DNV GL Technology Week: Latest Developments in Fatigue Analysis of Wellhead Systems

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01 November 2016
Agenda

- Introduction and Background
- Structural Well Integrity JIP
- DNVGL-RP-0142 – “Wellhead Fatigue Analysis”
- Case Studies
  - Rigid locked wellhead
  - Break 15 min.
  - Non-rigid locked wellhead
- Q&A
Well construction sequence
What is a wellhead?

- Main components
  - High pressure housing (HPH)
  - Low pressure housing (LPH)
- Functions
  - Pressure containment
  - Interface between BOP stack and well
  - Hang-off and seal-off casings
- Types
  - Unlocked (older designs)
  - Rigid-locked (newer)

http://petrowiki.org/Subsea_wellhead_systems
Examples of wellhead fatigue failures reported in literature

- 1983, Hopper, C.T., DOT, “Wellhead failure due to VIV”, West of Shetland
- 1989, Singgetham et. al “The industry has experienced multiple field failures in the last 10 years, primarily at the bottom of the high pressure housing (wellhead housing)…”
- 1991, Milberger et al., “Two wellhead failures in the field”
- 1990, King et al., “Fatigue failure of subsea development well in the UK Beryl field.”
- 2005, norsk Hydro Oil and Gas experienced abnormal BOP movements on a North sea subsea wellhead due to a fatigue failure of conductor weld.
Hotspots reported to have failed in service

Typical hotspots

Critical points ("hotspots"):
- Welds
- Connectors
- Notches/transitions in base material
- Welds near cement top
Fatigue damage accumulates during all connected operations

- Dynamic loads transferred to wellhead through connected riser due to:
  - Low frequency vessel motion
  - Wave frequency vessel motion
  - VIM
  - Direct wave loading on riser
  - VIV of riser
Why is wellhead fatigue an issue?

- Can have high consequences
  - crucial **structural element**
  - common **well barrier** during drilling
- No access for inspection
- Rigs and Blow Out Preventers (BOPs)
  - increasing in size, without corresponding design changes
  - Extended drilling time ~ 60 → 300 days
- Challenging to prove fatigue margin
  - Uncertainties in inputs, analysis methods etc.
Important factors, uncertainties

- Lack of established analysis methodology
- Many disciplines, parameters:
  - Hydrodynamics, rig motion
  - Riser analysis (water depth, BOP size)
  - Soil and template support
  - Interaction between pipes, friction contact
  - Material
- Lack of design, fabrication records and load history for existing wells
  → leads to conservative assumptions
- Not accessible for inspection
- Computationally demanding
  → Global and local analysis
- Load sharing between pipes
  → Conservative vs. non-conservative
  → difficult to generalise
Structural Well Integrity JIP

- JIP started in 2010
  - Phase 1: “Guideline for Structural Well Integrity”
  - Phase 2: DNVGL Recommended Practice “Wellhead Fatigue Analysis”, DNVGL-RP-0142

- Activities on validation of
  - Methodology
  - Input parameters
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Objective

- "Industry has identified that analyses to assess structural integrity of wellhead/casing systems need to use an aligned methodology to further improve the accuracy, consistency, and repeatability of results. This document provides a consolidated framework for assessing fatigue of wellhead/casing systems due to wave-induced loading. Other sources of fatigue damage which may be important are not addressed."

- "This RP does not prescribe nor mandate any specific analysis methodology or set of assumptions for wellhead fatigue analysis, but rather discusses the following aspects:
  - required inputs
  - overview of methodologies
  - pertinent modelling details to consider."
Scope and Applicability

“The scope of this RP addresses the full lifecycle of any offshore well system. The assessment of wellhead fatigue damage under this RP is applicable during all stages or types of operations when riser systems interface to the well, including drilling, completion, production, workover, and P&A. Fatigue accumulation continues until the riser is ultimately disconnected from the wellhead.”
Wellhead Fatigue Analysis Methodology
Coupled and Decoupled Approaches

(a) Coupled
- Global Analysis
  - Rig/ROD
  - Riser System
  - Wellhead System
  - Casing & Soil
- Local Analysis
  - Detailed FEA Models
- Analysis Outputs

