Ultrasonic Measurement of Loads in Bolts Used in Structural Joints

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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

[11] Koshti, A. M., “Estimation of Accuracy in Ultrasonic Preload Measurements,” Proceedings of SPIE – The International Society for Optical Engineering, 4335, 300-311 (2001).

Section 2

[12] Koshti, A. M., “Preload Measurement in Sleeve Bolts Using an Ultrasonic Technique,” Materials Evaluation, 54(2), 308-313, (1996).

[13] Koshti, A. M., “Preload Measurement in Sleeve Bolts Using an Ultrasonic Technique,” Proceedings of SPIE - The International Society for Optical Engineering, 2455, 406-418, (1995).

[14] Koshti, A. M., “Simulation of Ultrasonic Preload Measurement on a bolt in an Interference Fit Joint,” Proceedings of SPIE – The International Society for Optical Engineering, 4702, 423-437, (2002).

Section 3

[15] Koshti, A. M., “Ultrasonic Measurement of Bending of Bolt in a Shear Joint,” Experimental Mechanics, 36(4), 270-277, (1998).

[16] Koshti, A. M., “Simulation of Ultrasonic Measurement on a Bolt in a Shear Joint,” Proceedings of SPIE – The International Society for Optical Engineering, 4702, 411-422, (2002).

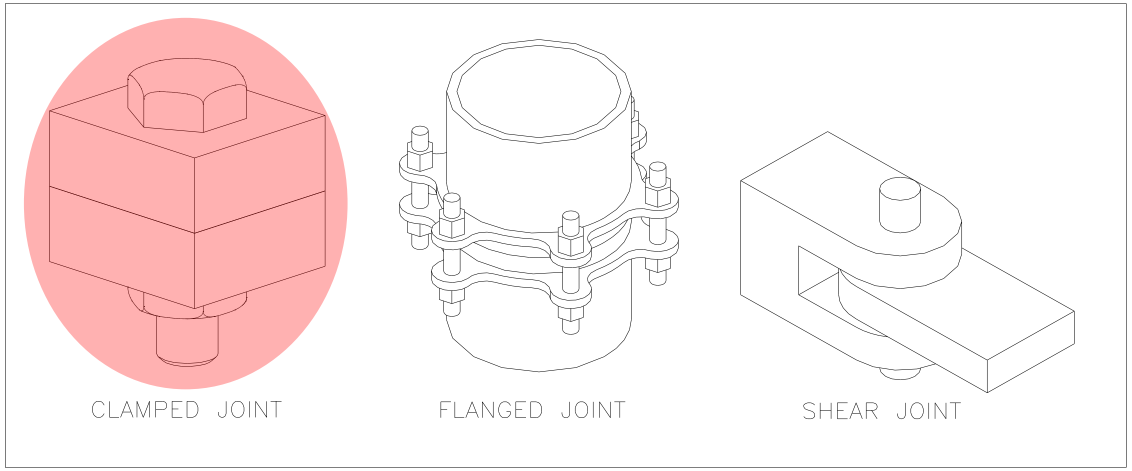
Section 4

[17] Koshti, A. M., “Effect of Bending on Ultrasonic Preload Measurements in Bolts,” Proceedings of SPIE – The International Society for Optical Engineering, 4335, 143-154, (2001).

Section 5

[18] Koshti, A. M., “Simulation of Effect of Bending Stress on the Ultrasonic Beam,” Proceedings of SPIE – The International Society for Optical Engineering, 4702, 148-156, (2002).

Section 1. Clamped Bolted Joint^{11}: Ultrasonic Set-up



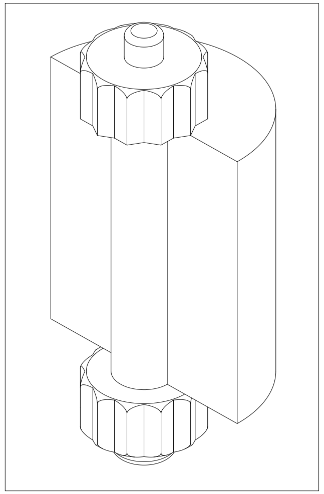


Figure 4. Cut away of a clamped joint

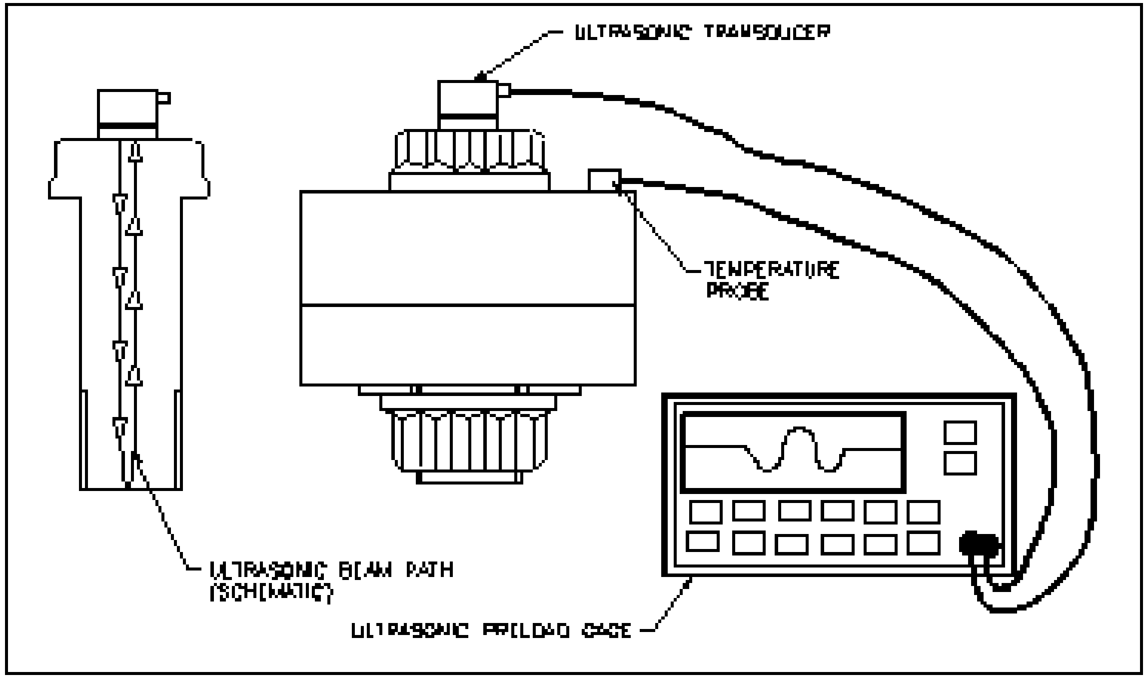


Figure 1 -- Ultrasonic preload configuration

1. Clamped Bolted Joint[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

Raymond Boltgage Equation

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

StressTel Boltmike Equation

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

P = Preload, lb,
A = Bolt ross 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,
δL_c = Temperature compensated ultrasonic stretch, in,
Y = Y intercept of calibration linear fit
α = Acoustoelastic constant
ε = 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[11]: Comparison of Preload Equations and Error Estimation

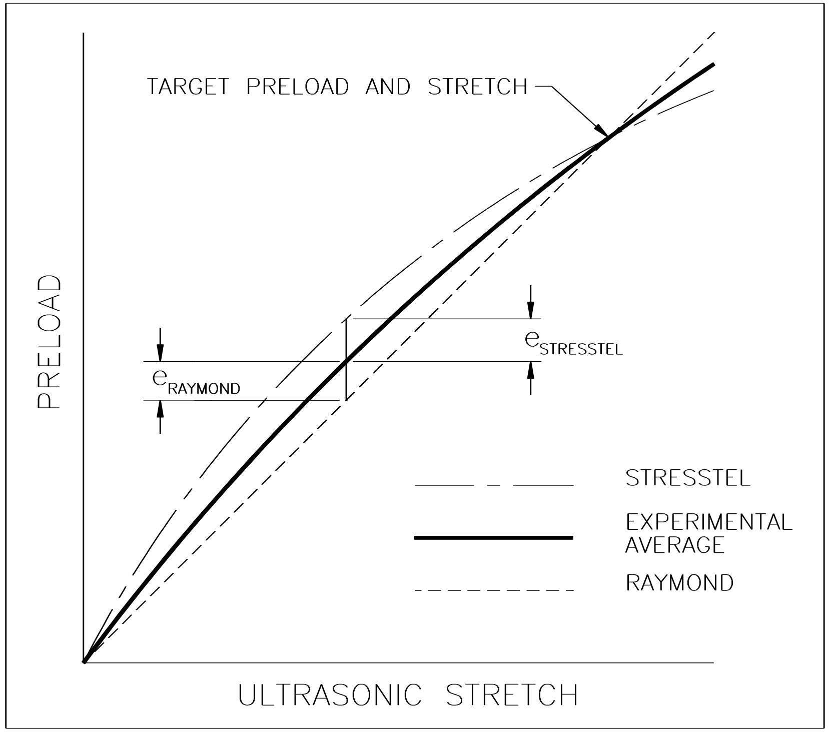


Figure 2 – Systematic errors

$$\left(\frac{\Delta P_R}{P_R}\right)^2 \cong \left(\frac{\Delta E}{E}\right)^2 + \left(\frac{\Delta V_m}{V_m}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta L_g}{L_g}\right)^2 + \left(\frac{\Delta \alpha}{1-\alpha}\right)^2 + \left(\frac{\Delta \delta L_c}{\delta L_c}\right)^2 + \left(\frac{\Delta Y}{P_R}\right)^2$$

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

1. Clamped Bolted Joint[11]: Example of Error Estimation

Parameter Description	Parameter Symbol	Engineering Units	SI units
Shank diameter	D	0.705 in	17.907 mm
Tolerance on the shank diameter	ΔD	0.001 in	0.0254 mm
Velocity setting	V	232494 in/sec	5.90535 x 10^6 mm/sec
Ultrasound velocity in the fastener	V_m	232494 in/sec	5.90535 x 10^6 mm/sec
Tolerance on the ultrasound velocity	ΔV	232.494 in/sec	5.90535 x 10^3 mm/sec
Young’s modulus	E	3.10 x 10^7 psi	21840.9 kg/mm^2
Tolerance on the Young’s modulus	ΔE	3.10 x 10^3 psi	2.1841 kg/mm^2
Effective length	L_{gR}	6.12 in	155.448 mm
Tolerance on the effective length	Δl	0.025 in	0.635 mm
Grip correction	g_R	0.649 in	16.485 mm
Actual length	L	8.5 in	215.9 mm
Acoustoelastic constant	α	-2.5714	-2.5714
Tolerance on the acoustoelastic constant	$\Delta\alpha$	0.00257	0.00257
Tolerance on the instrument calibration	$[\Delta\delta L_c]_{instrument}$	0.0003 in	0.00762 mm
Coupling error for the ultrasonic length	$[\Delta L_c]_{coupling}$	0.0003 in	0.00762 mm
Temperature coefficient	C_p	5.4 x 10^{-5} /ºF	9.72 x 10^{-5} /ºC
Tolerance on the temperature coefficient	ΔC_p	5.4 x 10^{-7}/ºF	9.72 x 10^{-7} /ºC
Operating temperature	T_i	80 ºF	26.7 ºC
Tolerance on the operating temperature	ΔT_i	0.5 ºF	0.28 ºC
Reference temperature	T_r	75 ºF	23.9 ºC
Targeted preload	P	53,000 lb	24091 kg

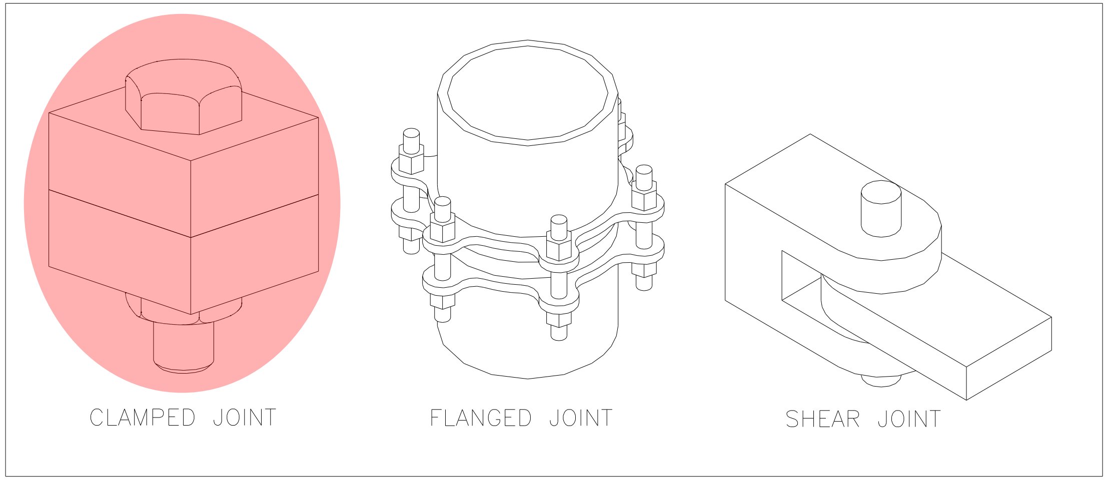
Computed Parameter	Symbol	Equation Number	Engineering Units	SI Units
Cross-sectional area	A		0.390 in^2	251.846 mm^2
Stress factor	K_R	6	0.28	0.28
Fractional tolerance on the stress factor	$\Delta K_R/K_R$	29	0.00092	0.00092
Fractional tolerance on the shank area	$\Delta A/A$	27	0.00284	0.00284
Fractional tolerance on the ultrasound velocity	$\Delta V/V$		0.001	0.001
Fractional tolerance on the Young’s modulus	$\Delta E/E$		0.0001	0.0001
Fractional tolerance on the effective length	$\Delta L_g/L_g$	28	0.00457	0.00457
Tolerance on the ultrasonic stretch due to the coupling	$[\Delta\delta L_c]_{coupling}$	36	0.0004 in	0.010 mm
Tolerance on the ultrasonic stretch due to the temperature	$[\Delta\delta L_c]_{temperature}$	37, 38, 39	0.0003 in	0.0076
Tolerance on the ultrasonic stretch	$\Delta\delta L_c$	34	0.0006 in	0.0152
Estimated ultrasonic stretch	δL_c	12b	0.0957 in	2.431
Elongation	δL_{cKR}	12a	0.0268	0.681
Estimated load factor	F'_R	10b	553,651.4 lbf/in	9,907.9 kg/mm
Tolerance on the load factor	$\frac{\Delta F'_R}{F'_R}$	31 or 32	0.00555	0.00555
Fractional preload measurement accuracy	$\frac{\Delta P_R}{P_R}$	33a or 26a	0.00846	0.00846
Preload measurement accuracy	ΔP_R	33	448 lb	204 kg

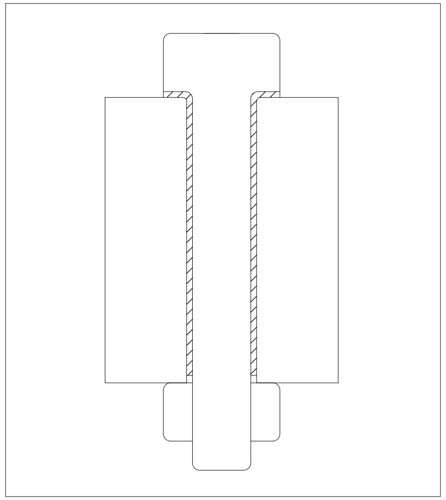
Section 2. Ultrasonic Measurements on a Bolt in an Interference Fit Joint[12,13,14]

Paper covers

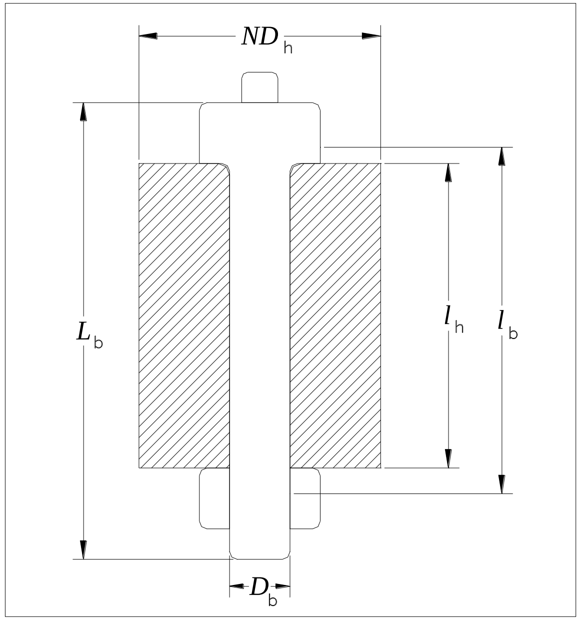
- Measurement of preload in interference fit joint bolts
  - Includes temperature compensation
- Measurement interference quantities such as
  - Diametrical interference and interference pressure
- Includes two configurations
  - Case I: Pull one of the ends in a universal testing machine – No nut turning, 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[12,13,14]: Cross Section of the Sleeve-bolt Joint and Regular Bolt Joint

