Design Study for API 4F Transition from ASD to LRFD

Phase 2-Final Report

Prepared for:
American Petroleum Institute
Washington, DC

9 August 2016
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Limitations of This Report

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Executive Summary

American Petroleum Institute (API) specification 4F\(^1\), specification for drilling and well servicing structures gives requirements and recommendations for the design of new steel derricks, masts, substructures and crown block assemblies. The current edition (fourth) of the API 4F specification refers to American Institute of Steel Construction (AISC) -1989\(^2\) specification for design of steel structures. The AISC -89 specification was based on the allowable stress design methodology.

Stress Engineering Services, Inc. (SES) was contracted by the American Petroleum Institute (API) to conduct a study of the impact of transitioning API specification 4F from the allowable stress design methodology specified in the AISC -1989 to the load and resistance factor (LRFD) design methodology specified in AISC-2005\(^3\).

The work awarded to SES is overseen by Task Group 1 (TG1) for Drilling Structures of the API Subcommittee on Drilling Structures & Equipment. (CSOEM/SC8). A steering committee was formed from the TG1 members to select load factors and address questions related to the design study. SES received beam element models of 5 representative drilling structures from the manufacturers. Figure 1 shows the screen shots of the drilling derrick and mast systems considered for the design study. Table 1 shows the details of the five rig structures.

Table 2 shows the loading conditions and load factors selected for the LRFD design methodology. The hook load was classified as a permanent load with a load factor of 1.3. The steering committee selected the load factors for the different loading conditions shown in Table 2.

SES issued the report\(^4\) for the design study summarizing the design study results and observations. Based on the results of the design study, the steering committee requested SES to continue the design study with additional sets of load factors. Therefore, in Phase2 of the design study, the steering committee selected two sets of load factors for Rig1 to Rig5. Table 3 shows the Phase2-Sensitivity 1 (Ph2-Sens1) load factors and Table 4 shows the Phase2-Sensitivity 2 (Ph2-Sens2) load factors. For Rig2 which is a land mast with substructure, the steering committee decided to perform the design study with a higher load factors for dead, hook, rotary and setback loads. Table 5 shows the Phase2-Sensitivity 3 (Ph2-Sens3) set of load factors selected for Rig2 structure.

### Table 1: Details of the Derrick and Mast Systems

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Type</th>
<th>Hook Load (kip)</th>
<th>No of Lines</th>
<th>Setback (kip)</th>
<th>Height (ft)</th>
<th>Reference Wind Speed (knots)</th>
<th>Base Elevation from Water Line (ft)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Operating</td>
<td>Unexpected</td>
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<tr>
<td>Rig 1</td>
<td>Mast</td>
<td>441</td>
<td>10</td>
<td>NA</td>
<td>92</td>
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<td>70</td>
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<tr>
<td>Rig 2</td>
<td>Mast &amp; Substructure</td>
<td>750</td>
<td>12</td>
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<tr>
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<td>Dual Derrick</td>
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<td>16 (14 (Aux)</td>
<td>1750</td>
<td>242</td>
<td>65.1</td>
<td>NA</td>
</tr>
<tr>
<td>Rig 5</td>
<td>Workover Mast</td>
<td>250</td>
<td>6</td>
<td>NA</td>
<td>104</td>
<td>25</td>
<td>60</td>
</tr>
</tbody>
</table>

**Notes:**
- NA refers to Not Available
Figure 1: Screen Shots of the Mast and Derrick Systems used for the API 4F Design Study
Figure 1 (Continued): Screen Shots of the Mast and Derrick Systems used for the API 4F Design Study

Rig 4
Dual Derrick

Rig 5
Workover Mast
### Table 2: Loads and Load Combinations for LRFD-05 (Phase 1)

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
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<td>0</td>
<td>130</td>
<td>100</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>130</td>
<td>100</td>
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<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
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<tr>
<td>3a</td>
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<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>130</td>
<td>130</td>
</tr>
</tbody>
</table>

Note:  
TE refers to Travelling Equipment

### Table 3: Loads and Load Combinations for LRFD-05 (Phase 2 - Sensitivity 1)

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
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<td>130</td>
<td>120</td>
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<td>120</td>
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<tr>
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<td>Operating</td>
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<td>120 TE</td>
<td>120</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
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Note:  
TE refers to Travelling Equipment
Table 4: Loads and Load Combinations for LRFD-05 (Phase2-Sensitivity 2)

<table>
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<th>Setback Load (%)</th>
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<td>110 TE</td>
<td>110</td>
<td>0</td>
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<tr>
<td>3a</td>
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<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>130</td>
<td>135</td>
</tr>
</tbody>
</table>

Note: TE refers to travelling equipment

Table 5: Loads and Load Combinations for LRFD-05 (Phase2-Sensitivity 3 for Rig2 Only)

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
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</thead>
<tbody>
<tr>
<td>1a</td>
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<td>168</td>
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<tr>
<td>1b</td>
<td>Operating</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>171.9</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>171.9</td>
<td>135</td>
</tr>
</tbody>
</table>

Note: TE refers to travelling equipment
Table 6: Effective Load Factors for Phase1 and Phase2 Study

<table>
<thead>
<tr>
<th>Load Factors</th>
<th>Effective Load Factor</th>
</tr>
</thead>
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<tr>
<td>AISC LRFD-05 with ASCE 7 Load Factors of 1.2 Dead + 1.6 Live</td>
<td>1.5</td>
</tr>
<tr>
<td>Phase1</td>
<td>1.3</td>
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<tr>
<td>Phase2-Sensitivity 1</td>
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<tr>
<td>Phase2-Sensitivity 2</td>
<td>1.45</td>
</tr>
<tr>
<td>Phase2-Sensitivity 3</td>
<td>1.71</td>
</tr>
</tbody>
</table>
Observation from Phase 1 and Phase 2 Study Results

The ASD-89 and LRFD-05 are different design philosophies. For a particular load case and structural configuration, the difference in the member size or the unity check ratio is due to the following factors:

1. Selection of partial load factors,
2. Second order effects,
3. Changes in Interaction equation to estimate the unity check ratio (to combine the force and moment effects)
4. Difference in member strength calculations between ASD-89 and LRFD-05

The LRFD specification was calibrated to the 1978 ASD specification at a live to dead load ratio of 3.0 and using an effective load factor of 1.5. The effective load factor is obtained from the partial load factors selected for the individual nominal loads.

To obtain a similar reliability index for a member design from LRFD-05 and ASD-89 the partial load factors should be selected such that the effective load factors for the gravity load case should be equal or higher than the 1.5. Table 6 shows the effective load factors for the AISC-05 and the different set of load factors selected for the Phase1 and Phase2 design study.

For Rig1 to Rig4 structures, the phase1 and phase2 design study results show that the Ph2-Sens2 load factors shown in Table 4 provide the best correlation between the LRFD-05 design and the Allowable Stress Design (ASD-89).

Typical designs performed using ASD-89 specification do not account for the second-order effects. For structures with adequate lateral stiffness, the increase in member force due to second-order effects are not significant and the second order to first order drift ratio is typically less than 1.1. On the other hand, for slender structures, the second-order effects can be significant. Therefore, the member forces are amplified significantly. The members in slender structure designed according to AISC-05 specification will have a higher UC ratio than the first order analysis methods used for the Allowable Stress Design methodology specified in AISC-89.

Path Forward

SES proposes the following work to finalize the load factors, analysis methodology and procedure to meet the AISC-05 specification

1. Complete Rig5 LRFD design study for all load cases.
   a. In the Phase2 design study, results were available only for the operational load case. Also additional sensitivity analyses are needed to account for the second order effects of the guyed structure.
2. Comparison of analysis and design procedures for Allowable Strength Design (ASD) and LRFD per the AISC specification.
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1. Introduction

American Petroleum Institute (API) specification 4F [1], specification for drilling and well servicing structures gives requirements and recommendations to design new steel derricks, masts, substructures and crown block assemblies. The current edition (fourth) of the API 4F specification refers to American Institute of Steel Construction (AISC) 1989 [2] specification for design of steel structures. The AISC -89 specification was based on allowable stress design methodology.


Stress Engineering Services, Inc. (SES) was contracted by the American Petroleum Institute (API) to conduct a study to determine the impact of transitioning API 4F from the allowable stress design methodology specified in the AISC -89 to the load and resistance factor (LRFD) design methodology in AISC -05. The contract was awarded on November 10, 2011 based on SES proposal submitted to API on September 27, 2011.

The work awarded to SES is overseen by Task Group for Drilling Structures (TG1) of the API Subcommittee on Drilling Structures & Equipment (CSOEM/SC8). A steering committee was formed to select load factors and address questions related to the design study.

