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Complete Stress Analysis of Sucker-Rod Pumping Installations

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Stress is defined as a material’s internal resistance per unit area when an external load is applied to it.

Stress analysis is the practice of evaluating the stress distribution within a given material.

Yield strength is the stress at which a material will begin to undergo plastic deformation.

Tensile strength is the maximum stress a material can withstand while pulled or stretched before it either fails or breaks.

There are two types of failures when dealing with sucker-rod pumps, tensile failures and fatigue failures.
Tensile failures are rare and occur when the rods are over-stressed, i.e. the force exerted on the material results in an axial pulling force overcoming the tensile strength of the material.

Fatigue failures can occur from repeated load variations within the rod string.

Rod failures are mostly attributed to fatigue breaks, which occur at stress levels well below the ultimate tensile strength or even below the yield strength of the steel rods.

Fatigue endurance limit for any material, pertaining to steel rods, is the maximum stress level at which the steel can sustain cyclic loading conditions for a minimum of ten million cycles.
FINITE DIFFERENCE MESH (1/2)

• Using finite differences to solve the wave equation allows for a space discretization, i.e. the formation of a mesh, a mesh is created in both time and space.

• Let $N$ be the number of recorded surface data points and $M$ be the total number of finite difference nodes along the rod string down the wellbore, such that $M$ is the last point above the pump.

• Let $\{i\}_{1}^{M}$ represent the vector of finite difference nodes along the rod string.

• Let $\{j\}_{1}^{N}$ represent the vector of sample points taken at the surface.
• The $i$ direction is positive downwards as the mesh progresses down the rod string, while the $j$ direction is taken to be the time increments between the surface data readings

• Allows each taper to be split into numerous smaller section as short as a few feet

• Position, load and therefore stress can be computed at any finite difference node

• In an effort to provide a complete and thorough stress analysis, the finite difference elements, or nodes, are selected in such a way that the $\Delta x$ or spacing in between each node is of similar magnitude for each taper
FAILURE PREVENTION

Three critical areas in preventing rod failure:

• Proper rod design and proper handling
  – Avoiding the creation of stress raisers caused by mechanical damage

• Appropriate pump-off control
  – fluid pound and gas pound cause shock waves in the rod string as the plunger hits the fluid

• Stress analysis
  – keep peak rod stress within safe limits
• Tapers in the rod string are comprised of different length and material

• The weight of the sucker-rod string is distributed along its length, meaning any rod element has to carry at least the weight of the rods below it

• Rod strings are subject to cyclic loading, which creates a pulsating tension on the rod string

• Changes in cross sectional area in the rod string create areas of concentrated local stress

• The use of a quasi-uniform mesh allows for a more detailed and practical analysis of the stress functions
CUBIC SPLINE INTERPOLATION (1/2)

- Enables for the computation of position, load and stress at any level down the rod string.
- Provides a way of interpolating the stress data, so that a stress value can be output at any level down the rod string.
- Stress data created is a series of values, which are taper specific.
- Progression of the stress data per taper follows a quasi linear behavior.
- Maximum tensile stress occurs at the bottom surface.
- Maximum compression stress occurs at the top surface.
• Cubic spline interpolation involves only four constants for each stress data point in order to approximate each taper

• Cubic splines being polynomials of third degree are therefore continuously differentiable on the taper interval, providing a continuous second derivative

• Calculus methods can therefore be used on the smooth cubic spline interpolant in order to search for possible stress raisers and imperfections in the stress data

• Using the stress versus depth data, a cubic spline interpolant is generated for each taper
Uniform normal stress \( \sigma = \frac{F}{A} \)

- The minimum stress, the maximum stress and the maximum allowable stress can be computed at any finite difference node down the rod string.
- The maximum allowable stress represents the maximum tension stress allowed in any particular element before the material properties of said element will undergo plastic deformation.
- The computation of the maximum allowable stress uses the minimum stress and the taper specific values of tensile strength and service.
Results: Example 1

Pump Fillage | 92.72 | Minimum Stress | 9425
F0up        | 7404   | Maximum Stress | 21218
F0down      | -311   | Max Allow Stress | 34052

