Ultrasonic Measurement of Loads in Bolts Used in Structural Joints

NESC NDE Face to Face Meeting, Michoud, LA
March 24, 2015

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Summary

- The paper is an overview of work by the author in measuring and monitoring loads in bolts using an ultrasonic extensometer.

- A number of cases of bolted joints are covered. These include,
  - a clamped joint with clearance fit between the bolt and hole,
  - a clamped joint with bolt in an interference fit with the hole,
  - a flanged joint which allows the flange and bolt to bend;
  - and a shear joint in a clevis and tang configuration.

- These applications were initially developed for measuring and monitoring preload in National Aeronautics and Space Administration (NASA) Space Shuttle Orbiter critical joints but are also applicable for monitoring loads in other critical bolted joints of structures such as transportation bridges and other aerospace structures.

- The papers cited here explain how to set-up a model to estimate the ultrasonic load factor and accuracy for the ultrasonic preload application in a clamped joint with clearance fit.

- The ultrasonic preload application for clamped joint with bolt in an interference fit can also be used to measure diametrical interference between the bolt shank and hole, as well as interference pressure on the bolt shank.

- Results of simulation and experimental data are given to demonstrate use of ultrasonic measurements in a shear joint.

- A bolt in a flanged joint experiences both tensile and bending loads. This application involves measurement of bending and tensile preload in a bolt.

- The ultrasonic beam bends due to bending load on the bolt. Results of a numerical technique to compute the trace of ultrasonic ray are presented.
List of Papers Included in This Paper

Section 1

Section 2

Section 3

Section 4

Section 5
Section 1. Clamped Bolted Joint\textsuperscript{11}: Ultrasonic Set-up

Figure 1 -- Ultrasonic preload configuration

Figure 4. Cut away of a clamped joint
1. Clamped Bolted Joint\textsuperscript{11}: Ultrasonic Measurement of Bolt Tension, Two Instruments

- Ultrasonic Method
  - Couple an ultrasonic transducer to one end of the bolt
  - Pulse/echo mode
  - Measure the apparent length of the bolt
  - Length measurement before and after application of the tension
  - Compute ultrasonic stretch
  - Preload is proportional to ultrasonic stretch

\textbf{Raymond Boltgage Equation}

\[ P_R = \left( \frac{AEK_R}{L} \right) \left( \frac{V_m}{V_i} \right) \delta L_c + Y \]

\textbf{StressTel Boltmike Equation}

\[ P_S = \left( \frac{V_m}{V} \right) \left( \frac{AE}{1 - \alpha} \right) \left( \frac{\delta L_c}{L + \delta L_c} \right) + Y \quad \alpha = \frac{\Delta V_m}{\varepsilon \cdot V_m} \]

\( P = \) Preload, lb
\( A = \) Bolt cross section area, in\(^2\)
\( E = \) Young’s modulus, lb/in\(^2\)
\( K_R = \) Raymond Stress factor (\(-0.3\) for steel),
\( L = \) Bolt effective length under tensile stress, in,
\( V_m = \) Ultrasonic velocity in material, in/sec,
\( V_i = \) Instrument setting for ultrasonic velocity, in/sec,
\( \delta L_c = \) Temperature compensated ultrasonic stretch, in,
\( Y = \) Y intercept of calibration linear fit
\( \alpha = \) Acoustoelastic constant
\( \varepsilon = \) Strain.

Raymond Boltgage is predecessor to extensometers by Bidwell Industrial Group, Middletown, CT, USA and StressTel Boltmike is predecessor to extensometers by General Electric Inspection Technology.
1. Clamped Bolted Joint\textsuperscript{11}: Comparison of Preload Equations and Error Estimation

\[ \left( \frac{\Delta P_R}{P_R} \right)^2 = \left( \frac{\Delta E}{E} \right)^2 + \left( \frac{\Delta V_m}{V_m} \right)^2 + \left( \frac{\Delta A}{A} \right)^2 + \left( \frac{\Delta L_g}{L_g} \right)^2 + \left( \frac{\Delta \alpha}{1 - \alpha} \right)^2 + \left( \frac{\Delta \delta L_c}{\partial L_c} \right)^2 + \left( \frac{\Delta Y}{P_R} \right)^2 \]

\[ (\Delta \delta L_c)^2 = \left( [\Delta \delta L_c]_{\text{coupling}} \right)^2 + \left( [\Delta \delta L_c]_{\text{temperature}} \right)^2 + \left( [\Delta \delta L_c]_{\text{instrument}} \right)^2 \]

*Figure 2 – Systematic errors*
1. Clamped Bolted Joint\textsuperscript{11}: Example of Error Estimation