SES issued the report [6] for the Phase1 design study summarizing the design study results, observations and path forward. Based on the design study results the steering committee and the task group requested SES to perform sensitivity studies on the load factors. In Phase2, the steering committee selected two sets of load factors for the Phase2 sensitivity study. In this report only the results for the Phase 2 sensitivity study are presented. Background information on the design study, design methodology and results for Phase1 design study are presented in SES Phase1 report [6].

1.1 List of Terms/Acronyms

Allowable Stress Design (ASD-89): A method of proportioning structural components such that the allowable stresses equals or exceeds the calculated stresses of the component under the action of the unfactored load combination. In this document, ASD-89 refers to the allowable stress design per AISC-1989 specification.

Allowable Strength Design (ASD-05): A method of proportioning structural components such that the allowable strength equals or exceeds the required strength of the component under the action of the unfactored load combinations. In this document, ASD-05 refers to the strength design per AISC-2005 specification.
Load and Resistance Factor Design (LRFD): A method of proportioning structural components such that the factored strength equals or exceeds the required strength of the component under the action of the factored load combination. In this document, LRFD-05 refers to the strength design per AISC-2005 specification.

P-Δ Effect: The second order effect on shear and moments of structural members induced by axial load on a laterally displaced structure.

P-δ Effect: The second order effect on shear and moments of structural members induced by axial load on the deformed member shape.

Unity Check (UC): The combined ratio of the actual axial stress or force to the allowable axial stress or force and actual bending stress or moment to allowable bending stress or moment. The combined ratio should be less than 1.0.

1.2 Design Methodologies

The allowable stress design method is a design philosophy in which the structural members and connections are designed so the stresses (axial, bending, shear, etc.) due to the design loads do not exceed the allowable stresses. The allowable stresses are obtained by applying safety factors to the material strength and minimum specified yield stress.

The LRFD methodology traces its origin back to the 1960s in response to structural failures that exposed deficiencies in the structural code, in either strength allowable or loads. The allowable stress design method was observed to result in inconsistent safety factors. The LRFD method was adopted to provide a more consistent safety factor.

The LRFD method applies load factors to the loads based on the known accuracy or reliability of the load values and a resistance factor to the material strength to account for uncertainties in materials. For instance, in building design, dead loads are well known and have a relatively low uncertainty where live loads can vary significantly. To account for this variability, the load factor is significantly higher for live loads. The LRFD method is designed to provide more consistent safety factors. AISC specifications since 1993 direct the designer to the ASCE 7 [7] publication, “Minimum Design Loads for Buildings and Other Structures,” for design loads and design load factors for various loads and load combinations unless otherwise specified. ASCE 7 specifies load combinations for both ASD and LRFD methodologies. The load factors given in ASCE 7 may not be appropriate in some cases for the design of drilling structures.

1.3 Work Organization

The work scope is discussed in section 2. Details of the mast and derrick structures selected for the study and the analysis approach are discussed in section 3. In section 4 results from the design study are presented. In section 5, additional work to complete the design study is discussed.
2. **Scope**

The following is the work scope for the API 4F Phase2 design study:

1. Classify all possible loads into appropriate categories as either permanent or variable loads, similar to API RP-2A, and recommend load factors for operating, expected and unexpected loading conditions.
2. Recommend partial load factors for API 4F load combinations
   a. The steering committee formed for the API 4F design study is responsible for selecting the load factors.
3. **Sensitivity Study**
   a. SES will repeat the design study for operational, expected and unexpected loading conditions with the new load factors for Rig 1 through Rig 5. Transportation and seismic load cases will not be included in the sensitivity study.
4. Report documenting the sensitivity study results for derricks and masts.

3. **Model Details and Analysis Approach**

Figure 1 shows the screen shots of the models provided by the participants for the design study. The details of the rig models are listed in Table 2. The load and weight breakdowns were obtained from the design reports and from the model input files. Rig 1 and Rig 2 are mast structures. Rig 3 and Rig 4 are derrick structures. Rig 4 is a dual derrick system. Rig 5 is a guyed mast structure.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Type</th>
<th>Hook Load (kip)</th>
<th>No of Lines</th>
<th>Set Back (kip)</th>
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<th>Reference Wind Speed (knots)</th>
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<td>6</td>
<td>NA</td>
<td>104</td>
<td>25</td>
<td>60</td>
</tr>
</tbody>
</table>

**Notes:**
- NA refers to “Not Available”
- **The work over mast model provided by the participant was developed in STAAD. SES converted the model from STAAD to StruCAD and then to SAP2000.**
3.1.1 Rig2 Model Modifications

During the Phase1 design study, some of the LRFD operating load cases did not converge for Rig2 and some members had very high UC due to the amplification of force and moments by second-order geometry effects (P-Δ). In the Phase2 design study, the load factors for the operational load case for Ph2-Sens2 and Ph2-Sens3 are higher than the Phase1 load factors. Because of the higher load factor for gravity and hook load for operational load cases, the analyses did not converge with the P-Δ effect.

The mast is connected to the substructure through the pedestal with pin connections. The pin connections are idealized in the model by using moment releases in the element attributes at the interface region between the mast and substructure. Also another reason for the non-convergence might be due to the removal of plate elements at the rig floor during StruCAD to SAP conversion. This might have reduced the lateral stiffness of some of the members in the substructure.

To resolve the non-convergence issue additional effort is needed to refine the element attributes and add missing plate elements. During the Phase2 progress meeting, the steering committee decided to separate the Rig2 model which was a combined mast and substructure model into two models. The Rig2 Mast model is a mast only model with pin boundary conditions at the end of the mast legs. The second model, Rig2 Substructure model, is a substructure only model. The reactions from the mast only model are transferred to the substructure model for further analysis and design study.

3.1.2 Rig5 Model Load Combinations

During the Phase2 design study work, it was noticed that the Rig5 STAAD model had only the operational load cases. Also, during the model conversion from STAAD to SAP the preload to the cables were not transferred properly. The original Rig5 designer provided additional models to SES which had expected and unexpected load cases. These models were received towards the end of the Phase2 work and therefore Rig5 results are not included in this report. If approved by API, a design study for Rig5 will be performed and included in the proposed follow up work.
Figure 1: Screen Shots of the Mast and Derrick Systems used for the API 4F Design Study
Figure 1 (Continued): Screen Shots of the Mast and Derrick Systems used for the API 4F Design Study
3.2 Analysis Approach

The analysis approach for the Phase2 design study is outlined below:

3.2.1 Load Cases and Load Combinations for Phase2 Design Study

Table 2 shows the design loading conditions for drilling structures provided in API 4F 4th Edition[1]. For the design study, only the operation, expected and unexpected (storm) loading conditions were selected. Directional wind loads were applied for all three selected load conditions. Analysis and design checks for unexpected (earthquake), erection and transportation loading conditions were not performed.

Table 2: Design Loadings for Drilling Structures (from API 4F [1])

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load</th>
<th>Hook Load</th>
<th>Rotary Load</th>
<th>Setback Load</th>
<th>Environmental Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>100% operating environment</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>100</td>
<td>TE</td>
<td>100</td>
<td>100</td>
<td>100% operating environment</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>100</td>
<td>TE</td>
<td>100</td>
<td>0</td>
<td>100% expected storm environment</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>100</td>
<td>TE</td>
<td>100</td>
<td>100</td>
<td>100% unexpected storm environment</td>
</tr>
<tr>
<td>3b</td>
<td>Unexpected</td>
<td>100</td>
<td>As applicable</td>
<td>As applicable</td>
<td>As applicable</td>
<td>100% earthquake</td>
</tr>
<tr>
<td>4</td>
<td>Erection</td>
<td>100</td>
<td>As applicable</td>
<td>As applicable</td>
<td>0</td>
<td>100% erection environment</td>
</tr>
<tr>
<td>5</td>
<td>Transportation</td>
<td>100</td>
<td>As applicable</td>
<td>As applicable</td>
<td>As applicable</td>
<td>100% transportation environment</td>
</tr>
</tbody>
</table>

3.2.2 Load Factors for Design Study

The load factors for the LRFD methodology were selected by the steering committee. Table 3 shows the LRFD load combinations and load factors used for the Phase1 design study. For the Phase2-sensitivity study the steering committee selected two sets of load factors for Rig1 to Rig5. Tables 4 and 5 show the load factors for the Phase2-Sensitivity1 (Ph2-Sens1) and Phase2-Sensitivity2 (Ph2-Sens2) respectively.
An additional set of load factors was also selected for Rig2 structure only. Table 6 shows the Phase2-Sensitivity3 (Ph2-Sens3) load factors. The higher set of load factors was selected for Rig2 primarily to study the effect of LRFD design on the substructure members.

Some of the rig structures received for the design study were designed using previous editions of the API 4F, and for some rig structures, all loads were not included in the load cases. SES used the model description, inputs from the original rig designer to classify the loads and the load cases.

