Analysis of Load Test Annex (LTA) Floor Anchor Lateral Stiffness Test Results

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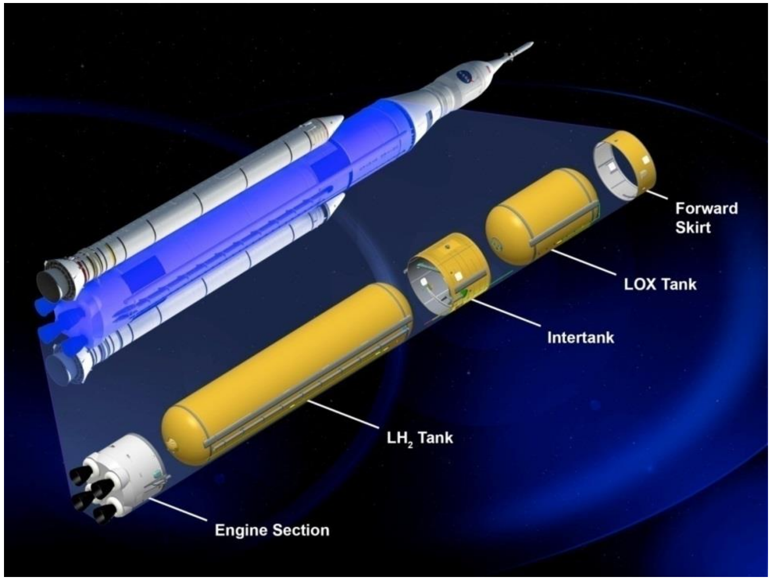
Overview

- SLS Stages Special Test Equipment (STE)
- Floor Anchor Point Capabilities
- Intertank (IT) Test Structure
- LTA Floor Anchor Test
- Data Reduction
- Specimen Behavior
- Multiple Linear Regression Analysis
- Comparative Analysis
- Summary and Conclusion

SLS Stages Special Test Equipment (STE)

- NASA Space Launch System (SLS) Core Stage (CS) Structural Qualification (SQ) testing is being performed at MSFC.
- Four SLS CS elements
  - Engine Section
  - LH2 Tank
  - Intertank
  - LOX Tank



- SLS STE includes
  - facilities
  - structural fixtures
  - mechanical load application hardware
  - access platforms
- Mechanical Structural Analysis Branch at MSFC providing stress analysis of STE.

LTA Floor Anchor Point Capabilities

Table 1. LTA Recommended Maximum Loads

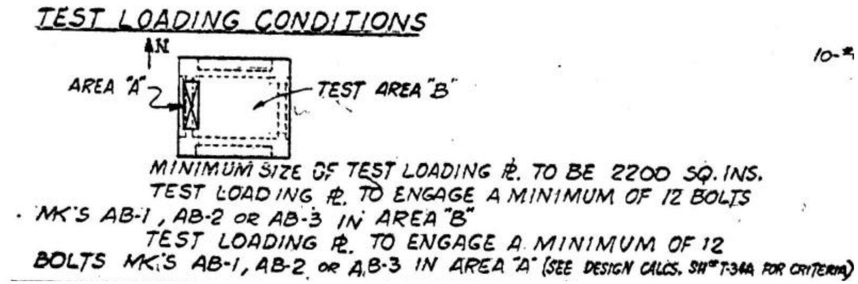
Load Test Annex (LTA)- Recommended Maximum Load Capability		
Area	Tensile (kips)	Shear (kips)
Area *B*, Full Load Capability	111	18
Area *A*, De-rated Load Capability	30	18

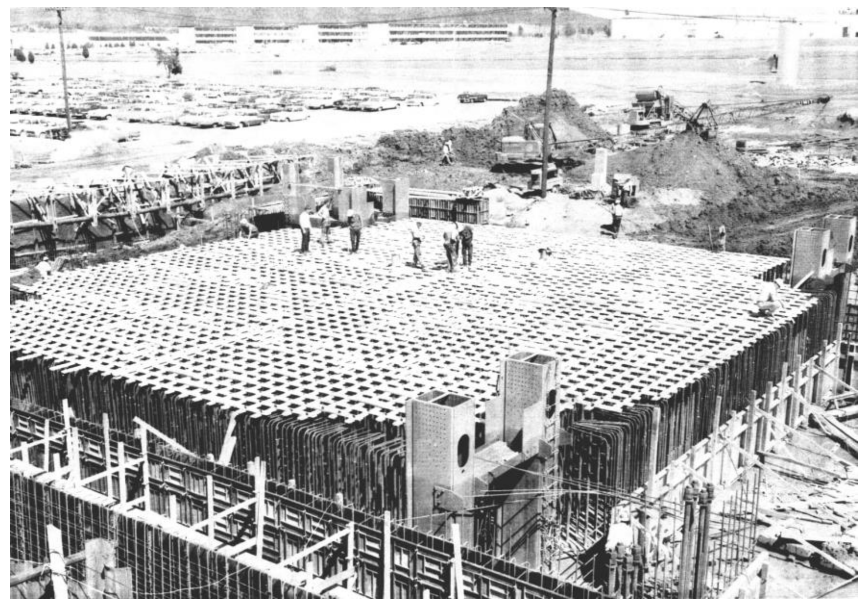
* The de-rated region of the LTA floor is comprised of the outer two rows of anchor points around the perimeter of the entire LTA floor.

** Reference NASA Stress Analysts' memo ED28-93-54 (08/23/1993)

*** Reference LTA Facilities Calculation Book, Section T (1962)

- The center region of the LTA load reacting floor is made up of 2,356 hold down anchor points.
- Anchors are arranged in a square pattern on 18" centers, with a 2.75"-8UN thread interface.
- Total concrete thickness
  - 11' primary floor area
  - 6' 1.25" overhang regions
- In the interest of maintaining the LTA floor's condition, it is prudent that the floor is not overloaded.