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Parameter Symbol</th>
<th>Engineering Units</th>
<th>SI units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shank diameter</td>
<td>$D$</td>
<td>0.705 in</td>
<td>17.907 mm</td>
</tr>
<tr>
<td>Tolerance on the shank diameter</td>
<td>$\Delta D$</td>
<td>0.001 in</td>
<td>0.0254 mm</td>
</tr>
<tr>
<td>Velocity setting</td>
<td>$V$</td>
<td>232494 in/sec</td>
<td>5.90535 x 10^6 mm/sec</td>
</tr>
<tr>
<td>Ultrasound velocity in the fastener</td>
<td>$V_u$</td>
<td>232494 in/sec</td>
<td>5.90535 x 10^6 mm/sec</td>
</tr>
<tr>
<td>Tolerance on the ultrasound velocity</td>
<td>$\Delta V$</td>
<td>232.494 in/sec</td>
<td>5.90535 x 10^6 mm/sec</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$E$</td>
<td>3.1 x 10^12 psi</td>
<td>21840.9 kg/mm(^2)</td>
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<td>Tolerance on the Young’s modulus</td>
<td>$\Delta E$</td>
<td>3.1 x 10^12 psi</td>
<td>2.1841 kg/mm(^2)</td>
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<tr>
<td>Effective length</td>
<td>$L_{e}$</td>
<td>6.12 in</td>
<td>155.448 mm</td>
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<tr>
<td>Tolerance on the effective length</td>
<td>$\Delta L_{e}$</td>
<td>0.025 in</td>
<td>0.635 mm</td>
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<tr>
<td>Grip correction</td>
<td>$g_r$</td>
<td>0.649 in</td>
<td>16.485 mm</td>
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<tr>
<td>Actual length</td>
<td>$L$</td>
<td>8.5 in</td>
<td>215.9 mm</td>
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<tr>
<td>Acoustoelastic constant</td>
<td>$\alpha$</td>
<td>-2.5714</td>
<td>-2.5714</td>
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<td>Tolerance on the acoustoelastic constant</td>
<td>$\Delta \alpha$</td>
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<td>0.00257</td>
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<tr>
<td>Tolerance on the instrument calibration</td>
<td>$[\Delta \delta_{L_{\text{cross}}}]$</td>
<td>0.0003 in</td>
<td>0.000762 mm</td>
</tr>
<tr>
<td>Coupling error for the ultrasonic length</td>
<td>$[\Delta \delta_{L_{\text{coupling}}}]$</td>
<td>0.0003 in</td>
<td>0.000762 mm</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>$C_T$</td>
<td>5.4 x 10^3/°F</td>
<td>9.72 x 10^3/°C</td>
</tr>
<tr>
<td>Tolerance on the temperature coefficient</td>
<td>$\Delta C_T$</td>
<td>5.4 x 10^3/°F</td>
<td>9.72 x 10^3/°C</td>
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<tr>
<td>Operating temperature</td>
<td>$T_o$</td>
<td>80 °F</td>
<td>26.7 °C</td>
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<tr>
<td>Tolerance on the operating temperature</td>
<td>$\Delta T_o$</td>
<td>0.5 °F</td>
<td>0.28 °C</td>
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<tr>
<td>Reference temperature</td>
<td>$T_r$</td>
<td>75 °F</td>
<td>23.9 °C</td>
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<tr>
<td>Targeted preload</td>
<td>$P$</td>
<td>53,000 lb</td>
<td>24091 kg</td>
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</table>

<table>
<thead>
<tr>
<th>Computed Parameter</th>
<th>Symbol</th>
<th>Equation Number</th>
<th>Engineering Units</th>
<th>SI Units</th>
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</thead>
<tbody>
<tr>
<td>Cross-sectional area</td>
<td>$A$</td>
<td>0.390 m(^2)</td>
<td>251.846 mm(^2)</td>
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<tr>
<td>Stress factor</td>
<td>$K_p$</td>
<td>$6$</td>
<td>$0.28$</td>
<td>$0.28$</td>
</tr>
<tr>
<td>Fractional tolerance on the stress factor</td>
<td>$\Delta K_p/K_p$</td>
<td>29</td>
<td>$0.00092$</td>
<td>$0.00092$</td>
</tr>
<tr>
<td>Fractional tolerance on the shank area</td>
<td>$\Delta A/A$</td>
<td>27</td>
<td>$0.00284$</td>
<td>$0.00284$</td>
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<tr>
<td>Fractional tolerance on the ultrasound velocity</td>
<td>$\Delta V/V$</td>
<td>$0.001$</td>
<td>$0.001$</td>
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<tr>
<td>Fractional tolerance on the Young’s modulus</td>
<td>$\Delta E/E$</td>
<td>$0.0001$</td>
<td>$0.0001$</td>
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<td>Fractional tolerance on the effective length</td>
<td>$\Delta L/L_o$</td>
<td>28</td>
<td>$0.00457$</td>
<td>$0.00457$</td>
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<tr>
<td>Tolerance on the ultrasonic stretch due to the coupling</td>
<td>$[\Delta \delta_{L_{\text{c coupling}}}]$</td>
<td>36</td>
<td>$0.0004$</td>
<td>$0.010$ mm</td>
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<td>Tolerance on the ultrasonic stretch due to the temperature</td>
<td>$[\Delta \delta_{L_{\text{cross}}}]$</td>
<td>37, 38, 39</td>
<td>$0.003$</td>
<td>$0.0076$</td>
</tr>
<tr>
<td>Tolerance on the ultrasonic stretch</td>
<td>$\Delta \delta_{L_o}$</td>
<td>34</td>
<td>$0.0006$</td>
<td>$0.0152$</td>
</tr>
<tr>
<td>Estimated ultrasonic stretch</td>
<td>$\delta_{L_o}$</td>
<td>$12b$</td>
<td>$0.0957$</td>
<td>$2.431$</td>
</tr>
<tr>
<td>Elongation</td>
<td>$\delta_{L_{\text{el}}}$</td>
<td>$12a$</td>
<td>$0.0268$</td>
<td>$0.681$</td>
</tr>
<tr>
<td>Estimated load factor</td>
<td>$F_o'$</td>
<td>$10b$</td>
<td>$553.651.4$ lbf/in</td>
<td>$9.907.9$ kg/mm</td>
</tr>
<tr>
<td>Tolerance on the load factor</td>
<td>$\Delta F_o'/F_o'$</td>
<td>31 or 32</td>
<td>$0.0055$</td>
<td>$0.0055$</td>
</tr>
<tr>
<td>Fractional preload measurement accuracy</td>
<td>$\Delta P_o/P_o$</td>
<td>33 or 26a</td>
<td>$0.00846$</td>
<td>$0.00846$</td>
</tr>
<tr>
<td>Preload measurement accuracy</td>
<td>$\Delta P_o$</td>
<td>$33$</td>
<td>$448$ lbf</td>
<td>$204$ kg</td>
</tr>
</tbody>
</table>

March 24, 2015

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Section 2. Ultrasonic Measurements on a Bolt in an Interference Fit Joint

