In this presentation, I will give brief comments on three different projects: the Ekofisk structural reassessment, the South Stream Pipelines, and the Ichthys offshore gas field development. I have spent several years on each of the first two projects, and expect to do so also for Ichthys.

These projects are all, in different ways, record-breaking mega projects.

I have chosen to present these projects because for each of them the application of structural reliability methods has been a key feature in the developing the technical solutions.
The title of my dissertation is Time Variant Reliability under Fatigue Degradation.

It considers welded steel structures, which comprise the vast majority of marine vessels and offshore structures.

Welded structures contain defects, which may lead to crack initiation and fatigue crack growth. The rigorous approach is a first passage formulation – the capacity decreases with time due to fatigue crack growth, and failure occurs when the stochastic load first exceeds the resistance.

The time variant model is difficult to code, often has numerical stability challenges, and is computationally intensive.

I developed a Time Invariant approximation that considers random variables rather than stochastic processes, easier to code, and much quicker to calculate. This approximation is always conservative, but it is a close upper bound – typically just a few percent larger probability of failure than the TV solution.

It is also demonstrated that the assumptions in the TI model are valid for almost all practical applications to marine structures.
Ekofisk Structural Reassessment

- Oil discovered in 1969, first production platforms installed early 1970’s
- Approx. 3.6 billion BOE produced (to 2011)
- 3 m subsidence observed in 1984 ⇐ increased risk of wave-in-deck
- Six platform decks raised 6 m in 1987
- By 2000, subsidence increased to 8 m
Ekofisk Structural Reassessment

Why reassess?

Main triggers are

– Subsidence
– Diffraction (for 2/4 R & P)

Hence focus on extreme wave events

Fatigue & corrosion controlled by

– Inspection, analysis & mitigation / strengthening

– A typical strengthening measure was filling braces, legs, and/or tubular joints with high strength grout, containing 2% volume of steel fibers (12.5mm long x 0.4 mm dia.) to provide increased ductility.
The Reserve Strength Ratio (RSR) is defined as the ratio of the platform’s pushover capacity divided by the 100 year load effect.


However, RSR is not a consistent measure of safety. The graph shows the relative probability of failure versus airgap for an example platform.

Airgap is defined as the height of the platform deck above the 100 year wave crest. The probability of failure for this example platform increases by an order of magnitude as the airgap decreases from 4m to 0m.
Ekofisk Structural Reassessment

A probabilistic approach was selected.
The target reliabilities were in accordance with Moan (1995), which showed that the implied safety levels as
– implicit in design codes
– cost-benefit analysis
– historical experience
are about
  4 x 10E-4 per annum for high consequence
  1 x 10E-3 per annum for economic consequences only

The operator had extreme wave warning procedures in effect, such that vulnerable platforms were shut-in and unmanned during storms. Hence the 10E-3 target applied in most cases.


South Stream Transport B.V. is planning to build a new pipeline system across the Black Sea to supply natural gas to southern Europe.

http://www.south-stream.info/en/

The offshore pipeline system will be part of the South Stream Pipeline and will extend from the Russian coast at Anapa to a landfall on the Bulgarian coastline near Varna, as shown in the sketch of the pipeline route. The factors listed below require the use of state of the art technology in order to achieve a successful outcome for the project:

- water depths that approach 2200m, in combination with a large pipeline diameter
- the Black Sea is an environment containing high levels of H2S on the continental slope and abyssal plain
- seabed conditions include steep slopes and geohazard risks

Four parallel 32” diameter pipelines, each of approximately 930 km., are planned.

The South Stream Pipeline Project has comprised the following phases:

- Feasibility Study: 2009
- Detailed Design: 2013 
- Installation: Q4 2014 –
South Stream Feasibility Study Comments - Technical Challenges

The major technical challenge is DEEP WATER, BIG PIPE!

- 32” pipeline in 2250 m water depth is a large step outside of industry experience:
  - South Stream is twice as deep as the deepest 32” pipe previously installed
- Wall thickness, even with optimistic design assumptions, is at the limit of pipe mill capability
- All existing deepwater installation vessels require modifications & upgrade to be able to install the 32” pipeline
General Information about the South Stream Project

- **63 bcm**
  - Annual capacity in billion cubic meters

- **2,250 m**
  - Maximum depth

- **4**
  - Number of pipelines

- **12 m**
  - Length of each pipe segment

- **920 km**
  - Length of Each Pipeline

- **32 inch**
  - Pipeline diameter of 813 mm

Total of 300,000 pipe joints, each 12 m long weighing almost 1 tonne per meter
The South Stream Pipelines

- Four Pipelines
- Each approximately 930km
- 812.8mm diameter, 39mm wall thickness
- SAWL 450 SFDU (C)
- DNV-OS-F101 (2010)
- Water depth 2200m

South Stream Pipelines

- Dimensioning load case is pipeline installation

- Critical location is the sag bend – subject to largest external pressure + bending moment
The Feasibility Study identified the need for qualification of new technology covering several aspects.