MSFC Load Test Annex (LTA) during construction phase.

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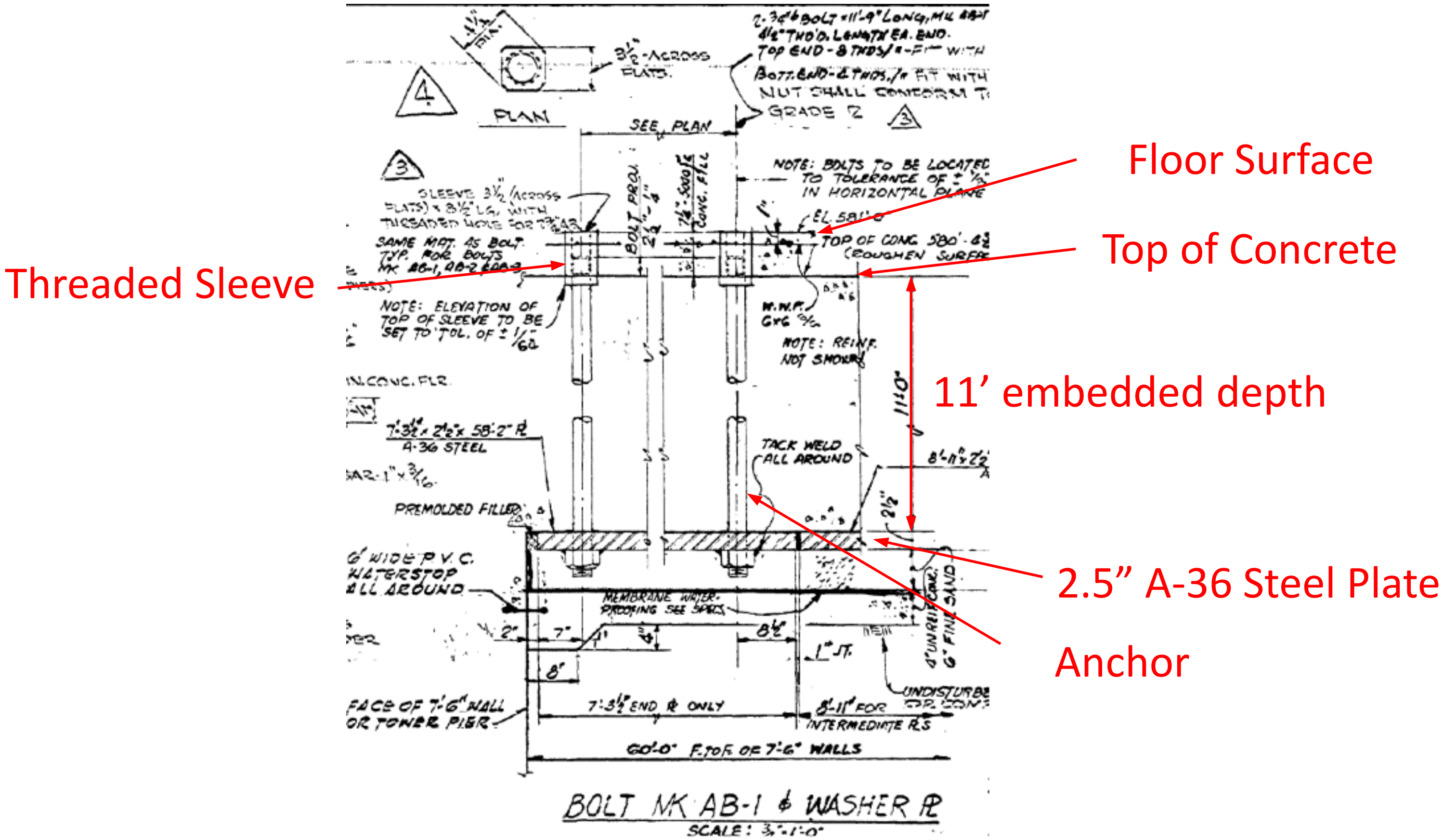

Drawing FE-C-4619-S-2, Zone E4, MK AB-1 Anchor Point Detail of the LTA 11ft Primary Floor

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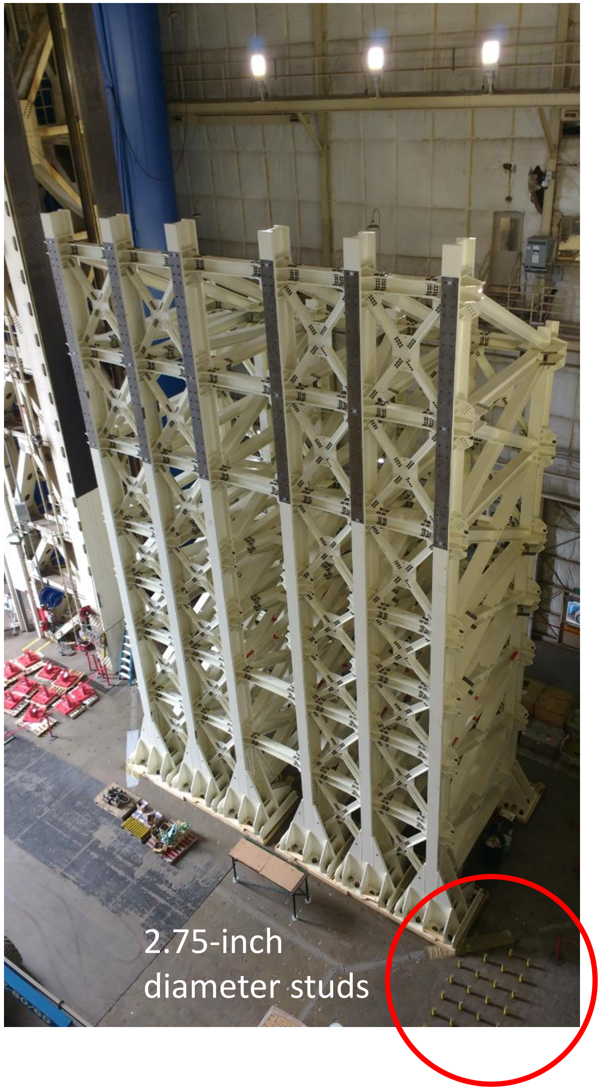
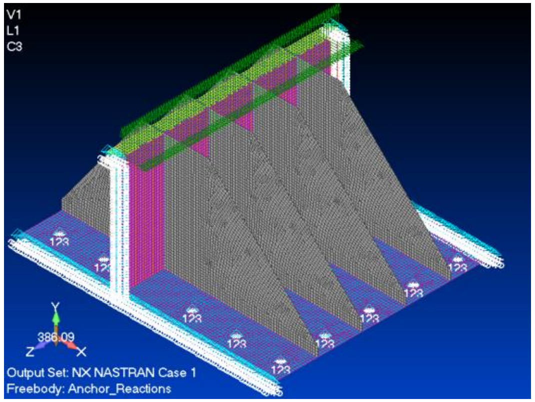
Intertank (IT) Test Structure