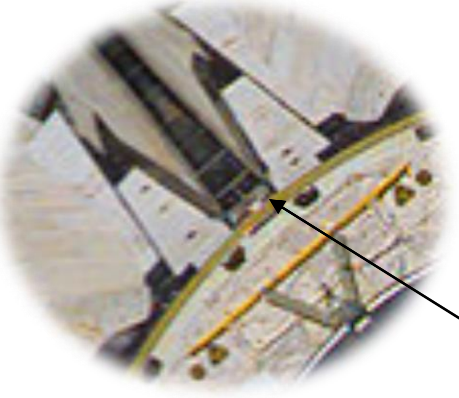




Sleeve Bolt Joint



Regular Interference Fit Joint



Two sleevebolts are used to attach forward end of vertical tail

2. Interference Fit Joint[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
Ultrasonic velocity	$\rho_0\left(V_0^{R}\right)^2 = \lambda + 2\mu + (2l+\lambda)\theta + (4m + 4\lambda + 10\mu)\varepsilon_{11},$
Preload and tensile strain	$P = EA\varepsilon_{11}$

2. Interference Fit Joint[12,13,14]: Analytical Model for Two Cases

CASE I: Bolt Pulled

Ultrasonic stretch with interference

$$\Delta L^i = \Delta t_{cs}^R \left(\frac{V^i}{2}\right) = l_{b0}^R \left(\frac{(1+\varepsilon_{11})}{(1+\beta\cdot\varepsilon_{11})} - 1\right)\left(\frac{V^i}{V_0^R}\right) = \varepsilon_{11} l_{b0}^R \left(\frac{1-\beta}{(1+\beta\cdot\varepsilon_{11})}\right)\left(\frac{V^i}{V_0^R}\right)$$

Ultrasonic stretch without interference

$$\Delta L^i = \Delta t_{cs}^R \left(V^i/2\right) = \varepsilon_{11} l_{b0}^R (1-\beta)\left(V^i/V_0^R\right)$$

Load factor without interference

$$W^{av} = \frac{P}{\Delta L^i} = \frac{AE_b}{l_{b0}^R(1-\beta)}\left(\frac{V_0^R}{V^i}\right)$$

CASE II: Nut Tightened

Ultrasonic stretch with interference

$$\Delta L^i = l_{bs}^{Te}\left(\frac{1+\varepsilon_{11}}{1+f_n} - 1\right)\left(\frac{1+\alpha\cdot\Delta T}{1+K_b\cdot\Delta T}\right)\left(\frac{V^i}{V_0^T}\right) = l_{bs}^{Te}\left(\frac{1+\varepsilon_{11}}{1+f_n} - 1\right)\left(\frac{1}{1+K_b\cdot\Delta T}\right)\left(\frac{V^i}{V_0^R}\right)$$

Ultrasonic stretch without interference

$$\Delta L^i = l_{bs}^{Te}\varepsilon_{11}(1-\beta)\left[1/(1+K_b\cdot\Delta T)\right]\left(V^i/V_0^R\right)$$

Effective length

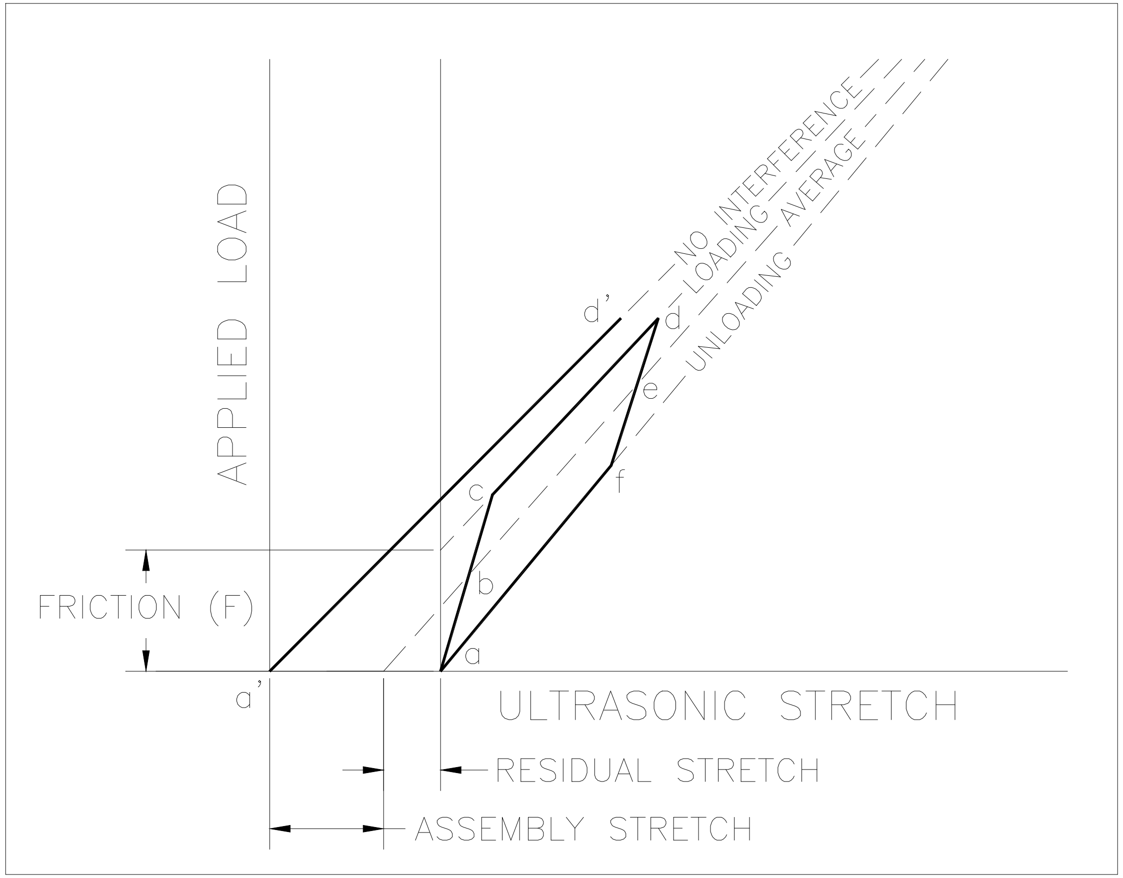
$$l_{bs}^{Te} = \frac{l_{b0}^{\mathrm{Re}} + l_{h0}^R\left(K_h \Delta T + \varepsilon_h + K_h \Delta T \varepsilon_h\right)}{1+\varepsilon_{11}}$$

Load factor

$$W^{av} = P/\Delta L^i$$

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

2. Interference Fit Joint[12,13,14]: Schematic of Preload Characteristic Curves



All characteristic lines theoretically meet and merge after exceeding a certain load when bolt interference is lost.

2 Interference Fit Joint[12,13,14]: Analytical Model for Friction and Pressure on Shank

Preload at nut end - Loading

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

Preload at nut end - Unloading

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

Frictional force to push bolt out of the hole

$$F_{\max}^{0} = f\pi D_{b0}^{T} l_{h0}^{T} Q_0$$

Shank pressure during – Loading and unloading

$$Q_L = \frac{Q_0 - C_4 P_{NL}}{1 - 0.5\pi C_4 f D_{b0}^{T} l_{h0}^{T}}$$

$$Q_U = \frac{Q_0 - C_4 P_{NU}}{1 + 0.5\pi C_4 f D_{b0}^{T} l_{h0}^{T}}$$

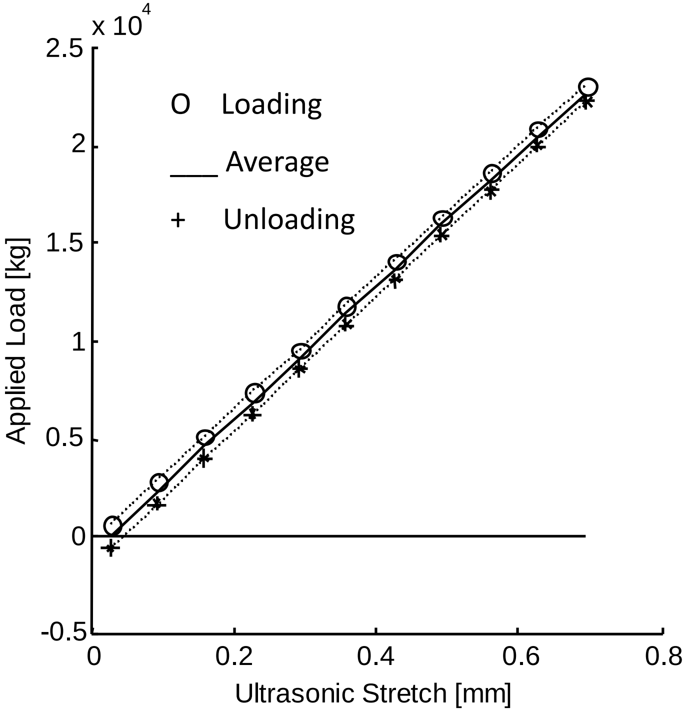
Load Factor - Loading

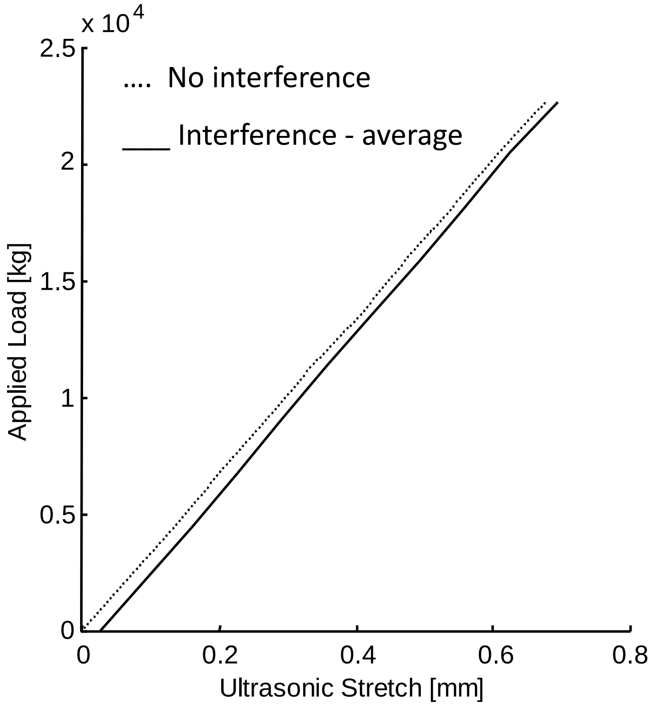
$$W_L = P_{NL} / \Delta L_{mL}^{i}$$

Preload characteristic equation

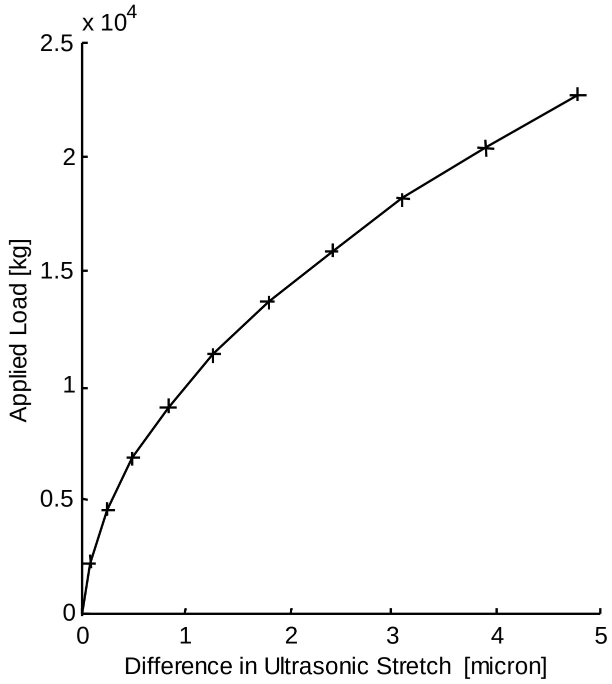
$$P = W \Delta L_{m}^{i} + Y$$

2. Interference Fit Joint[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.



(Case I – Case II)

Very small difference in this case

2. Interference Fit Joint[12,13,14]: Simulation Run Comparison with Experiments

Quantities defining the load characteristics			**Simulation**	**Experiment**
P_H^R	Residual preload	kg	1127	1123
ΔL_1^i	Assembly stretch	mm	0.0260	-
ΔL_2^i	Residual stretch	mm	0.0164	0.016
ΔL_0^i	Initial stretch	mm	0.0424	-
W_L	Load factor during loading	kg/mm	34,037	34,019
W_U	Load factor during unloading	kg/mm	34,447	34,460

Simulation based on the analytical model compares well with experiments.

2. Interference Fit Joint[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.

$$F_{\max} = f\pi D_{b0}^{T} l_{h0}^{T} Q_{\max}$$

- Determine interference pressure Q_0 using following Eq.

$$Q_{\max} = Q_0 / \left(1 + 0.5\pi C_4 f D_{b0}^{T} l_{h0}^{T}\right)$$

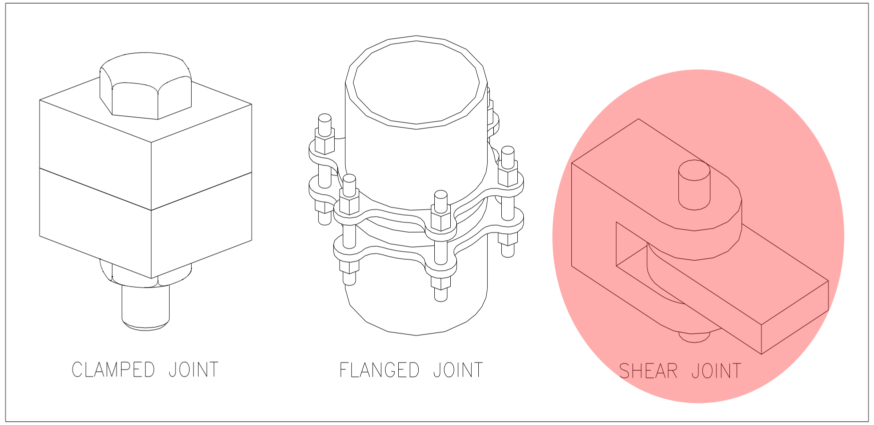
- Determine the interference from the interference pressure using following Eq.