These are addressed by the Material Testing Program for:
- Weldability testing
- H2S testing
- Collapse testing

Of these, the collapse testing is the most critical, and by far the most comprehensive program.

South Stream Transport B.V. procured pipe joints (each 12.2 m length) from each of five pipe mills. Four mills provided pipes 10 pipes joints each of two strengths: SMYS of 450 and 485 Mpa (approximately equivalent to X65 and X70 material). One pipe mill provided 10 pipe joints of only SMYS 450.
### Collapse test program

- Comprehensive collapse test
- 108 large scale tests + 54 ring tests
- 36 tests combined external pressure and bending
- both with and without heat treatment

<table>
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<th>MATERIAL SUPPLY</th>
<th>COLLAPSE TEST PROGRAM</th>
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<tbody>
<tr>
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Design and Material Challenges – Collapse

- As a result of the 2250m water depth, the main design challenge for the South Stream Project is the pipe material’s collapse properties.

- The key issues affecting the collapse properties are:
  - Pipe ovality (4 mm at pipe ends and body)
  - The material’s compressive properties.

- The hoop compressive properties will suffer as a result of the pipe forming and expansion processes.

- In order to recover the drop in compressive properties, it is desirable that the material has the ability to strain age during the pipe coating operation.

Figure 3.1: Compressive Hoop Strength Reduction due to UOE Forming
Collapse test program

Tests performed by CFER, Edmonton

Deepwater Experimental Chamber
- 8,000 psi MAOP
- 1.2 m clear inner diameter
- 10.3 inside length

Specimen after combined bending and external pressure test
South Stream - Probabilistic Wall Thickness Design Procedure

1. Material Testing Data
2. SUPERB Project
3. Project Go-bys (Blue Stream, Mardi Gras & Oman India)
4. Mills Statistical Data

- Define Collapse Limit States
  - DNV CN No. 39.6
  - DNV-OS-F101

- Collect Historical Data
- Define Variable PDFs

- FEA Verification
- INTECSEA Limit Surface

- Determine Pipeline Reliability
- Parametric Sensitivity
- Confirm Safety Class
South Stream Pipeline – Probabilistic Wall Thickness Design

- Design code, DNV-OS-F101 Submarine Pipelines states
  "As an alternative to the LRFD format specified and used in this standard, a
  recognised structural reliability analysis based design method may be applied"

- Materials test program provided statistical data for:
  - Material strength
  - Geometry (wall thickness, ovality)
  - Model uncertainty

- Structural reliability analysis confirmed
  - Min. wall thickness = 39 mm
  - Max. ovality = 0.5%
  - Min. compressive strength $R_{t0.23} = 369$ ; $R_{t0.5} = 450$ MPa

Fulfilled target safety level
**Ichthys Project - overview**

Key offshore facilities will include:
- Semi-submersible Central Processing Facility
- Floating Production Storage and Offloading
- Umbilicals, risers and flowlines
- 885 km export pipeline to Darwin
Ichthys Gas Export Pipeline –
Probabilistic Lateral Buckling Design

- Pipelines expand when subjected to internal pressure
  & elevated temperature
- Expansion leads to lateral buckling
- The integrity of pipeline with a potential for global buckling can be assured by two design concepts:
  - restraining the pipeline, maintaining the large compressive forces
  - releasing the expansion forces, causing it to buckle globally imposing curvatures on the pipeline
- Lateral buckling is acceptable if it is controlled, and strains remain within acceptance limits
- Snakelay identified as most cost effective & suitable lateral buckling control method
Ichthys Gas Export Pipeline –
Probabilistic Lateral Buckling Design

- Snakelay selected for lateral buckling control method
- Seven initiators
- Typical spacing between initiators: 2 to 3 km
- Buckle initiator radius: 2.75 & 3 km

Figure 4.1 Typical Snakelay Arrangement
Structural Reliability Analysis of Buckling

- Uncertainty modelling of
  - Critical buckling force, effective axial force & pipe-soil friction factors
- Apply SAFEBUCK methodology

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<th>Buckle Prob</th>
<th>Feed-in (m)</th>
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Professional Societies

- American Society of Mechanical Engineers (ASME)
- American Society of Civil Engineers (ASCE)

Technical & Professional Committee Activities

- ASCE Fatigue and Fracture Reliability Committee
- ASCE Committee on Reliability of Offshore Structures
  (Chair 1996-1998; member 1995-2002,)
- ISO TC67 SC2 WG12 Reliability-based methods in pipeline design (ISO 16708)
- ASME Pipelines Division (Chair 2005-2006; Executive Committee 2000 to present)
- ASME International Pipeline Conference (IPC)
  Organizing Committee and Offshore Track Chair (2002 to present)
- Elected Fellow ASME 2012