- During analysis of the IT structure, high shear reactions in certain areas of the flange were observed.
- A trade study was performed on a thick flange (4" plate) with several rows and columns of anchors.
- Baseline analysis with pinned boundary conditions (123) is conservative for stress and anchor tension and shear.
  - FEM is over-constrained using several anchor points with infinitely stiff constraints.
- Solution is to model anchors, considering the thickness of the grout (E = 568,000 psi) and the flange.
  - The shear reaction is significantly affected by the length of the stud.
- What are realistic values for the lateral resistance of the anchor bolts that attach to the threaded floor inserts?



Baseline LC1, Tension + Shear

Max Shear Load = 74,952 lbf

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Intertank (IT) Test Structure

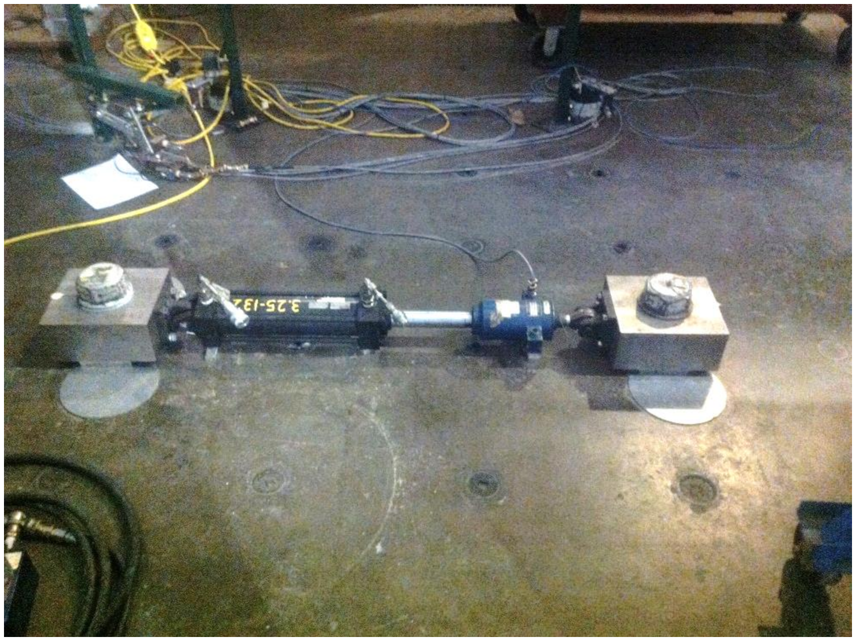
- The shear reaction is significantly affected by the boundary conditions assumed in the FEM.

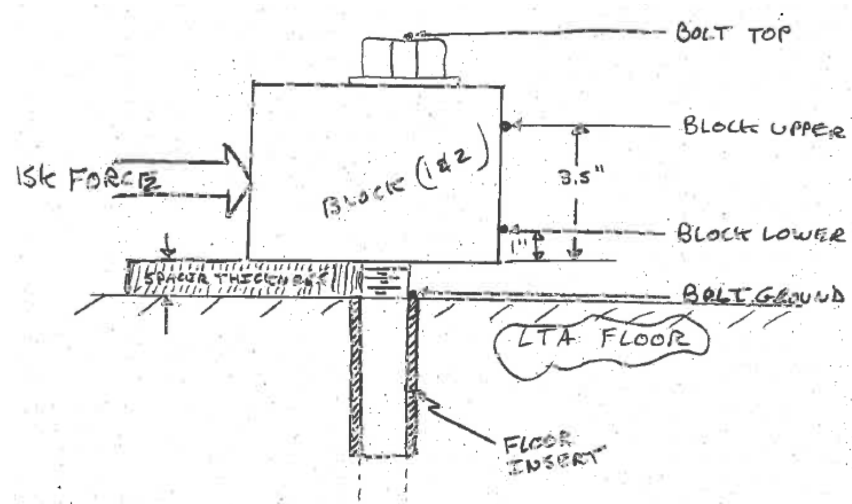
Shear Trade Study Percent Difference													
Results Summary		**LC1, Tension + Shear**				**LC2, Tension**				**LC3, Shear**			
				Anch. Max	Anch. Max			Anch. Max	Anch. Max			Anch. Max	Anch. Max
LC	Title	Disp.	Stress	Tension	Shear	Disp.	Stress	Tension	Shear	Disp.	Stress	Tension	Shear
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
1	Baseline	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	Fixed	-1.6	-1.0	-2.8	-2.2	-1.7	0.0	-2.8	-2.6	-0.6	0.0	-4.8	-0.7
3	Anchors 1"	3.0	0.0	-4.1	-39.6	3.4	0.7	-4.0	-42.7	1.8	0.0	-2.6	-17.3
4	Anchors 4"	14.0	0.8	-11.1	-69.1	13.9	2.3	-11.1	-76.8	10.7	0.1	-3.4	-19.9
5	Contact BL	-1.6	-0.9	13.2	-1.8	-1.7	0.0	15.7	-2.0	-3.0	0.8	166.4	0.8
6	Contact 2 Ptty Pin.	-0.3	-0.2	-0.2	-0.5	-0.7	0.1	-0.1	-0.4	-1.8	0.6	-2.8	0.4
7	Contact 3 Ptty Anch.	13.7	0.8	-11.1	-69.3	13.9	2.3	-11.1	-76.8	7.7	0.9	-7.4	-19.2