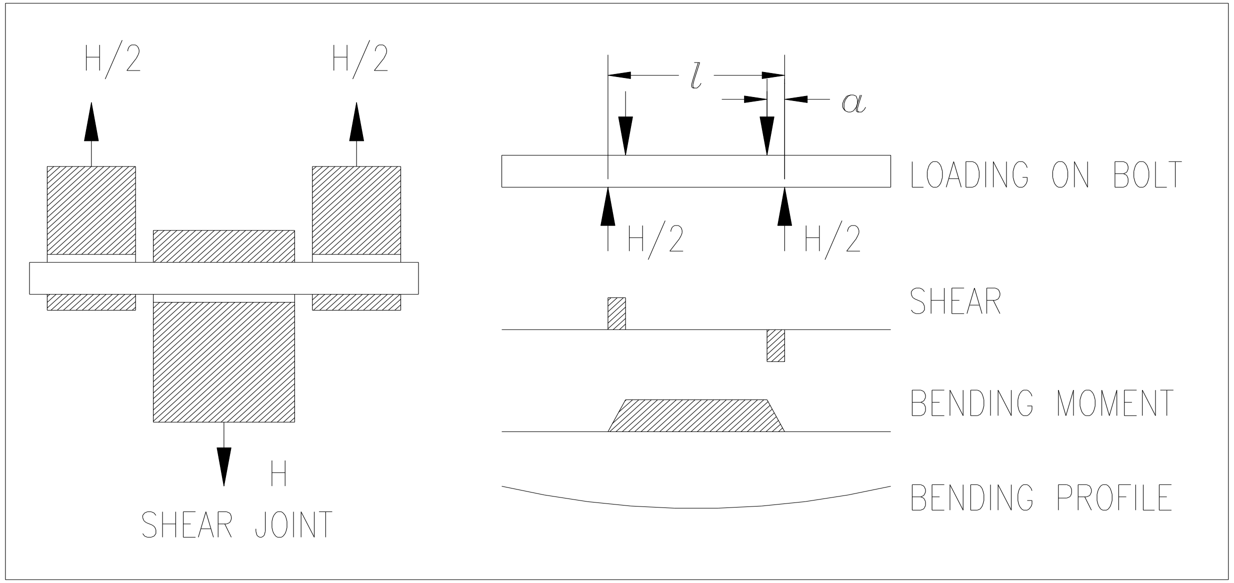
$$I_s^T = I_0^T = I^T = Q_0 C_3$$

2. Interference Fit Joint[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.

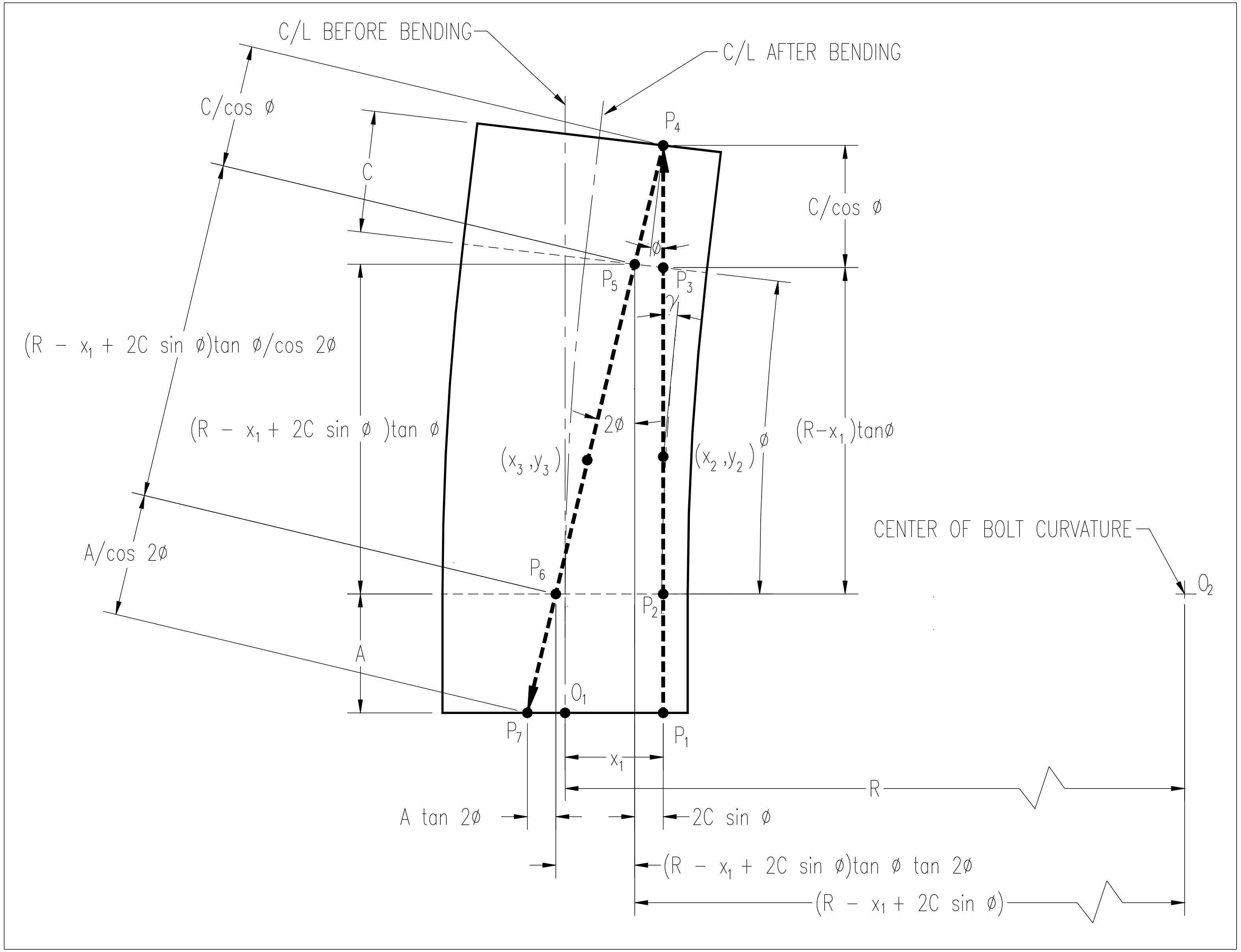
Section 3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Loading, shear force and bending moment on the bolt



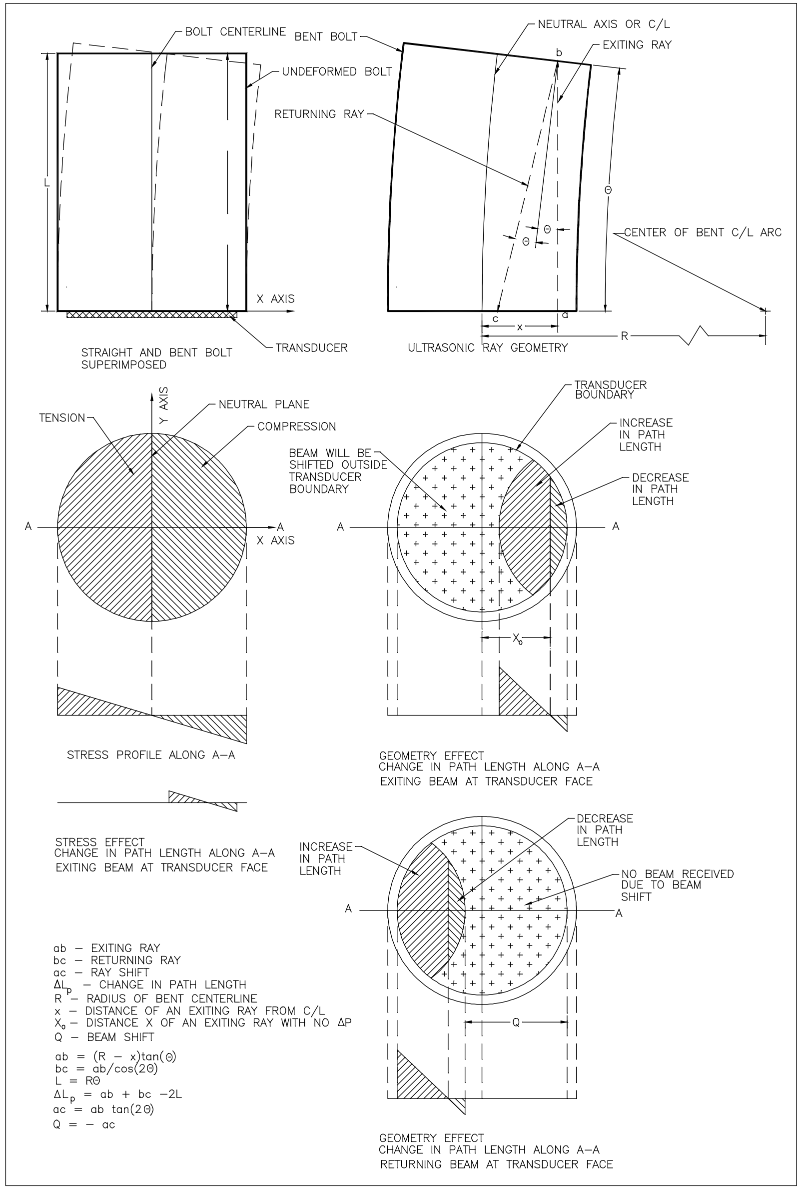


- Ray Tracing Analytical Model
  - No beam spread,
  - No beam-bending
  - No variation in the beam intensity normal to the direction of path.
  - The reflector reflects the wave back as a plane wave.
  - The bolt profile is an arc of a circle.

3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Ultrasonic Ray Path in a Bent Bolt



3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Ultrasonic Ray Path in a Bent Bolt



ab – EXITING RAY
bc – RETURNING RAY
ac – RAY SHIFT
ΔL_p – CHANGE IN PATH LENGTH
R – RADIUS OF BENT CENTERLINE
x – DISTANCE OF AN EXITING RAY FROM C/L
X_o – DISTANCE X OF AN EXITING RAY WITH NO ΔP
Q – BEAM SHIFT

$ab = (R - x)\tan(\Theta)$
$bc = ab/\cos(2\Theta)$
$L = R\Theta$
$\Delta L_p = ab + bc - 2L$
$ac = ab \tan(2\Theta)$
$Q = -ac$

3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Analytical Model

Radius, effective length and bending angle

$$R = \frac{l}{\phi}$$

Ray shift

$$Q = -2C\sin\phi - \left(\frac{l}{\phi} - x_1 - 2C\sin\phi\right)\tan\phi\tan 2\phi - A\tan 2\phi$$

Pulse transit time

$$t_1 = \frac{P_1P_2 + P_3P_4 + P_4P_5 + P_6P_7}{V_0} + \int_{P_2}^{P_3}\frac{ds}{V_{23}} + \int_{P_5}^{P_6}\frac{ds}{V_{56}}$$

Pulse transit time

$$t_1 = \frac{P_1P_2 + P_3P_4 + P_4P_5 + P_6P_7}{V_0} + \int_{P_2}^{P_3}\frac{dy}{V_{23}} + \sec 2\phi\int_{P_5}^{P_6}\frac{dy}{V_{56}}$$

Integration increment

$$\Delta y_{23} = \frac{(R - x_1)\tan\phi}{m_1}$$

Integration increment

$$\Delta y_{56} = \frac{(R - x_1 + 2C\sin\phi)\tan\phi}{m_1}$$

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[15,16]: Analytical Model

Radial Coordinate $r^c = R - r$

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

Stress $\sigma = \dfrac{M_{av} r^c}{I}$

Velocity $V = V_0\left(1 - \dfrac{c_1 r^c \cos^2\gamma}{R}\right)$

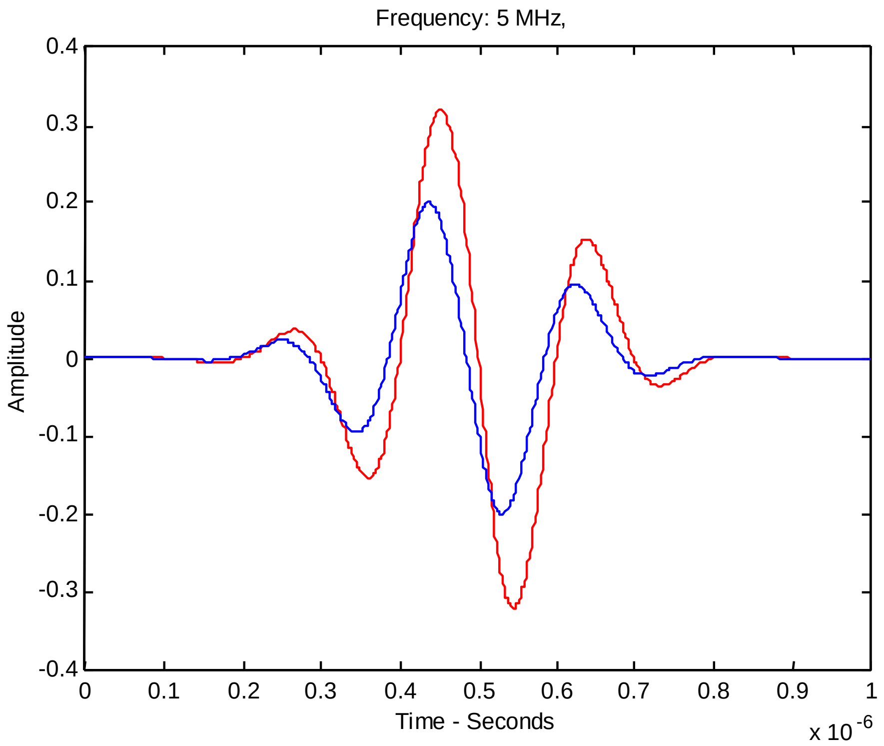
Received ultrasonic signal $U(t) = \displaystyle\iint_{A'} u(x_1, z, t)\,dx_1\,dz$

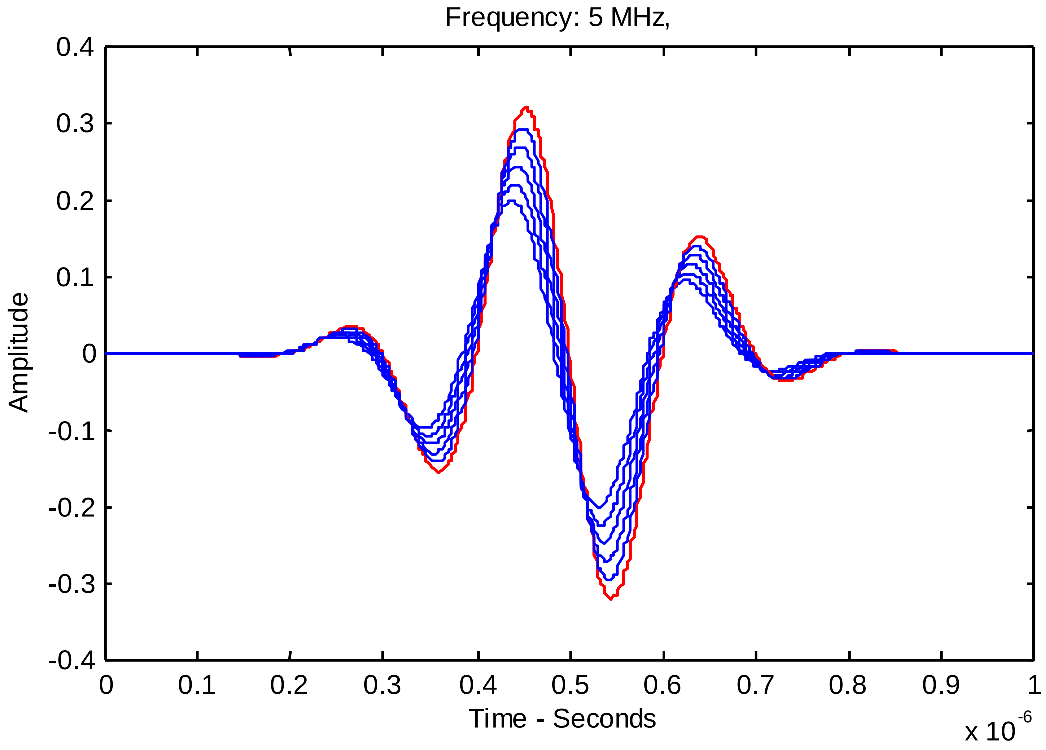
$$u(x_1, i) = -\frac{2\sin\left(2\pi c\left(\dfrac{i-1-\Delta i}{N}\right) + \pi\right) e^{-\alpha\left(2\pi\left(\frac{i-1-\Delta i}{N}\right) - \pi\right)^2}}{\pi {r_z}^2}$$

3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Values of Some Parameters Used in the Simulation

l	mm (in.)	95.5 (3.76)
A	mm (in.)	91.95 (3.62)
C	mm (in.)	28.45(1.12)
V_o	Mm/sec (in./sec)	5905347.6(232494)
E	Mpa, kg/mm^2 (psi)	21.3729 x 10^4, 21.8 x 10^3, (31 x 10^6)
c_1		-2.45
c		5
N		1024
f	Hz	5 x 10^6
a		1
r_z	mm (in.)	6.35 (0.25)
x_e	mm (in.)	1.5 (0.059)
x_1^f	mm (in.)	2.894 (0.114)
m_1		40
m_2		40
H	kg (lb)	45.5, 90.9, 136.4, 181.8, 227.3 (100, 200, 300, 400, 500.0)
I	mm^4 (in.^{4})	4.91 x 10^3(0.01179)
$\Delta\phi$	Radian for 45.45 kg (100 lb)	0.0006455
$\Delta U/H$	mm/kg, (in/lb) at 227.3 kg (500 lb)	-1.9 x 10^{-4} (-3.4 x 10^{-6})

3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Simulated Waveforms Before and After Bending Load Using the Analytical Model