Paper covers

- Measurement of preload in interference fit joint bolts
  - Includes temperature compensation
- Measurement interference quantities such as
  - Diametrical interference and interference pressure
- Includes two configurations
  - Case I: Pull one of the ends in a universal testing machine – No nut turning, not a bolted joint
  - Case II: Turning/torqueing the nut – Real life bolted joint
  - Popularly, for no interference Case I condition is used to approximate Case II!
  - Difference between the two cases
- Analytical model for ultrasonic measurements
  - Analytical model for clamped joint with no interference is derived as a special case of the above model diametrical interference set to zero.
  - Comparison of experiments with the simulation is provided.
2. Interference Fit Joint\textsuperscript{12,13,14}: Cross Section of the Sleeve-bolt Joint and Regular Bolt Joint

Two sleevebolts are used to attach forward end of vertical tail

Sleeve Bolt Joint

Regular Interference Fit Joint
2. Interference Fit Joint\textsuperscript{12,13,14}: Some Quantities and Equations in the Analytical Model

Bolt diameter
\[ D_{b0}^T = D_{b0}^R (1 + K_b \Delta T). \]

Temperature difference
\[ \Delta T = T - R. \]

Hole diameter
\[ D_{h0}^T = D_{h0}^R (1 + K_h \Delta T). \]

Bolt length
\[ l_{b0}^T = l_{b0}^R (1 + K_b \Delta T). \]

Hole length
\[ l_{h0}^T = l_{h0}^R (1 + K_h \Delta T). \]

Diametrical interference
\[ I^T = D_{b0}^T - D_{h0}^T. \]

Diametrical interference
\[ I^T = \Delta D_{ha}^T - \Delta D_{ba}^T. \]

Interference Pressure
\[ Q = Q_0 - C_4 P. \]

Tensile Preload
\[ P = \frac{\rho_0 \left(V_{0R}^2\right)^2}{EA} = \lambda + 2\mu + (2l + \lambda)\theta + (4m + 4\lambda + 10\mu)\varepsilon_{11}, \]

Preload and tensile strain
\[ P = EA\varepsilon_{11}. \]
2. Interference Fit Joint\textsuperscript{12,13,14}: Analytical Model for Two Cases

### CASE I: Bolt Pulled

Ultrasonic stretch with interference
\[
\Delta L^i = \Delta t_{cs}^R \left( \frac{V^i}{2} \right) = i_{b0}^R \left( \frac{1 + \varepsilon_{11}}{1 + \beta \cdot \varepsilon_{11}} \right) - 1 \left( \frac{V^i}{V_0^R} \right) = \varepsilon_{11} i_{b0}^R \left( 1 - \beta \right) \left( \frac{V^i}{V_0^R} \right)
\]

Ultrasonic stretch without interference
\[
\Delta L^i = \Delta t_{cs}^R \left( V^i / 2 \right) = \varepsilon_{11} i_{b0}^R \left( 1 - \beta \right) \left( V^i / V_0^R \right)
\]

Load factor without interference
\[
W^{av} = \frac{P}{\Delta L^i} = \frac{AE_b}{l_{b0}^R \left( 1 - \beta \right)} \left( \frac{V_0^R}{V^i} \right)
\]

### CASE II: Nut Tightened

Ultrasonic stretch with interference
\[
\Delta L^i = i_{bs}^T \left( 1 + \frac{\varepsilon_{11}}{1 + f_n} \right) - 1 \left( \frac{V^i}{V_0^R} \right) = i_{bs}^T \left( 1 + \frac{\varepsilon_{11}}{1 + f_n} \right) \left( \frac{1}{1 + K_b \cdot \Delta T} \right) \left( \frac{V^i}{V_0^R} \right)
\]

Ultrasonic stretch without interference
\[
\Delta L^i = i_{bs}^T \left( 1 - \beta \right) \left( 1 / (1 + K_b \cdot \Delta T) \right) \left( \frac{V^i}{V_0^R} \right)
\]

Effective length
\[
l_{bs}^T = \frac{i_{b0}^R + l_{h0}^R \left( K_h \Delta T + \varepsilon_h + K_h \Delta T \varepsilon_h \right)}{1 + \varepsilon_{11}}
\]

Load factor
\[
W^{av} = P / \Delta L^i
\]

These expressions are more accurate than used in Raymond and StressTel Boltgages.

March 24, 2015

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All characteristic lines theoretically meet and merge after exceeding a certain load when bolt interference is lost.
2 Interference Fit Joint\textsuperscript{12,13,14}: Analytical Model for Friction and Pressure on Shank

Preload at nut end - Loading

\[ P_{NL} = P + \left( \frac{f \pi D_{b0}^T l_{h0}^T Q}{2} \right) \]

Preload at nut end - Unloading

\[ P_{NU} = P - \left( \frac{f \pi D_{b0}^T l_{h0}^T Q}{2} \right) \]

Frictional force to push bolt out of the hole

\[ F^0_{\text{max}} = f \pi D_{b0}^T l_{h0}^T Q_0 \]

Shank pressure during – Loading and unloading

\[ Q_L = \frac{Q_0 - C_4 P_{NL}}{1 - 0.5 \pi C_4 f D_{b0}^T l_{h0}^T} \quad Q_U = \frac{Q_0 - C_4 P_{NU}}{1 + 0.5 \pi C_4 f D_{b0}^T l_{h0}^T} \]

Load Factor - Loading

\[ W_L = \frac{P_{NL}}{\Delta L^i_{mL}} \]

Preload characteristic equation

\[ P = W \Delta L^i_{mL} + Y \]
2. Interference Fit Joint\textsuperscript{12,13,14}: Simulation Run Results for Applied Load Versus the Ultrasonic Stretch for Various Cases

The two lines theoretically meet and merge after exceeding a certain load when Bolt interference is lost.