LTA Floor Anchor Test

- Testing was initiated by the Structural Strength Test Branch:
  - Conducted in the north and east areas of the Load Test Annex (LTA) floor.
  - 2.75-inch diameter bolts were selected for testing and are representative of the thread interface.
  - Bolt installations simulated various grout thicknesses.
  - The specimens were subjected to low-cycle loading/unloading to run the hysteresis out of the system.
  - Loading was continued to approximately 15 kips maximum (18 kips capacity).
  - LVDT’s provided a continuous record of deflection versus load up to 1/8 inch (3.18 mm) of deflection.
- The objective was to determine the effect of load input height upon the lateral resistance attainable.

LTA Floor Anchor Test

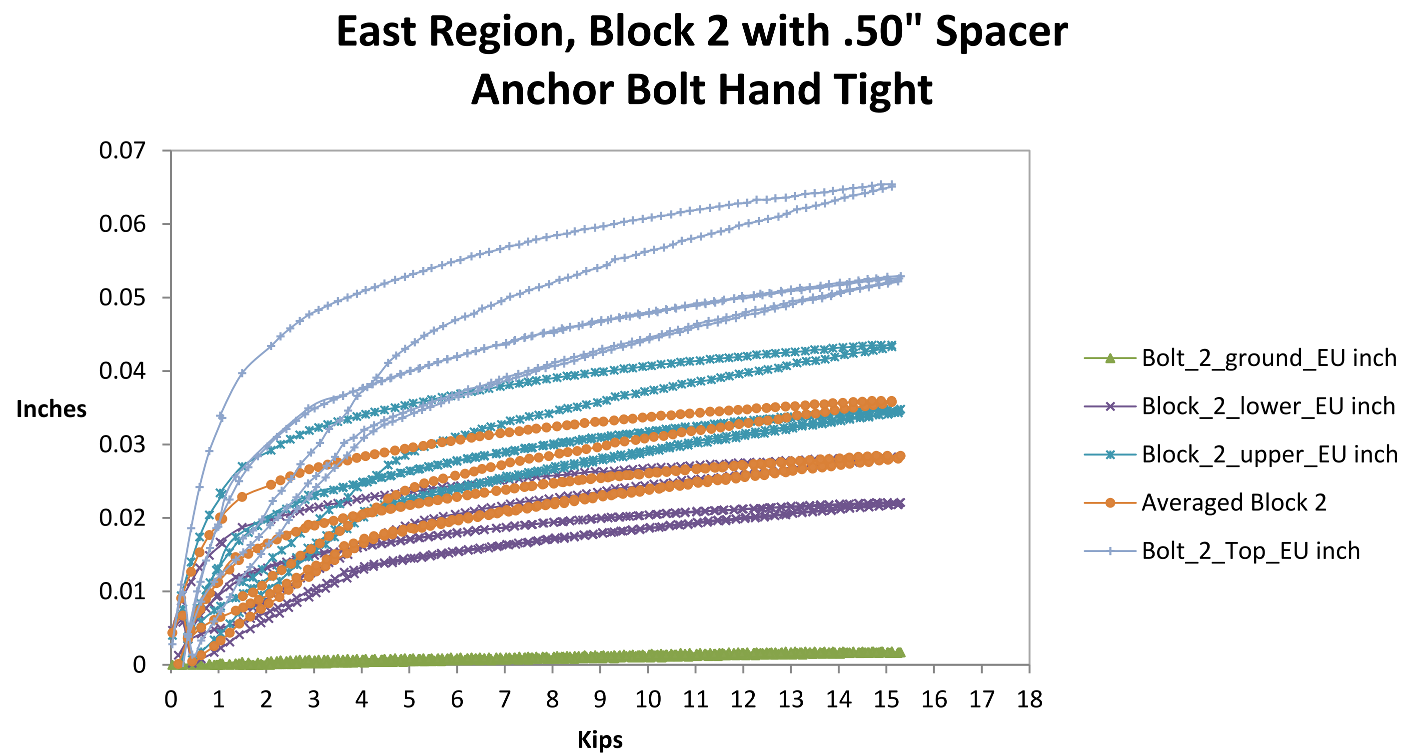




Spacer (inch)	Force[†] (inch)	LVDT Location[‡] (inch)			
		Ground	Lower	Upper	Bolt Top
0.5	2.815	—	1.5	4.0	8.0
0.75	3.065	—	1.75	4.25	8.25
1.0	3.315	—	2.0	4.5	8.5

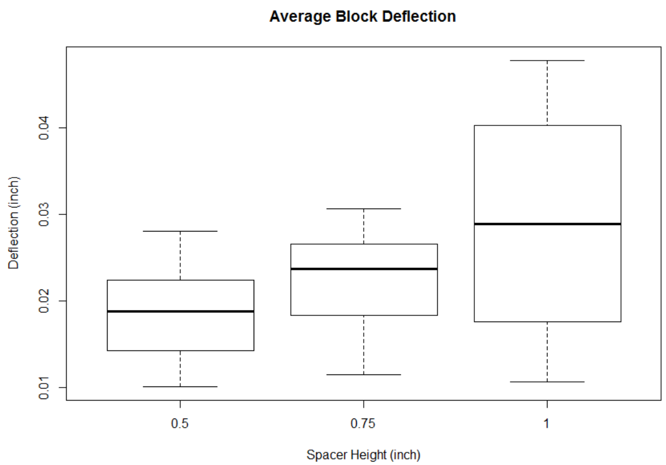
[†]Load point distance from floor
[‡]LVDT height from floor (symmetric to load point)

