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Sandia National Laboratories

# Fastener Failure Modeling

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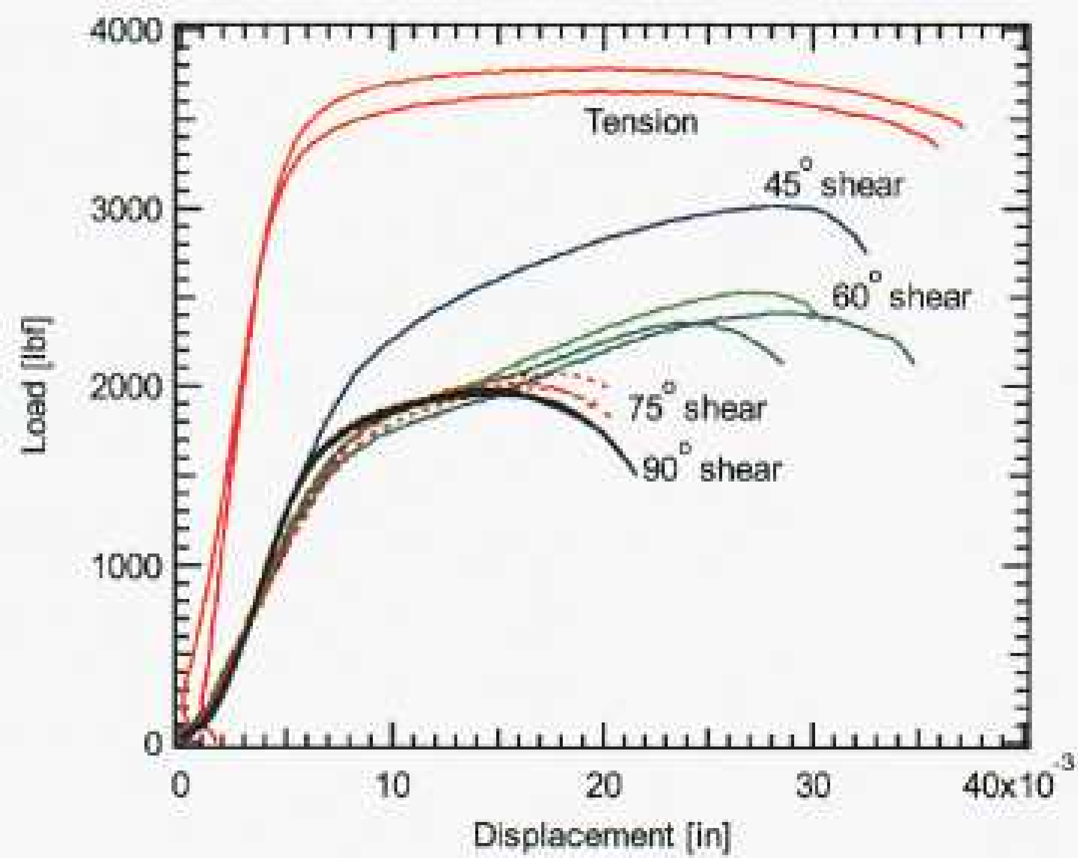
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