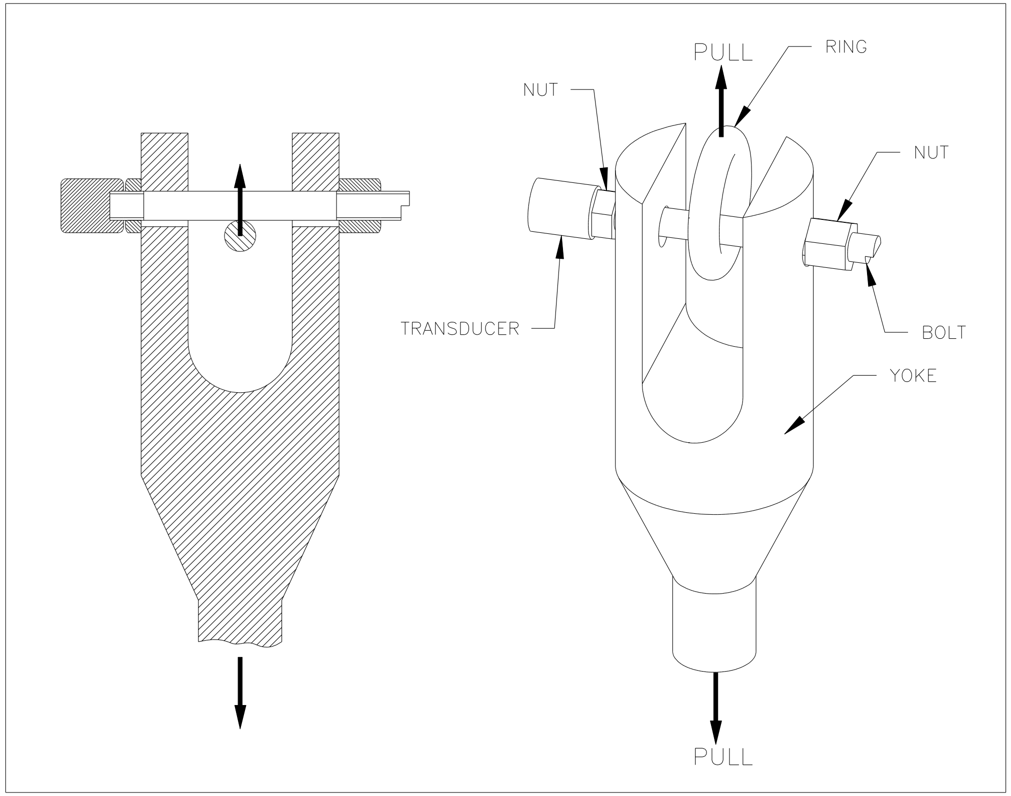




Red: Before shear load
Blue: After shear load

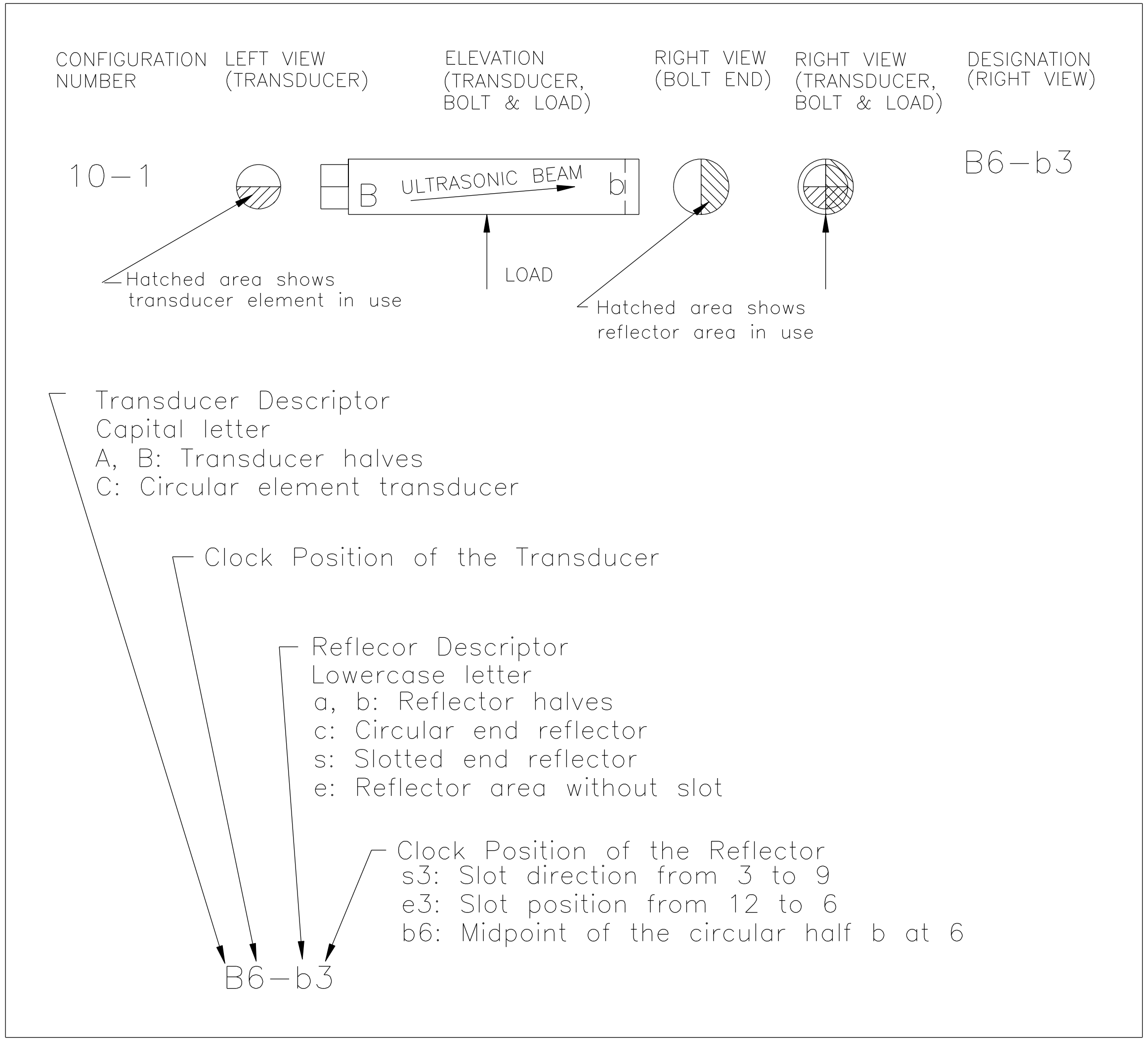
Progression of Wave form with increasing shear load

3. Ultrasonic Preload Measurement in Shear Joint[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[15,16]: Run Designation Scheme



CONFIGURATION NUMBER | LEFT VIEW (TRANSDUCER) | ELEVATION (TRANSDUCER, BOLT & LOAD) | RIGHT VIEW (BOLT END) | RIGHT VIEW (TRANSDUCER, BOLT & LOAD) | DESIGNATION (RIGHT VIEW)

10−1

B6−b3

Hatched area shows transducer element in use

Hatched area shows reflector area in use

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

Clock Position of the Transducer

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

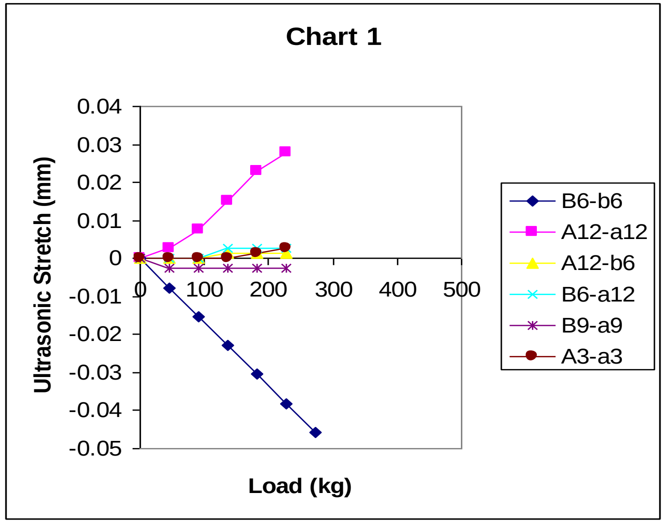
Clock Position of the Reflector
s3: Slot direction from 3 to 9
e3: Slot position from 12 to 6
b6: Midpoint of the circular half b at 6

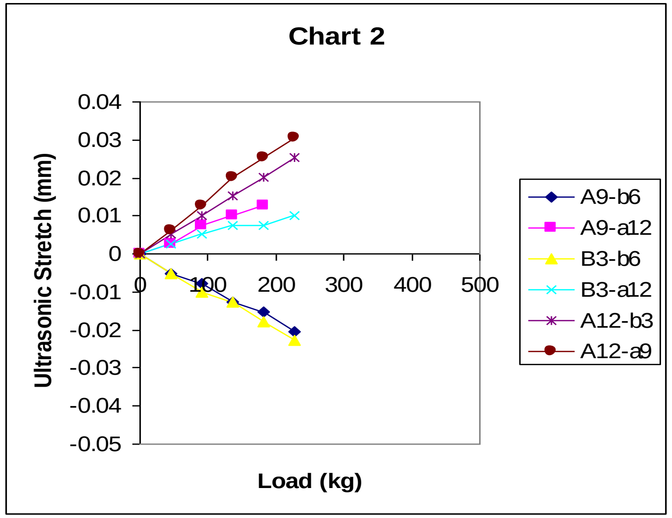
B6−b3

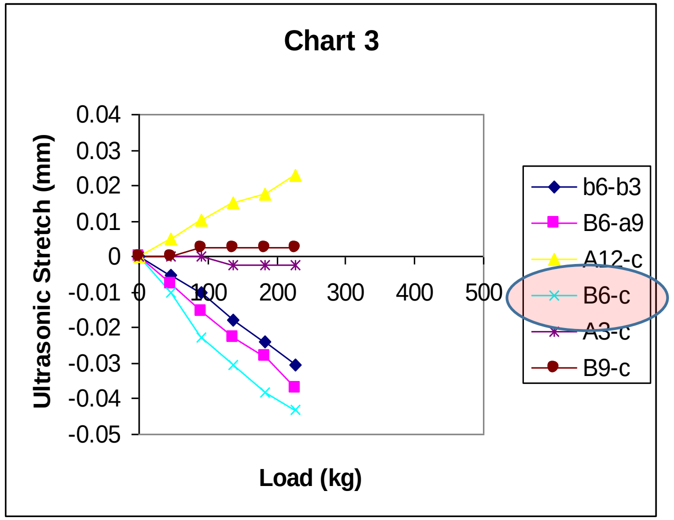
3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Run Configurations

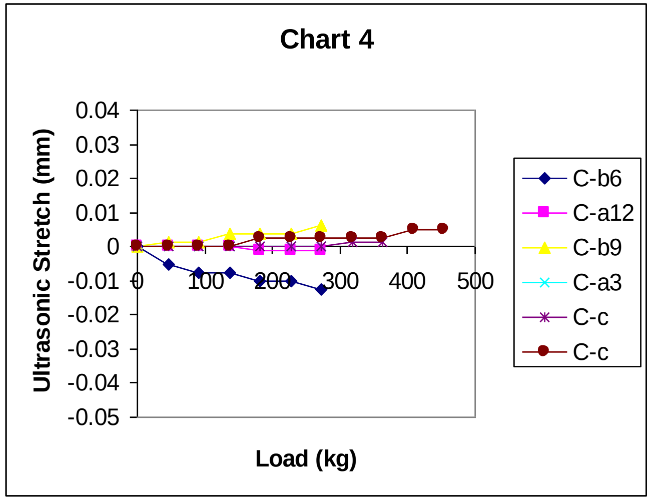
CONFIGURATION NUMBER	DESIGNATION
1	B6–b6
2	A12–a12
3	A12–b6
4	B6–a12
5	B9–a9
6	A3–a3
7–1	A9–b6
7–2	A9–a12
8–1	B3–b6
8–2	B3–a12
9–1	A12–b3
9–2	A12–a9
10–1	B6–b3
10–2	B6–a9
11	A12–c
12	B6–c
13	A3–c
14	B9–c
15–1	C–b6
15–2	C–a12
16–1	C–b9
16–2	C–a3
17	C–c
18	C–c
19–1	C–e6
19–2	C–s3
20–1	C–e3
20–2	C–s6
21–1	A6–e6
21–2	B12–e6
22–1	B9–e3
22–2	A3–e3
23–1	A3–s3
23–2	A3–e6
23–3	B9–e6
23–4	B9–s3

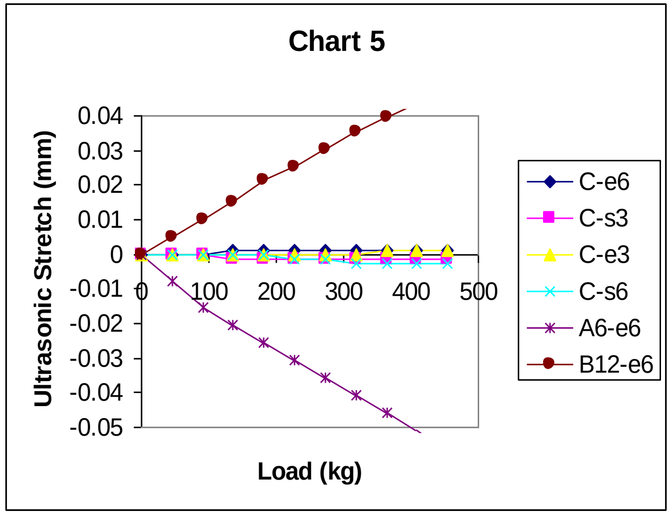
3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Ultrasonic Stretch versus Load Experimental Data