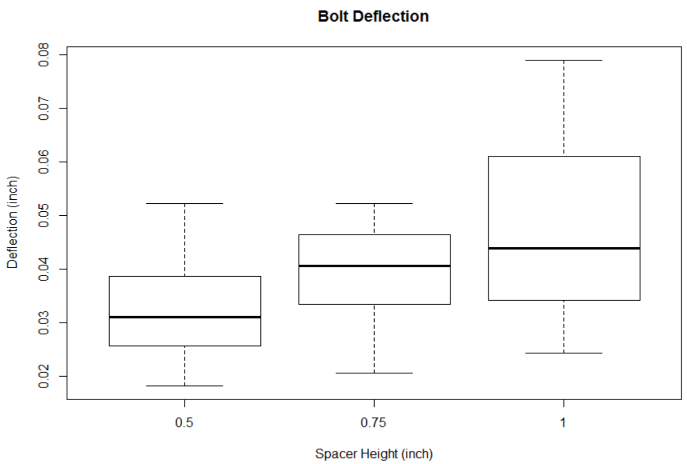
Data Reduction

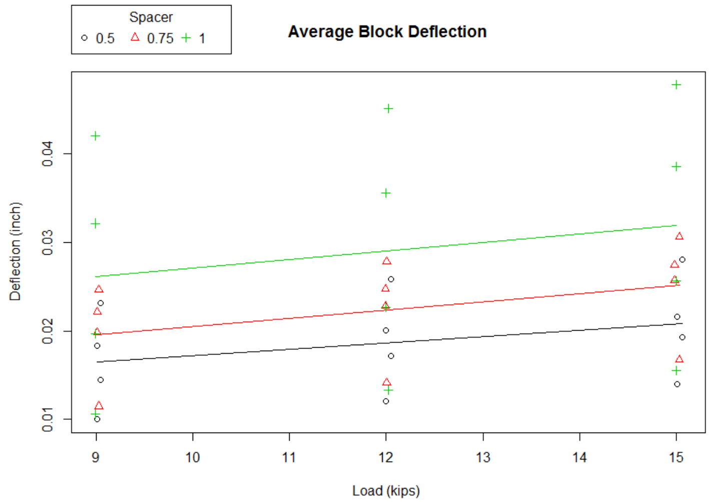


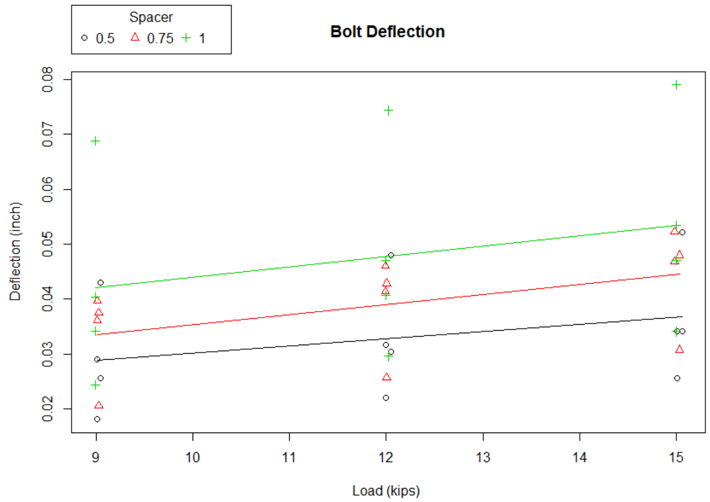
- The raw data consisted of load-deflection curves (up to 1/8 inch (3.18 mm) of bolt deflection from DAC EU files (0.1 sec sampling rate).
- Thirty-six observations at 9, 12 and 15 kips are used for the analysis.
- Data from both LVDTs mounted on each block were averaged to estimate the deflection at the load-point .

Specimen Behavior







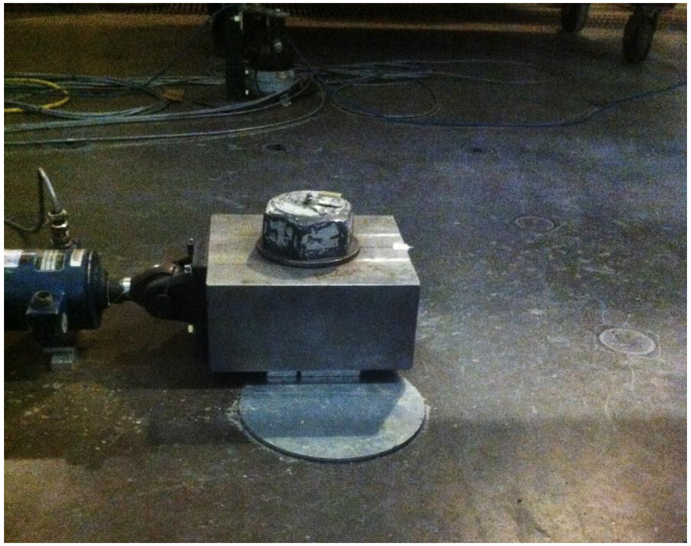


Specimen Behavior

Table 3. Load cycle data for the 0.5-inch spacer (East Region)

TIME	Block_2_lower_EU inch	Block_2_upper_EU inch	Bolt_2_Top_EU inch	Block_1_lower_EU inch	Block_1_upper_EU inch	Bolt_1_Top_EU inch	LC1_EU kips
LTA-Anchor-HalfInchSpacer-Torqued-042314							
11:13:45.717	0.0068	0.0091	0.0125	0.002	0.0026	0.0039	0.3997
11:16:45.318	0.026	0.0405	0.0612	0.0133	0.0217	0.0315	15.0205
11:25:15.000	0.0018	0.0024	0.0028	0.0007	0.0009	0.0018	0.0236
LTA-Anchor- HalfInchSpacer-HandTight-042314							
15:51:28.011	0.0047	0.004	0.0028	0.0036	0.0037	0.0037	0.0307
15:56:07.018	0.0218	0.0343	0.0522	0.0145	0.024	0.0342	15.0602
15:57:19.019	0.0013	-0.0011	-0.0044	0.0008	0.0009	0.0011	0.156

- Hand-tight case generally consistent at the start and end of the cycle; proportional at the peak load.
- Displacements from the torqued case are proportional throughout the cycle.
- Suggests prying, or rotation of the block, either at the spacer or floor.