# Introduction: Project Overview

Bolt Failure Curves



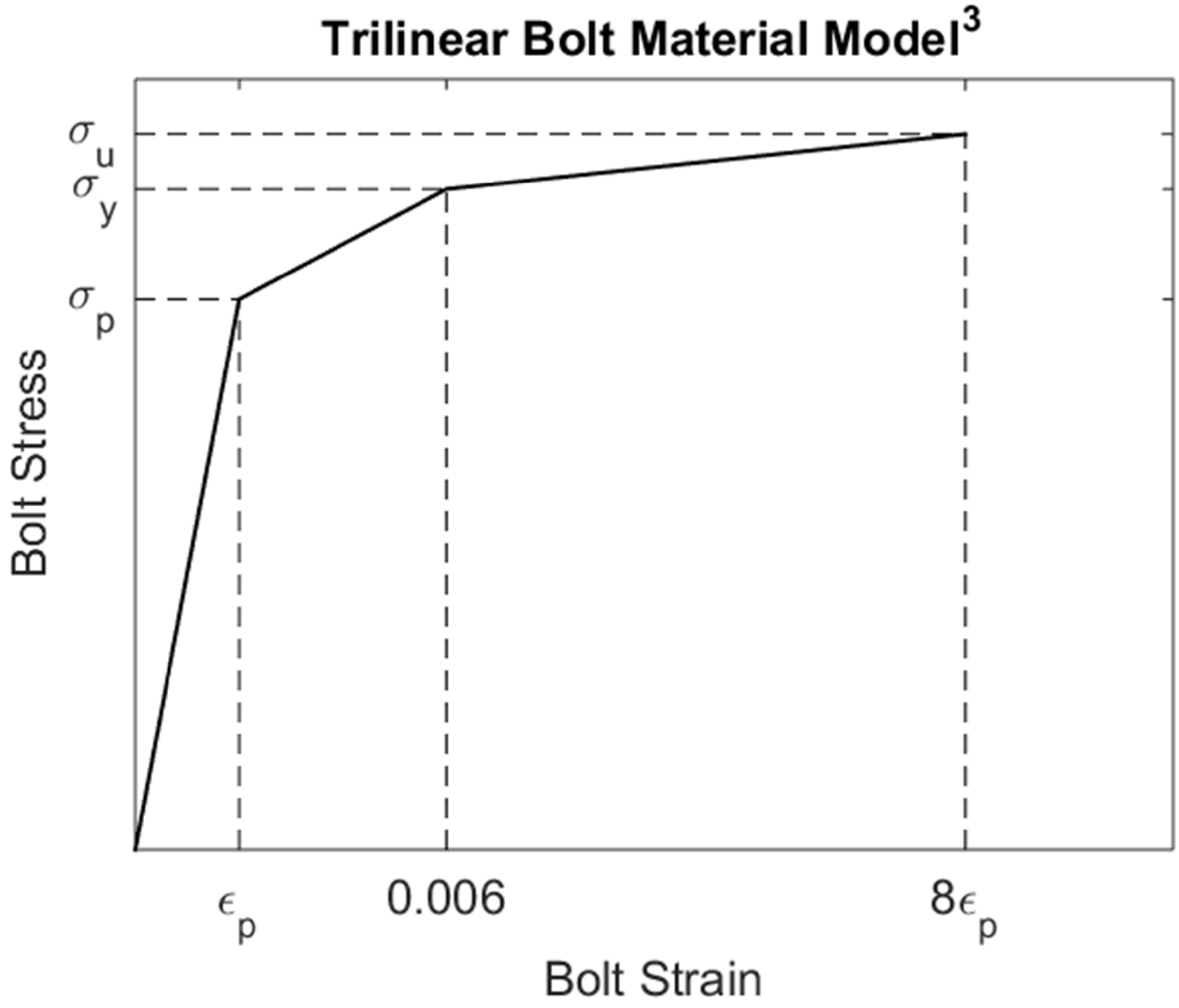

Motivation – Lack a fundamental understanding of force displacement relationship for fasteners, but this information is needed in structural simulations.

High fidelity fastener models are not feasible in large assemblies.

Goal – Develop reduced order model that reproduces the force vs. displacement curves for pure tension loading.


1. S. Lee *et al.*, *Experimental Results of Single Screw Mechanical Tests: a follow-up to SAND2005-6036*, SAND2006-3751, Sandia National Laboratories, Livermore, CA

# Introduction: Past Models



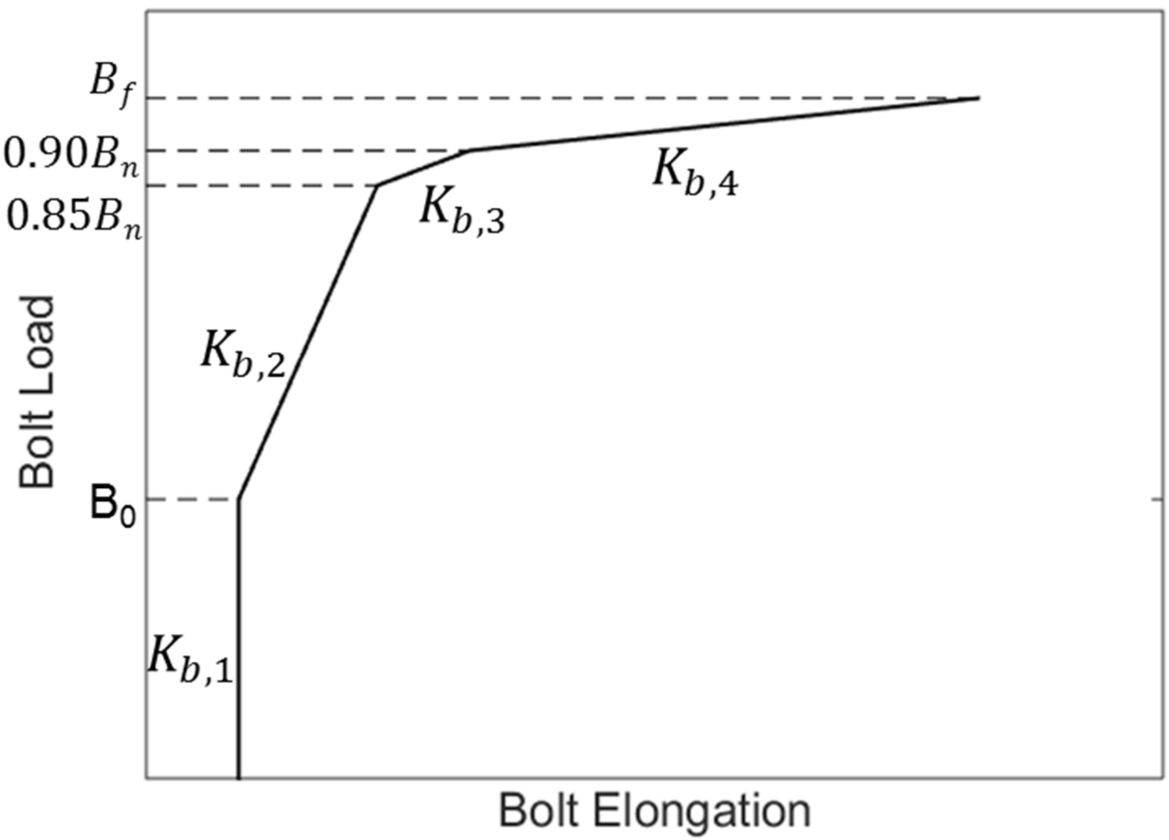

<u>Bolt Stress</u>
$\sigma_p \equiv$ proof stress
$\sigma_y \equiv$ yield stress
$\sigma_u \equiv$ ultimate stress

<u>Bolt Strain</u>
$\epsilon_p \equiv$ proof strain
$\epsilon_y \equiv 0.006$
$\epsilon_u \equiv 8\epsilon_p$


3. Sherbourne, Archibald N., Bahaari, Mohammed R. (1997). "Finite Element Prediction of End Plate Bolted Connection Behavior. I: Parametric Study," *Journal of Structural Engineering*, American Society of Civil Engineers, Vol. 123, No. 2, 157-164.