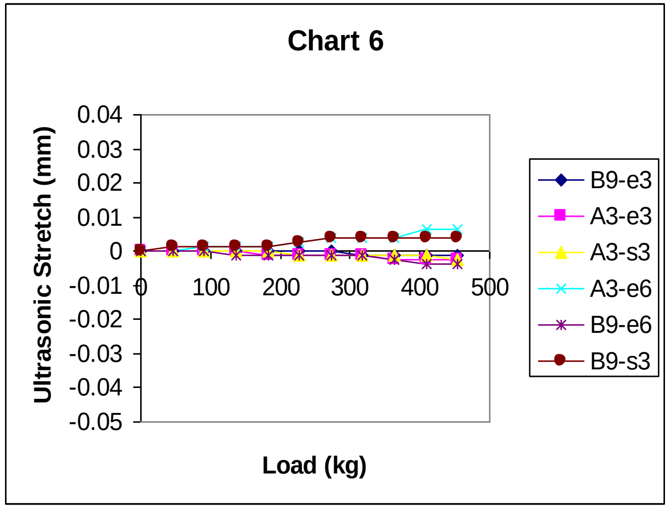




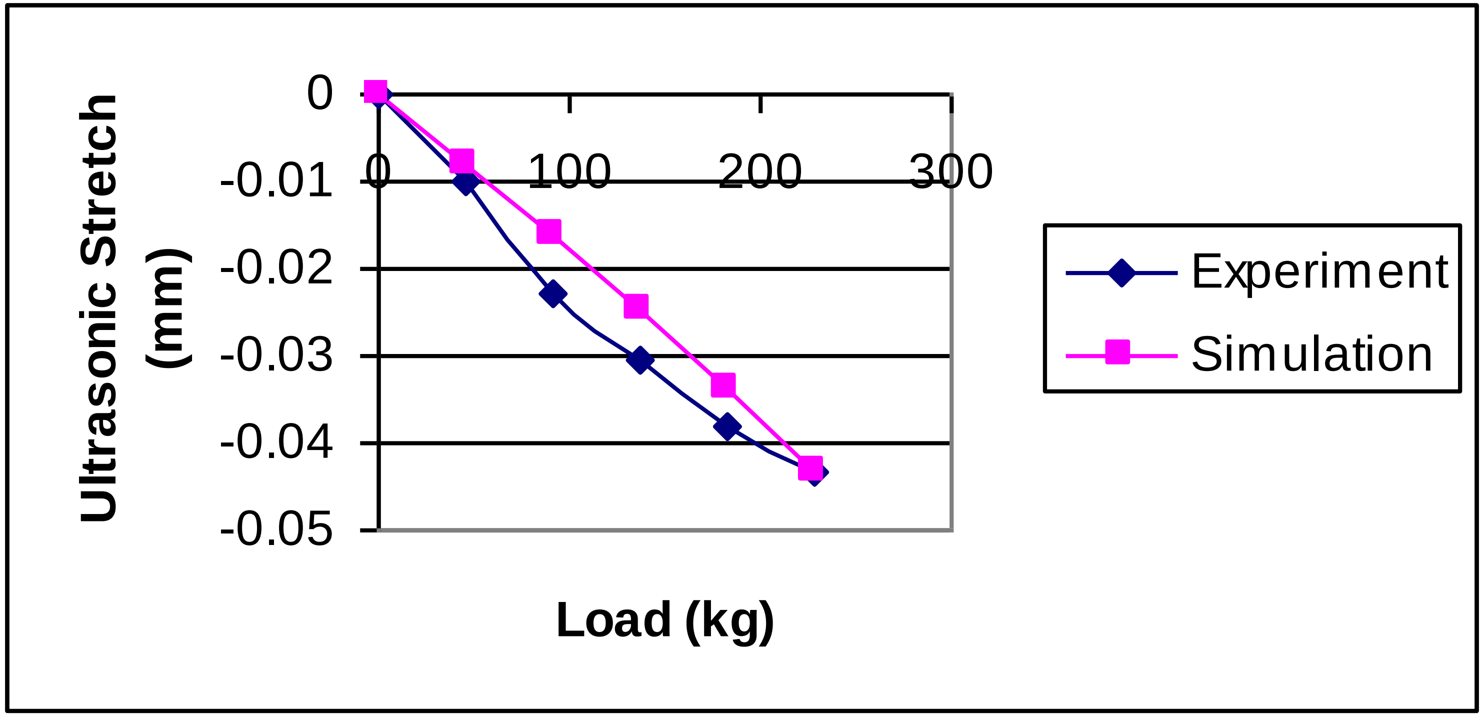








3. Ultrasonic Preload Measurement in Shear Joint[15,16]: Simulation versus Experiment



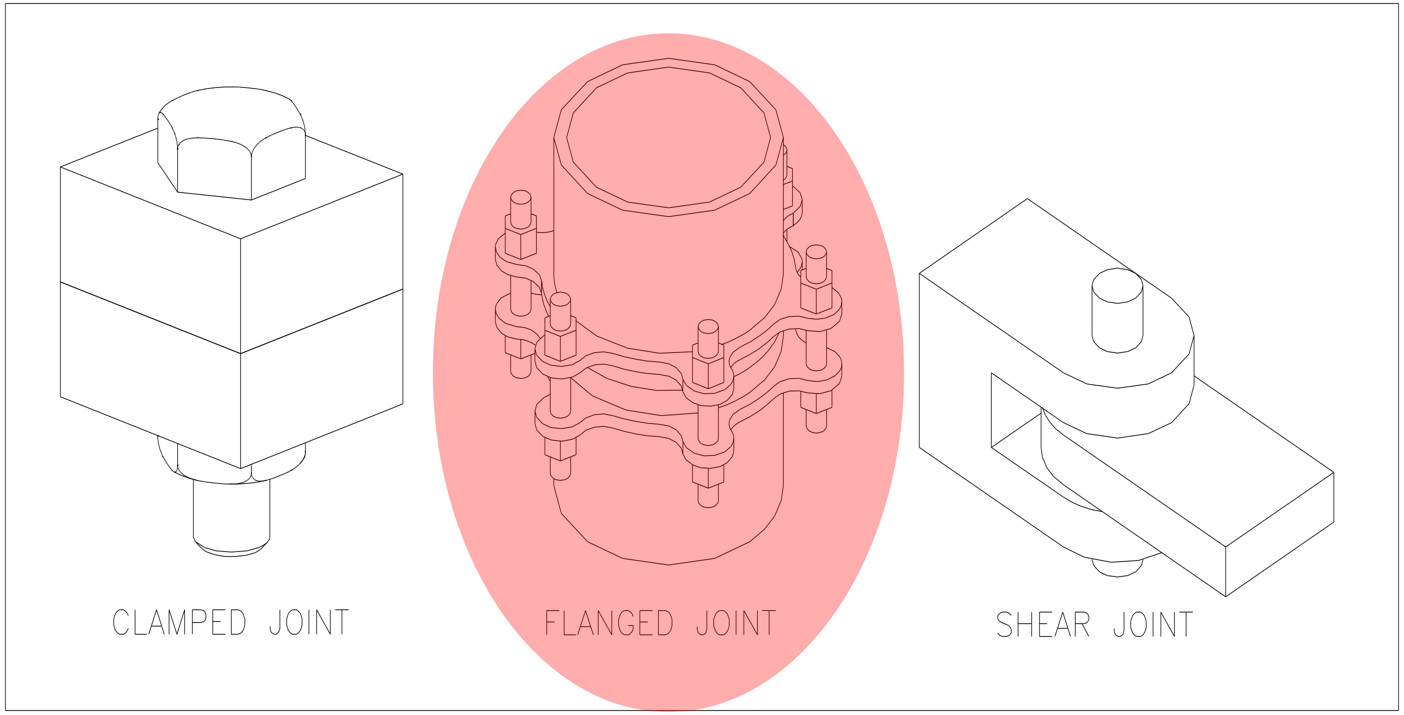
Experiment and Simulation of ultrasonic stretch versus load for run 12 (B6-c)

3. Ultrasonic Preload Measurement in Shear Joint[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

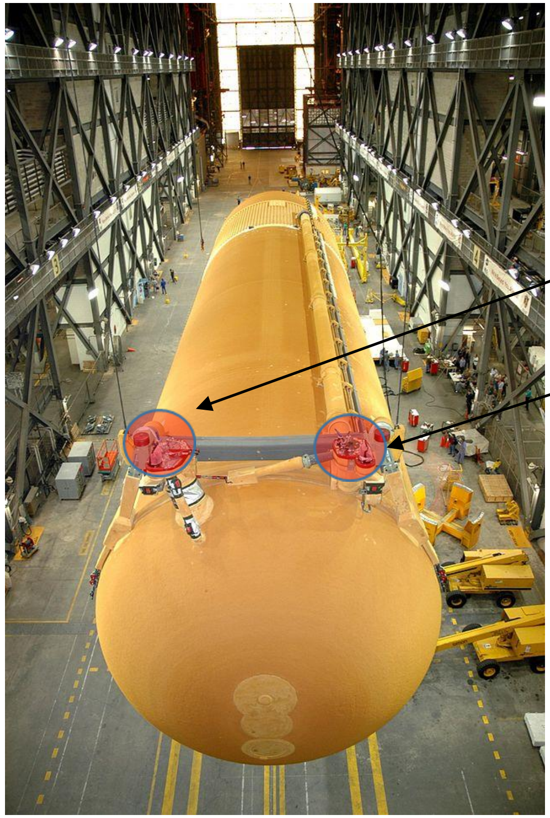
Section 4. Effect of Bolt Bending in Flanged Joint on Ultrasonic Measurements[17]

- Shuttle Booster Hold Down Post Bolts
- 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

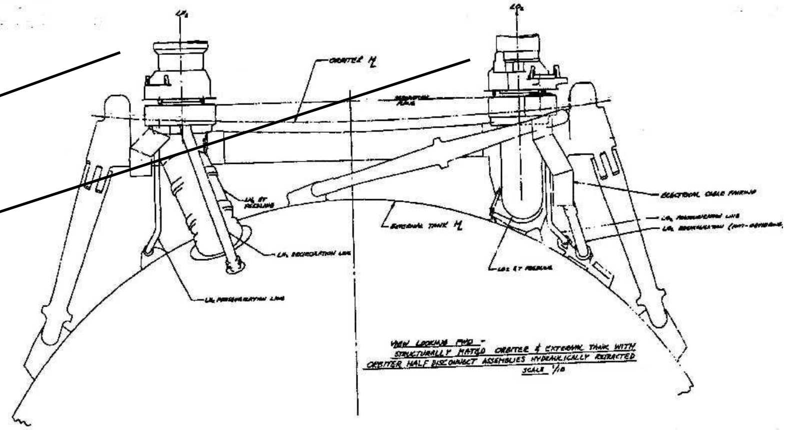


4. Flanged Joint on Ultrasonic Measurements[17]: Orbiter/External Tank Umbilical Mate

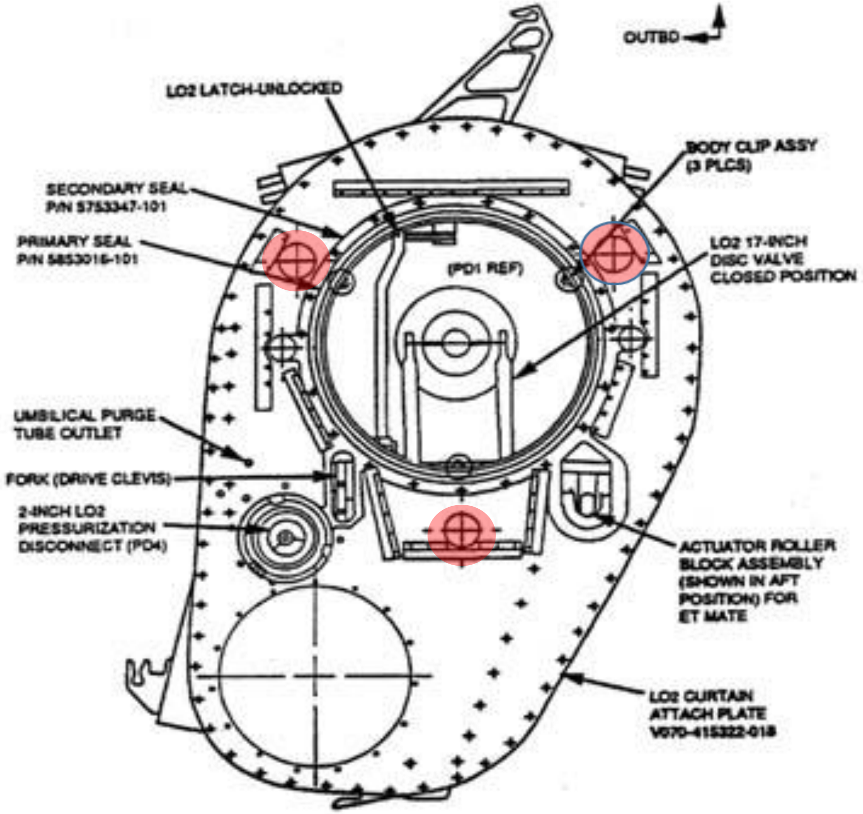
Umbilical ET Side Locations



Umbilical ET Side
Side View



Orbiter Side Liquid Oxygen Umbilical Plate



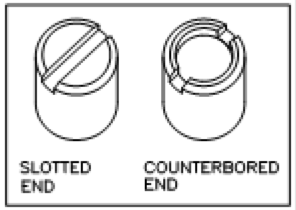
Orbiter/ET Umbilical Attach Bolts

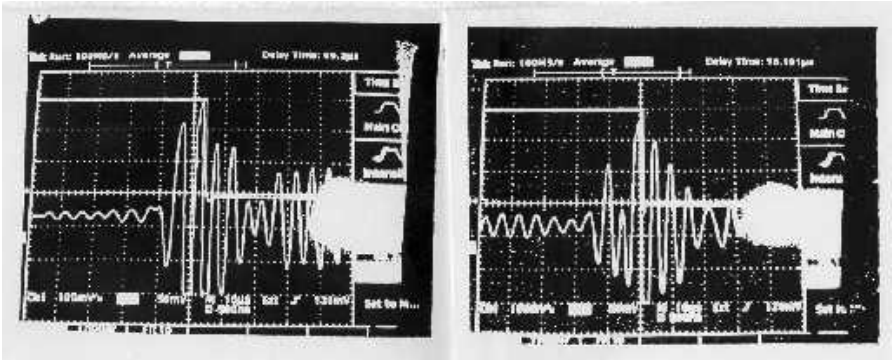
- Two umbilicals, Left one for liquid hydrogen and Right one for liquid oxygen
- Three 0.7” Dia. X 8” long MP35N bolts per umbilical, Flanged joint in a clearance fit, 45 to 61 kip load
- Provides structural joint and pressure on fluid line seals to prevent leakage.
- Three bolts of an umbilical are 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[17]: Ultrasonic Measurements on Umbilical Bolts

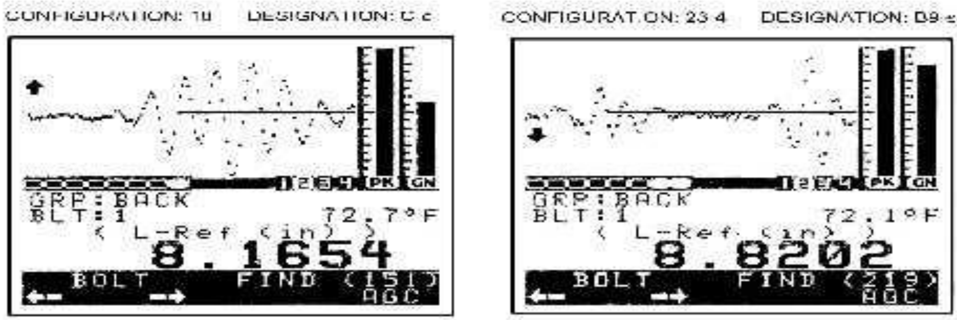
- Umbilical bolt measurements in original bolt configuration
  - Ultrasonic signal distorted causing unreliable readings
- Signal distorted due to bolt bending
  - Umbilical flanges bend under bolt tension and cause bolt bending
  - Typical bolt protrusion over the nut is ~1/8 in.
    - Bolt stretch = 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




Slotted End Before Preload **Slotted End After Preload**

Raymond boltgage signals


Counterbore Echo **Slot Echo** **Bolt End Echo**

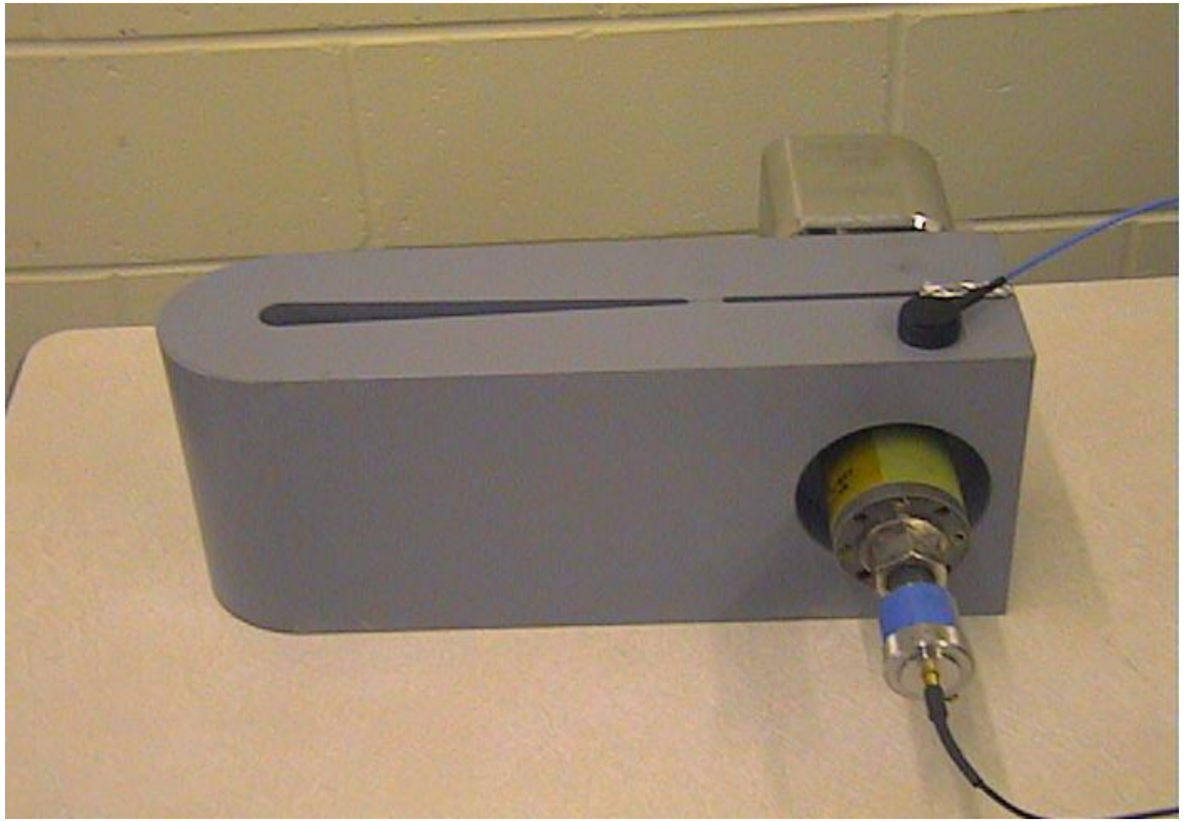
StressTel boltmike signals

4. Flanged Joint on Ultrasonic Measurements[17]: Test Fixtures with Umbilical Joint Hardware

- Simulated Joint with ultrasonic transducer and temperature probe

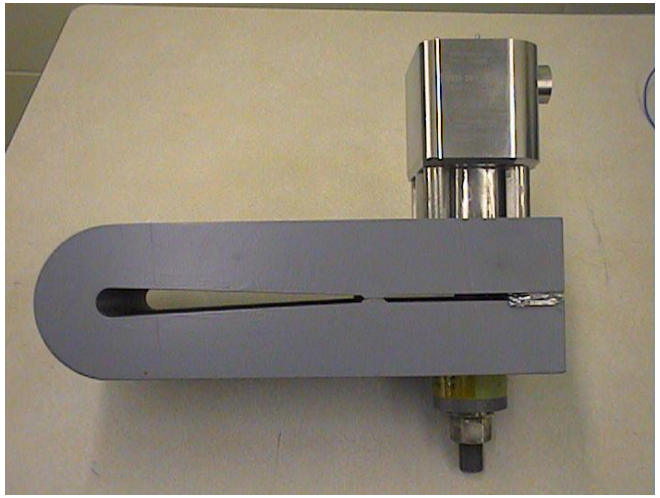
Long Fixture

Short Fixture



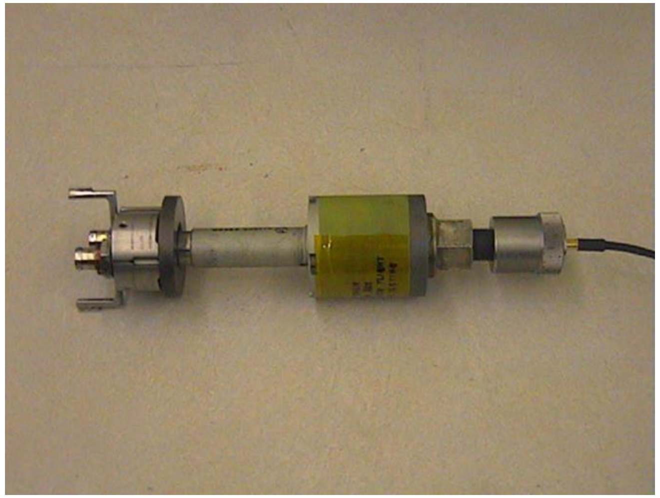
4. Flanged Joint on Ultrasonic Measurements[17]: Short Fixture with Umbilical Joint Hardware