**Table 3: Loads and Load Combinations for LRFD-05 (Phase 1)**

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>130</td>
<td>130</td>
<td>0</td>
<td>130</td>
<td>100</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>130</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>130</td>
<td>130</td>
</tr>
</tbody>
</table>

Notes:
TE refers to Traveling Equipment

**Table 4: Loads and Load Combinations for LRFD-05 (Phase2-Sensitivity1)**

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>130</td>
<td>120</td>
<td>0</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>120 TE</td>
<td>120</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>110</td>
<td>135</td>
</tr>
</tbody>
</table>

Note:
TE refers to Travelling Equipment
Table 5: Loads and Load Combinations for LRFD-05 (Phase2-Sensitivity2)

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>130</td>
<td>150</td>
<td>0</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>150 TE</td>
<td>150</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>110</td>
<td>135</td>
</tr>
</tbody>
</table>

Note:
TE refers to Travelling Equipment

Table 6: Loads and Load Combinations for LRFD-05 (Phase2-Sensitivity 3 for Rig2 Only)

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>180</td>
<td>168</td>
<td>0</td>
<td>171.9</td>
<td>100</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>171.9</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>171.9</td>
<td>135</td>
</tr>
</tbody>
</table>

Note:
TE refers to Travelling Equipment
3.2.3 Allowable Strength Design Load Factors

AISC -05 specification provides two methods of design, LRFD-05 and ASD-05. For the Phase1 design study, analyses and design checks were performed using LRFD-05 and ASD-05. The stability analysis requirements are the same for both design methodologies.

For ASD-05, the individual loads in load combinations do not have any load factor. However to achieve the same level of deformation and moment amplification, AISC-05 requires that the ASD-05 loads are multiplied by a uniform load factor to represent the strength load level. For the Phase1 design study, a load factor of 1.3 was selected for the ASD-05 design basis. Therefore all the ASD-05 load combinations were multiplied by a common load factor of 1.3. The analysis results were then divided by 1.3 to get the design forces and moments. Figure 2 illustrates the amplification of the ASD-05 nominal loads per AISC specification.

Table 7 shows the load combinations and load factors for the ASD-05 methodology. Phase1 results showed that the ASD-05 design results were conservative (higher UC ratio) than the LRFD-05 design. The higher UC ratio is due to two factors:

1. In ASD-05, all loads were amplified by a common load factor during the analysis and during design, the member force and moments are reduced by the common load factor. For structures with higher second-order effects, the amplification in ASD-05 increases the member force and moments than the LRFD-05.

2. In AISC-05, for each limit state the factor of safety (W) in ASD-05 methodology is scaled from the LRFD-05 resistance factor (?. To get similar design between ASD-05 and LRFD-05, the factor of safety (W) should be scaled based on the load factor. In AISC-05, the scale factor is 1.5, which is based on the partial load factor of 1.2 for dead load and 1.6 for live load. In the Phase1 design study, the load factors selected for the dead and hook loads are 1.3. However, the factor of safety was not scaled. Therefore the UC ratio was higher than the LRFD-05.

For the Phase2 sensitivity study, analyses and design checks were performed only using the LRFD-05 methodology. To perform the sensitivity study in ASD-05, for each set of load factors shown in Tables 4 to 6, a common load factor should be identified for each load case. Also, the default factor of safety in the design software should be modified to obtain a consistent design with LRFD-05.
Table 7: Loads and Load Combinations for ASD-05

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>100</td>
<td>100 TE</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>100</td>
<td>100 TE</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>100</td>
<td>100 TE</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Notes:
TE refers to Traveling Equipment

Figure 2: Amplifications of ASD Load Cases
4. Results & Conclusions

Analyses and design checks were performed for four rigs using the ASD-89 and LRFD-05 methods. The critical member unity check (UC) values are compared between the two specifications. In this section, a summary of the Phase2 load factor sensitivity study results and conclusions are provided. For comparison, the results from Phase1 design study are also repeated in this report. Phase2 design study results presented in the 2016 summer standards meeting is provided in Appendix A.

4.1 Design Results for ASD-89 and LRFD-05

Table 8 shows the number of members for Rig 1 to Rig 4 with UC values greater than 1.0 using the ASD-89 and LRFD-05 methods. The table shows the results for LRFD for Phase1 and Phase2 set of load factors. The AISC-89 specification allows an increase in allowable stresses by 33% from the basic allowable stresses for environmental load combinations such as wind and seismic loads combined with dead and live loads.

As mentioned earlier, for Rig2 with Ph2-Sens2 and Ph2-Sens3 load factor the analysis results started diverging due to excessive second-order effect and modeling assumptions. Therefore, the UC values shown for Rig2 in Table 8 are not valid. In Section 4.1.2 results for the modified Rig2 models are discussed in detail.

<table>
<thead>
<tr>
<th>Rig # (Total Number of Elements)</th>
<th>RIG #1 Bootstrap Mast (363)†</th>
<th>RIG #2 Mast with Substructure (924)‡</th>
<th>RIG #3 Derrick (1545)†</th>
<th>RIG #4 Dual Derrick (1149)‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASD ‘89 with 1/3rd stress increase</td>
<td>19</td>
<td>23</td>
<td>11</td>
<td>124</td>
</tr>
<tr>
<td>LRFD 05 Phase1</td>
<td>5</td>
<td>67</td>
<td>21</td>
<td>140</td>
</tr>
<tr>
<td>LRFD-05 Phase2-Sens1</td>
<td>3</td>
<td>41</td>
<td>20</td>
<td>128</td>
</tr>
<tr>
<td>LRFD-05 Phase2-Sens2</td>
<td>18</td>
<td>202†</td>
<td>30</td>
<td>138</td>
</tr>
<tr>
<td>LRFD-05 Phase2-Sens3</td>
<td>Not Performed</td>
<td>93</td>
<td>Not Performed</td>
<td>Not Performed</td>
</tr>
</tbody>
</table>

Notes:
† Represents the number of members in the model
‡ Several operational load cases did not converge
4.1.1 Rig 1 Design Results

Figure 3 shows the UC values of each member for Rig 1 using the ASD-89 and LRFD-05 design methodology for the Phase 1 load factors. The UC values correspond to the critical load combination for each member. Each point represents a member in Rig 1. The X and Y ordinate value of a point shows the UC values for ASD-89 and LRFD-05 respectively. If there is no significant difference in the design specification and the selection of load factors, the points will align along the diagonal line.

Interpretation of UC Results Plot: In Figure 3 the results are zoned into three regions and the interpretation of the results in each zone is explained below.

Region A: In Figure 3, members shown in Region A have UC values less than or equal to 1.0 and are acceptable per the design code. If the selected load factors and LRFD design methodology are equivalent to ASD-89 then the mean value of the UC for members in this region will be close to 1.0 with a very small standard deviation (less than 0.1).

Region B: Members in this region have higher UC for ASD-89 compared to the LRFD-05 method. The possible reasons for this are:

1. Lower load factors selected for the LRFD method
2. Conservative capacity estimates for different limit states and
3. Conservative combination of axial and bending stresses in the interaction equation

Region C: Members in this region have higher UC for LRFD-05 compared to the ASD-89 method. The possible reasons for this are:

1. Higher load factors for the LRFD method
2. Significant second order effects due to slenderness of the structure and
3. Additional limit states which were not checked in the ASD-89 specification

Mean and standard deviation of the UC ratio and the correlation coefficient (correlation) of the UC values between LRFD-05 and ASD-89 are also show in Figure 3. The UC ratio is the ratio of the UC values from LRFD-05 and ASD-89. The correlation coefficient gives an indication of how strongly the two UC values are related. The correlation value ranges from -1 to +1. A correlation value of +1 indicates that the variables are positively correlated (an increase in one value corresponds to an increase in another).

A correlation value of -1 indicates that the variables are negatively correlated (an increase in one value corresponds to a decrease in another). A value of 0 indicates that the two variables are poorly correlated.

For Rig 1, the mean value and correlation are closer to 1. Several members have higher UC for the ASD-89 method than the LRFD-05 method. In Figure 3, two members with a high UC for LRFD-05 are identified as members 340 and 341. These members are modeled as tubular sections. In AISC-05,
tubular sections are referred to as Hollow Structural Shapes (HSS). The interaction equation for HSS subjected to combined torsion, shear, flexure and axial force is given in Table 9. In AISC-89 specification, the interaction does not account for torsion and shear effects in the tubular section.

