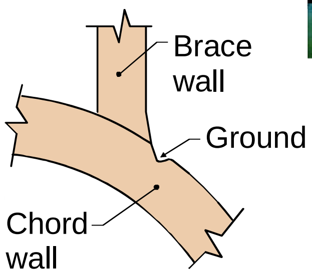
Case	$D_{allowable}$	Implied reliability level: Service life (20 years) P_f	Implied reliability level: Max annual hazard rate
1	1	10^{-1}	10^{-2}
2	0.33	10^{-2}	$2{*}10^{-3}$

ALS



- **Initial and modified inspection/ monitoring plan**

  - method, frequency



NDE diver inspection or LBB

- **Repair** (grinding, welding,..steel…)

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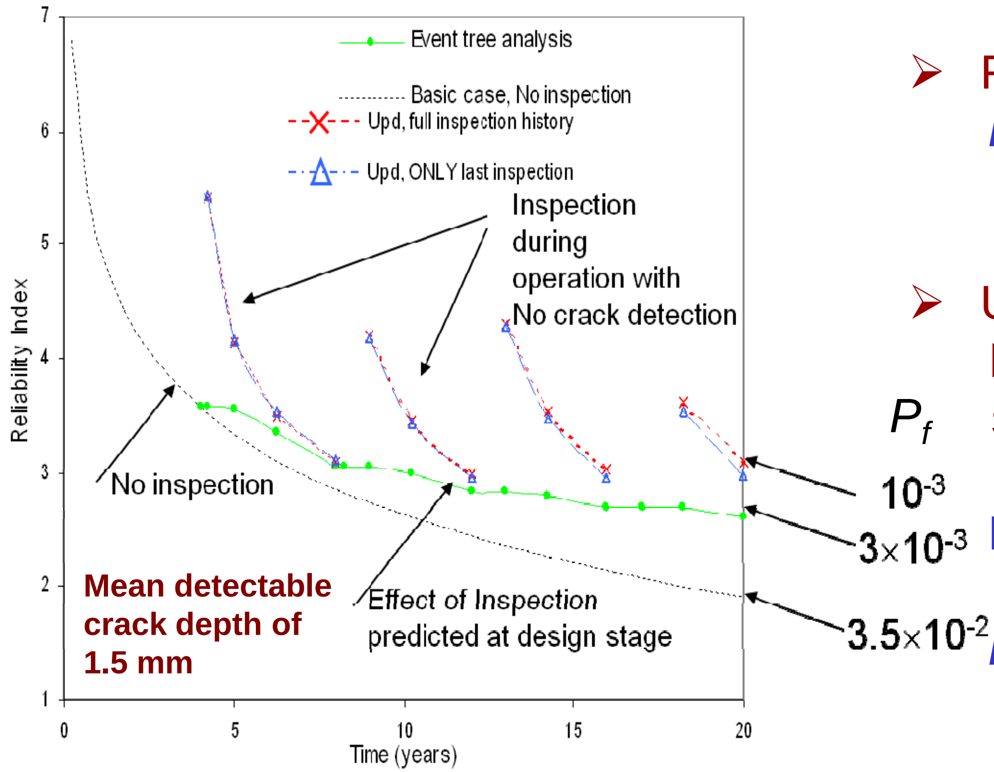
Reliability based inspection planning w.r.t. fatigue



- 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, ….): :

Example: *no crack is detected*:

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

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

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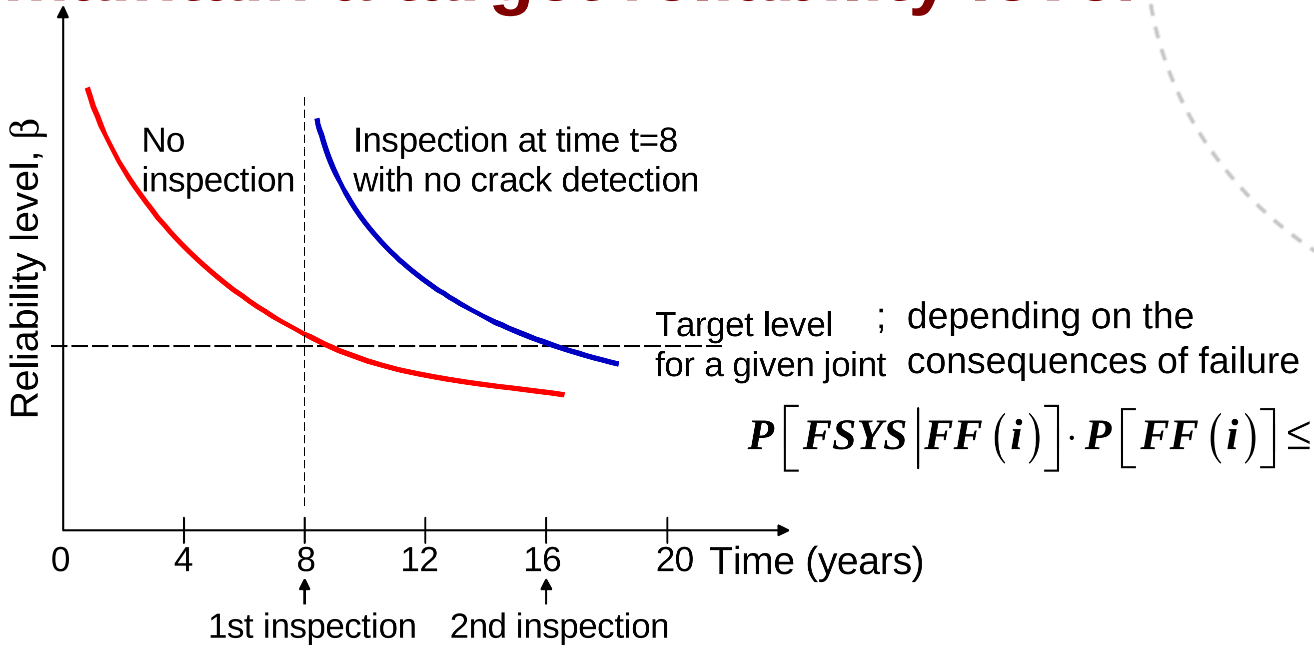
In-service scheduling of inspections to maintain a target reliability level



$$P\left[FSYS \middle| FF(i)\right] \cdot P\left[FF(i)\right] \leq P_{FT}$$

Inspection sceduling 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

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Target safety level

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

Fatality consequences	Consequences – other than fatalities		
	High	Medium	Low
Manned, non-evacuated	PSL 1	PSL 1	PSL 1
Manned, evacuated	PSL 1	PSL 2	PSL 2
Un-manned	PSL 1	PSL 2	PSL 3

- 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)

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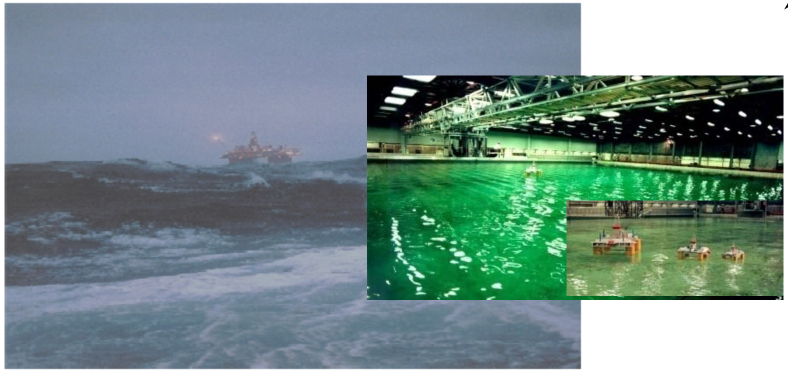
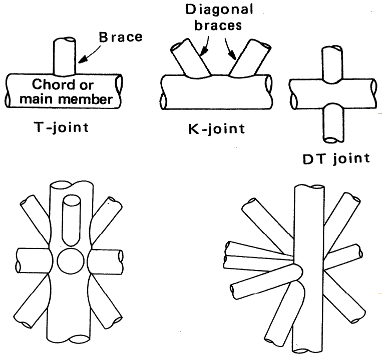
Developing and validating methods