Test Assembly

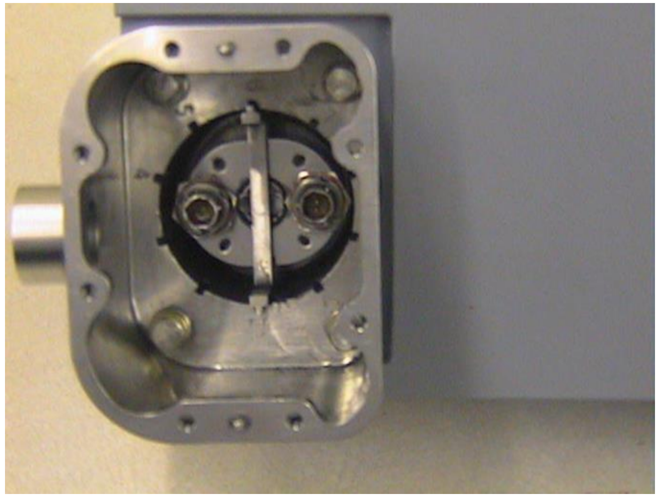


Test Assembly with Ultrasonic Transducer

Joint Assembly without Fixture

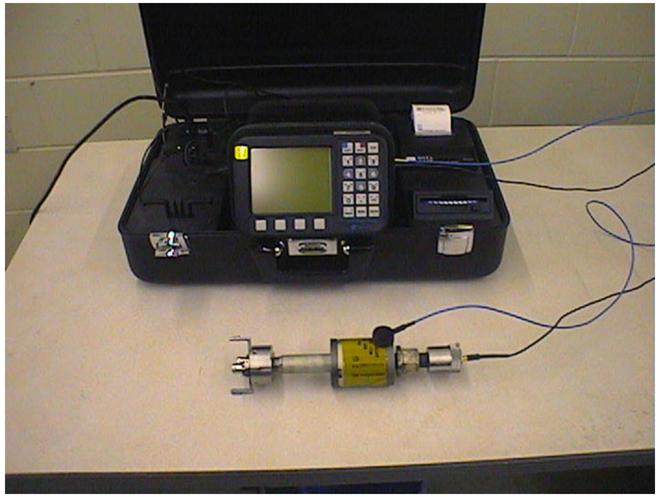


Top View

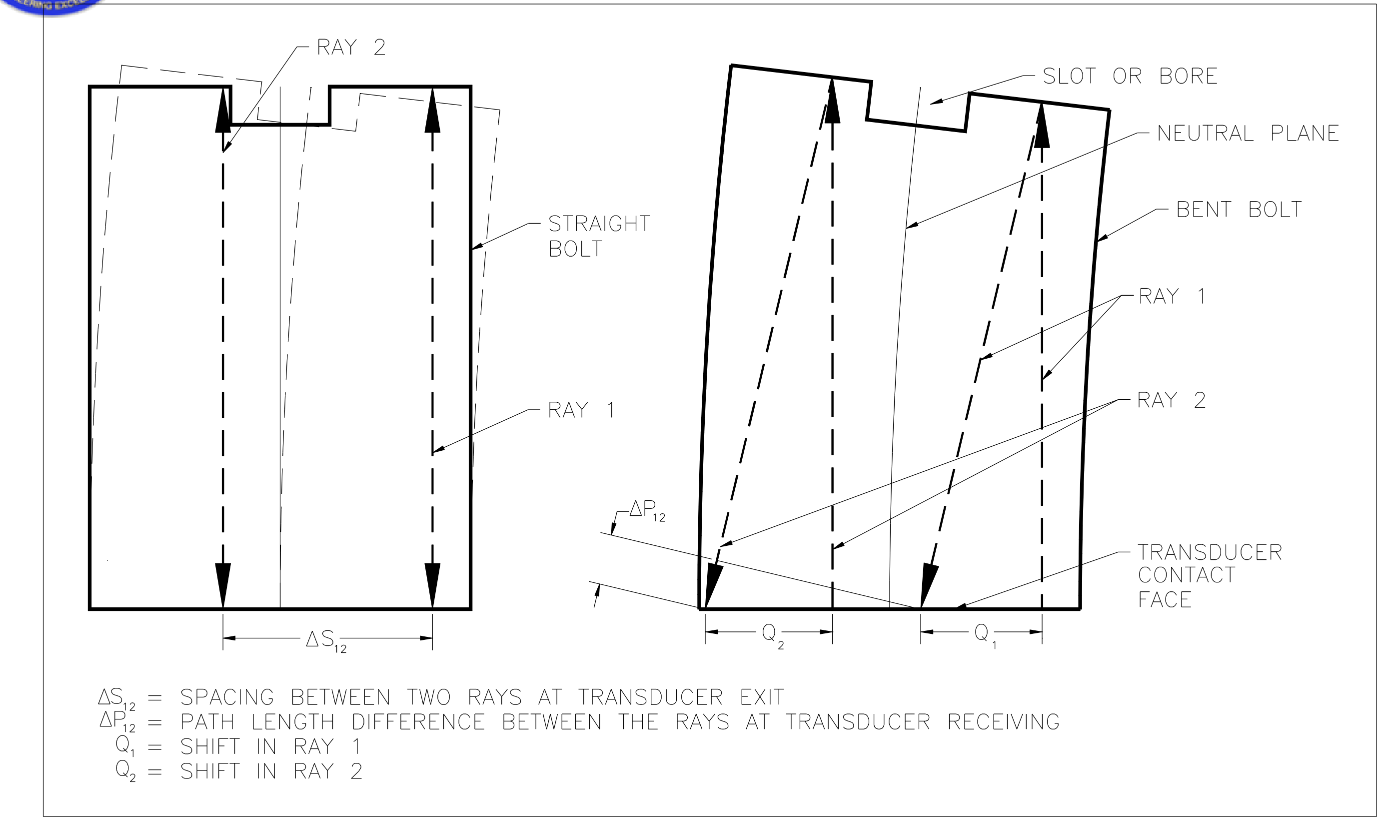


Assembly Parts

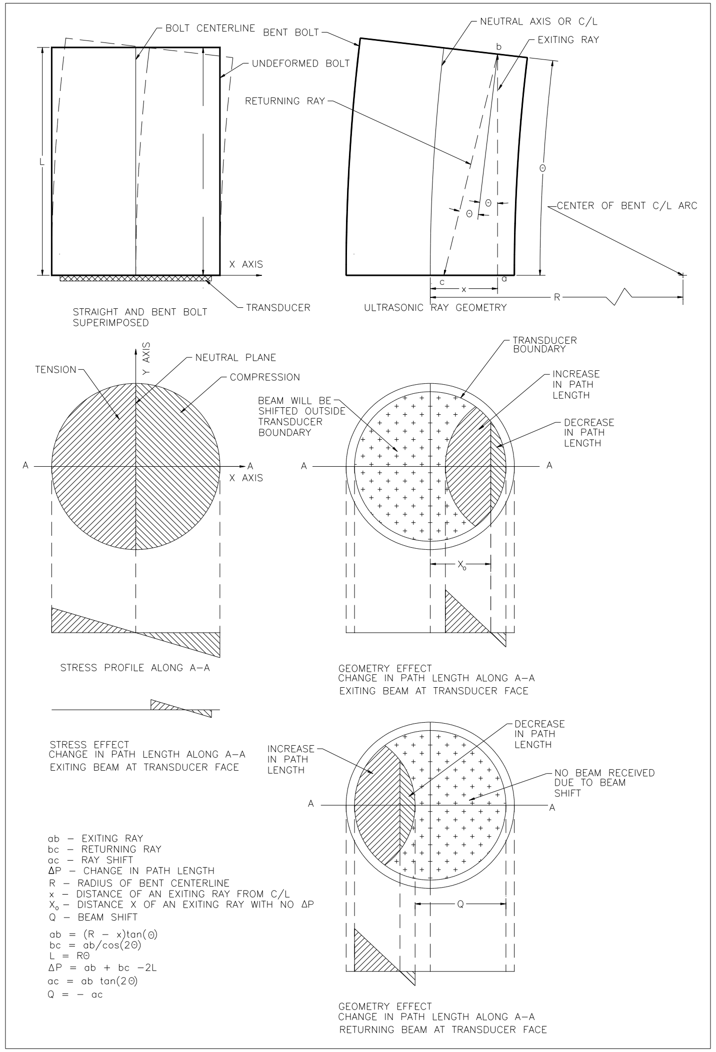
Boltmike with Temperature Probe



4. Flanged Joint on Ultrasonic Measurements[17]: Analytical Model with Geometric and Bending Effect



ΔS_{12} = SPACING BETWEEN TWO RAYS AT TRANSDUCER EXIT
ΔP_{12} = PATH LENGTH DIFFERENCE BETWEEN THE RAYS AT TRANSDUCER RECEIVING
Q_1 = SHIFT IN RAY 1
Q_2 = SHIFT IN RAY 2



ab – EXITING RAY
bc – RETURNING RAY
ac – RAY SHIFT
ΔP – CHANGE IN PATH LENGTH
R – RADIUS OF BENT CENTERLINE
x – DISTANCE OF AN EXITING RAY FROM C/L
X_o – DISTANCE X OF AN EXITING RAY WITH NO ΔP
Q – BEAM SHIFT

$ab = (R - x)\tan(\Theta)$
$bc = ab/\cos(2\Theta)$
$L = R\Theta$
$\Delta P = ab + bc - 2L$
$ac = ab\tan(2\Theta)$
$Q = -ac$

Phase change due to Geometry and bending effect.

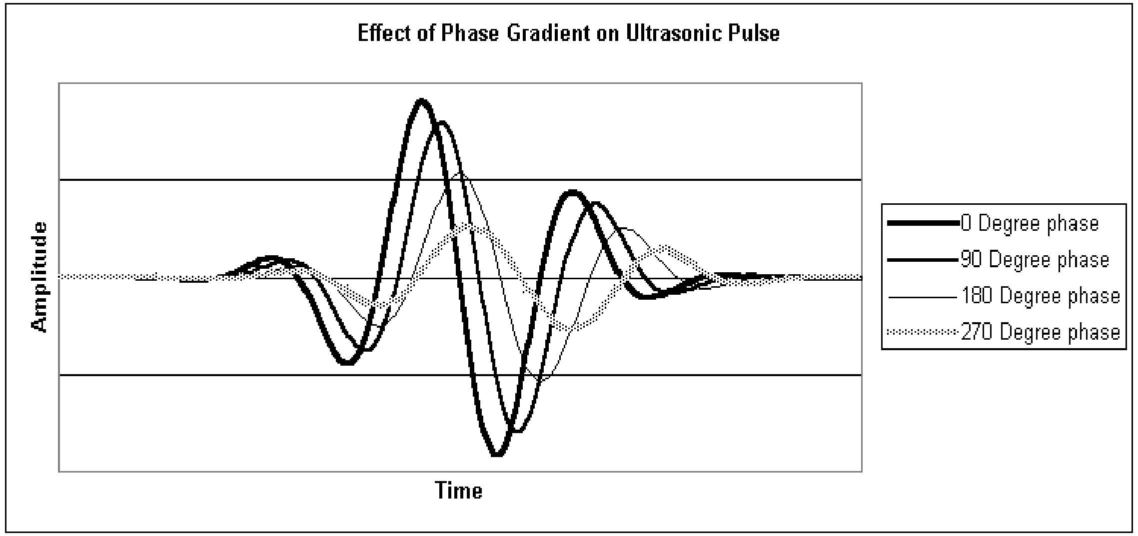
$$\Delta\phi_{Gb} = \left(\frac{2\pi}{\lambda}\right)\left[\left(\frac{L}{\theta} - x\right)\tan 2\theta - 2L - \frac{2\theta'}{S}\left(x + \frac{Q}{4}\right)\right]$$

Ultrasonic signal response.

$$U(t) \propto \iint_A u(x,y,t)dxdy$$

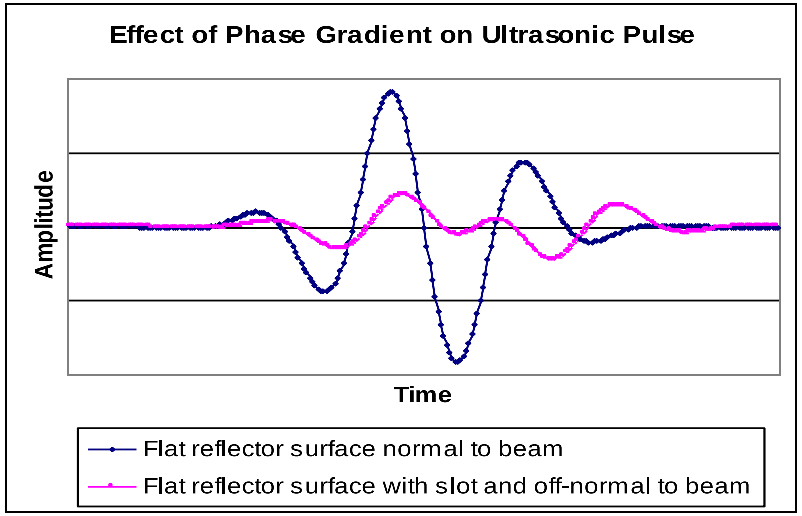
4. Flanged Joint on Ultrasonic Measurements[17]: Comparison of Simulated Signals

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



Beam shift, signal shift, and loss of signal amplitude

Effect of Phase Gradient with Slot



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

Stress Effect

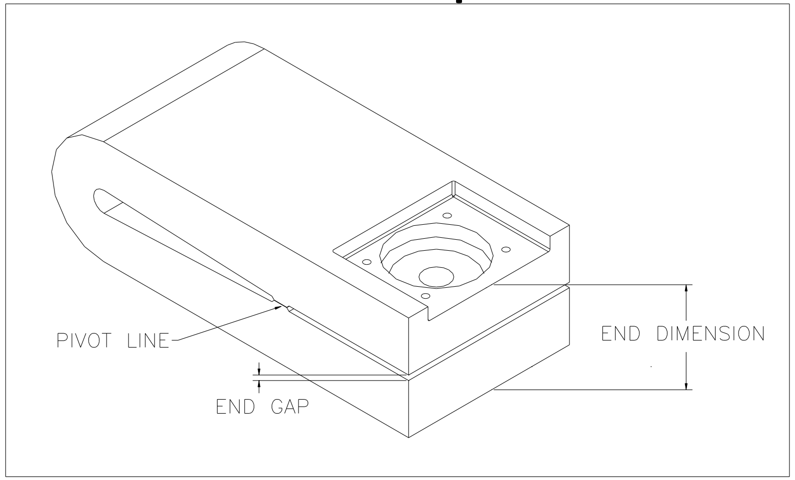
- Bolt tension increases the path length
  - Ultrasonic stretch = 3 x Physical stretch
- Bolt bending results in bending stress in the bolt
  - On tensile region the path length increases
  - On the compressive side the path length decreases
- The bending stress results in slight bending of the beam 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