(b) Decoupled
- Global Analysis
  - Rig/ROD
  - Riser System
  - Simplified/Equivalent Stiffness
- Local Analysis
  - Wellhead System
  - Casing & Soil
- Analysis Outputs

Legend:
- Inputs to Analysis
- Analysis Procedure in RP
- Intermediate Analysis Results
- Final Analysis Outputs

1st Decoupling
2nd Decoupling
Decoupled Analyses Flowcharts

Method 2

Method 3
Rigid locked wellhead fatigue analysis case study
Case Study for a Rigid-Locked Wellhead System

- Case study undertaken to perform wellhead fatigue analysis for a rigid-locked wellhead system within the framework provided by DNVGL-RP-0142

- Objectives:
  - Develop three different coupled riser analysis global FE models with varying degrees of complexity in the modeling details of the wellhead and casing system
  - Perform numerical simulations with the three models to obtain global bending moment loads at different sections of the wellhead and casing system and derive stress histories for fatigue calculations either directly or using the predicted bending moment loads
  - Benchmark the performance of the different global models and the different methods of selecting the bending moment loads to drive the fatigue analysis

- Goal:
  - Provide insight into the level of modeling detail required in global and local models and how to perform fatigue analysis for rigid-locked wellhead systems
Case Study Global Model Description

- Three FEA models created to model the drill riser system as following:
  1. Coupled 3D model
  2. Coupled pipe-in-pipe beam model
  3. Coupled composite beam model
- Water depth: 140m
- Wellhead datum elevation: EL.(-)136.5m
- Concrete top elevation: EL.(-)146.5m
- Two flexible joints:  
  - Lower flexible joint @ EL.(-)122.716m  
  - Upper flexible joint @ EL.(+)27.5m  
- Four tensioners @ EL.(+)5.05m with tension 563.5kN
- No internal pressure is applied
- All global analysis, static or dynamic, includes geometric nonlinearity

<table>
<thead>
<tr>
<th>Component</th>
<th>Component Length</th>
<th>Elevation top of component relative to mean water level</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH datum stick up</td>
<td>3.500</td>
<td>-136.500</td>
</tr>
<tr>
<td>Spacer Spool</td>
<td>0.648</td>
<td>-135.852</td>
</tr>
<tr>
<td>BOP below COG</td>
<td>3.551</td>
<td>-132.301</td>
</tr>
<tr>
<td>BOP above COG</td>
<td>3.113</td>
<td>-129.188</td>
</tr>
<tr>
<td>LMRP below LFJ rotation center</td>
<td>3.987</td>
<td>-125.201</td>
</tr>
<tr>
<td>LMRP above LFJ rotation center</td>
<td>2.485</td>
<td>-122.716</td>
</tr>
<tr>
<td>Riser pup joint 10'</td>
<td>3.048</td>
<td>-119.668</td>
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<tr>
<td>75' riser joint buoyant rating 2500'</td>
<td>22.86</td>
<td>-96.808</td>
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<tr>
<td>75' riser joint buoyant rating 2500'</td>
<td>22.86</td>
<td>-73.948</td>
</tr>
<tr>
<td>75' riser joint slick</td>
<td>22.86</td>
<td>-51.088</td>
</tr>
<tr>
<td>75' riser joint slick</td>
<td>22.86</td>
<td>-28.228</td>
</tr>
<tr>
<td>Riser pup joint 75'</td>
<td>22.86</td>
<td>-5.368</td>
</tr>
<tr>
<td>SJ - Outer barrel below gooseneck</td>
<td>6.556</td>
<td>1.188</td>
</tr>
<tr>
<td>SJ - Outer barrel btw Tens ring &amp; Gooseneck</td>
<td>2.916</td>
<td>4.104</td>
</tr>
<tr>
<td>SJ - Outer barrel &amp; tension ring</td>
<td>0.946</td>
<td>5.050</td>
</tr>
<tr>
<td>SJ - above tension ring</td>
<td>12.695</td>
<td>17.745</td>
</tr>
<tr>
<td>SJ - Inner barrel</td>
<td>7.833</td>
<td>25.578</td>
</tr>
<tr>
<td>UFJ below rotation center</td>
<td>1.922</td>
<td>27.500</td>
</tr>
<tr>
<td>UFJ above rotation center &amp; Diverter (to overflow)</td>
<td>4.420</td>
<td>31.920</td>
</tr>
</tbody>
</table>
Coupled 3D Model - Global Model Geometry