**Table 9: Interaction Equation for Hollow Structural Shape (HSS) with Significant Torsion**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Analysis Type</th>
<th>Interaction Equation</th>
</tr>
</thead>
</table>
| AISC 1989             | First Order                    | \[
\frac{f_a}{F_a} + \frac{c_{mx}f_{bx}}{F_{bx}} + \frac{c_{my}f_{by}}{F_{by}} \]
(Axial and Bending Stress) |
| AISC 2005 LRFD & ASD  | Requires Second Order  
(P-Δ and P-δ)  
1) Direct Analysis Method  
2) Effective Length Method  
3) Amplified First Order  
4) First Order Method | \[
\left(\frac{P_r}{P_c} + \frac{M_r}{M_c}\right) + \left(\frac{V_r}{V_c} + \frac{T_r}{T_c}\right)^2 \]
(Axial Force, Bending Moment, Shear and Torsion) |
Figure 4 shows the UC values for Rig1 for Ph2-Sens1 load factors. The Ph2-Sens1 load factors are lower than the Phase1 values. The results show that the lower load factors for Ph2-Sens1 reduced the mean value and the UC values are biased towards the ASD-89.

Figure 5 shows the UC values for Rig 1 for Ph2-Sens2 load factors. The mean values for the UC ratio is above 1.0 and the correlation coefficient is close to 1.0. For Rig1, UC values for LRFD_05 using Ph2-Sens2 load factors and ASD-89 provide the best correlation.
Figure 4: Rig 1 Critical Load Case UC Results – Ph2-Sens1

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.898
UC Ratio Std. Dev: 0.236
UC Correlation: 0.90
N= 363
Figure 5: Rig 1 Critical Load Case UC Results – Ph2-Sens2
4.1.2 **Rig 2 Design Results**

The Rig2 model was separated into a mast only model and a substructure only model. Design check results for both the Rig2 models are shown below for the Phase1 and Phase2 load factors.

4.1.2.1 **Rig2-Mast Only Model Results**

All load cases converged for the Rig2 mast model with pin boundary condition. The structure was stable for all the higher load factors.

Figure 6 shows the UC values of Rig2 mast only model using the ASD-89 and LRFD-05 design specification for Phase1 load factors. Figures 7 to 9 show the UC values for Rig2 mast for Ph2-Sens1, Ph2-Sens2, and Ph-2 Sens3 load factors respectively.

For Ph2-Sens3 load factors, the mean ratio of the UC ratio between LRFD-05 and ASD-89 is 1.323 which indicates that the LRFD design is conservative than the ASD design. The higher UC values are due to the higher load factors for dead, hook, rotary and setback loads for all the load cases. At higher load factors the second order effects are significant and therefore the UC values are higher compared to the ASD-89 values.

In Figure 9, the members in Region C have significantly higher UC for LRFD-05 than ASD-89 and the UC values is greater than the acceptable limit of 1.0. A screen shot of the SAP model with high UC values for Rig2 mast model is shown in Appendix A.
Figure 6: Rig 2 Mast Critical Load Case UC Results – Phase 1

Ratio = LRFD-05/ASD-89
UC Ratio Mean: **0.996**
UC Ratio Std. Dev: **0.306**
UC Correlation: **0.94**
N= 234
Figure 7: Rig 2 Mast Critical Load Case UC Results – Ph2-Sens1

Ratio = LRFD-05/ASD-89
UC Ratio Mean: **0.990**
UC Ratio Std. Dev: **0.329**
UC Correlation: **0.93**
N= 234
Figure 8: Rig 2 Mast Critical Load Case UC Results – Ph2-Sens2

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.099
UC Ratio Std. Dev: 0.357
UC Correlation: 0.93
N= 234
Table 10 shows the displacement of the mast for an operational load combination (LC 111 in the model) which is the critical load combination for most of the members for the LRFD-05 design. The displacement value at the top of the mast as shown in Figure 10 is given for both the LRFD-05 and ASD-89 models. For the ASD-89 model, a nonlinear load combination for LC 111 was created to see the impact of the second-order effects. For the LRFD-05 models, the displacement includes the effect of second order analysis and load factors.

Comparison of the displacement value between ASD-89 and LRFD-05 shows that for the mast model there is significant amplification of the moments due to the inclusion of second order effects (P-Δ effects) in the analysis. The second order effect is generally higher for load combinations with high gravity and lateral loads such as the operational and unexpected load combinations.
Figure 10: Rig 2 Mast Critical Load Case UC Results – Ph2-Sens3

Table 10: Rig 2 Mast Displacement for an Operational Load Case (LC: 111)

<table>
<thead>
<tr>
<th>Translation /Rotation</th>
<th>Phase1 (ASD-89)</th>
<th>Phase 1 (LRFD-05)</th>
<th>Phase2 Sens1 (LRFD-05)</th>
<th>Phase2 Sens2 (LRFD-05)</th>
<th>Phase2 Sens3 (LRFD-05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without P-delta</td>
<td>with P-delta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ux</td>
<td>1.512</td>
<td>2.272</td>
<td>3.244</td>
<td>2.883</td>
<td>4.310</td>
</tr>
<tr>
<td>Uz</td>
<td>-0.833</td>
<td>-0.857</td>
<td>-1.118</td>
<td>-1.038</td>
<td>-1.284</td>
</tr>
<tr>
<td>Rx</td>
<td>-0.0009</td>
<td>0.0009</td>
<td>-0.0012</td>
<td>-0.0011</td>
<td>-0.0014</td>
</tr>
<tr>
<td>Ry</td>
<td>0.0006</td>
<td>0.00145</td>
<td>0.0023</td>
<td>0.0019</td>
<td>0.0033</td>
</tr>
<tr>
<td>Rz</td>
<td>-0.0117</td>
<td>-0.0205</td>
<td>-0.0353</td>
<td>-0.0288</td>
<td>-0.0536</td>
</tr>
</tbody>
</table>

Notes:
Translation (Ux, Uy and UZ) unit is inches
Rotation (Rx, Ry and RZ) units is radians
4.1.2.2 Rig2-Substructure Model Results

Figure 11 shows the UC values of Rig2 substructure only model using the ASD-89 and LRFD-05 design specification for Phase1 load factors. Figures 12 to 14 shows the UC values for Rig2 substructure model for Ph2-Sens1, Ph2-Sens2, and Ph-2 Sens3 load factors respectively.

For Ph2-sens3 load factors, the mean ratio of the UC ratio between LRFD-05 and ASD-89 is 1.372 which indicates that the LRFD design is more conservative (higher UC value) than the ASD design due to the higher load factors for dead, hook, rotary and setback loads for all the load cases. At higher load factors the second order effects are significant and therefore the UC values are higher compared to the ASD-89 values.

![Figure 11: Rig 2 Substructure Critical Load Case UC Results – Phase1](image)
Figure 12: Rig 2 Substructure Critical Load Case UC Results – Ph2-Sens1

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.134
UC Ratio Std. Dev: 0.878
UC Correlation: 0.82
N= 688
Figure 13: Rig 2 Substructure Critical Load Case UC Results – Ph2-Sens2

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.206
UC Ratio Std. Dev: 0.862
UC Correlation: 0.86
N= 688
Figure 14: Rig 2 Substructure Critical Load Case UC Results – Ph2-Sens3
4.1.3  **Rig 3 Design Results**

Figure 15 shows the critical UC values of each member for Rig 3 using the ASD-89 and LRFD-05 design specifications. Mean and standard deviation of the UC ratio and the correlation of the UC values between LRFD-05 and ASD-89 are also show in Figure 15. In Rig 3 some members were modeled with high stiffness (dummy members) to transfer the loads. Depending on the section classification, the UC values of the dummy members are not correct and therefore the UC values of the dummy members were removed from the statistical analysis.

![Figure 15: Rig 3 Critical Load Case UC Results-Phase1](image-url)

- **Ratio** = LRFD-05/ASD-89
- **UC Ratio Mean**: 0.907
- **UC Ratio Std. Dev**: 0.207
- **UC Correlation**: 0.94
- **N=1484 (without dummy members)**
Figure 16 shows the critical UC values of each member for Rig 3 using the ASD-89 and LRFD-05 design specifications for Ph2-Sens1 load factors. As expected the mean value for Ph2-Sens1 load factors is lower than the Phase1 load factors.
Figure 17 shows the critical UC values of each member for Rig 3 using the ASD-89 and LRFD-05 design specifications for Ph2-Sens2 load factors. The mean value of the UC ratio for Ph2-Sens2 load factors is higher than Phase1 and Ph2-Sens1 load factors.

![Graph showing critical load case UC results for Rig 3 under Ph2-Sens2 load factors.](image)

**Figure 17: Rig 3 Critical Load Case UC Results - Ph2-Sens2**

- **Ratio** = LRFD-05/ASD-89
- UC Ratio Mean: **0.949**
- UC Ratio Std. Dev: **0.206**
- UC Correlation: **0.95**
- **N** = 1484
4.1.4 Rig 4 Design Results

Figure 18 shows the critical UC values of each member for Rig 4 using the ASD-89 and LRFD-05 design methodology for Phase 1 load factors. For Rig 4, the second order amplification is not significant. The results show that the design is biased towards ASD-89. This implies that there is significant difference in design results due to the selection of the load factors.