# Introduction: Past Models

**Swanson Bolt Stiffness Model**[4]




<u>Bolt Force</u>

$B_0 \equiv$ pretension

$B_n \equiv$ tensile capacity

$B_f \equiv$ fracture load

<u>Bolt Stiffness</u>

$$K_b = K_{elastic}$$
$$K_{b,1} = 1000K_b$$
$$K_{b,2} = K_b$$
$$K_{b,3} = 0.10K_b$$
$$K_{b,4} = 0.05K_b$$

- Predicts yield and ultimate loads, but requires knowledge of fracture strain for a given material.

4. Swanson, James A. (1999). “Characterization of the Strength, Stiffness, and Ductility Behavior of T-Stub Connections,” *Ph.D. Dissertation,* Georgia Institute of Technology, Atlanta, Georgia.

# Introduction: Test Matrix

- Five different grade bolts tested in tension to fracture.
- Diameters vary from very small (< 1/4 in) to very large (1.25 in).

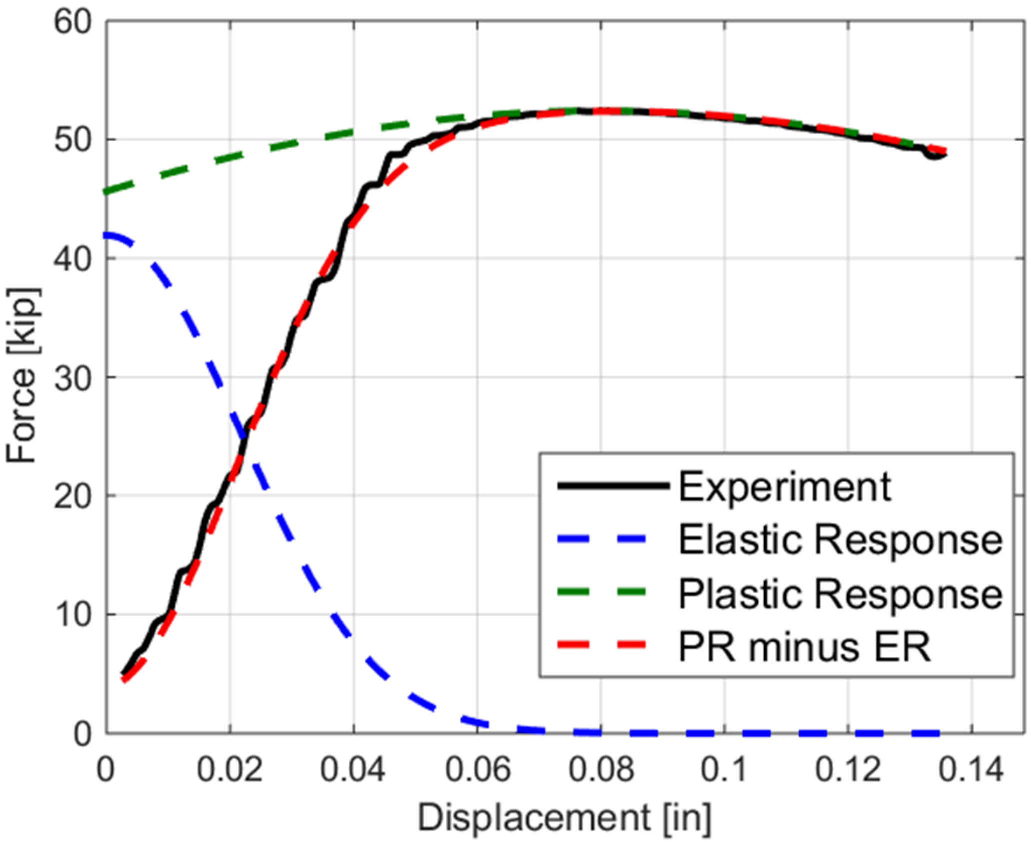
| Alloy/Grade | AISI 8740[1] | 302HQ[1] | ASTM A286[1] | ASTM A325[2] | ASTM A490[2] |
|---|---|---|---|---|---|
| **Bolt Size** | #8-32 UNC | #10-32 UNF | #8-32 UNC<br>#10-32 UNF | 3/4"-10 UNC<br>1"-8 UNC | 3/4"-10 UNC<br>1 1/4"-7 UNC |
| **Bolt Lengths [in]** | 5/8 | 5/8 | 5/8 | 1.75, 2, 2.25, 3, 3.75, 6 | 1.75, 2, 2.25, 3, 3.75, 5, 6 |
| **Gage Lengths [in]** | 0.125, 0.28, 0.375 | 0.25, 0.375 | 0.25 | 0.6, 0.75, 1, 1.2, 2.5 | 0.6, 0.75, 1, 1.2, 2, 3.5, 4, 4.5 |
| **Speed [in/s]** | 0.0002 | 0.0002, 2 | 0.0002, 0.01, 1, 2 | 0.0003, 0.0006 | 0.0003, 0.0006 |

1. Lee, Sangwook (Simon) et al. (2006). *Experimental Results of Single Screw Mechanical Tests: a follow-up to SAND2005-6036*. Tech. rep: SAND2006-3751, Livermore, CA: Sandia National Laboratories.

2. Wade, Patrick M. (2006). “Characterization of High-Strength Bolt Behavior in Bolted Moment Connections”. MSc. North Carolina State University.