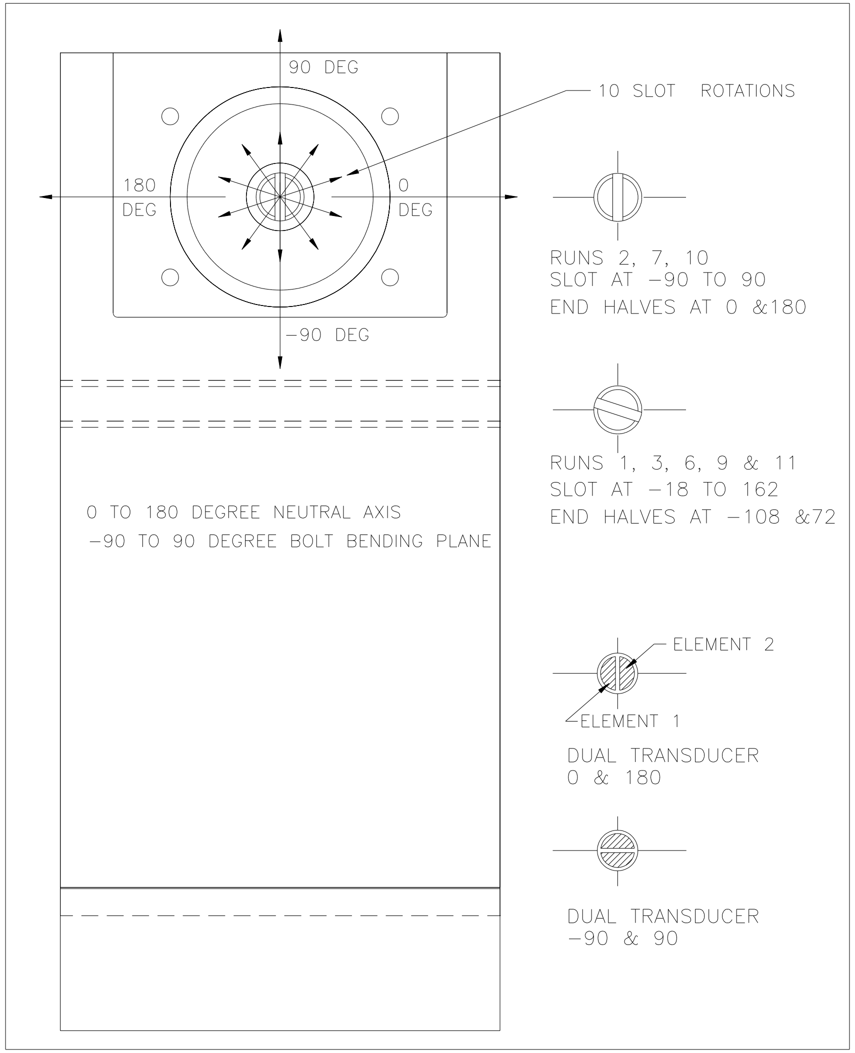
4. Flanged Joint on Ultrasonic Measurements[17]: Bolt and Transducer Orientations in the Fixture, End Gap

End Gap



End gap as a measure of bending load

Bolt and Transducer Orientations



Reference Runs

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

Run and configuration	Fixture	Bolt	Reflector	Reflector angles	Transducer	Transducer angle	Stretch at 54% nominal load, mm (in.)	Stretch at 100% nominal load, mm (in.).
R1A	Short	Slotted	End	72 & -108	Single	N/A	0.927 (0.0365)	1.824 (0.0718)
R1B	Short	Slotted	Slot	-18 & 162	Single	N/A	0.917 (0.0361)	1.803 (0.0710)
R2A	Short	Counterbored	End	N/A	Single	N/A	0.927 (0.0365)	1.867 (0.0735)

4. Flanged Joint on Ultrasonic Measurements[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

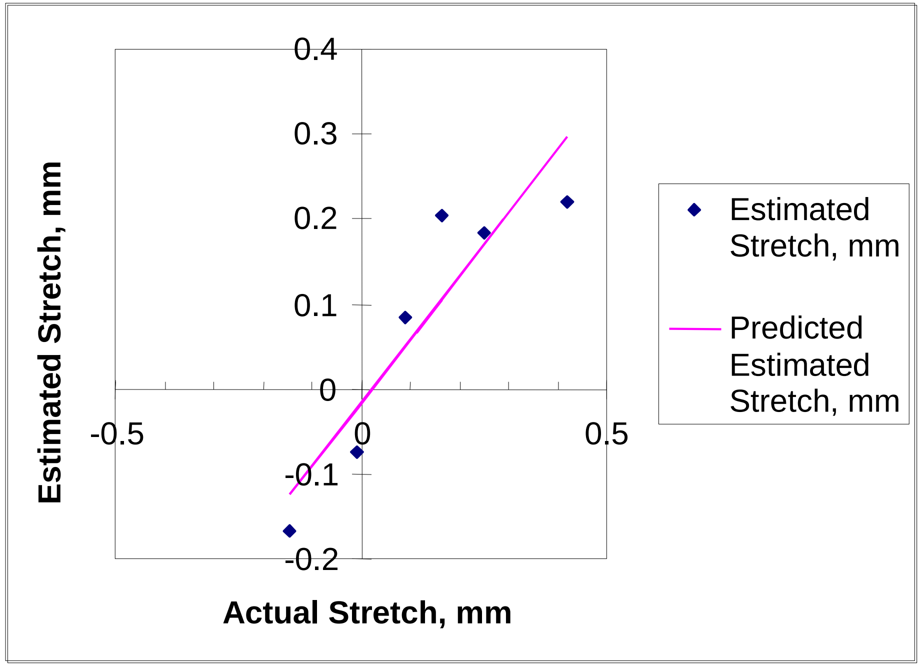
Run and configuration	Fixture	Bolt end	Reflector	Reflector angles, Deg.	Transducer type	Transducer angle, Deg.	Relative stretch (%) at 54 % of nominal load, mm	Relative stretch (%) at 100 % of nominal load, mm
1A	Long	Slotted	End	72 & -108	Single	N/A	4.4	2.8
1B	Long	Slotted	Slot	-18 & 162	Single	N/A	5.5	4.5
1C	Long	Slotted	End	72 & -108	Dual	72	-4.4	-6.5
1D	Long	Slotted	End	72 & -108	Dual	-108	25.2	21.2
2A	Long	Slotted	End	0 & 180	Single	N/A	11.0	8.1
2B	Long	Slotted	Slot	90 & -90	Single	N/A	8.6	7.6
2C	Long	Slotted	End	0 & 180	Dual	180	14.5	13.0
2D	Long	Slotted	End	0 & 180	Dual	0	11.8	12.8
3A	Long	Slotted	End	72 & -108	Single	N/A	4.7	1.9
3B	Long	Slotted	Slot	-18 & 162	Single	N/A	6.4	5.6
3C	Long	Slotted	Slot	-18 & 162	Dual	0	10.2	12.5
3D	Long	Slotted	Slot	-18 & 162	Dual	180	3.0	2.8
3E	Long	Slotted	End	72 & -108	Dual	0	7.1	0.8
3F	Long	Slotted	End	72 & -108	Dual	180	7.4	-8.6
4A	Long	Counterbored	End	N/A	Single	N/A	17.0	10.1
4B	Long	Counterbored	End	N/A	Dual	180	10.4	Distorted
4C	Long	Counterbored	End	N/A	Dual	0	9.3	Distorted
4D	Long	Counterbored	End	N/A	Dual	90	5.2	-4.6
4E	Long	Counterbored	End	N/A	Dual	-90	40.3	29.4
5A	Short	Counterbored	End	N/A	Single	N/A	9.86	8.84
5B	Short	Counterbored	End	N/A	Dual	180	22.7	Distorted
5C	Short	Counterbored	End	N/A	Dual	0	8.49	Distorted
5D	Short	Counterbored	End	N/A	Dual	90	-0.82	-7.6
5E	Short	Counterbored	End	N/A	Dual	-90	27.39	22.58
6A	Short	Slotted	End	72 & -108	Single	N/A	7.1	1.9
6B	Short	Slotted	Slot	-18 & 162	Single	N/A	5.0	6.1
6C	Short	Slotted	End	72 & -108	Dual	72	-7.4	-6.1
6D	Short	Slotted	End	72 & -108	Dual	-108	23.8	24.8
6E	Short	Slotted	Slot	-18 & 162	Dual	-18	12.2	12.0
6F	Short	Slotted	Slot	-18 & 162	Dual	162	4.2	4.9
7A	Short	Slotted	End	0 &180	Single	N/A	7.7	-7.1
7B	Short	Slotted	Slot	90 &-90	Single	N/A	7.5	8.5
7C	Short	Slotted	End	0 &180	Dual	180	18.1	19.1
7D	Short	Slotted	End	0 &180	Dual	0	13.2	Distorted
7E	Short	Slotted	Slot	90 &-90	Dual	90	-4.2	-3.4
7F	Short	Slotted	Slot	90 &-90	Dual	-90	23.0	23.7
7G	Short	Slotted	End	0 &180	Dual	90	-5.2	-5.0
7H	Short	Slotted	End	0 &180	Dual	-90	20.3	20.8

4. Flanged Joint on Ultrasonic Measurements[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

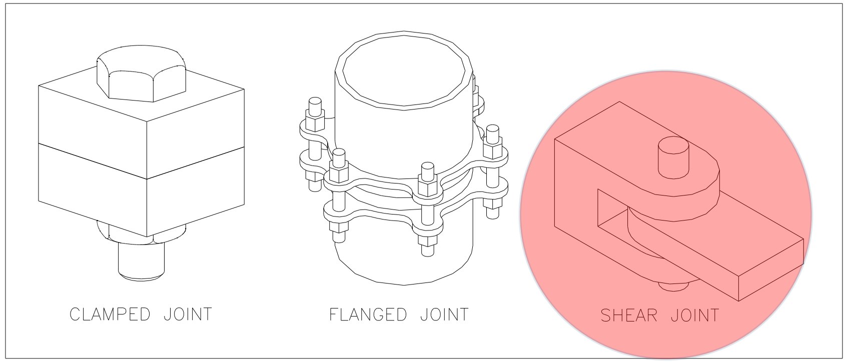
Run and configuration	Transducer angle, degree	% of nominal load	Chosen ray distance x, mm (in.)	Chosen angle q, degree	Ray shift, Q, mm (in.)	Estimated stretch, mm (in.)	Actual stretch, mm, (in.)
5A	N/A	54	-1.01 (-0.04)	0.4	-2.8 (-0.11)	0.083 (0.0033)	0.0914 (0.0036)
5A	N/A	100	-1.77 (-0.07)	0.6	-4.26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



4. Flanged Joint on Ultrasonic Measurements[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[18]



This model assumes

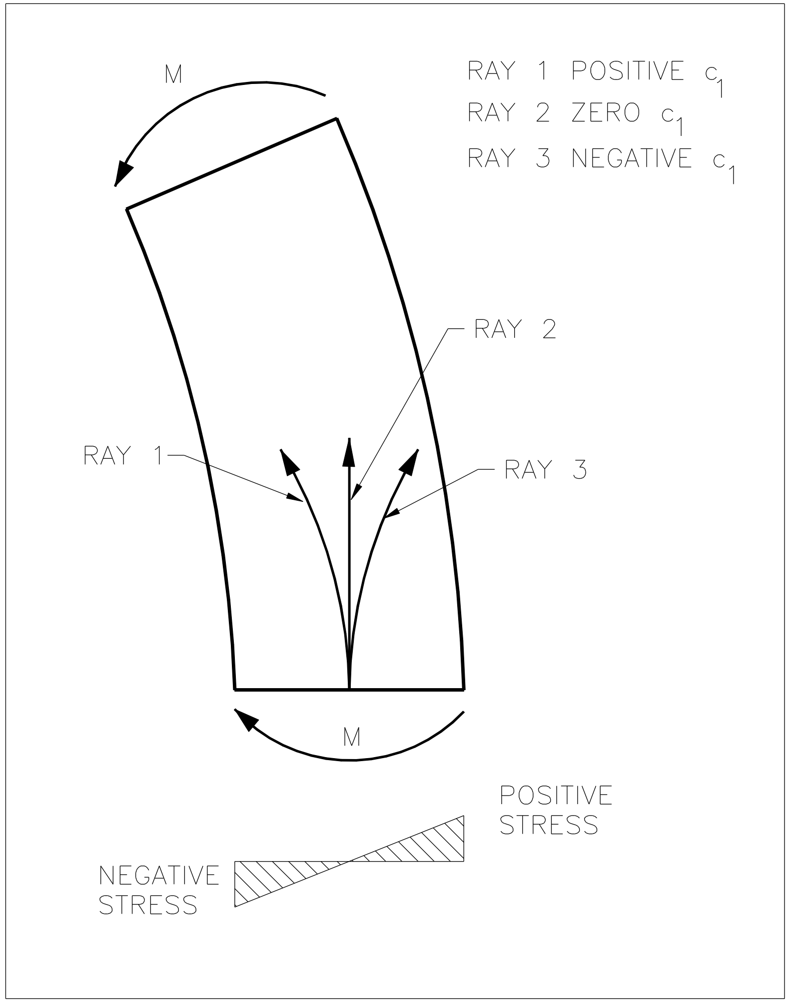
No beam spread.

The bolt profile is an arc of a circle.

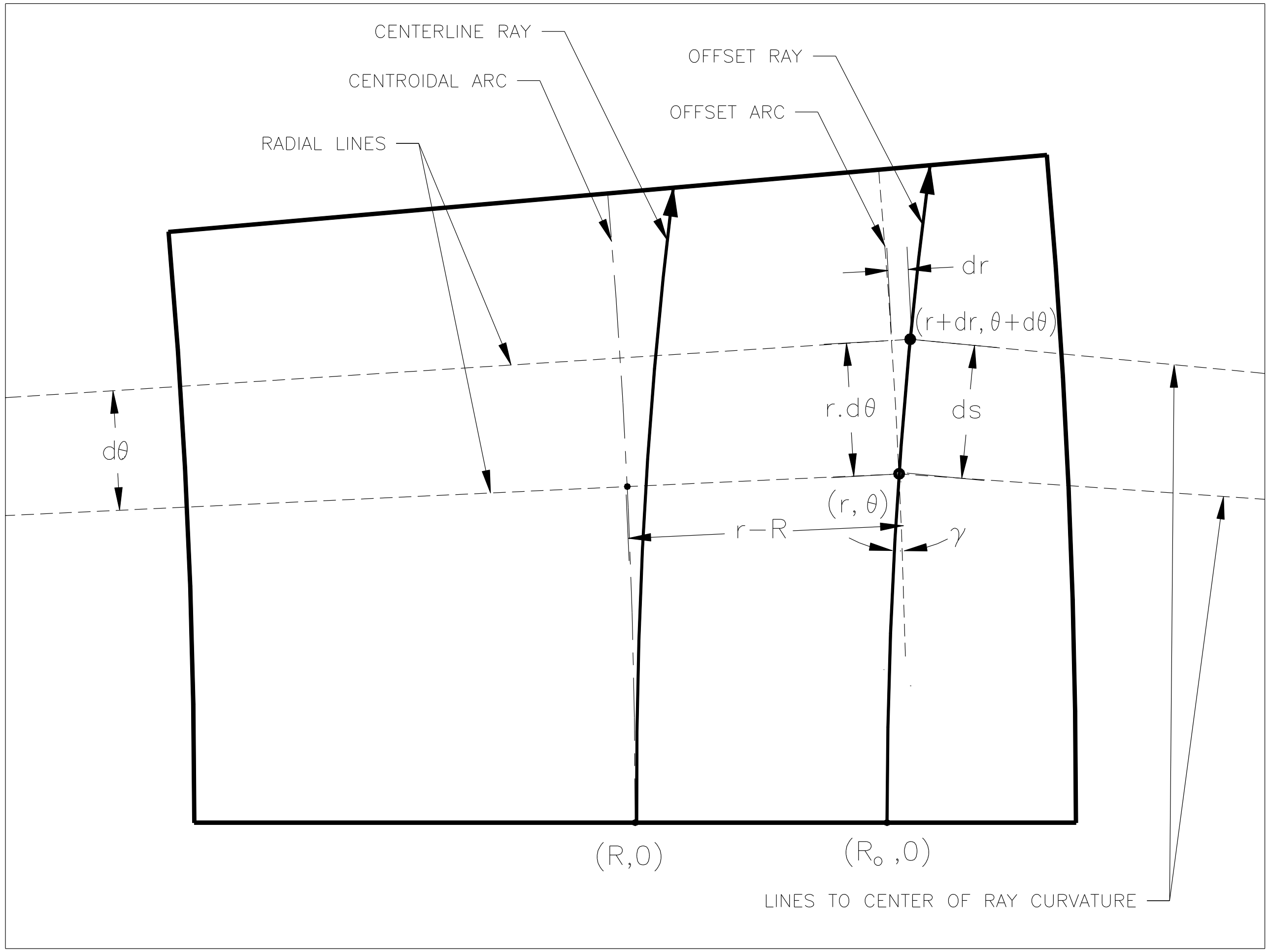
The bolt has a constant cross sectional area and square ends.

The bending is applied by two moments, one at each end of the bolt. The moments are equal in magnitude but opposite in rotation.