![Figure 18: Rig 4 Critical Load Case UC Results – Phase 1](image)

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.860
UC Ratio Std. Dev: 0.194
UC Correlation: 1.0
N = 1149
Figure 19 shows the critical UC values for each member for Rig 4 using the ASD-89 and LRFD-05 design methodology for Ph2-Sens1 load factors.

The mean value of the UC ratio for the Ph2-sens1 load factor is higher than the Phase1 value even though the load factors for the operational load cases in Ph2-Sesn1 is lower than the Phase1 load factors. In Phase1 report, it was shown that for Rig4, the unexpected load case was the critical load case for most of the members. For unexpected and expected load cases, the environmental load factor in Ph2-Sens1 is 1.35 compared to 1.3 in Phase1. This increase in the environmental load factor increased the UC ratio mean value closer to 1.0.

![Figure 19: Rig 4 Critical Load Case UC Results -Ph2-Sens1](image-url)
Figure 20 shows the critical UC values for each member for Rig 4 using the ASD-89 and LRFD-05 design methodology for the Ph2-Sens2 load factors. The mean value of the UC ratio for the Ph2-sens2 load factor is higher than the Ph2-Sens1 with a lower standard deviation and high correlation coefficient. However, the UC for members highlighted in Figure 20 and named Region B are below the diagonal line, which implies that the member has higher UC value using the ASD-89 method than the LRFD-05 method. Similarly the UC for members highlighted and named Region C are above the diagonal line, which implies that the member has higher UC values using the LRFD-05 method than the ASD-89 method.

The UC values shown in Figure 20 are the critical UC for each member from operation, unexpected and expected load cases. UC values for a single operation load case and expected load cases are plotted to understand further the reason for the high UC for some members in ASD-89 and for other members in LRFD-05.

![Figure 20: Rig 4 Critical Load Case UC Results - Ph2-Sens2](image)

**Region A**

**Region B**

**Region C**

**Ratio = LRFD-05/ASD-89**

UC Ratio Mean: **0.966**

UC Ratio Std. Dev: **0.175**

UC Correlation: **1.0**

N= 1149
Figure 21 shows the UC plot for Rig 4 an operating load case (LC 502 in the Rig4 model) using the ASD-89 and LRFD-05 for the Ph2-Sens2 load factors. In Figure 21, UC value for a diagonal brace member (Member #845) in the setback side is highlighted.

Figures 22 and 23 show the detailed UC calculation of member 845 using ASD-89 and LRFD-05 method respectively. Rig4 is a dual derrick and has high lateral and torsional stiffness and therefore the second-order effect is negligible. The forces and moments between the ASD-89 and LRFD-05 shown in the calculation are different by the effective load factor of 1.4 (1.3*Dead+1.5*Hook). The high UC value for member 845 using the ASD-89 is due to the interaction equation used for combining the axial and bending stresses. Table 11 shows the interaction equations used for combining the stresses in the ASD-89 and LRFD-05 methods. In the ASD-89 method, to account for the member deformation effects (P-δ) effects, the allowable bending stress is reduced by the \(1 - \frac{f_a}{F_{ex}}\) term in the interaction equation. When the member, has high axial and bending stress, the above term can be conservative and can increase the UC in the ASD-89 method.

![Figure 21: Rig 4 Operating Load Case 502 UC Results -Ph2-Sens2](image-url)
Figure 22: Rig 4 Critical Load Case ASD-89 UC Results- Ph2-Sens2
Figure 23: Rig 4 Critical Load Case LRFD-05 UC Results -Ph2-Sens2
### Table 11: Interaction of Axial Force and Flexure Comparison

<table>
<thead>
<tr>
<th>Specification</th>
<th>Analysis Type</th>
<th>Interaction Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISC 1989</td>
<td>First Order</td>
<td>( \frac{f_a}{F_a} + \frac{c_{mx} f_{bx}}{\left(1 - \frac{f_a}{F_{ex}}\right) F_{bx}} + \frac{c_{my} f_{by}}{\left(1 - \frac{f_a}{F_{ey}}\right) F_{by}} ) (Axial and Bending Stress)</td>
</tr>
</tbody>
</table>
| AISC 2005 LRFD & ASD | Requires Second Order (P-Δ and P-δ) | 1) Direct Analysis Method  
2) Effective Length Method  
3) Amplified First Order  
4) First Order Method |
|               |               | \( \frac{P_r}{P_c} + \frac{8}{9} \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) \) (Axial Force and Bending Moment) |
Figure 24 shows the UC plot for Rig4 an expected load case (LC 602 in Rig4 model) using the ASD-89 and LRFD-05 for Ph2-Sens2 load factors. The results shows that the UC for the Ph2-Sens2 load factors selected for the LRFD-05 are comparable to the ASD-89 method.

![Figure 24: Rig 4 Expected Load Case 602 UC Results-Ph2-Sens2](image-url)
4.2 Conclusions

The primary objective of the design study was to understand the impact of transitioning API specification 4F from the allowable stress methodology specified in AISC-1989 to the LRFD methodology specified in AISC-2005 specification.

In the LRFD method, the required strength is determined by performing structural analysis for the appropriate load combinations. The nominal loads in the load combinations are factored by partial load factors. In the AISC-05 specification the load combinations and load factors are based on ASCE 7 standards. The load combinations and load factors in ASCE 7 are suitable for building and building like structures. The AISC LRFD methodology is based on: 1) probabilistic modes of load and resistance; 2) a calibration of the LRFD provisions to the 1978 edition of the AISC specification for selected members; and 3) comparative design studies of representative structures.

The LRFD calibration to the 1978 edition is based on a live load to dead load ratio of 3, and the effective load factor for gravity loads is 1.5. For gravity load cases, if the second-order effects are negligible then any combination of partial load factors which gives an effective load factor of 1.5 will provide a comparable design between LRFD-05 and ASD-89 specification.

For the API 4F design study, the steering committee selected load factors for dead loads, hook loads, rotary loads, setback loads and environmental loads for operation, unexpected and expected load cases from design codes such as DNV [8] and API RP2A LRFD [9]. The partial load factors were not based on load statistics pertaining to drilling derricks or masts. In the LRFD method, the member design depends primarily on the partial load factor selected for the various load cases and the second order effects. Due to differences in the design methodology between LRFD-05 and ASD-89, a single set of load factors will not provide an equivalent design for every member in a derrick or mast.

Table 12 shows the effective load factor for a gravity load case. The first row in Table 12 is for the primary gravity load case for building structure. The effective load factor for the other load factors selected for the Phase1 and Phase2 design study is also shown in Table 12. It should be noted that the effective load factor is based on only the gravity load case. Other load cases where the environmental loads are dominant are not used to calculate the effective load factor. The effective load factor for the Ph2-Sens2 is closer to the effective load factor used for calibration, and the LRFD design based on the Ph2-Sens2 load factor is expected to be closer to the ASD-89 design.

The results from the Phase1 and Phase2 design study show that the Ph2-Sens2 load factors provide the best correlation between LRFD-05 and ASD-89 for Rig1 to Rig4 structures. The results from the Ph2-Sens3 load factors for Rig2 mast and substructure models showed that the UC value for the LRFD-05 design is considerably higher than the ASD-89 approach for most of the members.
Table 12: Effective Load Factors for Phase 1 and Phase 2 Study

<table>
<thead>
<tr>
<th>Load Factors</th>
<th>Effective Load Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISC LRFD-05 with ASCE 7 Load Factors of 1.2 Dead +1.6 Live</td>
<td>1.5</td>
</tr>
<tr>
<td>Phase 1</td>
<td>1.3</td>
</tr>
<tr>
<td>Phase 2-Sensitivity 1</td>
<td>1.225</td>
</tr>
<tr>
<td>Phase 2-Sensitivity 2</td>
<td>1.45</td>
</tr>
<tr>
<td>Phase 2-Sensitivity 3</td>
<td>1.71</td>
</tr>
</tbody>
</table>

Typical designs performed using the ASD-89 specification do not account for the second-order effects. For structures with adequate lateral stiffness, the increase in member force due to second-order effects are not significant and the second order to first order drift ratio is typically less than 1.1. On the other hand, for slender structures, the second-order effects can be significant. Therefore, the member forces are amplified significantly. The members in slender structure designed according to the AISC-05 specification will have a higher UC ratio than the first order analysis methods used for the Allowable Stress Design methodology specified in AISC-89.