Very small difference in this case

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March 24, 2015

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2. Interference Fit Joint\textsuperscript{12,13,14}: Simulation Run Comparison with Experiments

<table>
<thead>
<tr>
<th>Quantities defining the load characteristics</th>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_R^H$ Residual preload</td>
<td>kg</td>
<td>1127</td>
</tr>
<tr>
<td>$\Delta L_1^i$ Assembly stretch</td>
<td>mm</td>
<td>0.0260</td>
</tr>
<tr>
<td>$\Delta L_2^i$ Residual stretch</td>
<td>mm</td>
<td>0.0164</td>
</tr>
<tr>
<td>$\Delta L_0^i$ Initial stretch</td>
<td>mm</td>
<td>0.0424</td>
</tr>
<tr>
<td>$W_L$ Load factor during loading</td>
<td>kg/mm</td>
<td>34,037</td>
</tr>
<tr>
<td>$W_U$ Load factor during unloading</td>
<td>kg/mm</td>
<td>34,447</td>
</tr>
</tbody>
</table>

Simulation based on the analytical model compares well with experiments.
2. Interference Fit Joint\textsuperscript{12,13,14}: Analytical Model, Determination of Bolt Interference

- Method to measure the interference between the bolt and hole without removing the bolt.
  - The bolt is subjected to a loading/unloading cycle without removing it from the hole.
  - The ultrasonic stretch is measured and the load characteristics are plotted.
- Measure the friction $F$ and residual stretch. Using Preload versus ultrasonic stretch plot.
- Determine the maximum interference pressure from the friction using following Eq.

$$F_{\text{max}} = f\pi D_b^T l_h^T Q_{\text{max}}$$

- Determine interference pressure $Q_0$ using following Eq.

$$Q_{\text{max}} = Q_0 / (1 + 0.5\pi C_4 f D_b^T l_h^T)$$

- Determine the interference from the interference pressure using following Eq.

$$I_s^T = I_0^T = I^T = Q_0 C_3$$
2. Interference Fit Joint\textsuperscript{12,13,14}: Conclusions

- An analytical model for ultrasonic tensile preload measurements on a bolt in a joint given.
  - The model covers two cases of the joint, with and without the diametrical interference.
  - The model accounts for change in the joint temperature.

- Paper provides results of a computer application based on the model that simulates the ultrasonic preload gage to provide preload from the transit time measurements.

- The model in this paper considers both, the constant effective length (machine pull) and the variable effective length (nut torque).

- The paper provides an ultrasonic technique to measure the interference pressure and the diametrical interference of a bolt in a joint.

- The simulated characteristics compare well with the experimental results.
Section 3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Loading, shear force and bending moment on the bolt

- Ray Tracing Analytical Model
  - No beam spread,
  - No beam-bending
  - No variation in the beam intensity normal to the direction of path.
  - The reflector reflects the wave back as a plane wave.
  - The bolt profile is an arc of a circle.
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Ultrasonic Ray Path in a Bent Bolt

![Diagram of Ultrasonic Ray Path in a Bent Bolt]

\[ \frac{R - x_i + 2C \sin \phi}{\tan \phi} \cos 2\phi \]

\[ \frac{A}{\cos 2\phi} \]

\[ \frac{C}{\cos \phi} \]

\[ \frac{C/L \text{ BEFORE BENDING}}{C/L \text{ AFTER BENDING}} \]

\[ \text{CENTER OF BOLT CURVATURE} \]

\[ (R - x_i + 2C \sin \phi) \tan \phi \]

\[ (R - x_i) \tan \phi \]

\[ (R - x_i + 2C \sin \phi) \tan \phi \tan 2\phi \]

\[ (R - x_i + 2C \sin \phi) \]

\[ (R - x_i + 2C \sin \phi) \]
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Ultrasonic Ray Path in a Bent Bolt
3. Ultrasonic Preload Measurement in Shear Joint\(^{15,16}\): Analytical Model

Radius, effective length and bending angle

\[ R = \frac{l}{\phi} \]

Ray shift

\[ Q = -2C \sin \phi - \left( \frac{l}{\phi} - x_i - 2C \sin \phi \right) \tan \phi \tan 2\phi - A \tan 2\phi \]

Pulse transit time

\[ t_1 = \frac{P_1 P_2 + P_3 P_4 + P_4 P_5 + P_6 P_7}{V_0} + \int_{p_2}^{p_5} \frac{ds}{V_{23}} + \int_{p_5}^{p_6} \frac{ds}{V_{56}} \]

Integration increment

\[ \Delta y_{23} = \frac{(R - x_i) \tan \phi}{m_1} \]

Integration increment

\[ \Delta y_{56} = \frac{(R - x_i + 2C \sin \phi) \tan \phi}{m_1} \]

Ray returning point

\[ x_1^f = \frac{x_e + 2C \sin \phi + (R + 2C \sin \phi) \tan \phi \tan 2\phi + A \tan 2\phi}{1 + \tan \phi \tan 2\phi} \]
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Analytical Model

Radial Coordinate

\[ r^c = R - r \]

Velocity

\[ V = V_0 \left( 1 + c_1 \varepsilon_v \right) \]

Stress

\[ \sigma = \frac{M_{av} r^c}{I} \]

Velocity

\[ V = V_0 \left( 1 - \left. \frac{c_1 r^c \cos^2 \gamma}{R} \right) \right. \]