- Response analysis of nominal wave- and wind-induced load effects validated by
  - in-service experiences

    (Mandatory in the inital development of the Norwegian oil and gas industry)
  - laboratory test data
- Response analysis of hot spot stresses validated by laboratotory testing
- Resistance (laboratory testing)
- In-service damages (due to design, fabrication and operational error)

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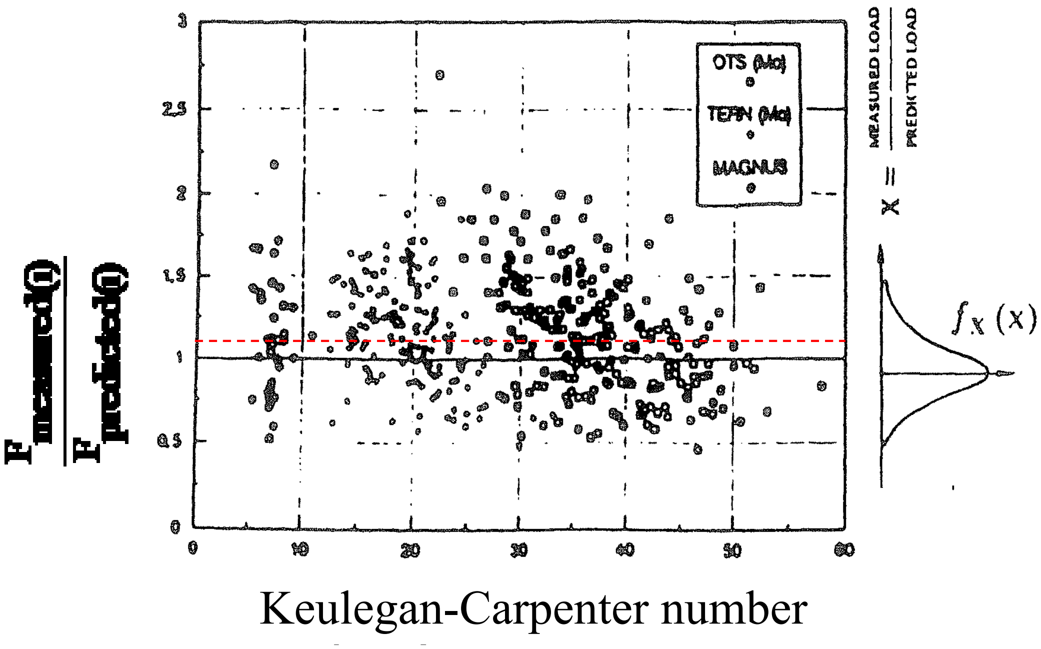
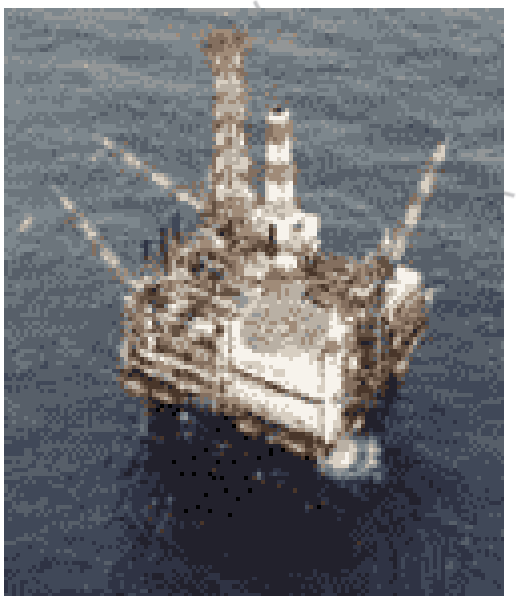
Estimate of uncertainty in the global wave load on jackets – base shear force of the Magnus and Tern jackets:





The Magnus platform

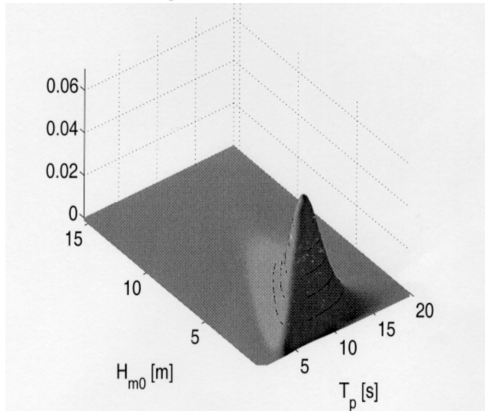
Model uncertainty = $\dfrac{F_{measured(i)}}{F_{predicted(i)}}$

ISO 19900
load analysis procedure

Mean = 1.06

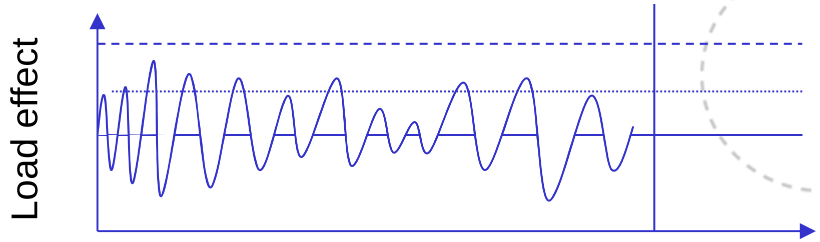
$$\text{COV} = \frac{\sigma}{\mu} \equiv 25\%$$

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



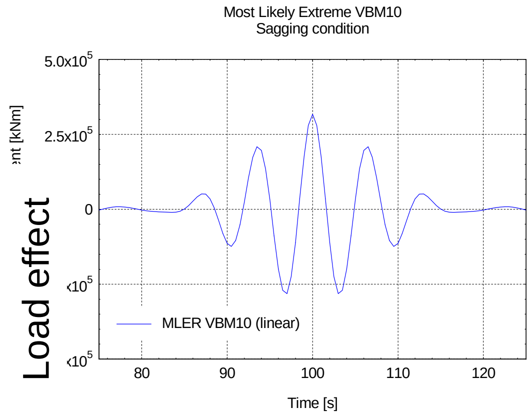
- ➢ long term analysis

  (all sea states)



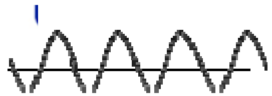
- ➢ extreme response based on some sea sea states

  - 3 hour irregular wave sequence
    (by contour line method)



  - wave episode (of random waves)

  - regular (design) wave



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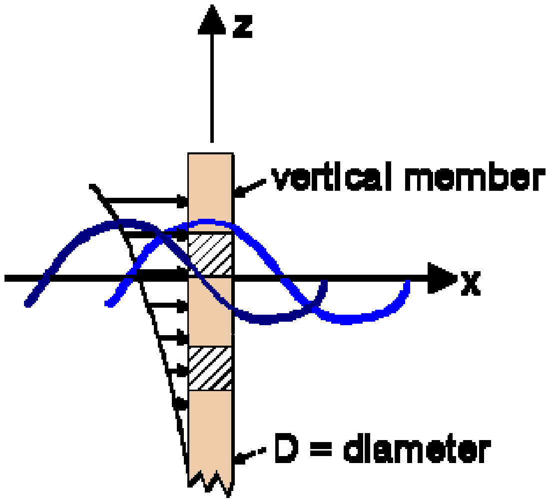
Wave loading on slender members

Morison formula: $q = q_D + q_I$ where the drag force: $q_D = ½ \; C_D \, \rho \, D \, v_x \, |v_x|$



ρ - density of water
C_D - drag coefficient

Wave force
$q = q_D + q_I$

Drag force
$q_D = ½ \; C_D \, \rho \, D \, v_x \, |v_x|$

Drag force pr. unit length
$v_x = \sin(\omega t)$
$q_D \; \alpha \; v_x \, |v_x| = \sin(\omega t)|\sin(\omega t)|$
$= 0.85 \sin(\omega t) - 0.17 \sin(3 \omega t) - 0.02 \sin(5 \omega t)$
$+ \ldots\ldots$