# Model Development

Model force as $F(\delta) = \phi_1(\delta)F_{elastic} + \phi_2(\delta)F_{plastic}$




For response functions choose,

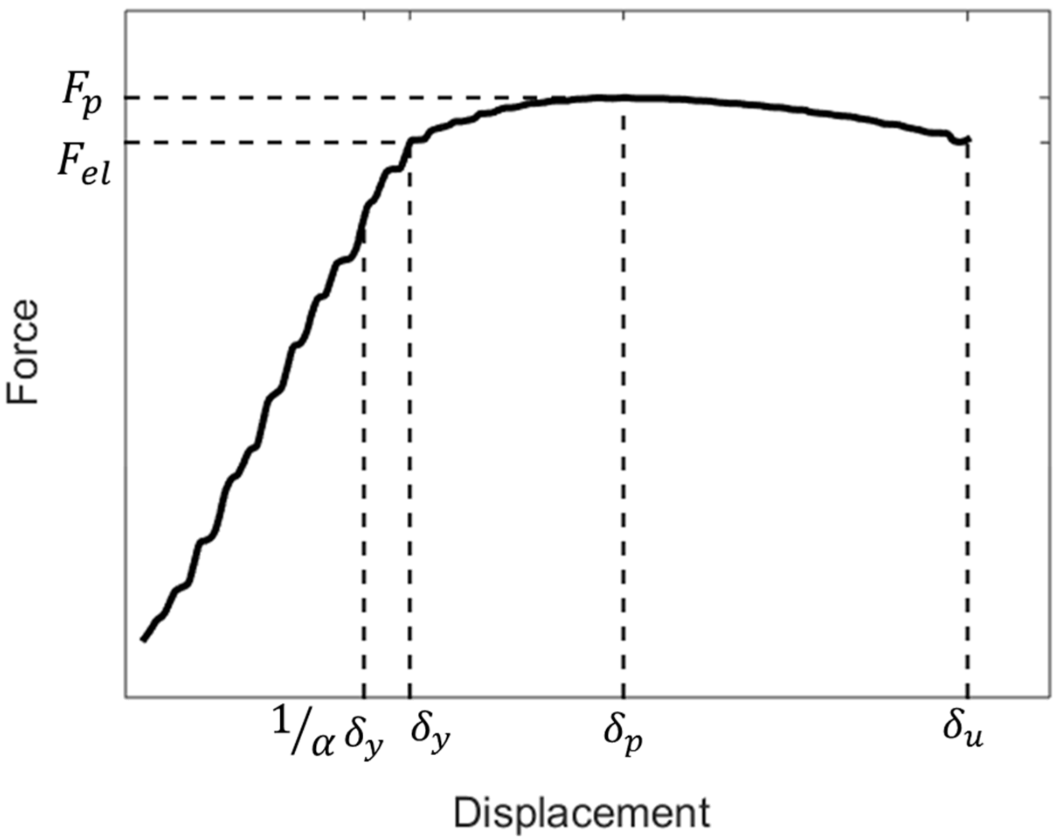
$$\phi_1(\delta) = -e^{-\left(\frac{\delta}{\delta_{el}}\right)^2}$$

$$\phi_2(\delta) = e^{-\left(\frac{\delta-\delta_{pl1}}{\delta_{pl2}}\right)^2}$$

$$F(\delta) = -F_{el}e^{-\left(\frac{\delta}{\delta_{el}}\right)^2} + F_{pl}e^{-\left(\frac{\delta-\delta_{pl1}}{\delta_{pl2}}\right)^2}$$

# Model Development

$$F(\delta) = -F_{el}e^{-\left(\frac{\delta}{\delta_{el}}\right)^2} + F_{pl}e^{-\left(\frac{\delta-\delta_{pl1}}{\delta_{pl2}}\right)^2}$$




- The majority of the elastic portion must occur before the yield point, thus,

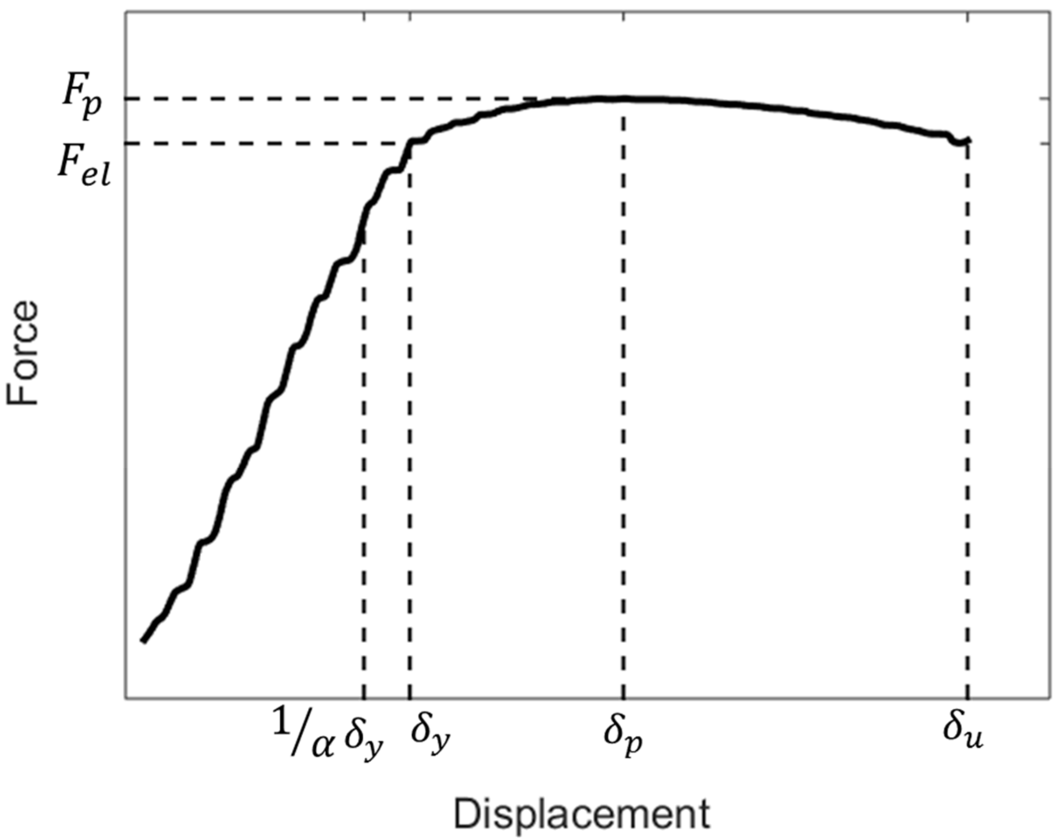
$$\delta_{el} = \frac{1}{\alpha}\delta_y, \qquad \alpha > 1$$