Received ultrasonic signal

\[ U(t) = \int \int u(x_1, z, t) dx_1 dz \]

\[ u(x_1, i) = -\frac{2 \sin \left( 2\pi c \left( \frac{i - 1 - \Delta i}{N} \right) + \pi \right) e^{-\alpha \left( 2\pi \left( \frac{i - 1 - \Delta i}{N} \right) - \pi \right)^2}}{\pi r_i^2} \]
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Values of Some Parameters Used in the Simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l )</td>
<td>mm (in.)</td>
<td>95.5 (3.76)</td>
</tr>
<tr>
<td>( A )</td>
<td>mm (in.)</td>
<td>91.95 (3.62)</td>
</tr>
<tr>
<td>( C )</td>
<td>mm (in.)</td>
<td>28.45(1.12)</td>
</tr>
<tr>
<td>( V_0 )</td>
<td>Mm/sec (in./sec)</td>
<td>5905347.6(232494)</td>
</tr>
<tr>
<td>( E )</td>
<td>Mpa, kg/mm(^2) (psi)</td>
<td>21.3729 \times 10^6, 21.8 \times 10^6, (31 \times 10^6)</td>
</tr>
<tr>
<td>( c_1 )</td>
<td></td>
<td>-2.45</td>
</tr>
<tr>
<td>( c )</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>( N )</td>
<td></td>
<td>1024</td>
</tr>
<tr>
<td>( f )</td>
<td>Hz</td>
<td>5 \times 10^6</td>
</tr>
<tr>
<td>( a )</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>mm (in.)</td>
<td>6.35 (0.25)</td>
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<tr>
<td>( x_e )</td>
<td>mm (in.)</td>
<td>1.5 (0.059)</td>
</tr>
<tr>
<td>( \lambda_1^{-1} )</td>
<td>mm (in.)</td>
<td>2.894 (0.114)</td>
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<tr>
<td>( m_1 )</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>( m_2 )</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>( H )</td>
<td>kg (lb)</td>
<td>45.5, 90.9, 136.4, 181.8, 227.3 (100, 200, 300, 400, 500.0)</td>
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<tr>
<td>( I )</td>
<td>mm(^4) (in.(^4))</td>
<td>4.91 \times 10^4(0.01179)</td>
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<tr>
<td>( \Delta \phi )</td>
<td>Radian for 45.45 kg (100 lb)</td>
<td>0.0006455</td>
</tr>
<tr>
<td>( \Delta U/H )</td>
<td>mm/kg, (in/lb) at 227.3 kg (500 lb)</td>
<td>-1.9 \times 10^{-4} (-3.4 \times 10^{-6})</td>
</tr>
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</table>
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Simulated Waveforms Before and After Bending Load Using the Analytical Model

Red: Before shear load  
Blue: After shear load

Progression of Wave form with increasing shear load
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Measurements On a Bolt in a Shear Bending Set-up

- Study effect of bolt bending on ultrasonic measurements
- Used slotted, counterbored and stepped end bolts
- Used single and dual element transducers in pulse/echo mode
- Simply supported at ends, load in the center
- Load from 0 to 455 kg (1,000 lb) with steps of 45.5 kg (100 lb)
- 23 runs
3. Ultrasonic Preload Measurement in Shear Joint: Run Designation Scheme

- Transducer Descriptor:
  - Capital letter:
    - A, B: Transducer halves
    - C: Circular element transducer

- Reflector Descriptor:
  - Lowercase letter:
    - a, b: Reflector halves
    - c: Circular end reflector
    - s: Slotted end reflector
    - e: Reflector area without slot

- Clock Position of the Transducer
- Clock Position of the Reflector

- B6-b3:
  - Hatched area shows transducer element in use
  - Hatched area shows reflector area in use
### 3. Ultrasonic Preload Measurement in Shear Joint: Run Configurations

<table>
<thead>
<tr>
<th>Run Configuration</th>
<th>Elevation</th>
<th>Front (L)</th>
<th>Rear (R)</th>
<th>Front (L)</th>
<th>Rear (R)</th>
<th>Elevation</th>
<th>Front (L)</th>
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<td>C-c</td>
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<td></td>
<td>B9-05</td>
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</table>

March 24, 2015

Ajay M. Koshti, NASA Johnson Space Center, Houston, TX. Conference: NESC NDE TDT Face to Face Meeting, Michoud, LA
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Ultrasonic Stretch versus Load Experimental Data

**Chart 1**

- Ultrasonic Stretch (mm) vs Load (kg)
- Data points for B6-b6, A12-a12, A12-b6, B6-a12, B9-a9, A3-a3

**Chart 2**

- Ultrasonic Stretch (mm) vs Load (kg)
- Data points for A9-b6, A9-a12, B3-b6, B3-a12, A12-b3, A12-a9

**Chart 3**

- Ultrasonic Stretch (mm) vs Load (kg)
- Data points for A9-b6, A9-a12, B3-b6, B3-a12, A12-b3, A12-a9

**Chart 4**

- Ultrasonic Stretch (mm) vs Load (kg)
- Data points for C-b6, C-a12, C-b9, C-a3, C-c, C-c

**Chart 5**

- Ultrasonic Stretch (mm) vs Load (kg)
- Data points for C-e6, C-s3, C-e3, C-s3, C-c, A6-e6, B12-e6

**Chart 6**

- Ultrasonic Stretch (mm) vs Load (kg)
- Data points for B9-e3, A3-e3, A3-s3, A3-e3, B9-e6, B9-e6, B9-s3

March 24, 2015

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3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Simulation versus Experiment

Experiment and Simulation of ultrasonic stretch versus load for run 12 (B6-c)

Experiment and Simulation of ultrasonic stretch versus load for run 12 (B6-c)
3. Ultrasonic Preload Measurement in Shear Joint\textsuperscript{15,16}: Conclusions

- Ultrasonic measurements can be linear with bending for small amount of bending.
- For larger amount of bending the ultrasonic measurements become erratic due to excessive signal distortion.
  - Although phased array transducers with full matrix capture and custom processing would eliminate the issues with distortion.
- Ultrasonic measurements can be used to measure:
  - Bending loads in some bolts
  - Combined tensile and bending loads in some bolts
- The experiment and simulation show a similar relationship between the ultrasonic stretch and applied load in the experimental load range.
- The analytical model forms basis for the method of measuring bending loads using ultrasonic measurements.
  - The model is used here applicable for all shear/bending load configurations given here.
- It would be desirable to incorporate effect of beam-bending in the model.
Section 4. Effect of Bolt Bending in Flanged Joint on Ultrasonic Measurements