Slamming loads

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

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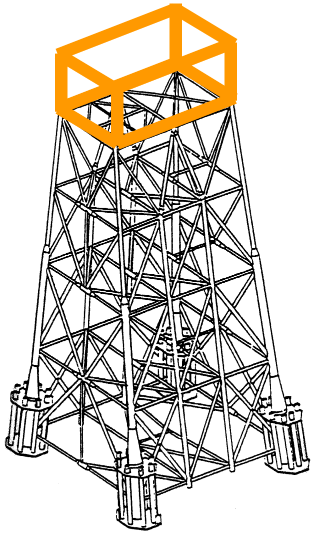
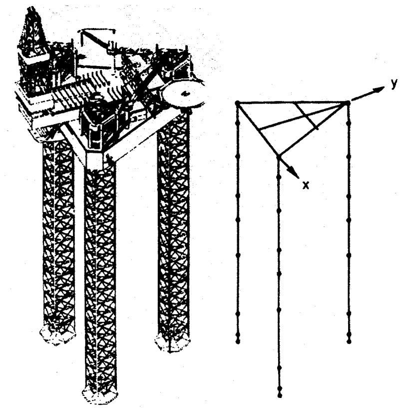
Dynamic analysis

- Stochastic wave loads
- Natural periods (2.5 s, 3.5 s)