- $F_{el}$ remains a free variable, but assume that

$$F(\delta_y) \equiv F_{el}$$

# Model Development

$$F(\delta) = -F_{el}e^{-\left(\alpha\frac{\delta}{\delta_y}\right)^2} + F_{pl}e^{-\left(\frac{\delta-\delta_{pl1}}{\delta_{pl2}}\right)^2}$$




- Plastic response centered at peak displacement and peak force:

$$\delta_{pl1} \equiv \delta_p$$
$$F_{pl} \equiv F_p$$

- Plastic response has small curvature, thus

$$\delta_{pl2} > \delta_u$$

- Define

$$\delta_{pl2} \equiv \delta_p + \delta_u$$

# Model Development

$$F(\delta) = -F_{el}e^{-\left(\alpha\frac{\delta}{\delta_y}\right)^2} + F_p e^{-\left(\frac{\delta-\delta_p}{\delta_p+\delta_u}\right)^2}$$

- At this point the free variables are $F_{el}$ and $\alpha$, and $\delta_y$ is the displacement where the force $F_{el}$ occurs.
- An initial optimization is ran to identify $\alpha$ and $F_{el}$

| A286 #8-32 UNC 5/8 in Length | | | | |
|---|---|---|---|---|
| Gage Length [in] | Speed [in/s] | R^2 | alpha | Fp/Fel |
| 0.15 | 0.0002 | 0.9992 | 1.50 | 1.18 |
| 0.25 | 0.0002 | 0.9990 | 1.46 | 1.21 |
| 0.25 | 0.0002 | 0.9990 | 1.55 | 1.18 |
| 0.25 | 0.0002 | 0.9979 | 1.52 | 1.22 |
| 0.25 | 0.0002 | 0.9967 | 1.61 | 1.18 |
| 0.25 | 0.0002 | 0.9992 | 1.38 | 1.24 |
| 0.25 | 0.0002 | 0.9987 | 1.38 | 1.25 |
| 0.15 | 2 | 0.9973 | 1.36 | 1.17 |
| 0.25 | 2 | 0.9986 | 1.37 | 1.22 |
| 0.25 | 2 | 0.9988 | 1.45 | 1.20 |
| Mean | | | 1.46 | 1.21 |

- The values of $\alpha$ and $F_p/F_{el}$ are similar
- Suppose that

$$\alpha \equiv \frac{F_p}{F_{el}}$$

Then…

# Model Development

$$F(\delta) = F_p\left[-\frac{1}{\alpha}e^{-\left(\alpha\frac{\delta}{\delta_y}\right)^2} + e^{-\left(\frac{\delta-\delta_p}{\delta_p+\delta_f}\right)^2}\right]$$

- At this point the free variable is $\alpha$, and $\delta_y$ is the displacement where the force $\frac{F_p}{\alpha}$ occurs.
- Rerunning the optimization to identify $\alpha$

| A286 #8-32 UNC 5/8 in Length | | | | |
|---|---|---|---|---|
| Gage Length [in] | Speed [in/s] | R^2 | alpha | Fp/Fy |
| 0.15 | 0.0002 | 0.9963 | 1.26 | 1.26 |
| 0.25 | 0.0002 | 0.9973 | 1.27 | 1.27 |
| 0.25 | 0.0002 | 0.9955 | 1.27 | 1.27 |
| 0.25 | 0.0002 | 0.9953 | 1.28 | 1.28 |
| 0.25 | 0.0002 | 0.9937 | 1.27 | 1.27 |
| 0.25 | 0.0002 | 0.9981 | 1.27 | 1.27 |
| 0.25 | 0.0002 | 0.9975 | 1.28 | 1.28 |
| 0.15 | 2 | 0.9954 | 1.23 | 1.23 |
| 0.25 | 2 | 0.9978 | 1.26 | 1.26 |
| 0.25 | 2 | 0.9968 | 1.26 | 1.26 |
| Mean | | | 1.27 | 1.27 |