- Shuttle Booster Hold Down Post Bolts
  - Two 2” Dia. Inconel 718 bolts
  - Loaded to 115 to 155 kip
  - Clamped joint, clearance fit

- Orbiter/747 Aft Attach Bolts
  - Two 2” Dia. Inconel 718 bolts
  - Loaded to 115 to 155 kip
  - Clamped joint, clearance fit

- Vertical Tail Forward Attach Bolts
  - Two 1” Dia. MP35N bolts
  - Loaded to 50 kip
  - clamped joint, interference fit
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Orbiter/External Tank Umbilical Mate

Orbiter/ET Umbilical Attach Bolts

Two umbilicals, Left one for liquid hydrogen and Right one for liquid oxygen

Three 0.7” Dia. X 8” long MP35N bolts per umbilical, Flanged joint in a clearance fit, 45 to 61 kip load

Provides structural joint and pressure on fluid line seals to prevent leakage.

Three bolts of an umbilical are preloaded simultaneously using hydraulic tensioners. The tensioners pull the bolt and allow the nut to be tightened by a small torque.
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Ultrasonic Measurements on Umbilical Bolts

- Umbilical bolt measurements in original bolt configuration
  - Ultrasonic signal distorted causing unreliable readings
- Signal distorted due to bolt bending
  - Umbilical flanges bend under bolt tension and cause bolt bending
  - Typical bolt protrusion over the nut is \(1/8\) in.
    - Bolt stretch = 0.022 in
    - Flange bending, flange compression/sagging, nut compression
  - Bolt protrusion is a measure of flange bending
- Estimated end to end Bolt Bending < 1 degree

- Bolt End Configurations
  - Old bolt had a slot in the end
    - The slot provides a separate echo
    - The end (back) provides a relatively stronger echo
    - Ultrasonic measurements are possible on both echoes
  - Modified bolt has a 1/2” counterbore
    - The counterbore echo is measurable

\begin{figure}
\centering
\includegraphics[width=\textwidth]{UltrasonicGraphs.png}
\caption{Ultrasonic Graphs}
\end{figure}

\textbf{Slotted End Before Preload} \quad \textbf{Slotted End After Preload}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{UltrasonicEnds.png}
\caption{Ultrasonic End Configurations}
\end{figure}

Raymond boltgage signals

StressTel boltmike signals
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Test Fixtures with Umbilical Joint Hardware

- Simulated Joint with ultrasonic transducer and temperature probe
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Short Fixture with Umbilical Joint Hardware

**Test Assembly**

**Test Assembly with Ultrasonic Transducer**

**Joint Assembly without Fixture**

**Top View**

**Assembly Parts**

**Boltmike with Temperature Probe**

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4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Analytical Model with Geometric and Bending Effect

Phase change due to Geometry and bending effect.

\[ \Delta \phi_{Gb} = \left( \frac{2\pi}{\lambda} \right) \left( \frac{L}{\theta} - x \right) \tan 2\theta - 2L - \frac{2\theta'}{S} \left( x + \frac{Q}{4} \right) \]

Ultrasonic signal response.

\[ U(t) \propto \int \int_u(x, y, t) dx dy \]
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Comparison of Simulated Signals

Effect of Phase Gradient on a Flat Reflector (Without Slot)

Beam shift, signal shift, and loss of signal amplitude

Stress Effect
• Bolt tension increases the path length
  • Ultrasonic stretch = 3 \times \text{Physical stretch}
• Bolt bending results in bending stress in the bolt
  • On tensile region the path length increases
  • On the compressive side the path length decreases
• The bending stress results in slight bending of the beam away from the compressive side

Geometry Effect
• Path length of rays decrease in the compressive region
• Path length increases in the tensile region
• Part of the beam is lost due to beam shift
• Signal width increases but amplitude decreases

Effect of Phase Gradient with Slot

Beam shift, signal shift, loss of signal amplitude, and higher signal distortion.

March 24, 2015

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4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Bolt and Transducer Orientations in the Fixture, End Gap

End gap as a measure of bending load

Reference Runs

Short fixture, single element transducer, edge shimmed, Gap closing = 0.203 mm (0.008 in.)

<table>
<thead>
<tr>
<th>Run configuration</th>
<th>Fixture</th>
<th>Bolt</th>
<th>Reflector</th>
<th>Reflector angles</th>
<th>Transducer</th>
<th>Transducer angle</th>
<th>Stretch at nominal load, mm (in.)</th>
<th>54% Stretch at nominal load, mm (in.)</th>
<th>100% Stretch at nominal load, mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1A</td>
<td>Short</td>
<td>Slotted</td>
<td>End</td>
<td>72 &amp; -108</td>
<td>Single</td>
<td>N/A</td>
<td>0.927 (0.0365)</td>
<td>1.824 (0.0718)</td>
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<tr>
<td>R1B</td>
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<td>Slot</td>
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<td>0.927 (0.0365)</td>
<td>1.867 (0.0735)</td>
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</tr>
</tbody>
</table>
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Summary of Regular Runs

- Gap closing
  - Short fixture: 2.1 mm (0.083 in.)
  - Long fixture: 2.74 mm (0.108 in.)
- Three measurement points
  - Zero load
  - 54\% nominal load: 41,370 kPa (6,000 psi) hydraulic pressure
  - 100\% nominal load: 77,222 kPa (11,200 psi) hydraulic pressure
- Ten regular runs
  - Short and long fixture
  - One slotted and one counterbored bolt
  - Two orientations for the slotted bolt
  - Single and dual element transducer in each run
  - Many orientations for the dual transducer