In AISC-05, member design can be performed using LRFD design methodology with factored load combinations or using the Allowable Strength Design (ASD-05) methodology with unfactored load combinations. However, to achieve the same second order effects, the ASD load combinations should be factored by a uniform factor during analyses; and during member design, the forces and bending moments are divided by the uniform load factor. The stability analysis requirements are the same for the LRFD-05 and ASD-05 methodologies. The advantage of using the ASD-05 methodology is that the partial load factors need not be selected for each load case. All the load cases can be multiplied by a single load factor (for example 1.6) during analysis and scaled back by the same factor during design. If the structure has significant amplification due to second order effects then ASD-05 design will be conservative/heavier than the ASD-89 design.

5. Future Work

SES proposes the following work as a continuation of the design study to finalize the load factors, analysis methodology and procedure to meet the AISC-05 specification.

1. Complete Rig5 LRFD study

2. Comparison of analysis and design procedures for Allowable Strength Design (ASD) and LRFD per the AISC specification.
6. References


7. ASCE (2005), Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-05, American Society of Civil Engineers, Reston, VA.


Appendix A: Design Results
API 4F Design Study: ASD-89 to LRFD-05

Phase 2 - Load Factor Sensitivity Results

Date: 27 June 2016

Prepared for: API
Prepared by: Sathish Ramamoorthy, PhD, PE

Taking on your toughest technical challenges.
Phase 2 – Approved Tasks

- Classify all possible loads into appropriate categories as either permanent or variable loads, similar to API RP-2A, and recommend load factors for all loading conditions.
- Select partial load factors for API 4F load combinations
  - SES recommends the load factors specified in API RP 2A-LRFD [5]. The steering committee formed for the API 4F transition study will be responsible for selecting the load factors.
- Sensitivity Study
  - SES will repeat the design study for operational, expected and unexpected loading conditions with the new set of load factors for Rig 1 through Rig 5.
  - Transportation and seismic load cases will not be included in the sensitivity study.
- Report documenting the sensitivity study results for derricks and masts.
Phase2-Deliverables Status

• Load factors for Operation, Unexpected and Expected load conditions are selected by the steering committee for design study
  ▪ Task Group to recommend load factors for operation, unexpected and expected load case.
  ▪ Load factors for other load cases not selected.

• Code Comparison Study for Five Different Rigs
  ▪ Rig1, Rig2, Rig3 and Rig 4 Completed
    – Rig2 had convergence issues with higher load factors due to buckling issues. (Not resolved. Details discussed in the Results Section)
  ▪ For Rig 5 only the operational load case is completed.
    – Cable tension was not applied correctly in the model.

• Report Documenting the Sensitivity Study
  ▪ Draft Report will be issued in July 2016
Outline

• Review Phase 2 Load Factors
  ▪ Basis of AISC LRFD calibration and Load factors

• Review Phase 2 Sensitivity Study Results
  ▪ Results for Rig1 to Rig4.
  ▪ Emphasis on Rig2 –Land Rig (Mast and Substructure)
  ▪ Rig 5 (Workover mast is incomplete at this time)

• Nonlinear analysis
  ▪ Convergence Issues for Rig2

• Path Forward
  ▪ Recommend Load Factors
  ▪ Decide on follow-up work
# Model Details

Provided to SES for Design Study

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Type</th>
<th>Hook Load (kip)</th>
<th>No of Lines</th>
<th>Set Back (kip)</th>
<th>Height (ft)</th>
<th>Reference Wind Speed (knots)</th>
<th>Elevation from Water Line (ft)</th>
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</thead>
<tbody>
<tr>
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<td></td>
<td></td>
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<td></td>
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<td>Operating</td>
<td>Unexpected</td>
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<tr>
<td>Rig 1</td>
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<td>42</td>
<td>70</td>
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<td>Rig 2</td>
<td>Mast &amp; Substructure</td>
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<td>500</td>
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<td>1750</td>
<td>242</td>
<td>65.1</td>
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<td></td>
<td></td>
<td>1500 (Aux)</td>
<td>14 (Aux)</td>
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<tr>
<td>Rig 5**</td>
<td>Workover Mast</td>
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<td>6</td>
<td>NA</td>
<td>104</td>
<td>25</td>
<td>60</td>
</tr>
</tbody>
</table>

**Notes:**
- Analytical models for Rig1 to Rig 4 were originally developed in StruCAD and converted to SAP 2000
- **Rig 5**, Analytical model was developed in STAAD and converted to SAP2000
- **NA**: Not available
Rig Structures - Mast

Rig1
Offshore Mast

Rig2
Land Mast

Rig5
Workover Mast
Rig Structures- Derrick

Rig3
Single Derrick

Rig4
Dual Derrick
API 4F–4th Edition
(AISC- ASD 1989 Spec)

- API 4F load combinations
  - API 4F - Table 7.1 – Design Loadings for Drilling Structures

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads</th>
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</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>100</td>
<td>TE</td>
<td>100</td>
<td>100</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>100</td>
<td>TE</td>
<td>100</td>
<td>0</td>
<td>100% Expected Environment</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>100</td>
<td>TE</td>
<td>100</td>
<td>100</td>
<td>100% Unexpected Environment</td>
</tr>
<tr>
<td>3b</td>
<td>Unexpected</td>
<td>100</td>
<td>As Applicable</td>
<td>As Applicable</td>
<td>As Applicable</td>
<td>100% Earthquake</td>
</tr>
<tr>
<td>4</td>
<td>Erection</td>
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<td>As Applicable</td>
<td>As Applicable</td>
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</tr>
<tr>
<td>5</td>
<td>Transportation</td>
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<td>As Applicable</td>
<td>As Applicable</td>
<td>As Applicable</td>
<td>100% Transportation Environment</td>
</tr>
</tbody>
</table>

TE → Weight of all travelling equipment and drill lines suspended from the crown
LRFD Methodology
AISC-05 Specification

• Demand and Capacity
  \[ R_u \leq \phi R_n \]
  \( R_u \) = required strength using LRFD load combinations
  \( R_n \) = nominal strength, specified in chapters B through K
  \( \phi \) = resistance factor, specified in chapters B through K

• For Design Study
  - Load Factors (adapted from DNV & API-RP-2A LRFD code)
  - Resistance Factors (from AISC-05 Specification)
### API 4F–LRFD

**Phase 1- Design Study Load Factors**

- **API 4F load combinations**
  - **API 4F - Table 7.1 – Design Loadings for Drilling Structures**

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>130</td>
<td>130</td>
<td>0</td>
<td>130</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>130</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>0</td>
<td>130% Expected Environment</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>130</td>
<td>130 TE</td>
<td>130</td>
<td>130</td>
<td>130% Unexpected Environment</td>
</tr>
</tbody>
</table>

TE ➔ Weight of all travelling equipment and drill lines suspended from the crown
**API 4F–LRFD**

**Phase 2- Sensitivity Study using API RP 2A**

- **API 4F load combinations-Sensitivity 1**

  - **API 4F - Table 7.1 – Design Loadings for Drilling Structures**

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>130</td>
<td>120</td>
<td>0</td>
<td>120</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>120 TE</td>
<td>120</td>
<td>120</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>0</td>
<td>135% Expected Environment</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>110</td>
<td>135% Unexpected Environment</td>
</tr>
</tbody>
</table>

TE ➔ Weight of all travelling equipment and drill lines suspended from the crown
API 4F–LRFD
Phase 2- Sensitivity Study using API RP 2A

- **API 4F load combinations-Sensitivity 2**

  - **API 4F - Table 7.1 – Design Loadings for Drilling Structures**

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads</th>
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</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>130</td>
<td>150</td>
<td>0</td>
<td>150</td>
<td><strong>100% Operating Environment</strong></td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>150 TE</td>
<td>150</td>
<td>150</td>
<td><strong>100% Operating Environment</strong></td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>0</td>
<td><strong>135% Expected Environment</strong></td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>110</td>
<td><strong>135% Unexpected Environment</strong></td>
</tr>
</tbody>
</table>

TE $\rightarrow$ Weight of all travelling equipment and drill lines suspended from the crown
API 4F–LRFD
Phase 2- Sensitivity Study using API RP 2A

• API 4F load combinations- Sensitivity 3
  – Only for Rig 2 Structure (Suggested by Denny Wong @ DrillMecInc)

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads</th>
</tr>
</thead>
<tbody>
<tr>
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<td>168</td>
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<td>100% Operating Environment</td>
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<tr>
<td>1b</td>
<td>Operating</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>171.9</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>180</td>
<td>168 TE</td>
<td>168</td>
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<tr>
<td>3a</td>
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<td>180</td>
<td>168 TE</td>
<td>168</td>
<td>171.9</td>
<td>135% Unexpected Environment</td>
</tr>
</tbody>
</table>

TE ➔ Weight of all travelling equipment and drill lines suspended from the crown
Background on “Calibration” of LRFD to ASD

• First LRFD Code “Calibration”
  ▪ 1986 LRFD (ϕ) factor calibrated to Allowable Stress Design Methodology (1978 specification) at live load to dead load ratio (L/D) ratio of 3.0 for selected member and limit states

• 2005- Combined Specification (LRFD and ASD)
  ▪ Allowable Strength Design, ASD-05 Safety factor (Ω) was calibrated to (ϕ) at a L/D ratio of 3 for ASCE 7-2005 load factors.