Multiple Linear Regression Analysis

- Data must be metric or appropriately transformed.
- Regression model relates deflection to applied load, spacer and block number.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$$

- Block number, x_3, with two levels is directly entered as a predictor variable, coded as -1 and 1.
- Load and spacer height are coded as follows,

$$x_1 = \frac{Load - 12}{3},\ x_2 = \frac{Spacer - 0.75}{0.25}$$

- Why use coded design variables?
  - Model coefficients are directly comparable.
  - Estimated with the same precision.
  - Very effective for determining the relative size of factor effects.
- Least squares method chooses coefficients so that the sum of the errors, ε, is minimized.

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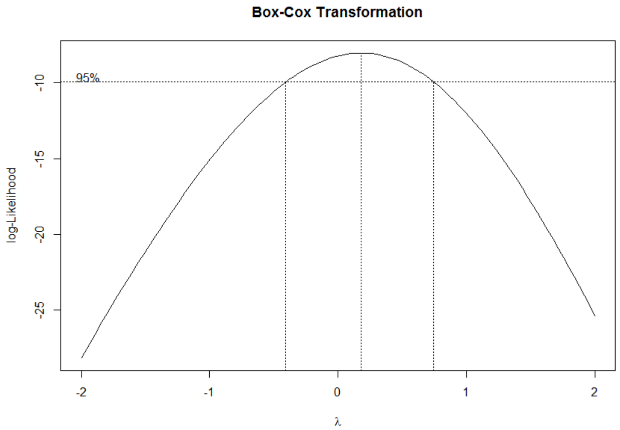
Multiple Linear Regression Analysis

- Transformation of the response variable (deflection):
  - Stabilize response variance.
  - Make the distribution of the response variable closer to the normal distribution.
  - Improve the fit of the model to the data.
- Selecting a Transformation
  - Plot log S_i vs. log y_i
  - Estimate α - Slope of line
  - Use α to select transformation - Table 3-9 (Montgomery, 8th Ed.)
  - Box-Cox Method (Implemented in R)



■ **TABLE 3.9**
Variance-Stabilizing Transformations

Relationship Between σ_y and μ	α	$\lambda = 1 - \alpha$	Transformation	Comment
$\sigma_y \propto$ constant	0	1	No transformation	
$\sigma_y \propto \mu^{1/2}$	1/2	1/2	Square root	Poisson (count) data
$\sigma_y \propto \mu$	1	0	Log	
$\sigma_y \propto \mu^{3/2}$	3/2	$-1/2$	Reciprocal square root	
$\sigma_y \propto \mu^2$	2	-1	Reciprocal	

Average Block Deflection - ANOVA for *y** = ln(*y*)

```
Analysis of Variance:

           Df Sum Sq Mean Sq F value   Pr(>F)
x1          1 0.3761  0.3761   7.626 0.009450 **
x2          1 0.8585  0.8585  17.407 0.000215 ***
x3          1 2.8727  2.8727  58.247 1.07e-08 ***
Residuals  32 1.5782  0.0493
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2221 on 32 degrees of freedom
R-squared: 0.722, Adjusted R-squared: 0.696
PRESS: 2.011329, Predicted R-squared: 0.646
F-statistic: 27.76 on 3 and 32 DF, p-value: 4.932e-09

Coefficients:

              Estimate Std. Error     t value     Pr(>|t|)
(Intercept) -3.8352590 0.03701354 -103.617733 5.180960e-42
x1           0.1251853 0.04533214    2.761513 9.449557e-03
x2           0.1891349 0.04533214    4.172203 2.153744e-04
x3           0.2824860 0.03701354    7.631965 1.070942e-08
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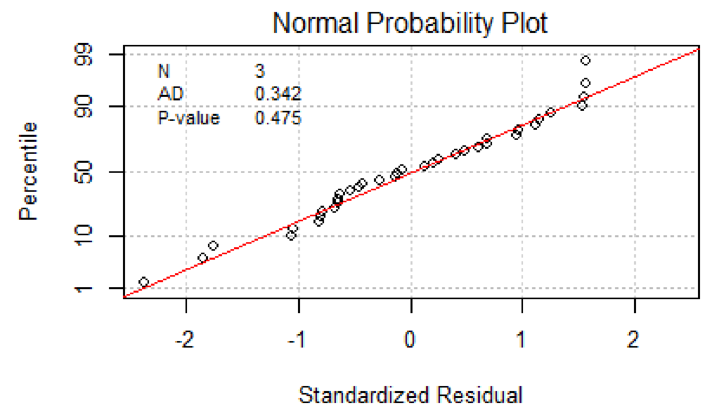
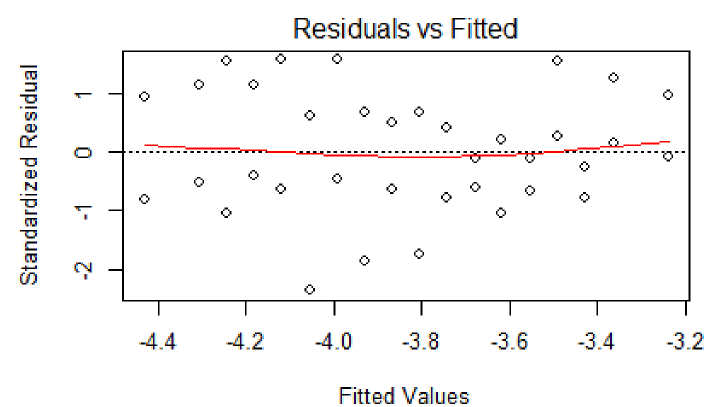




$\hat{y}^*_{block} = -3.835 + 0.125x_1 + 0.189x_2 + 0.282x_3; \qquad \hat{y}_{block} = e^{ln(\hat{y}^*_{block})}$

Bolt Top Deflection (North Region) - ANOVA for *y** = 1/*y*