<table>
<thead>
<tr>
<th>Taper 1</th>
<th>Taper 2</th>
<th>Taper 3</th>
<th>Taper 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rods</td>
<td>90</td>
<td>114</td>
<td>66</td>
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<tr>
<td>Length of rods</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<tr>
<td>Type of rod</td>
<td>N97</td>
<td>N97</td>
<td>N97</td>
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</tbody>
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Results: Example 1
Results: Example 2

<table>
<thead>
<tr>
<th></th>
<th>Taper 1</th>
<th>Taper 2</th>
<th>Taper 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rods</td>
<td>127</td>
<td>127</td>
<td>10</td>
</tr>
<tr>
<td>Length of rods</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Type of rod</td>
<td>D</td>
<td>D</td>
<td>SK</td>
</tr>
</tbody>
</table>

Pump Fillage: 92.72
F0up: 7404
F0down: -311
Minimum Stress: 11044
Maximum Stress: 20669
Max Allow Stress: 34962

Sept. 16 - 19, 2014 2014 Sucker Rod Pumping Workshop
Results: Example 2
Results: Example 3

<table>
<thead>
<tr>
<th>Pump Fillage</th>
<th>Minimum Stress</th>
<th>Maximum Stress</th>
<th>Max Allow Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0up</td>
<td>6407</td>
<td>21071</td>
<td>54022</td>
</tr>
<tr>
<td>F0down</td>
<td>632</td>
<td>21071</td>
<td>54022</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of rods</th>
<th>Length of rods</th>
<th>Type of rod</th>
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</thead>
<tbody>
<tr>
<td>101</td>
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<td>N97</td>
</tr>
<tr>
<td>116</td>
<td>25</td>
<td>N97</td>
</tr>
<tr>
<td>52</td>
<td>25</td>
<td>N97</td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>SK</td>
</tr>
</tbody>
</table>

For positions:
- Taper 1: 101 rods, 25 inches, N97
- Taper 2: 116 rods, 25 inches, N97
- Taper 3: 52 rods, 25 inches, N97
- Taper 4: 12 rods, 25 inches, SK
Results: Example 3

Stress Analysis: Example 3

Stress, lbs/ln*ft

Depth, feet

Min Stress
Max Stress
Max Allow Stress
Results: Example 4

Downhole Card: Example 4

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Pump Fillage</td>
<td>95.73</td>
<td>Minimum Stress</td>
<td>9425</td>
<td></td>
</tr>
<tr>
<td>F0up</td>
<td>3082</td>
<td>Maximum Stress</td>
<td>21218</td>
<td></td>
</tr>
<tr>
<td>F0down</td>
<td>-1030</td>
<td>Max Allow Stress</td>
<td>34052</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Taper 1</th>
<th>Taper 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rods</td>
<td>87</td>
<td>195</td>
</tr>
<tr>
<td>Length of rods</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Type of rod</td>
<td>D</td>
<td>D</td>
</tr>
</tbody>
</table>
Results: Example 4

![Stress Analysis: Example 4](image)

- Stress, lbs/in²
- Depth, feet
- Min Stress
- Max Stress
- Max Allow Stress

$4 \times 10^4$
The ability to compute stress values at any depth down the rod string allows for a better management of rod string life.

When the dogleg severity of the wellbore path is above a certain risk angle, it is then possible to focus on the stress values at that point and in the vicinity of that point, providing a better picture of the loads and stresses for that particular rod section.

This can be of critical value for anticipating rod failures.

Some sections of the rod string as mentioned above are more sensitive than others and therefore require a more detailed in depth analysis.

A methodology for computing minimum stress, maximum stress and maximum allowable stress at multiple finite difference elements down the rod string is necessary.
CONCLUSION (2/2)

• This methodology relies on the accurate computation of downhole data.

• Capability to compute interpolated stress values at any depth allows the user in-depth inspection of the stress distribution at a certain point or series of points, completing the optimal stress analysis picture. One of the biggest problems when using sucker-rod pumps on a well is rod failure.

• Based on the in-depth stress analysis, and the detailed results on the loading of any particular section of the rod string, the user can anticipate what the life of a rod, taper or installation is going to yield.
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