• Other L to D ratio, different load combinations will not provide the same results, but will be close.
## SAP Analysis Results (AISC-89 vs. AISC-2005)

### Phase 1

**Number of Elements with UC > 1.0**

<table>
<thead>
<tr>
<th>Rig # (Total Number of Elements)</th>
<th>RIG #1 Bootstrap Mast (363)</th>
<th>RIG #2 Mast with Substructure (924)</th>
<th>RIG #3 Derrick (1545)</th>
<th>RIG #4 Dual Derrick (1149)</th>
<th>RIG #5 Workover Mast (467)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASD ‘89 W/O 1/3</td>
<td>24</td>
<td>31</td>
<td>20</td>
<td>301</td>
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</tr>
<tr>
<td>ASD ‘89 W/ 1/3</td>
<td>19</td>
<td>23</td>
<td>11</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>ASD 05 P-Δ Factor 1.3</td>
<td>27</td>
<td>106‡</td>
<td>41</td>
<td>216</td>
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<tr>
<td>LRFD 05</td>
<td>5</td>
<td>67</td>
<td>21</td>
<td>140</td>
<td></td>
</tr>
</tbody>
</table>

‡ One of the Operational Load Cases did not converge and is excluded from design
**SAP Analysis Results (AISC-89 vs. AISC-2005)**  
**Phase 1 and Phase 2**  
**Number of Elements with UC > 1.0**

<table>
<thead>
<tr>
<th>Rig # (Total Number of Elements)</th>
<th>RIG #1 Bootstrap Mast (363)</th>
<th>RIG #2 Mast with Substructure (924)</th>
<th>RIG #3 Derrick (1545)</th>
<th>RIG #4 Dual Derrick (1149)</th>
<th>RIG #5 Workover Mast (467)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASD '89 W/ 1/3</td>
<td>19</td>
<td>23</td>
<td>11</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>LRFD 05 Phase1</td>
<td>5</td>
<td>67</td>
<td>21</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>LRFD-05 Phase2-Sens1</td>
<td>3</td>
<td>41</td>
<td>20</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>LRFD-05 Phase2-Sens2</td>
<td>18</td>
<td>202‡</td>
<td>30</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>LRFD-05 Phase2-Sens3</td>
<td>Not Performed</td>
<td>93</td>
<td>Not Performed</td>
<td>Not Performed</td>
<td></td>
</tr>
</tbody>
</table>

‡ Several Operational Load Cases did not converge.
Rig 1
Results
Rig 1 Results (ASD-89 vs. LRFD-05-Phase1)
Critical Load Case

ASD-89 results are with 1/3rd Stress Increase

LRFD-05 results are without 1/3rd Stress Increase

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.915
UC Ratio Std. Dev: 0.241
UC Correlation: 0.91
N= 363
Rig 1 Results (ASD-89 vs. LRFD-05-Phase2-Sens1)
Critical Load Case

Ratio = LRFD-05/ASD-89
UC Ratio Mean: **0.898**
UC Ratio Std. Dev: **0.236**
UC Correlation: **0.90**
N= 363
Rig 1 Results (ASD-89 vs. LRFD-05-Phase2-Sens2) Critical Load Case

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.009
UC Ratio Std. Dev: 0.288
UC Correlation: 0.91
N= 363
Rig1-Critical Load Case

<table>
<thead>
<tr>
<th>Statistics</th>
<th>LRFD_Ph1</th>
<th>LRFD_Ph2_S1</th>
<th>LRFD_Ph2_S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC Ratio Mean</td>
<td>0.915</td>
<td>0.898</td>
<td>1.009</td>
</tr>
<tr>
<td>UC Ratio SD</td>
<td>0.241</td>
<td>0.236</td>
<td>0.288</td>
</tr>
<tr>
<td>UC Correlation</td>
<td>0.91</td>
<td>0.90</td>
<td>0.91</td>
</tr>
</tbody>
</table>
## Rig1- Displacements

### LRFD Operational Load Case (SCAD17-NL)

<table>
<thead>
<tr>
<th>Translation/Rotation</th>
<th>Phase1 (ASD-89)</th>
<th>Phase 1</th>
<th>Phase2 Sens1</th>
<th>Phase2 Sens2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without P-delta</td>
<td>with P-delta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ux</td>
<td>1.894</td>
<td>2.329</td>
<td>2.896</td>
<td>2.695</td>
</tr>
<tr>
<td>Uy</td>
<td>0.205</td>
<td>0.330</td>
<td>0.527</td>
<td>0.450</td>
</tr>
<tr>
<td>Uz</td>
<td>-0.629</td>
<td>-0.655</td>
<td>-0.845</td>
<td>-0.784</td>
</tr>
<tr>
<td>Rx</td>
<td>-0.0008</td>
<td>-0.0010</td>
<td>-0.0014</td>
<td>-0.0013</td>
</tr>
<tr>
<td>Ry</td>
<td>0.0035</td>
<td>0.0045</td>
<td>0.0057</td>
<td>0.0053</td>
</tr>
<tr>
<td>Rz</td>
<td>0.0011</td>
<td>0.0018</td>
<td>0.0030</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

**Units:**
- Translation: *inches*
- Rotation: *radians*
Rig 2

Results
Rig2-Model Details

Members with Tension/Compression limit, moment releases (member attributes) and soil springs
Rig2- Substructure

Rig2 operating load cases had convergence issues for higher load factor (Phase2 load factors).
Some of the factors contributing to the non-convergence are:
1) Plate elements at the rig floor is removed during StruCAD to SAP conversion
2) Element Attributes
3) Spring elements

Needs further assessment to understand the cause of the non-convergence.

- Moment Releases (Mx, My)
- Releases (P, T, Mx, My)
Rig 2
Mast Only Results
Rig2- Mast Only Model

The substructure of the mast is removed and the legs are pinned. Analysis for the Phase1 and Phase2 load factors were performed and all load cases converged.

- Moment Releases (Mx, My)
Rig 2-Mast Only
Results Critical Load Case-UC Values
Rig2- Mast Only Displacements

LRFD Operational Load Case (SCAD111-NL)

<table>
<thead>
<tr>
<th>Translation /Rotation</th>
<th>Phase1 (ASD-89)</th>
<th>Phase1</th>
<th>Phase2 Sens1</th>
<th>Phase2 Sens2</th>
<th>Phase2 Sens3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without P-delta</td>
<td>with P-delta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ux</td>
<td>1.512</td>
<td>2.272</td>
<td>3.244</td>
<td>2.883</td>
<td>4.310</td>
</tr>
<tr>
<td>Uz</td>
<td>-0.833</td>
<td>-0.857</td>
<td>-1.118</td>
<td>-1.038</td>
<td>-1.284</td>
</tr>
<tr>
<td>Rx</td>
<td>-0.0009</td>
<td>0.0009</td>
<td>-0.0012</td>
<td>-0.0011</td>
<td>-0.0014</td>
</tr>
<tr>
<td>Ry</td>
<td>0.0006</td>
<td>0.00145</td>
<td>0.0023</td>
<td>0.0019</td>
<td>0.0033</td>
</tr>
<tr>
<td>Rz</td>
<td>-0.0117</td>
<td>-0.0205</td>
<td>-0.0353</td>
<td>-0.0288</td>
<td>-0.0536</td>
</tr>
</tbody>
</table>

Units:
Translation: *inches*
Rotation: *radians*
Rig 2 Results (ASD-89 vs. LRFD-05-Phase1)

Critical Load Case

Mast Only

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.996
UC Ratio Std. Dev: 0.306
UC Correlation: 0.94
N= 234
Rig 2 Results (ASD-89 vs. LRFD-05-Phase2-Sens1)

Critical Load Case

Mast Only

CriticalLoadCase_LRFD05_Phase2_Sens1

CriticalLoadCase_ASD89

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.990
UC Ratio Std. Dev: 0.329
UC Correlation: 0.93
N= 234
Rig 2 Results (ASD-89 vs. LRFD-05-Phase2-Sens2)
Critical Load Case

Mast Only

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.099
UC Ratio Std. Dev: 0.357
UC Correlation: 0.93
N= 234
Rig 2 Results (ASD-89 vs. LRFD-05-Phase2-Sens3)  
Critical Load Case  
Mast Only  

Ratio = LRFD-05/ASD-89  
UC Ratio Mean: 1.323  
UC Ratio Std. Dev: 0.554  
UC Correlation: 0.88  
N= 234
Rig 2
Substructure Only Results
Rig 2 Results (ASD-89 vs. LRFD-05-Phase1) Critical Load Case