- Water Surf. EL(+)0m
- Seabed EL(-)140m
- EL(+)31.92m
- EL(-)138.5m
- EL(-)145.59m
- EL(-)144.5m
- EL(-)146.4m
- EL(-)146.5m
- Cement
- EL(-)147.7m
Coupled 3D Model – Global Model Interactions

- Tensioner
- MPC Slider
- Flex. Joint
- Soil Springs
- MPC Slider
- Riser to Wellhead constraint
- Tie at Shoulder
- Tie at FlatEnd
- Shell to solid constraint
- Frictionless contact
- Above EL(-)136.5m – same as 3D model
- Between cement and high pressure casing – MPC slider
- Between cement and low pressure casing – bind together through shared nodes
Coupled Composite Beam Model – Global Model

- Above EL(-)136.5m – same as 3D model
- Soil – Nonlinear springs
Model Validation

- Static mean position - effective tension distribution
- Static vessel offset – bending moment at wellhead
- Modal analysis
- Dynamic Analysis - 0 m vessel offset
  - Regular wave: T = 2.7 seconds
  - Regular wave: T = 4.7 seconds
  - Regular wave: T = 9.1 seconds
  - Irregular wave
    - Top motions from a MODU operated drilling riser system in relatively shallow water
    - Applied in one direction
    - 1300 sec duration with 50 sec ramp
    - Used in fatigue analysis
Static mean (no offset) position – Effective tension

Effective Tension Along Riser

-3000 -2000 -1000 0 1000 2000 3000

60 40 20 0 -20 -40 -60 -80 -100 -120 -140 -160

Distance to Riser Top (m) Effective Tension (kN)

-3D Model  Pipe-in-Pipe Beam Model  Composite Beam Model
Static vessel offset – Wellhead bending moment

Vessel Offset VS Moment @ WHD

-1,800
-1,600
-1,400
-1,200
-1,000
-800
-600
-400
-200
0

Moment at Wellhead (kN-m)

0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0

Vessel Displacement (m)

3D Model
Pipe-in-Pipe Beam Model
Composite Beam Model
Static vessel offset – Weld section bending moment

Moment @ 2m below WHD

Moment at 2m below WHD (kN-m)

Vessel Displacement (m)

-2,000
-1,500
-1,000
-500
0

Moment @ 9.9m below WHD

Moment at 9.9m From WHD (kN-m)

Vessel Displacement (m)

-2,000
-1,500
-1,000
-500
0

3D Model
Pipe-in-Pipe Beam Model
Composite Beam Model
### Natural Mode Frequencies – Coupled Global Model

<table>
<thead>
<tr>
<th>Mode #</th>
<th>3D Model</th>
<th>Pipe-in-pipe Beam Model</th>
<th>Composite Beam Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.75</td>
<td>8.82</td>
<td>8.73</td>
</tr>
<tr>
<td>2</td>
<td>4.46</td>
<td>4.56</td>
<td>4.44</td>
</tr>
<tr>
<td>3</td>
<td>3.04</td>
<td>3.23</td>
<td>3.00</td>
</tr>
<tr>
<td>4</td>
<td>2.26</td>
<td>2.30</td>
<td>2.25</td>
</tr>
<tr>
<td>5</td>
<td>1.51</td>
<td>1.52</td>
<td>1.51</td>
</tr>
</tbody>
</table>

**Diagram: **
- **Period (s)**
- **Mode Number**
- 3D Model
- PIP Beam Model
- Composite Beam Model
Bending Moment Comparison @ WHD

- Period #1 - 2.7s
- Period #2 - 4.7s
- Period #3 - 9.1s
- Irregular wave STDEV
- Irregular wave MaxValue

<table>
<thead>
<tr>
<th></th>
<th>3D Model</th>
<th>PIP Model</th>
<th>Composite Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period #1</td>
<td>1.00</td>
<td>1.07</td>
<td>0.99</td>
</tr>
<tr>
<td>Period #2</td>
<td>1.00</td>
<td>1.05</td>
<td>1.08</td>
</tr>
<tr>
<td>Period #3</td>
<td>1.00</td>
<td>1.00</td>
<td>1.01</td>
</tr>
<tr>
<td>STDEV</td>
<td>1.00</td>
<td>1.00</td>
<td>1.01</td>
</tr>
<tr>
<td>MaxValue</td>
<td>1.00</td>
<td>1.00</td>
<td>1.01</td>
</tr>
</tbody>
</table>
Fatigue Damage Locations of Interest in Case Study – Pipe Welds