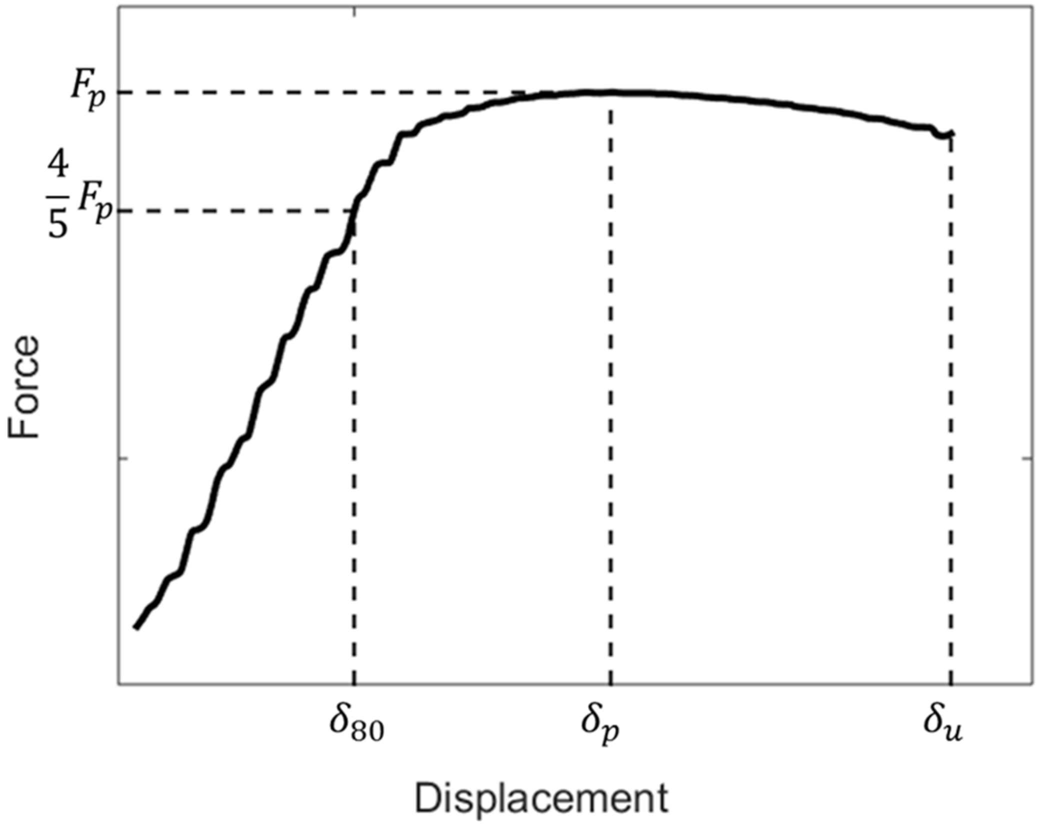
- $\alpha = 1.27$ on average, but is still a free variable…
- Suppose that

$$\alpha \equiv 1.25$$

Then…

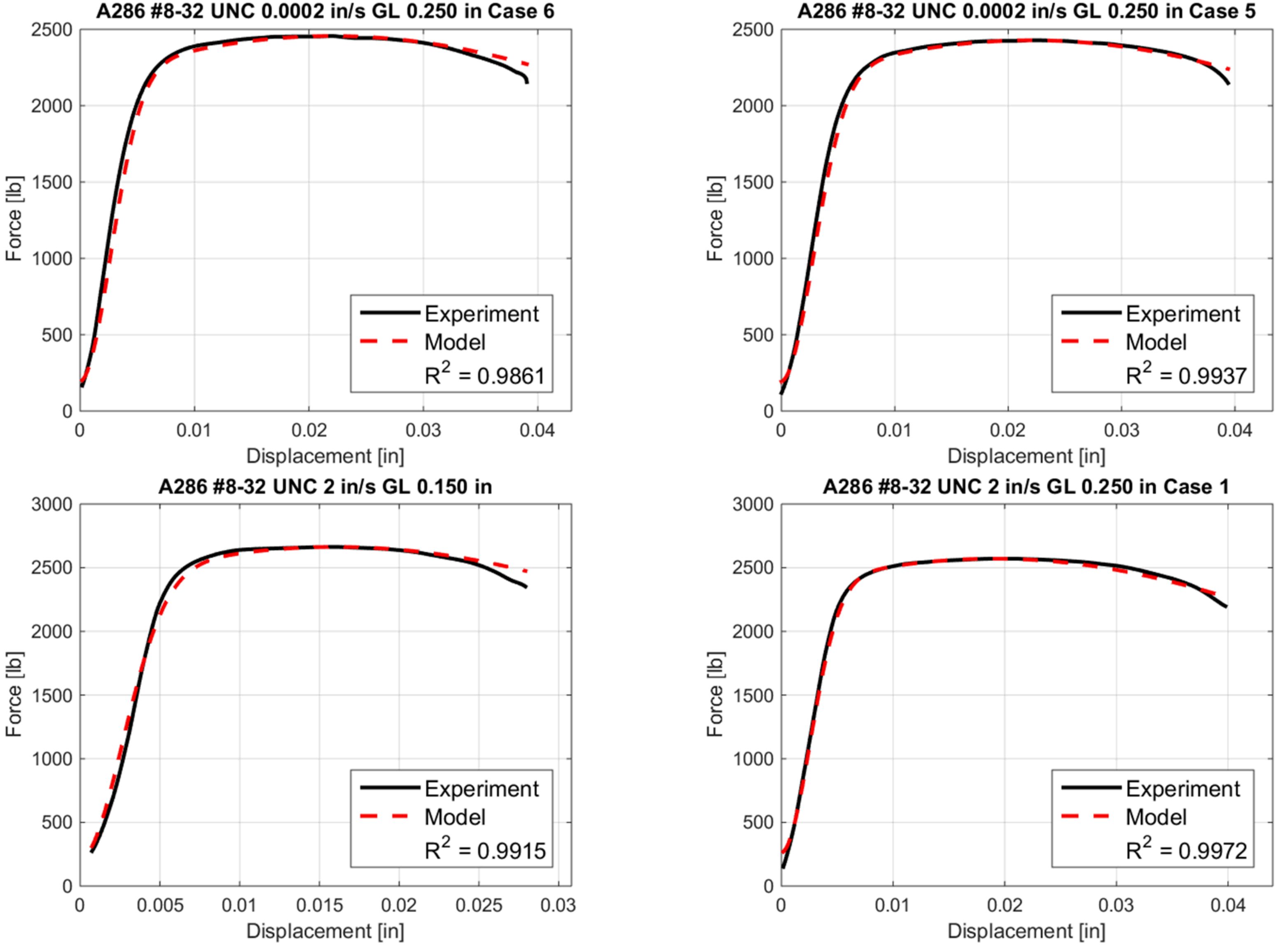
# Model Development

$$F(\delta) = F_p\left[-\frac{4}{5}e^{-\left(\frac{5}{4}\frac{\delta}{\delta_{80}}\right)^2} + e^{-\left(\frac{\delta-\delta_p}{\delta_p+\delta_f}\right)^2}\right]$$