<table>
<thead>
<tr>
<th>Run</th>
<th>Configuration</th>
<th>Fixture</th>
<th>Reflector type</th>
<th>Transducer type</th>
<th>Reflector angle, Deg.</th>
<th>Transducer angle, Deg.</th>
<th>Relative stretch (%) at 54% load, %</th>
<th>Relative stretch (%) at 100% load, %</th>
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<td>6D</td>
<td>Short</td>
<td>Slotted</td>
<td>End</td>
<td>72 &amp; -108</td>
<td>Dual</td>
<td>-108</td>
<td>23.8</td>
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<td>End</td>
<td>-18 &amp; 162</td>
<td>Dual</td>
<td>-18</td>
<td>12.2</td>
<td>12.0</td>
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<td>Slotted</td>
<td>End</td>
<td>-18 &amp; 162</td>
<td>Dual</td>
<td>162</td>
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<td>4.9</td>
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<td>End</td>
<td>90 &amp; 90</td>
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<td>90</td>
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<td>0 &amp; 180</td>
<td>Dual</td>
<td>-90</td>
<td>20.3</td>
<td>20.8</td>
</tr>
</tbody>
</table>

March 24, 2015

Ajay M. Koshti, NASA Johnson Space Center, Houston, TX. Conference: NESC NDE TDT Face to Face Meeting, Michoud, LA
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Actual and Estimated Relative Stretch

- Used single ray analysis
- Shows some corroboration with the analytical model
- More variation in actual measurements

Table 3: Comparison of theoretically estimated stretch with actual stretch

<table>
<thead>
<tr>
<th>Run and configuration</th>
<th>Transducer angle, degree</th>
<th>% of nominal load</th>
<th>Chosen distance, mm (in.)</th>
<th>Chosen angle ( \alpha ), degree</th>
<th>Ray shift, ( Q ), mm (in.)</th>
<th>Estimated stretch, mm (in.)</th>
<th>Actual stretch, mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 5A</td>
<td>N/A</td>
<td>54</td>
<td>-1.01 (-0.04)</td>
<td>0.4</td>
<td>-2.8 (-0.11)</td>
<td>0.083 (0.0033)</td>
<td>0.0914 (0.0036)</td>
</tr>
<tr>
<td>Run 5A</td>
<td>N/A</td>
<td>100</td>
<td>-1.77 (-0.07)</td>
<td>0.6</td>
<td>-4.26 (-0.17)</td>
<td>0.2030 (0.0080)</td>
<td>0.1651 (0.0065)</td>
</tr>
<tr>
<td>Run SD</td>
<td>90</td>
<td>54</td>
<td>3.048 (0.12)</td>
<td>0.4</td>
<td>-2.84 (-0.11)</td>
<td>-0.0745 (-0.0029)</td>
<td>-0.0076 (-0.0003)</td>
</tr>
<tr>
<td>Run SD</td>
<td>90</td>
<td>100</td>
<td>4.572 (0.18)</td>
<td>0.6</td>
<td>-4.26 (-0.17)</td>
<td>-0.1675 (-0.0066)</td>
<td>-0.1422 (-0.0056)</td>
</tr>
<tr>
<td>Run SE</td>
<td>-90</td>
<td>54</td>
<td>-3.556 (-0.14)</td>
<td>0.4</td>
<td>-2.84 (-0.11)</td>
<td>0.1824 (0.0072)</td>
<td>0.2540 (0.0100)</td>
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<tr>
<td>Run SE</td>
<td>-90</td>
<td>100</td>
<td>-2.032 (-0.08)</td>
<td>0.6</td>
<td>-4.26 (-0.17)</td>
<td>0.2178 (0.0086)</td>
<td>0.4216 (0.0166)</td>
</tr>
</tbody>
</table>

\textsuperscript{17} Ajay M. Koshti, NASA Johnson Space Center, Houston, TX. Conference: NESC NDE TDT Face to Face Meeting, Michoud, LA
4. Flanged Joint on Ultrasonic Measurements\textsuperscript{17}: Results and Conclusions

- **Results**
  - Relative ultrasonic stretch ranged from -8% to 40%
  - More relative stretch in certain orientations
  - Distortion
    - More distortion in the signal for certain orientations
    - Counterbore echo has less distortion than end echo
    - The slot echo has the least distortion
  - Certain slot clocking orientations are more favorable for measurement
    - Slot measurement: -18 to 162 degrees gives 6.4% increase
    - End halves measurement: 72 to 108 degrees 2.8% increase
  - Counterbore echo gives stronger echo but gives up to 15.6% increase in the ultrasonic stretch

- **Conclusions**
  - Larger reflector gives higher amplitude echo but distortion and relative stretch are high
  - The end halves give different distortion and relative stretch depending upon the angular orientation
    - The distortion is relatively high because of the spacing between the halves and the size of the halves
  - The slot gives different distortion and relative stretch depending upon the angular orientation
    - The slot echo is weak compared to the end echo
    - The slot echo (8.6% max) has less distortion and relative stretch compared to the end echo (11% max, some completely distorted)
Section 5. Simulation of Effect of Bending Stress on Ultrasonic Beam

This model assumes:

- No beam spread.
- The bolt profile is an arc of a circle.
- The bolt has a constant cross-sectional area and square ends.
- The bending is applied by two moments, one at each end of the bolt. The moments are equal in magnitude but opposite in rotation.
5. Simulation of Effect of Bending Stress on Ultrasonic Beam: Ultrasonic Ray, Bolt Geometry and Analytical Model

Bending stress \( \sigma = \frac{M(r - R)}{I} \)

Radius, effective length and bending angle \( R = \frac{l}{\varphi} \)

Bending angle \( \varphi = \frac{Ml}{EI} \)

Hooke’s law \( \varepsilon = \frac{\sigma}{E} \)