WHD – 2m

WHD – 9.9m
Coupled 3D Model

- Damage from stresses computed by 3d coupled analysis is the basis of comparison and is used as the denominator in relative damage calculations
  - At time t, derive components of hot spot stresses (HSS) at locations of interest to develop time traces of these component HSS
  - If global 3D solid model is of insufficient refinement to produce accurate HSS, employ SCFs from local analysis
    - Only considering pipe welds ground smooth: No SCF, stress state directly computed from global 3D solid model at weld determines HSS
  - From the component HSS derive a $\sigma_{\text{prin}}$ time trace and cycle count
    - At any time t, compute maximum and minimum $\sigma_{\text{prin}}$. Choose the stress with the greatest absolute value. Use ASTM rainflow cycle counting algorithm.
  - Damage comparisons in case study are relative; use one-slope S-N curve, $m=3$
- In this study, only considering pipe welds: no significant multi-axiality, $\sigma_{\text{prin}} \approx$ longitudinal stress
Coupled Beam Models (PIP and Composite)

- Driving moment versus component stress relationships derived from local analysis
- At time t, superimpose component stresses due to $M_{xx}$ and $M_{yy}$ at station points around circumference with those due to axial preload to develop time traces of component stresses
  - In this study, unidirectional wave: only $M_{yy}$ active
  - From the component stresses derive a $\sigma_{\text{prin}}$ time trace and cycle count
- Driving Moments
  - Total moment at wellhead datum
  - Total moment at the section of interest
  - Moment in individual pipes at the section of interest
    - For composite beam analysis, individual moments determined by application of $M_{\text{hp}} = \beta M_{\text{tot}}$; $M_{\text{lp}} = (1-\beta)M_{\text{tot}}$
    - Fatigue damage comparison in case study also includes damage driven by moments and moment-to-stress relationships for 3D coupled model
      - Comparison is pure methodology, not modeling
Local Analysis

- Model below the WHD, includes axial preload and applied load steps, NL geom
- Moment-to-stress relationship
  - Local model must be of sufficient refinement to compute hot spot component stresses at welds
  - In this study, only considering pipe welds:
    - Local model is same as global 3D solid model
    - Stress taken directly at weld is the hot spot stress
  - Relationships computed at station points around circumference
  - In this study, unidirectional wave: consider 0° and 180° positions
    - Consider stress at outer diameter: weld toe fatigue
  - Local analysis in this case study performed by applying
    - Static offsets to the top of the global model (moment-to-shear ratio ~ 18.3m)
    - Moment and shear at wellhead datum in the ratio recommended by DNV GL Method statement (13.784m; distance from LFJ to WHD)
    - Moment and shear at wellhead datum in the ratio determined by linear regression of moments and shears computed by 3D coupled dynamic analysis
Regression to Determine Moment-to-Shear Ratio at WHD

Value used in local analysis is 15.0936
Moment-to-Direct ($\sigma_z$) Stress Curves from Local Analysis using Regression Ratio

- The moment-to-stress relationships based on the individual driving moment are linear with a slope of $1/S$
- The moment-to-stress relationships based on the total moment are essentially linear (functions of $\beta$, which does not vary drastically in the local analysis)
- The moment-to-stress relationships based on the WHD moment are non-linear at the -9.9m datum
Determination of $\beta$ for Composite Beam Analysis

- Only the local analysis that produces moment-to-stress relationships and the time trace of total bending moment are available for consideration
  - From the local analysis produce plots of total moment versus $\beta$
  - The value of $\beta$ used in fatigue analysis is determined either by:
    - Interpolate appropriate value of $\beta$ and thus the individual moments at any time $t$
    - Analyze the time traces of total moments to find a representative moment with which to enter the moment-$\beta$ relationship to find a single value of $\beta$ to use throughout the fatigue damage calculation
      - Use the significant peak amplitude, defined as the average of the top 1/3 absolute value maximum and minimum peaks in the total moment time trace, as the representative moment. (Note: mean total moment is zero).
      - Use the ratio of the section moment in the HP pipe to the sum of the section moments from both pipes
      - Use the ratio of the moment of inertia in the HP pipe to the sum of the moments of inertia from both pipes
Determination of Single Value of $\beta$ from Moment-to-$\beta$ Relationship