  - excitation by 2ω, 3 ω,…where
    ω is the wave frequency

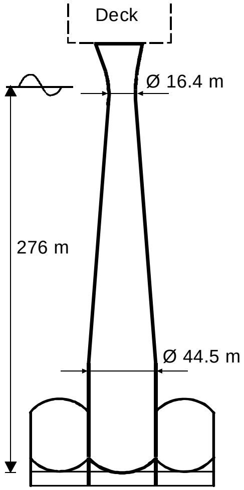


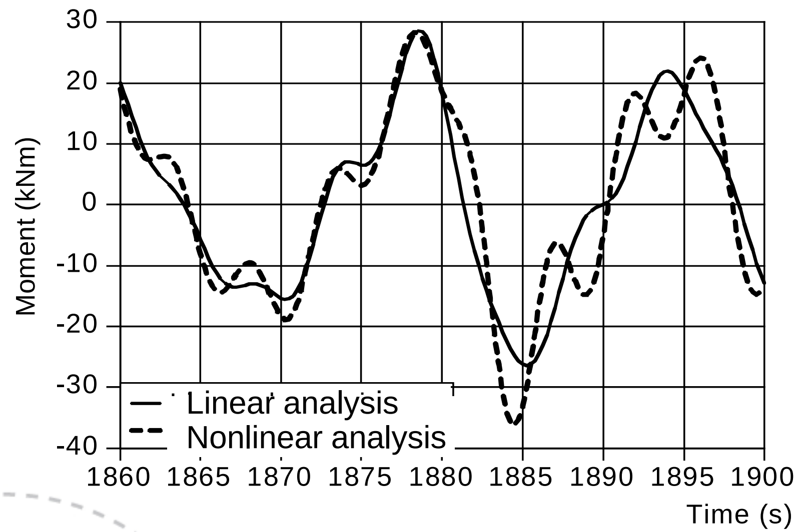


Response analysis methods of different refinement

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

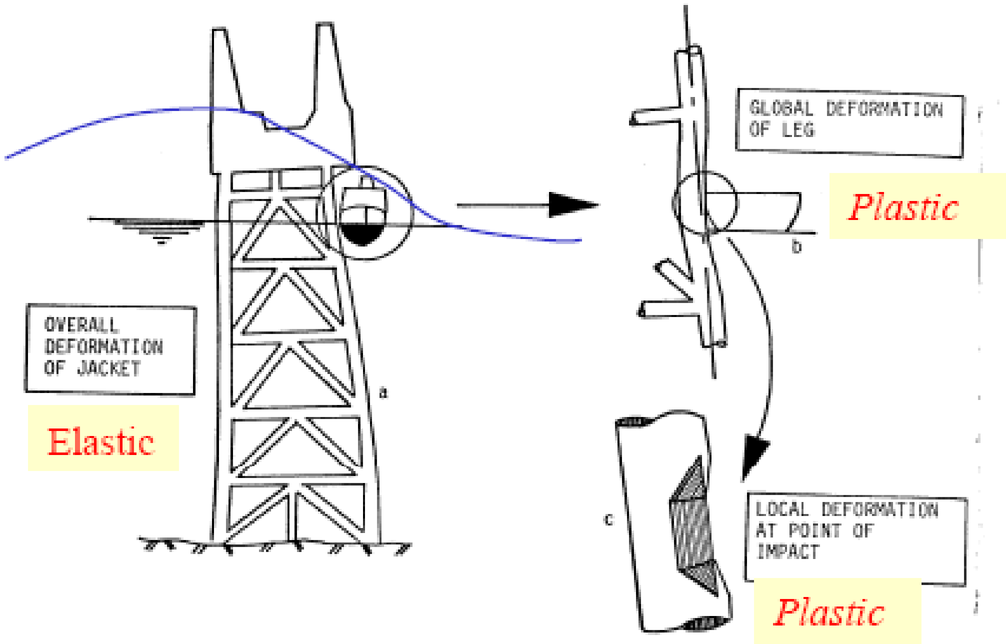
- The new phenomenon was discovered (while the Draugen platform was being built) and remedied

- What about monopiles ?

Design against accidental actions according to e.g. NORSOK

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

Ship collisions,



Step1

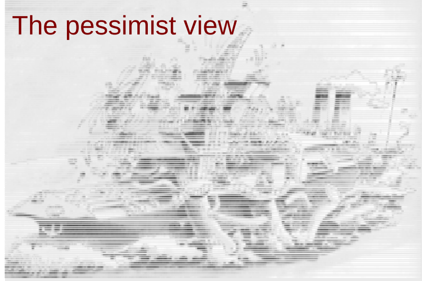
Damage due to accidental actions and abnormal env. loads, return period **10000 years** - nonlinear structural behavior accpeted

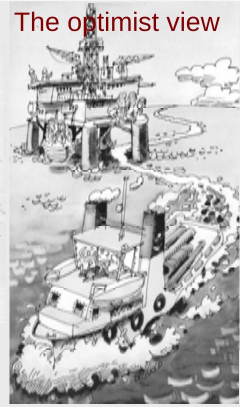
Step 2

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 prob. (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

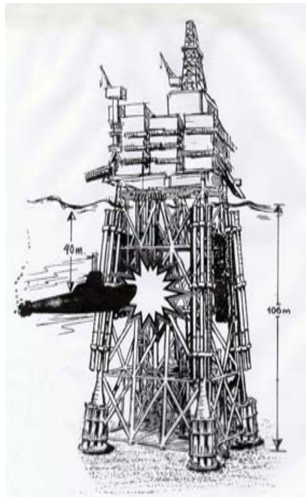




Risk assessment is required

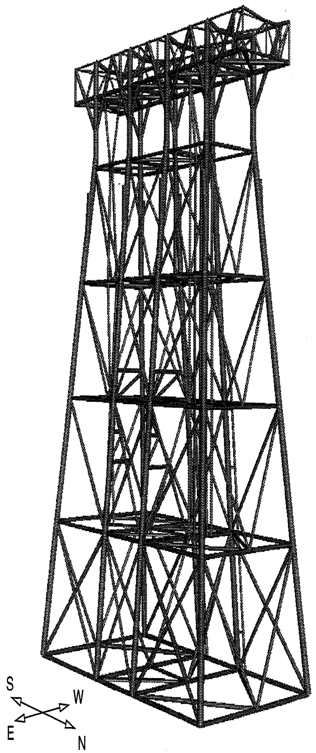
- **Collision at Ekofisk field in the North Sea in June 2009 – with a kinetic energy of 60 MJ**