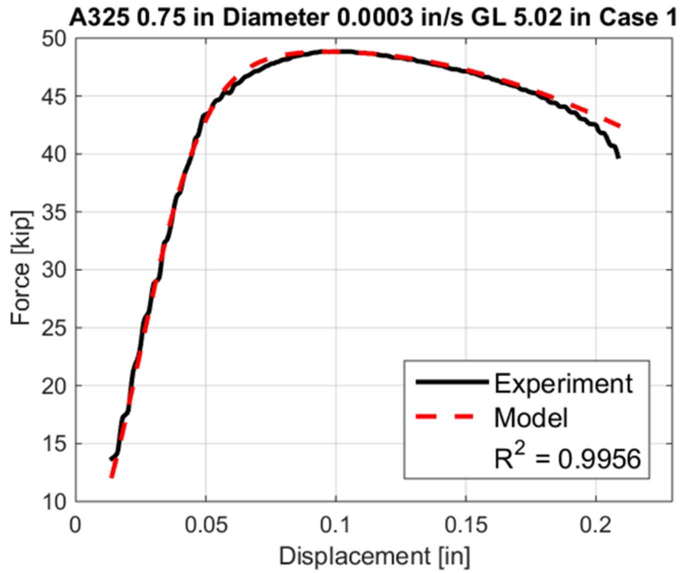


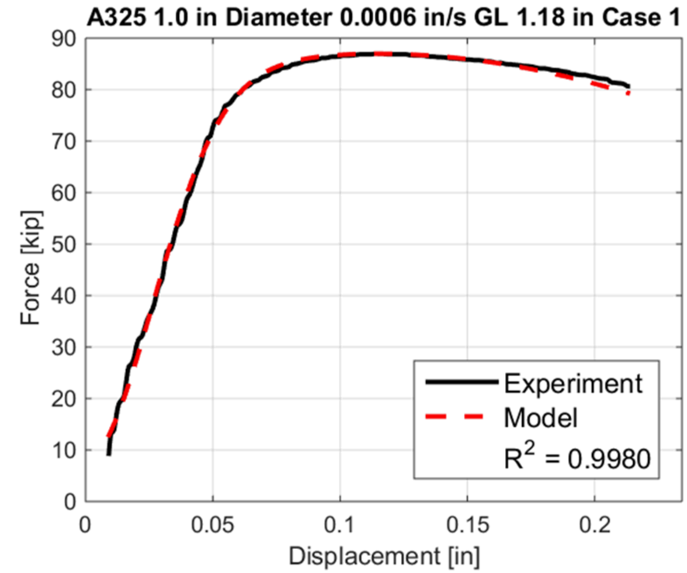

| A286 #8-32 UNC 5/8 in Length | | |
|---|---|---|
| Gage Length [in] | Speed [in/s] | R^2 |
| 0.15 | 0.0002 | 0.9924 |
| 0.25 | 0.0002 | 0.9933 |
| 0.25 | 0.0002 | 0.9939 |
| 0.25 | 0.0002 | 0.9896 |
| 0.25 | 0.0002 | 0.9919 |
| 0.25 | 0.0002 | 0.9937 |
| 0.25 | 0.0002 | 0.9861 |
| 0.15 | 2 | 0.9915 |
| 0.25 | 2 | 0.9972 |
| 0.25 | 2 | 0.9958 |