Values used in fatigue analysis:
Datum-2m: 0.37305
Datum-9.9m: 0.4
Relative Fatigue Damage from Composite Beam Analysis for Various Methods for Computing $\beta$

- Use of interpolation or significant peak amplitude produces accurate fatigue damage predictions
- Use of section moment ratio not as good but not bad
- Use of moment of inertia ratio not good

In subsequent damage comparisons, plot damage from use of significant peak $\beta$
Relative Fatigue Damage given the Individual Driving Moment

- Results are independent of M-to-V ratio applied in local analysis
- 3D model results are spot on, verifying driving moment methodology
- Results from both beam models are accurate
  - PIP results better, but least accurate composite beam result within 5% on stress
Relative Fatigue Damage given the Total Driving Moment

- Results again independent of M-to-V ratio applied in local analysis
- 3D model results again spot on, and results from both beam models again accurate
  - PIP results again better, and least accurate composite beam result again within 5% on stress
- Total as accurate as individual moment
Relative Fatigue Damage given the WHD Driving Moment

- Results dependent on local M-to-V ratio
  - Top offset results are inaccurate and non-conservative at -9.9m, slightly non-conservative at -2m
  - Method results equally inaccurate but conservative at -9.9m, slightly conservative at -2m
  - Regression results similar to individual, total moment results
Conclusions – Fatigue Damage at Welds

- Use of the total bending moment at the section of interest to drive the fatigue analysis is independent of the M-to-V ratio applied in the local analysis and yields an accurate damage estimate regardless of global analysis method.

- Use of the individual bending moment at the section of interest to drive the fatigue analysis is independent of the M-to-V ratio applied in the local analysis –
  - If the global analysis explicitly models the individual pipes, the damage estimate is accurate regardless of the global analysis method
  - If composite beam analysis is used, employing a value of $\beta$ based on interpolation of the moment-to-$\beta$ relationship (general) or one based on the significant peak amplitude (not?) produces accurate damage estimates

- Use of the bending moment at the WHD to drive the fatigue analysis is dependent on the M-to-V ratio applied in the local analysis. For all global analysis methods,
  - Applying a top offset (18.3m) yields inaccurate, non-conservative damage estimates at the -9.9m datum and is slightly non-conservative at -2m.
  - Applying the method statement ratio (13.784m) yields accurate, conservative damage estimates at the -9.9m datum and is slightly conservative at -2m.
Conclusions – Fatigue Damage at Welds

- Applying a ratio determined by linear regression of the 3D coupled analysis results produces an accurate damage estimate.
- Note that if an uncoupled global analysis approach were used that accurately computed the WHD moment and shear, use of linear regression to determine the M-to-V ratio used in the local analysis would be equally accurate.

- The damage computed from the composite beam model is greater than that computed from the other global models regardless of driving bending moment definition, local analysis method or fatigue location.
- This is likely caused by increased bending stiffness of the composite beam model between the housing connection and the top of cement because the high and low pressure casings are implicitly required to maintain the same bending curvature.

- For conservatism, efficiency and accuracy, for coupled analysis would recommend
  - Composite beam global model
  - Total driving moment at sections of interest for moment-to-stress curves
  - Local M-to-V ratio determined by regression of global analysis results
Fatigue Damage Locations of Interest in Case Study – Base Metal

Sub-model used in local analysis to determine:
- Moment-to-stress relationships
- SCFs to transform nominal stresses from 3D coupled analysis to peak stresses
Coupled 3D Model