Substructure Only

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.136
UC Ratio Std. Dev: 0.820
UC Correlation: 0.85
N= 688
Rig 2 Results (ASD-89 vs. LRFD-05-Phase2-Sens1)

Critical Load Case

Substructure Only

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.134
UC Ratio Std. Dev: 0.878
UC Correlation: 0.82
N= 688
Rig 2 Results (ASD-89 vs. LRFD-05-Phase2-Sens2)

Critical Load Case

Substructure Only

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.206
UC Ratio Std. Dev: 0.862
UC Correlation: 0.86
N= 688
Rig 2 Results (ASD-89 vs. LRFD-05-Phase2-Sens3) Critical Load Case

Substructure Only

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 1.372
UC Ratio Std. Dev: 0.860
UC Correlation: 0.89
N= 688
Rig 3
Results
Rig 3 Results (ASD-89 vs. LRFD-05-Phase1)  
Critical Load Case
Rig 3 Results (ASD-89 vs. LRFD-05-Phase2-Sens2)

Critical Load Case

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.949
UC Ratio Std. Dev: 0.206
UC Correlation: 0.95
N= 1484
## Rig3- Displacements

### LRFD Operational Load Case (SCAD60-NL)

<table>
<thead>
<tr>
<th>Translation/Rotation</th>
<th>Phase 1 (ASD-89)</th>
<th>Phase 1</th>
<th>Phase 2 Sens1</th>
<th>Phase 2 Sens2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without P-delta</td>
<td>with P-delta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ux</td>
<td>0.124</td>
<td>0.127</td>
<td>-0.069</td>
<td>-0.032</td>
</tr>
<tr>
<td>Uy</td>
<td>1.037</td>
<td>1.063</td>
<td>1.394</td>
<td>1.286</td>
</tr>
<tr>
<td>Uz</td>
<td>-1.036</td>
<td>-1.035</td>
<td>-1.348</td>
<td>-1.259</td>
</tr>
<tr>
<td>Rx</td>
<td>-0.0017</td>
<td>-0.0018</td>
<td>-0.0024</td>
<td>-0.0022</td>
</tr>
<tr>
<td>Ry</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Rz</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

### Units:
- Translation: *inches*
- Rotation: *radians*
Rig 4
Results
Rig 4 Results (ASD-89 vs. LRFD-05-Phase1)

Critical Load Case

![Graph showing the comparison of critical load cases](image)

- Ratio = LRFD-05/ASD-89
- UC Ratio Mean: 0.957
- UC Ratio Std. Dev: 0.188
- UC Correlation: 1.0
- N = 1149
Rig 4 Results (ASD-89 vs. LRFD-05-Phase2-Sens1)

Critical Load Case

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.951
UC Ratio Std. Dev: 0.184
UC Correlation: 1.0
N= 1149
Rig 4 Results (ASD-89 vs. LRFD-05-Phase2-Sens2)

Critical Load Case

Ratio = LRFD-05/ASD-89
UC Ratio Mean: 0.966
UC Ratio Std. Dev: 0.175
UC Correlation: 1.0
N = 1149
Rig 4 Results (ASD-89 vs. LRFD-05) Phase 1

**Operating**
LRFD-05: 1.3*Dead +1.3*Hook+1.0*Wind
ASD-89: 1.0(Dead +Hook +Wind)

**Expected**
LRFD-05: 1.3*Dead +1.3*Hook+1.3*Wind
ASD-89: 1.0*(Dead +Hook +Wind)
Rig 4 Results (ASD-89 vs. LRFD-05)
Phase 2-Sens1

Operating
LRFD-05: 1.3*Dead +1.2*Hook+1.0*Wind
ASD-89: 1.0(Dead +Hook +Wind)

Expected
LRFD-05: 1.3*Dead +1.1*Hook+1.35*Wind
ASD-89: 1.0*(Dead +Hook +Wind)
Rig 4 Results (ASD-89 vs. LRFD-05)  
Phase 2-Sens2

**Operating**  
LRFD-05: 1.3*Dead +1.5*Hook+1.0*Wind  
ASD-89: 1.0(Dead +Hook +Wind)

**Expected**  
LRFD-05: 1.3*Dead +1.1*Hook+1.35*Wind  
ASD-89: 1.0*(Dead +Hook +Wind)
## Rig4- Displacements

**LRFD Operational Load Case (SCAD501-NL)**

<table>
<thead>
<tr>
<th>Translation/Rotation</th>
<th>Phase 1 (ASD-89)</th>
<th>Phase 1</th>
<th>Phase 2 Sens1</th>
<th>Phase 2 Sens2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without P-delta</td>
<td>with P-delta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ux</td>
<td>1.676</td>
<td>1.700</td>
<td>1.842</td>
<td>1.801</td>
</tr>
<tr>
<td>Uy</td>
<td>-0.029</td>
<td>-0.038</td>
<td>-0.062</td>
<td>-0.057</td>
</tr>
<tr>
<td>Uz</td>
<td>-1.202</td>
<td>-1.211</td>
<td>-1.547</td>
<td>-1.475</td>
</tr>
<tr>
<td>Rx</td>
<td>0.0001</td>
<td>0.0001</td>
<td>-0.0002</td>
<td>0.0002</td>
</tr>
<tr>
<td>Ry</td>
<td>-0.0066</td>
<td>-0.0067</td>
<td>-0.0088</td>
<td>-0.0082</td>
</tr>
<tr>
<td>Rz</td>
<td>0.0011</td>
<td>0.0011</td>
<td>0.0015</td>
<td>0.0013</td>
</tr>
</tbody>
</table>

**Units:**
- Translation: *inches*
- Rotation: *radians*
Rig5

• Current model has operational Load case.
• Received Models for Unexpected and Expected Load Cases
• Cable Tension, Nonlinear analysis Parameters
Observations and Discussion of Results (1/3)

- Based on the Phase1 and Phase2 results. The following load factors provide the best correlation.

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Loading Condition</th>
<th>Dead Load (%)</th>
<th>Hook Load (%)</th>
<th>Rotary Load (%)</th>
<th>Setback Load (%)</th>
<th>Environmental Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Operating</td>
<td>130</td>
<td>150</td>
<td>0</td>
<td>150</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>1b</td>
<td>Operating</td>
<td>130</td>
<td>150 TE</td>
<td>150</td>
<td>150</td>
<td>100% Operating Environment</td>
</tr>
<tr>
<td>2</td>
<td>Expected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>0</td>
<td>135% Expected Environment</td>
</tr>
<tr>
<td>3a</td>
<td>Unexpected</td>
<td>130</td>
<td>110 TE</td>
<td>110</td>
<td>110</td>
<td>135% Unexpected Environment</td>
</tr>
</tbody>
</table>
Observations and Discussion of Results (2/3)

• Derrick/Mast Modeling (Structure Idealization)
  ▪ Modeling of member attributes, springs, dummy member and offsets affects nonlinear analysis.
    – Nonlinear analysis are sensitive to model assumptions and several solutions are possible depending on the load factors.
  ▪ AISC Stability methods requires to account for second order effects
    • Direct Analysis Method, eliminates use of “K” factors. However requires addition of “notional loads” to meet the specification requirements.
  ▪ If the second order effect is less (less than 1.5 for LRFD load combination) then “Effective Length” method can be used.
Observations and Discussion of Results (3/3)

• No significant change in member strength calculation
  ▪ No significant change in estimating member strength for tension, compression, bending, shear and torsion limit states

• In general, member design results do not change significantly with change in design code if
  ▪ Second order effects (P-Δ and P-δ) are not significant
## AISC Specification - Comparison

<table>
<thead>
<tr>
<th>Specification</th>
<th>Analysis Type</th>
<th>Interaction Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISC 1989</td>
<td>First Order</td>
<td>$\frac{f_a}{F_a} + \frac{c_{mx}f_{bx}}{\left(1 - \frac{f_a}{F_{ex}'}\right)F_{bx}} + \frac{c_{my}f_{by}}{\left(1 - \frac{f_a}{F_{ey}'}\right)F_{by}}$</td>
</tr>
<tr>
<td></td>
<td>Second-order effect due to member deformation (P-δ) is accounted in the interaction equation</td>
<td>(Axial and Bending Stress)</td>
</tr>
<tr>
<td>AISC 2005 LRFD &amp; ASD</td>
<td>Requires Second Order (P-Δ and P-δ)</td>
<td>$\frac{P_r}{P_c} + \frac{8}{9} \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right)$</td>
</tr>
</tbody>
</table>
Path Forward for API 4F Transition to LRFD

• Recommend Load Factors for Operation, Unexpected and Expected load cases.
• Select load factors for other load cases.
• Design study focused on the global analysis and member limit states.
  ▪ Connections and local member checks comparisons were not performed.