Strain \( \varepsilon_f = \frac{(r - R)}{R} \)

Velocity \( V_s = V_0 \left( 1 + c_1 \varepsilon_v \right) \)

Velocity \( V_s = V_0 \left( 1 + b \left[ r - R \right] \left[ 1 - \left( \frac{dr}{ds} \right)^2 \right] \right) \)

\( b = \frac{c_1}{R} \)
5. Simulation of Effect of Bending Stress on Ultrasonic Beam\textsuperscript{18}: Ray, Orthogonal Curve, and Analytical Solution

\begin{align*}
\text{Curvature} \quad \kappa & \approx \frac{dV_s / dr}{V_s} \approx \frac{|b|}{1 + b(r - R)} \\
\text{Ray equation – second order} \quad r'' &= \left(1 - r'^2\right) \frac{1 + b \left(1 - r'^2\right) (R - 2r)}{r \left[1 + b \left(1 - r'^2\right) (r - R)\right]} \\
\text{Coupled pair of first order equations - Runge-Kutta} \quad r'_1 &= \left(1 - r_1^2\right) \frac{1 + b \left(1 - r_1^2\right) (R - 2r_2)}{r_2 \left[1 + b \left(1 - r_1^2\right) (r_2 - R)\right]} \\
&= r'_2 \\
r'_2 &= r'_1
\end{align*}
5. Simulation of Effect of Bending Stress on Ultrasonic Beam: Numerical Solution for Ray Path

<table>
<thead>
<tr>
<th>s, cm</th>
<th>r'</th>
<th>r, cm</th>
<th>θ'</th>
<th>θ' Average</th>
<th>Δs, cm</th>
<th>θ' : Δs</th>
<th>θ</th>
<th>x, cm</th>
<th>y, cm</th>
<th>dy/dx</th>
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<td>0</td>
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Ray Path

AJAY M. KOSHTI, NASA Johnson Space Center, Houston, TX. Conference: NESC NDE TDT Face to Face Meeting, Michoud, LA
5. Simulation of Effect of Bending Stress on Ultrasonic Beam: Ray Path in Bent Bolt Without Ray Bending
5. Simulation of Effect of Bending Stress on Ultrasonic Beam\textsuperscript{18}: Return Trip of Ray

\[ \delta_1 = 0.012\text{cm} \]
\[ \delta_2 = \alpha C \]
\[ \delta_3 = (l + C)(\alpha + 2\varphi) \]
\[ \delta_4 \approx \delta_1 \]
\[ \delta_5 = 2A(\alpha + \varphi) \]

Ray shift

\[ Q = \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 \]
### Without ray bending

<table>
<thead>
<tr>
<th>Effective length, ( l ) cm</th>
<th>( A ) cm</th>
<th>( C ) cm</th>
<th>( \phi ) rad</th>
<th>( R ) cm</th>
<th>( Stretch\ Slope ) mm/kg</th>
<th>% Difference from actual slope</th>
<th>Ray Shift, ( Q ) cm</th>
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</thead>
<tbody>
<tr>
<td>6.4</td>
<td>10.8</td>
<td>4.4</td>
<td>0.0014</td>
<td>4535</td>
<td>-8.0 \times 10^{-4}</td>
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<td>7.62</td>
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<td>3.81</td>
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<td>9.6</td>
<td>9.2</td>
<td>2.8</td>
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<td>0</td>
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</table>

### With ray bending

<table>
<thead>
<tr>
<th>( A ) cm</th>
<th>( C ) cm</th>
<th>( l ) cm</th>
<th>( \phi )</th>
<th>( \alpha )</th>
<th>( \delta_{\phi} ) cm</th>
<th>( \delta_{\alpha} ) cm</th>
<th>( \delta_{\beta} ) cm</th>
<th>( \delta_{\gamma} ) cm</th>
<th>Ray Shift, ( Q ) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8</td>
<td>4.4</td>
<td>6.4</td>
<td>0.0014</td>
<td>0.0029</td>
<td>0.012</td>
<td>0.0128</td>
<td>0.0616</td>
<td>0.012</td>
<td>0.0929</td>
</tr>
</tbody>
</table>
5. Simulation of Effect of Bending Stress on Ultrasonic Beam\textsuperscript{18}: Conclusions

- The work provides an analytical model that describes the effect of bending stress on the path of an ultrasonic ray.
- The paper attempts to explain the effect of beam bending on the ultrasonic measurements of bending loads in a bolt.
- It is shown that the ray bending is a major contributor to the beam shift and therefore affects the stretch slope to some extent.
- The paper provides a numerical method to trace the path of incident (non-reflected) ray.
- The ray and therefore the beam bend in an opposite direction to the physical bending direction of bolt.
Conclusions

• Ultrasonic preload measurement applications for many bolt configurations are provided in author’s cited papers11-18.

• The first of the applications involves the ultrasonic measurement of preload in the interference fit bolt or sleeve bolt. The friction on the shank of the interference fit bolt affects the ultrasonic preload measurements. A theoretical model, which forms the basis for the application, is provided.

• A second application of bolts in a shear joint is considered. A theoretical model and results of simulation of the bending measurement are provided. The bending measurement theory and the simulation forms the basis for this application as well the flanged joint application.

• A bolt in a flanged joint experiences both the tensile and bending loads. The third application involves measurement of the bending and tensile preload in the flanged joint bolt.

• Ultrasonic beam in a bolt bends due to bending stress in the bolt, if under bending load. A theoretical model governing this phenomenon is given. A numerical technique to compute the ultrasonic beam profile for a beam passing through bending stress is presented.

• A procedure to estimate accuracy of the ultrasonic preload measurements in the original bolt configuration by the two makes of commercial ultrasonic extensometers is provided. The relationships between the corresponding parameters of the two makes are provided. A precise analytical model for computing the preload characteristic curve in the original configuration is also provided.