```
Analysis of Variance:

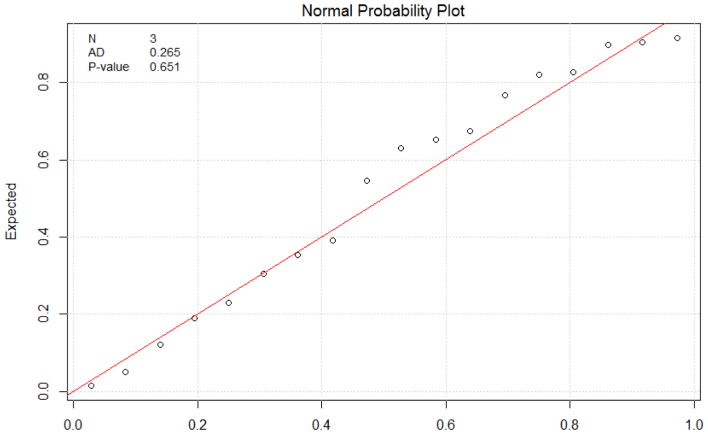
             Df Sum Sq Mean Sq F value   Pr(>F)    
x1            1  267.3   267.3   28.96 9.68e-05 ***
x2            1  673.8   673.8   73.00 6.31e-07 ***
x3            1 1360.8  1360.8  147.44 8.04e-09 ***
Residuals    14  129.2     9.2                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

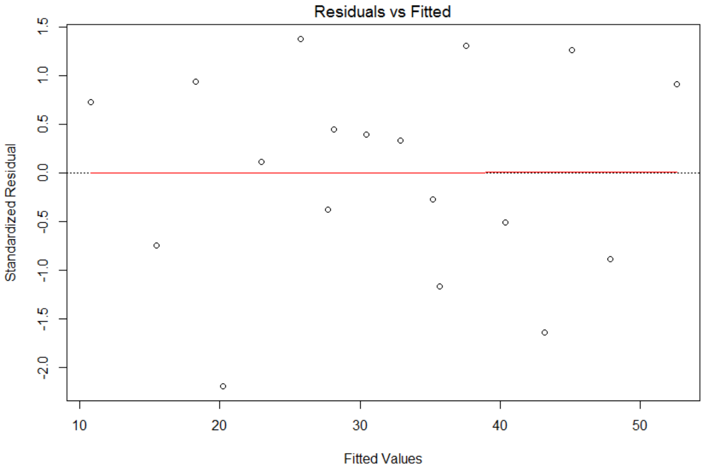
Residual standard error: 3.038 on 14 degrees of freedom
R-squared: 0.947, Adjusted R-squared: 0.935
PRESS: 230.6105, Predicted R-squared: 0.905
F-statistic: 83.13 on 3 and 14 DF, p-value: 3.676e-09

Coefficients:

              Estimate Std. Error    t value     Pr(>|t|)
(Intercept) 31.674491  0.7160750  44.233484 1.919494e-16
x1          -4.719669  0.8770092  -5.381551 9.677819e-05
x2          -7.493263  0.8770092  -8.544110 6.314609e-07
x3          -8.694924  0.7160750 -12.142478 8.037167e-09
```

$$\hat{y}^*_{bolt(N)} = 31.674 - 4.72x_1 - 7.493x_2 - 8.695x_3;\ \hat{y}_{bolt(N)} = 1/\hat{y}^*_{bolt(N)}$$





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Comparative Analysis

Table 4. Summary of Mean Stiffness from Fitted Models

Spacer (inch)	L (inch)	Mean Stiffness, k (kips/in.)			
		Block 1	Bolt 1	Block 2	Bolt 2
0.5	2.815	1773.7	1440.2	1008.1	575.0
0.75	3.065	1468.1	1020.3	834.4	320.7
1.00	3.315	1215.1	671.7	690.6	137.7

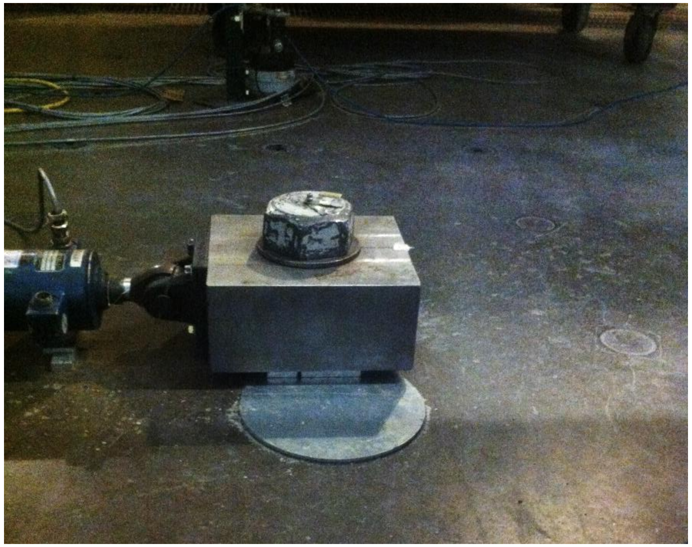
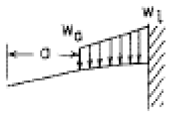


Table 5. Roark's Solution for Various Beam Loadings and Supports

Spacer (inch)	L (inch)	Mean Stiffness, k (kips/in.)	
case 1a.	Left end free, right end fixed (cantilever)		
	$k = 3EI/L^3$ when a = 0		
0.5	2.815	8731.3	
0.75	3.065	6764.3	
1.00	3.315	5346.4	
case 1b.	Left end guided, right end fixed		
	$k = 12EI/L^3$ when a = 0		
0.5	5.13	5770.6	
0.75	5.38	5003.0	
1.00	5.63	4365.6	
case 2a.	Left end free, right end fixed (cantilever)		
	$k = 8EI/L^3$ when a = 0; $w_a = w_l$		
0.5	5.13	3847.1	
0.75	5.38	3335.3	
1.00	5.63	2910.4	

2.75-8UN Bolt (A354)
Minor Dia. = 2.5987 in.
E = 29E6 psi
$I = 2.2387\ in^4$

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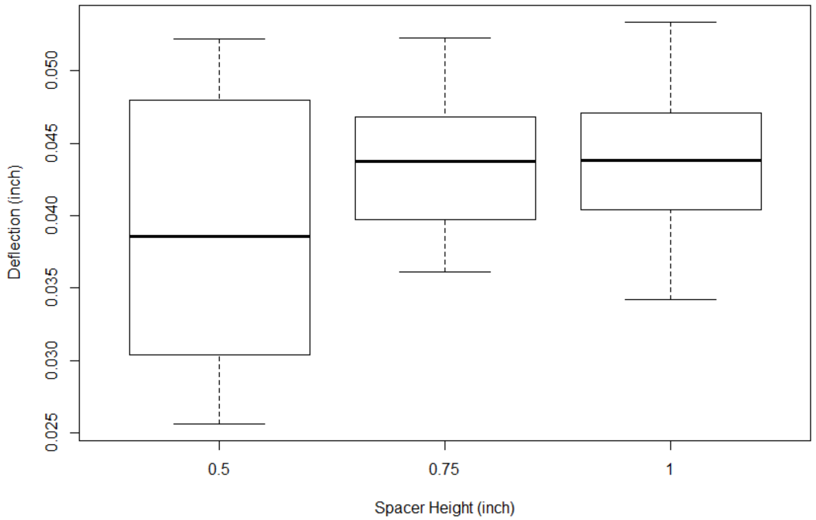
Summary and Conclusion

- The primary objective of this experiment was to evaluate the effects of applied load and spacer thickness on the deflection of anchor bolts.
- Empirical models were based on tests of isolated anchor bolts loaded in shear.
- It is possible that prying, or rotation of the blocks occurred during test.
  - Measured angular displacement ($r\ \Delta\theta$) would underestimate the lateral stiffness of the bolt.
- The LTA floor is an active component during test.
  - Anchor points react tension and shear loads.
  - Concrete reacts a compressive load and shear loads.
- The test program did not examine installation of a group of bolts or a lateral load combined with tension.
- The approach adopted by the Mechanical Structural Analysis Branch to model anchors in finite element analyses is conservative.
  - This is based on the assumption that the boundary condition in the FEM is rigid.
  - Stud length equal to the thickness of the grout plus half the thickness of the flange.

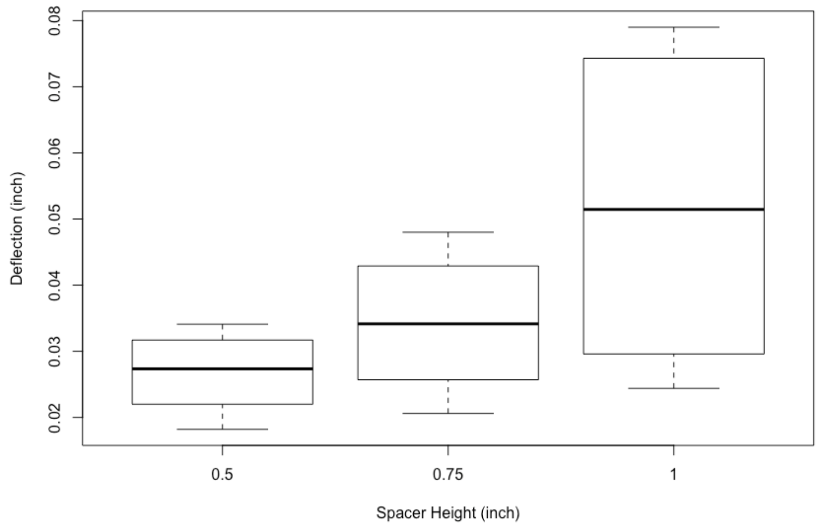
BACKUP SLIDES

Bolt Top Deflection

East Region



North Region



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Bolt Top Deflection - ANOVA for *y** = ln(*y*)

```
Analysis of Variance:

            Df Sum Sq Mean Sq F value   Pr(>F)
x1           1 0.4387  0.4387    8.72 0.005856 **
x2           1 0.7595  0.7595   15.10 0.000483 ***
x3           1 1.3576  1.3576   26.98 1.13e-05 ***
Residuals   32 1.6100  0.0503
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2243 on 32 degrees of freedom
R-squared: 0.614, Adjusted R-squared: 0.577
PRESS: 2.034107, Predicted R-squared: 0.512
F-statistic: 16.93 on 3 and 32 DF, p-value: 9.125e-07

Coefficients:

              Estimate Std. Error    t value     Pr(>|t|)
(Intercept) -3.2803978 0.03738354 -87.749790 1.038789e-39
x1           0.1351986 0.04578530   2.952883 5.856358e-03
x2           0.1778885 0.04578530   3.885275 4.829027e-04
x3           0.1941948 0.03738354   5.194659 1.127999e-05
```