- Damage from stresses computed by 3d coupled analysis is the basis of comparison and is used as the denominator in relative damage calculations
  - At time \( t \), derive components of nominal stresses along notches of interest to develop time traces of these component HSS
  - Since global 3D solid model is of insufficient refinement to produce accurate peak stresses, apply SCF determined from local analysis for each component stress to produce time traces of component peak stress
  - Procedure to compute SCFs introduces additional uncertainty
  - From the component peak stresses derive a \( \sigma_{\text{prin}} \) time trace and cycle count
    - In this study, \( \sigma_{\text{prin}} \) along the notch \( \equiv \) stress along radius of notch
    - In lieu of principal stress, ASME approach: \( \frac{1}{\sqrt{2}} \sqrt{(\Delta \sigma_x - \Delta \sigma_y)^2 + \cdots + 6\Delta \tau_{xy}^2 + \cdots} \)
  - Use high strength steel S-N curve in RP C203: one-slope, \( m=4.7 \), high mean tensile stress
  - No mean stress correction: not fundamental to comparison of analysis models and methods
Local Analysis

- Moment-to-stress relationship
  - Global 3D solid model is of insufficient refinement to compute peak component stresses at the notches
  - Use local submodel that lies below contact areas and contains notches
    - Submodel off of previous local analysis at every load step
  - Consider only M-to-V ratio at WHD recommended by method statement (reflects regression of composite beam global analysis results)
    - M-to-V ratio applied at WHD adversely affects welded results when using WHD driving moment at the -9.9m weld location
    - Notch datum at -1.6m; all applied ratios should be sufficiently accurate
  - Relationships computed at station points around circumference
    - In this study, unidirectional wave: consider peak stress location along notches at 0° and 180° positions

- Same local analysis used to determine
  - \( \beta \) for composite beam fatigue analysis driven by individual moments
  - SCFs for 3D coupled analysis
Moment-to-Direct Stress along Notch Radius Curves from Local Analysis

- The moment-to-stress relationships based on the individual driving moment are linear.
- Those based on the other driving moments are nearly linear.
Determination of Single Value of $\beta$ from Moment-to-$\beta$ Relationship

Values used in fatigue analysis: 0.4
Determination of SCFs from Moment-to-SCF Relationship

Values used in fatigue analysis:

- Bending HP $S_{11}$: 1.40
- Bending $S_{22}$: 2.20
- Bending LP $S_{11}$: 1.45
- Bending $S_{11}$: 2.45
- Axial HP $S_{11}$: 1.45
- Axial $S_{22}$: 1.70
- Axial LP $S_{11}$: 1.55
- Axial LP $S_{22}$: 3.0
- SCF for all other stresses = 1.0
Relative Fatigue Damage from Composite Beam Analysis for Various Methods for Computing $\beta$

- Use of interpolation or significant peak amplitude produces accurate fatigue damage predictions
- Use of section moment ratio not as good ($m=4.7$ accentuates differences)
- Use of moment of inertia ratio not good at all

In subsequent damage comparisons, plot damage from use of significant peak $\beta$
Relative Fatigue Damage

- More variability in the 3D model results, reflecting variability in SCFs and m=4.7
- Results using the total driving moment are most accurate
- Results using the WHD driving moment are consistently conservative
- Results from the composite beam model are consistently the most conservative
Demonstration of ASME Approach

- Use von Mises form of component stress ranges: \( \frac{1}{\sqrt{2}} \sqrt{(\Delta \sigma_x - \Delta \sigma_y)^2 + \cdots + 6\Delta \tau_{xy}^2 + \cdots} \)
  - Now recommended in RP C203 → **Not** the von Mises stress!!!!!!!
  - multi-axial weld alternative \( \sqrt{\Delta \sigma^2 + 0.81\Delta \tau^2} \) → use PDMR to cycle count \( \{\sigma, \tau\} \)

- Cannot currently cycle count full von Mises form; instead, assuming stress components are in phase
  - Cycle count driving moment → driving moment histogram
  - Use moment-to-stress curves to convert moment ranges to component stress ranges
  - Use von Mises form to compute fatigue stress parameter
    - As a check, also compute \( \sigma_{\text{prin}} \) stress range from component stress ranges; should give same damage as computed directly from stress time traces

- To demonstrate calculation of damage
  - Use composite beam model, total driving moment
  - Use damage computed directly from stress time traces as basis for comparison

- Use same high strength steel S-N curve: one-slope \( m=4.7 \), no mean correction
Stress Time Histories from 3D Coupled Analysis