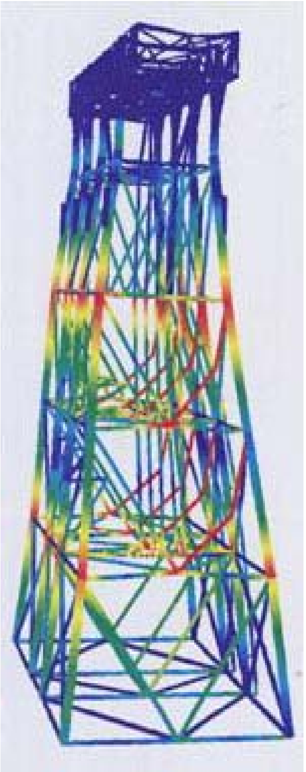
Submarine U27 hitting the Oseberg B

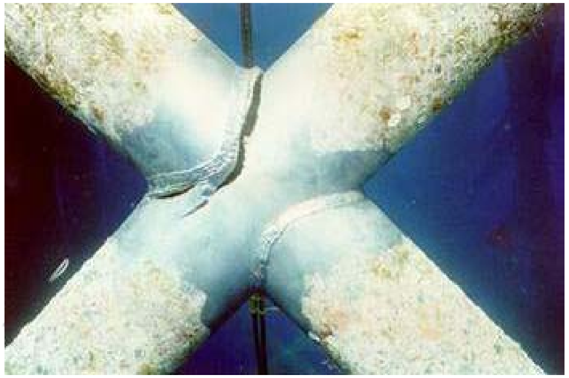


28

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…)

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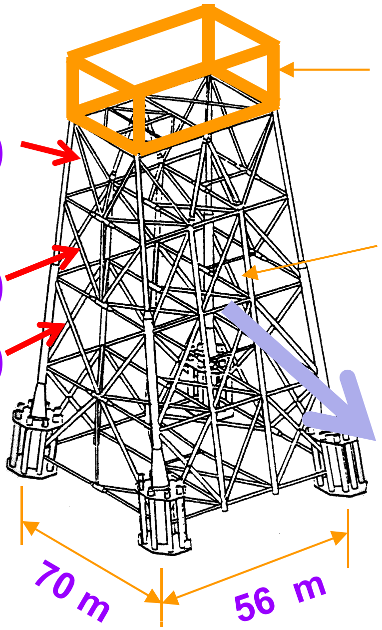
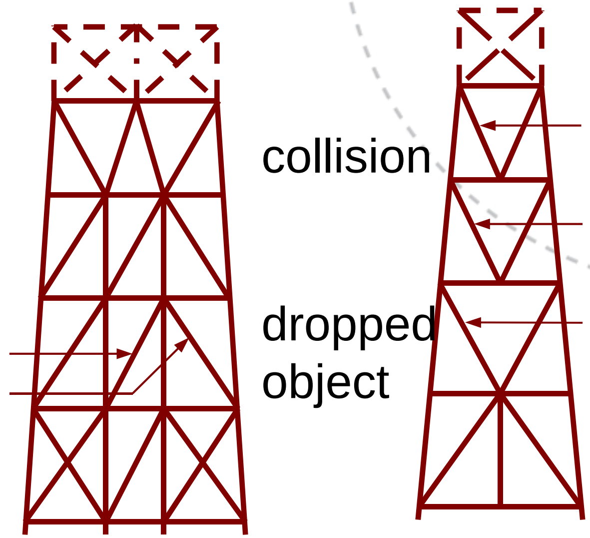
Residual global ultimate strength after damage
(due to collison, dropped objects, "fatigue failure")





Broad-side and end view.
Deck model indicated by dashed line

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

Ultimate strength	Broad side loading		
	Brace 261	Brace 363	Brace 463
Ultimate strength F_{ult} / F_{H100}	2.73	2.73	2.73
Residual strength $F_{ult(d)} / F_{ult}$	1.0	0.76	1.0

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)

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