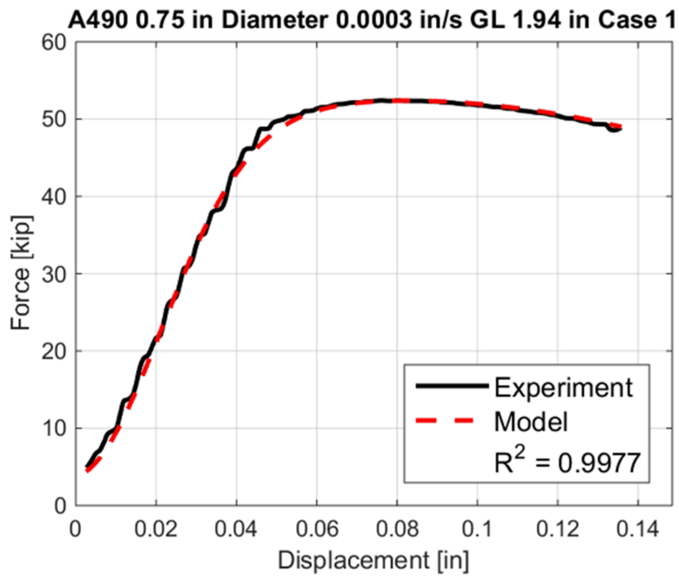
# Model Results: Small Bolt Diameter

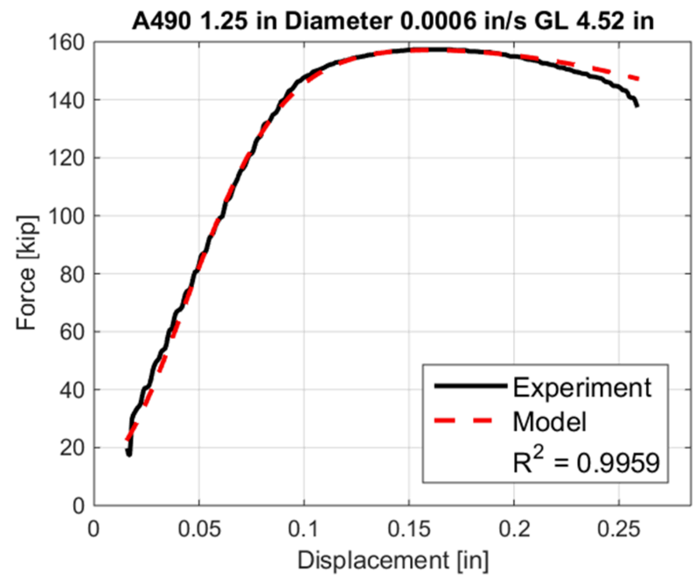


# Model Results: Large Bolt Diameter



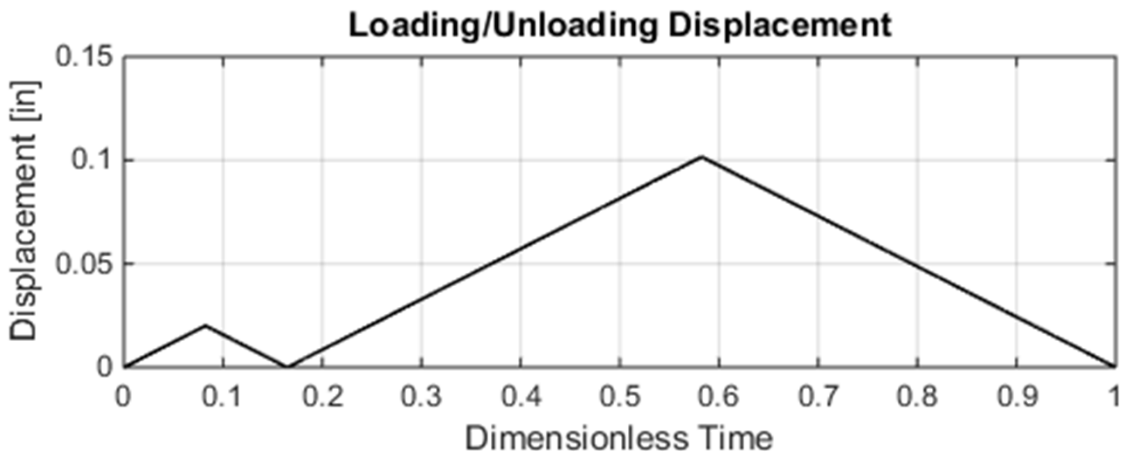



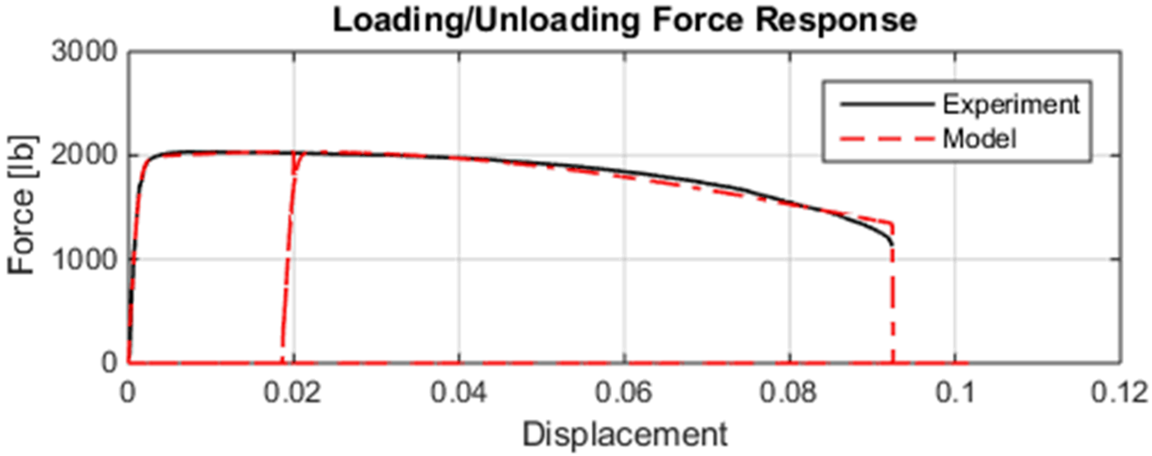



# Model Unloading & Failure



$$F(\delta) = F_p\left(-\frac{4}{5}e^{-\left(\frac{5(\delta-h)}{4\ \delta_{80}}\right)^2} + e^{-\left(\frac{\delta-\delta_p}{\delta_u+\delta_p}\right)^2}\right)\left(H(\delta-h) - H(\delta-du)\right)$$




$F \equiv$ Bolt force
$\delta \equiv$ Bolt displacement

$F_p \equiv$ Peak force

$\delta_{80} \equiv$ Displacement at $0.8F_p$
$\delta_p \equiv$ Peak displacement
$\delta_u \equiv$ Ultimate displacement

$H \equiv$ Heaviside function
$h \equiv$ Permanent deformation at unloading

# Conclusions & Future Work

## Conclusions

- Created reduced order model that reproduces force displacement curves for pure tension.
- Reduced model from 2 free variables to zero free variables – no optimization is required, but model is fully empirical.
- Model matches experiments with high R-squared values (>0.98)

## Future Work

- Investigate other types of response functions.
- Extend model(s) for pure shear and mixed loading conditions.
- Verify models further with additional experiments.