![Graph showing stress time histories for HP NOTCH S11, HP NOTCH S22, LP NOTCH S11, and LP NOTCH S22.](image-url)
Relative Fatigue Damage using von Mises Form

- $\sigma_{\text{prin}}$ damage from moment histograms agrees closely with that from stress time traces, validating histogram method and indicating in-phase stress components.
- Von Mises form produces significantly different, and in this case less, damage.
  - The sign of $\sigma_{11}$ and $\sigma_{22}$ in-phase, reducing VM stress range and damage.
Non-rigid locked wellhead fatigue analysis case study
Case Study for a Non-rigid Locked Wellhead

- Three numerical models created:
  1. Fully coupled 3D FE riser and wellhead model
  2. Decoupled global riser model
  3. 3D FE local model of the wellhead system
- Water depth: 140m
- Wellhead datum elevation: EL.(-)136.5m
- Concrete top elevation: EL.(-)146.5m
- Two flexible joints:
  - Lower flexible joint @ EL.(-)122.716m
  - Upper flexible joint @ EL.(+)27.5m
- Four tensioners @ EL.(+)5.05m with tension 563.5kN
- Hotspot elevation: EL.(-)138.5m
Details of the fully coupled 3D FE model
**Decoupled Model**

- Motivation: Decoupled model is computationally more efficient.
- Soil and casing interaction embedded in lateral and rotational spring stiffness.
- Fatigue driving stress calculated using wellhead loads and load-to-stress curve.
Decoupling Methodology

- Decoupling spring properties calculated by applying static offsets or rotations at specific points along riser and measuring the response at the wellhead datum (force/displacement, moment/rotation).
  - Method 1: offset riser top
  - Method 2: offset lower flex joint
  - Method 3: offset/rotate wellhead datum
Decoupled Model Spring Stiffness

Translational Spring Stiffness

Rotational Spring Stiffness

Ungraded
Local Analysis: Hotspots and Load to Stress Curves

BM to SF ratio equal to distance from lower flex joint to wellhead datum.

Hotspot located at welds between HPH and Surface Casing and LPH and Conductor.
Model Validation

- Static vessel offset – bending moment at wellhead
- Modal analysis
- Dynamic analysis - 0 m vessel offset
  - Regular wave: $T = 2.7$ seconds
  - Regular wave: $T = 4.7$ seconds
  - Regular wave: $T = 9.1$ seconds
  - Irregular wave
Static vessel offset – Wellhead bending moment and shear force
Natural Mode Shapes and Frequencies
Regular Wave Analysis – Wellhead Bending Moments

BM normalized using Coupled Model results.
Regular Wave Analysis – Hotspot Stresses Coupled 3D Model

Conductor Weld

Surface Casing Weld
Irregular Wave Analysis: BM at Wellhead Datum

<table>
<thead>
<tr>
<th>Bending Moment (Nm)</th>
<th>Mean</th>
<th>% diff.</th>
<th>Min.</th>
<th>% diff.</th>
<th>Max.</th>
<th>% diff.</th>
<th>Std. Dev.</th>
<th>% diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupled</td>
<td>-1.420E+03</td>
<td>0.0%</td>
<td>-1.255E+06</td>
<td>0.0%</td>
<td>1.305E+06</td>
<td>0.0%</td>
<td>5.679E+05</td>
<td>0.0%</td>
</tr>
<tr>
<td>Decoupled (Method 1)</td>
<td>-1.457E+03</td>
<td>2.6%</td>
<td>-1.447E+06</td>
<td>11.7%</td>
<td>1.296E+06</td>
<td>-0.7%</td>
<td>5.677E+05</td>
<td>0.0%</td>
</tr>
<tr>
<td>Decoupled (Method 2)</td>
<td>-1.415E+03</td>
<td>-0.4%</td>
<td>-1.412E+06</td>
<td>9.0%</td>
<td>1.284E+06</td>
<td>-1.6%</td>
<td>5.626E+05</td>
<td>-0.9%</td>
</tr>
<tr>
<td>Decoupled (Method 3)</td>
<td>-1.190E+03</td>
<td>-16.2%</td>
<td>-1.320E+06</td>
<td>1.9%</td>
<td>1.267E+06</td>
<td>-2.9%</td>
<td>5.492E+05</td>
<td>-3.3%</td>
</tr>
</tbody>
</table>
Fatigue Damage Rate Calculation