Bending moments, stress and rays



5. Simulation of Effect of Bending Stress on Ultrasonic Beam[18]: Ultrasonic Ray, Bolt Geometry and Analytical Model



Bending stress $\sigma = M(r-R)/I$

Radius, effective length and bending angle $R = l/\varphi$

Bending angle $\varphi = Ml/EI$

Hooke's law $\varepsilon = \sigma/E$

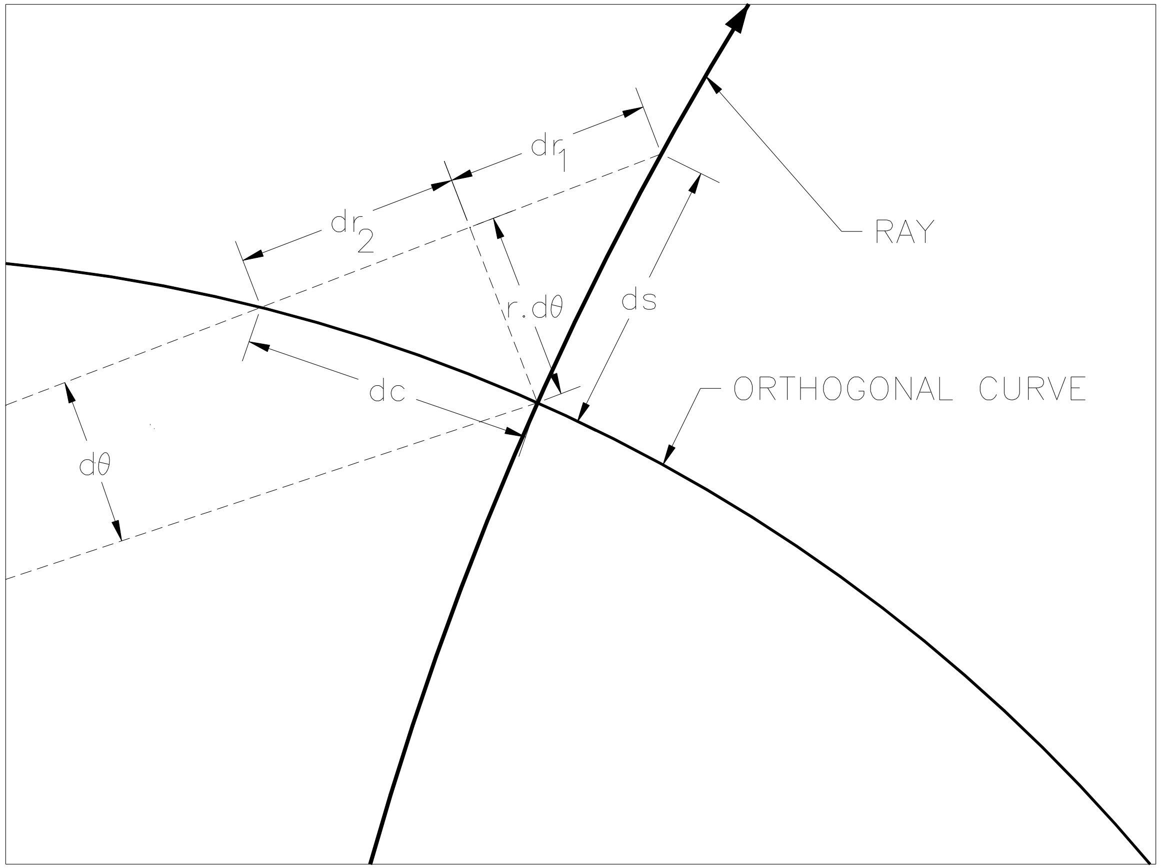
Strain $\varepsilon_f = (r-R)/R$

Velocity $V_s = V_0(1 + c_1\varepsilon_v)$

Velocity $V_s = V0(1 + b[r-R][1 - \{dr/ds\}^2])$

$b = c_1/R$

5. Simulation of Effect of Bending Stress on Ultrasonic Beam[18] : Ray, Orthogonal Curve, and Analytical Solution



Curvature $\kappa \cong \dfrac{|dV_s / dr|}{V_s} \cong \dfrac{|b|}{[1+b(r-R)]}$

Ray equation – second order

$$r'' = \frac{(1-r'^2)}{r}\left[\frac{1+b(1-r'^2)(R-2r)}{1+b(1-r'^2)(r-R)}\right]$$

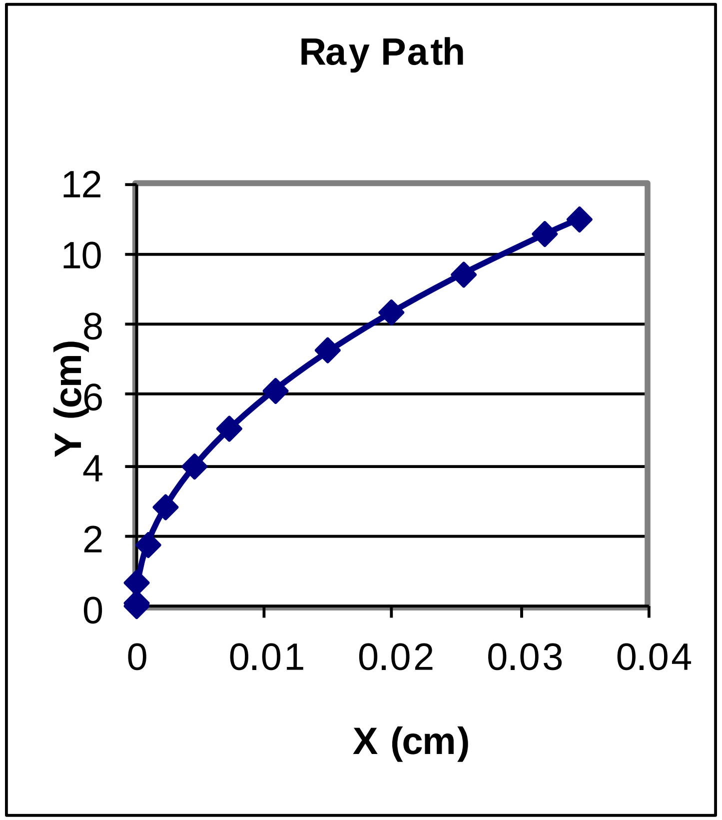
Coupled pair of first order equations - Runge-Kutta

$$r_1' = \frac{(1-r_1{}^2)}{r_2}\left[\frac{1+b(1-r_1{}^2)(R-2r_2)}{1+b(1-r_1{}^2)(r_2-R)}\right]$$

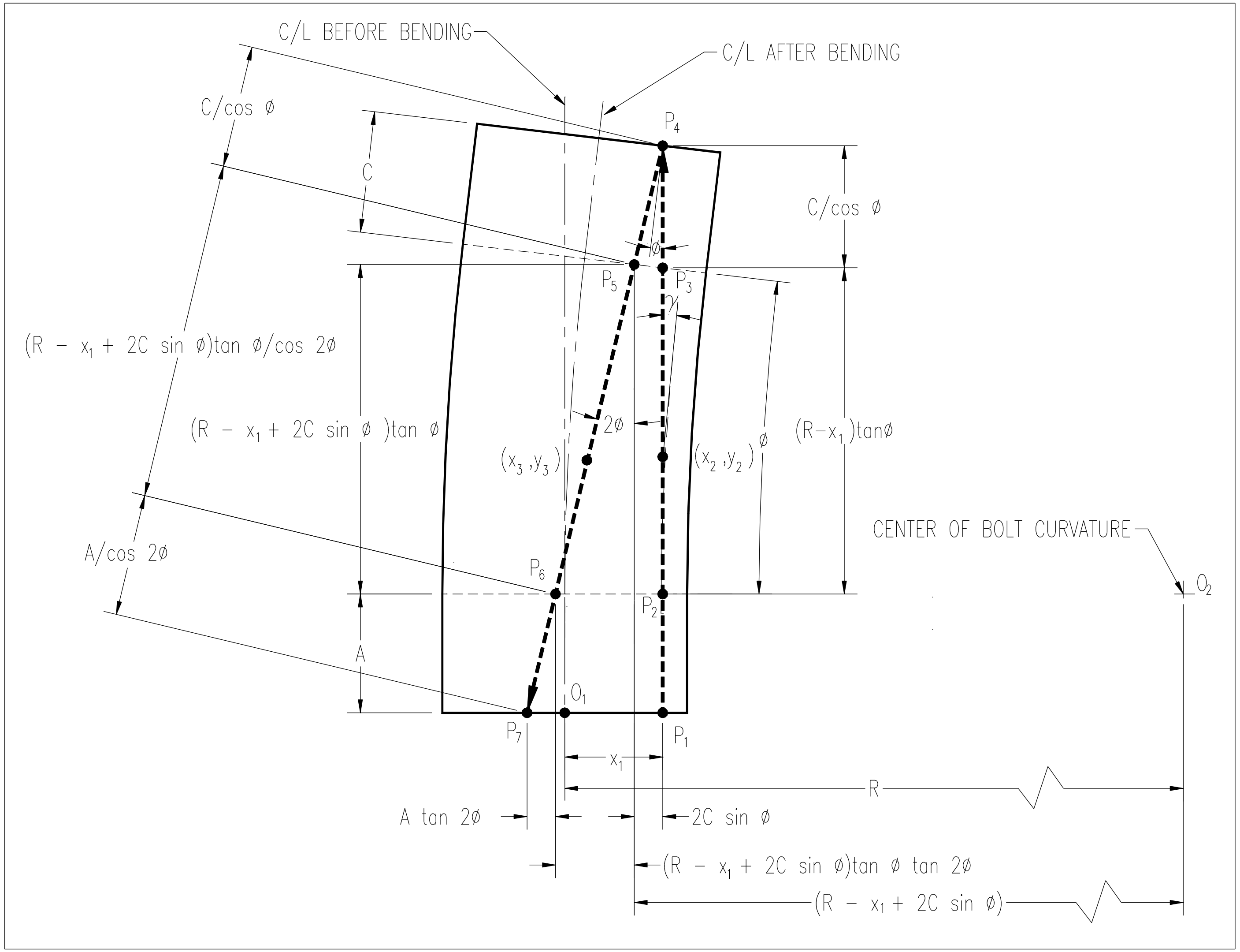
$$r_2' = r_1$$

5. Simulation of Effect of Bending Stress on Ultrasonic Beam[18] : Numerical Solution for Ray Path

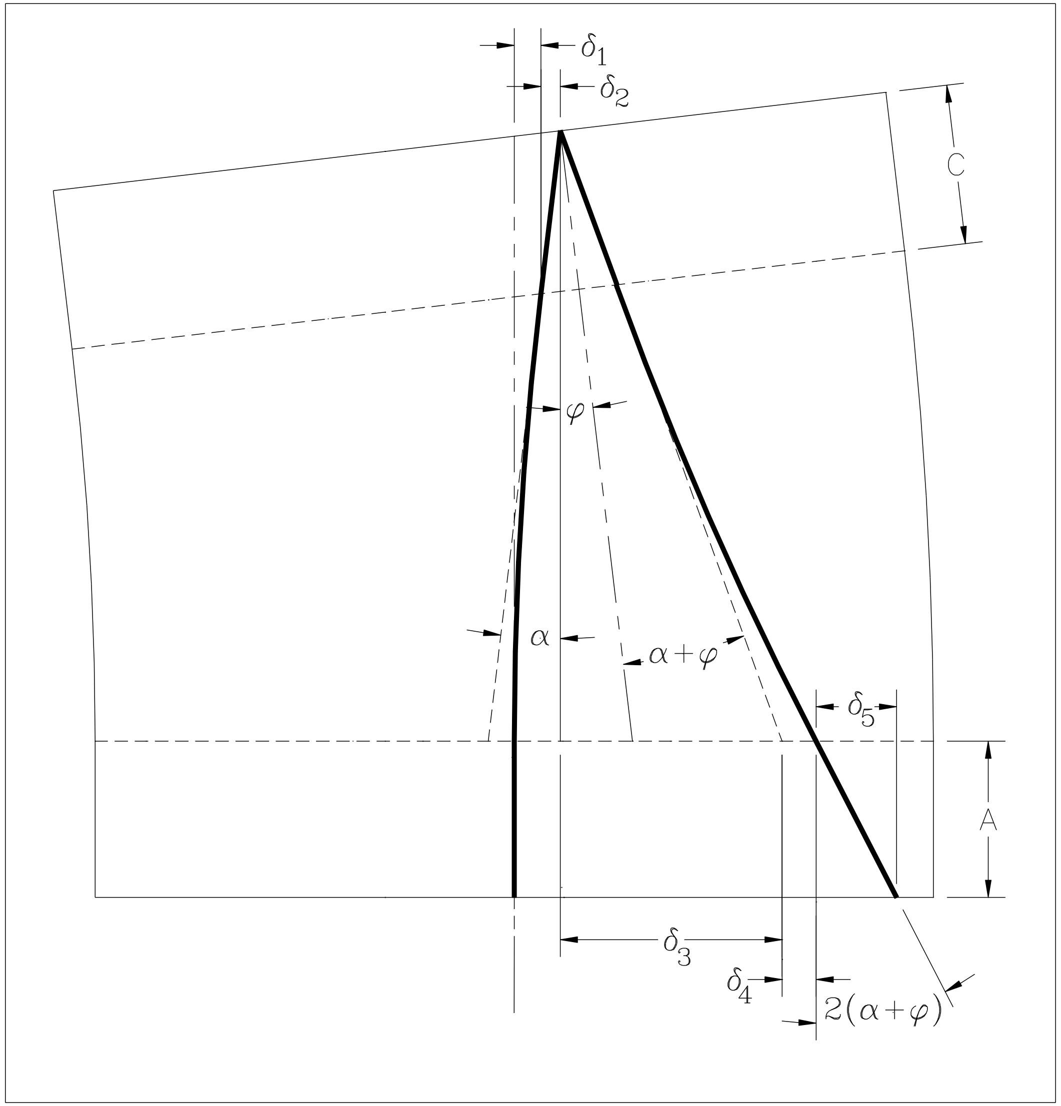
s, cm	r'	*r*, cm	θ'	θ' *Average*	Δs cm	$\theta' \cdot \Delta s$	θ	*x*, cm	*y*, cm	*dy/dx*
0	0	4535.0000	0.000221	0	0	0	0	0	0	
0.1073	0.00008	4535.0000	0.000221	0.000221	0.107	2.37E-05	2.37E-05	2.73E-06	0.107	39295
0.644	0.00048	4535.0002	0.000221	0.000221	0.537	0.000118	0.000142	0.000109	0.644	5037
1.744	0.0012998	4535.0011	0.000221	0.000221	1.1	0.000243	0.000385	0.000798	1.744	1598
2.844	0.0021197	4535.0030	0.000221	0.000221	1.1	0.000243	0.000627	0.002122	2.844	830
3.944	0.0029395	4535.0058	0.000221	0.000221	1.1	0.000243	0.00087	0.004082	3.944	561
5.044	0.0037594	4535.0095	0.000221	0.000221	1.1	0.000243	0.001112	0.006676	5.044	424
6.144	0.0045792	4535.0141	0.000221	0.000221	1.1	0.000243	0.001355	0.009905	6.144	340
7.244	0.005399	4535.0196	0.000221	0.000221	1.1	0.000243	0.001597	0.013769	7.244	284
8.344	0.0062188	4535.0259	0.000221	0.000221	1.1	0.000243	0.00184	0.018269	8.344	244
9.444	0.0070386	4535.0332	0.000221	0.000221	1.1	0.000243	0.002082	0.023404	9.444	214
10.544	0.0078584	4535.0414	0.00022	0.00022	1.1	0.000243	0.002325	0.029173	10.544	191
11	0.0081982	4535.0451	0.00022	0.00022	0.456	0.000101	0.002426	0.031751	10.999	177



5. Simulation of Effect of Bending Stress on Ultrasonic Beam[18] : Ray Path in Bent Bolt Without Ray Bending



5. Simulation of Effect of Bending Stress on Ultrasonic Beam[18] : Return Trip of Ray



$$\delta_1 = 0.012cm$$

$$\delta_2 = \alpha C$$

$$\delta_3 = (l + C)(\alpha + 2\varphi)$$

$$\delta_4 \cong \delta_1$$

$$\delta_5 = 2A(\alpha + \varphi)$$

Ray shift

$$Q = \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5$$

5. Simulation of Effect of Bending Stress on Ultrasonic Beam[18] : Ray Shift

Without ray bending

Effective length, l cm	A cm	C cm	φ *rad*	R, cm	*Stretch Slope* mm/kg	% Difference from actual slope	Ray Shift, Q cm
6.4	10.8	4.4	0.0014	4535	-8.0 x 10^{-4}	-55.9	0.0616
7.62	10.2	3.81	0.0021	3628	-1.17 x 10^{-4}	-38.2	0.0887
8.9	9.5	3.2	0.0028	3175	-1.6 x 10^{-4}	-14.7	0.1208
9.6	9.2	2.8	0.0032	2984	-1.9 x 10^{-4}	0	0.1394

With ray bending

A, cm	C, cm	l, cm	φ	α	δ_1, cm	δ_2, cm	δ_3, cm	δ_4, cm	δ_5, cm	Ray Shift, Q cm
10.8	4.4	6.4	0.0014	0.0029	0.012	0.0128	0.0616	0.012	0.0929	0.1912

5. Simulation of Effect of Bending Stress on Ultrasonic Beam[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 papers[11-18].
- 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.