- Coupled Model – use direct stress from hotspots
- Decoupled Models – compute wellhead BM and then load to stress curve
- Local quasi-static analysis – Tension, BM and SF from coupled model applied to local model; direct stress from hotspots
- Time domain simulations, rainflow cycle counting and SN curve approach
- All damage rates (DR) normalized using results of Coupled Model
Fatigue Damage Rates – Coupled, Quasi-static, Load to Stress
Fatigue Damage Rates – Coupled vs Decoupled Approaches

Ungraded
Fatigue Damage Rates - Irregular Wave Analysis

Irregular Wave Motion

Coupled (Direct Stress)  Local Quasi-Static (Direct Stress)  Coupled (BM to Stress)  Decoupled (Method 1)  Decoupled (Method 2)  Decoupled (Method 3)

Conductor Weld  Surface Casing Weld

1.00  1.00  0.96  0.97  0.85  0.91  1.00  0.96  0.97  0.96  0.76  0.95
Conclusions

- Fully coupled analysis computationally expensive compared to decoupled analysis
- Decoupled approach successful in predicting global wellhead loads
- Hotspot stress using decoupled approach (load-to-stress) under-predicted
  - Load-to-stress deviates at higher BM
  - Results sensitive to BM/SF ratio used for developing load-to-stress curve
- Satisfactory results from quasi-static analysis
- Global wellhead loads (BM & SF) along with local quasi-static analysis may provide optimal accuracy, efficiency and speed
- Results specific to the system studied
- More studies needed to generalize conclusions
ISOPE 2016 paper: Fatigue Analysis of Non-rigid Locked Wellhead

Rhodes, Greece, June 26–July 1, 2016
Copyright © 2016 by the International Society of Offshore and Polar Engineers (ISOPE)
ISBN 978-1-689653-88-3; ISSN 1098-6189

Fatigue Analysis of Non-rigid Locked Wellhead

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ABSTRACT

This paper presents the findings of a numerical study on the evaluation of fatigue damage of a non-rigid locked wellhead due to wave loads. This study is consistent with the recommend practice (RP) DNVGL-RP-0142, released in April of 2015. For the case study presented herein, a mobile offshore drilling unit (MODU) operated drilling riser system in relatively shallow water is selected. Two models are developed: (a) a fully coupled three-dimensional (3D) finite element (FE) model that includes the riser, the wellhead, the casing, the cement and the soil represented by P-y springs, and (b) a global riser model that utilizes the decoupling method between the BOP and wellhead interface (wellhead datum). Note that the fully coupled model includes a local model of the wellhead system that can be analyzed separately to produce load-to-stress curves for use with the global riser model. Comparisons of fatigue results using three methods are presented: (a) hotspot stress taken directly from the fully coupled 3D model, (b) stress calculated using wellhead bending moment and load-to-stress curves, and (c) hotspot stress from the local wellhead model analyzed using synchronous time series of tension, bending moment and shear force at the wellhead datum, taken from the fully coupled analysis.

KEY WORDS: subsea wellhead, wave fatigue, non-rigid direct wave loading of the riser, as well as vortex-induced vibration. The motion due to these vibrations is transmitted to the wellhead system and can lead to fatigue issues in the wellhead system.

The fatigue damage assessment of a wellhead system is a challenging problem because of a large number of inputs required, not all of which may be readily available. In addition, complex modelling requirements exist and multiple analysis methods are available. Consequently, analysts may obtain vastly different results for the same wellhead system depending upon the assumptions about inputs, modeling details and the selected analysis method. The Structural Well Integrity Joint Industry Project (JIP) was initiated in 2010 to address the zone and provide a framework for fatigue assessment of the wellhead system to improve the accuracy, consistency and repeatability of the results. The efforts of the ongoing JIP have resulted in DNVGL-RP-0142 that addresses the wave load induced vibrations fatigue [1]. The work presented in this paper is based on operating within the framework provided by the RP.

The objective of this paper is to present the wellhead fatigue analysis of a non-rigid locked wellhead system using two numerical modeling approaches. The first approach uses an FE model in which the drilling riser and the wellhead system including the soil (represented by P-y curves) are included. This method of including all the elements of the
Questions?

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