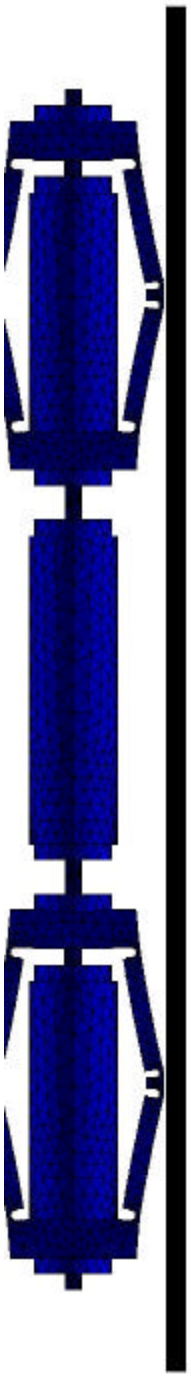

Design and Modeling of an Electrostrictive Inchworm Actuator

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University of Victoria

E. Prasad and D. Waechter

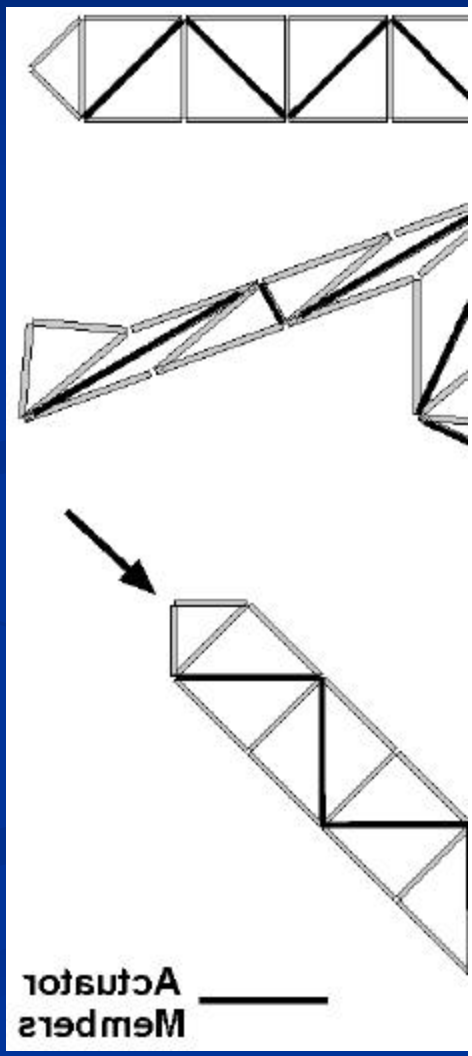
Sensor Technology Ltd.

Contents

- Motivation
- Actuator specifications
- Past actuator designs
- Conceptual actuator design iterations
- Actuator modeling
- Parametric optimization
- Actuator prototyping
- Applications
- Conclusions

Motivation

- Use in adaptive structures
  - Vibration control
  - Shape control
  - Increased structural strength
- Replace hydraulic actuators
  - Bulky pump equipment
  - Fluids are:
    - Carcinogenic
    - Flammable
    - Water polluting



Actuator Specifications

- Specifications set by the funding company: Sensor Technology Limited

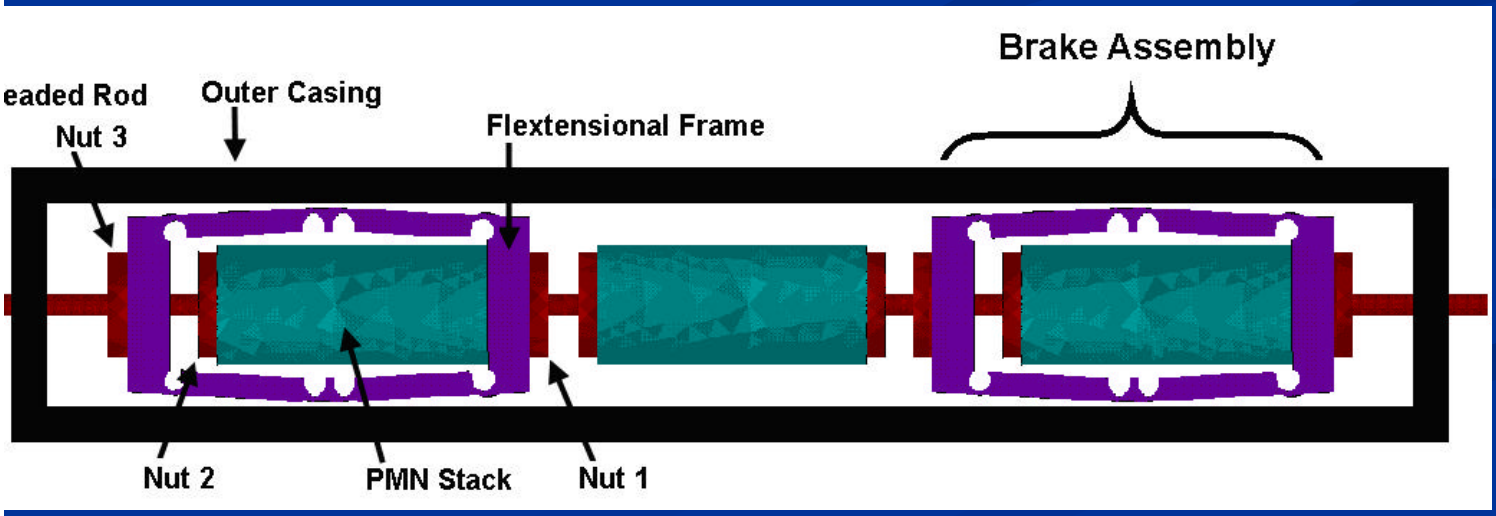
- Stroke: 15mm
- Maximum Voltage: 200V
- Pushing force: 20N

Final Design

Final design – incorporates threaded rod and nuts

Advantages

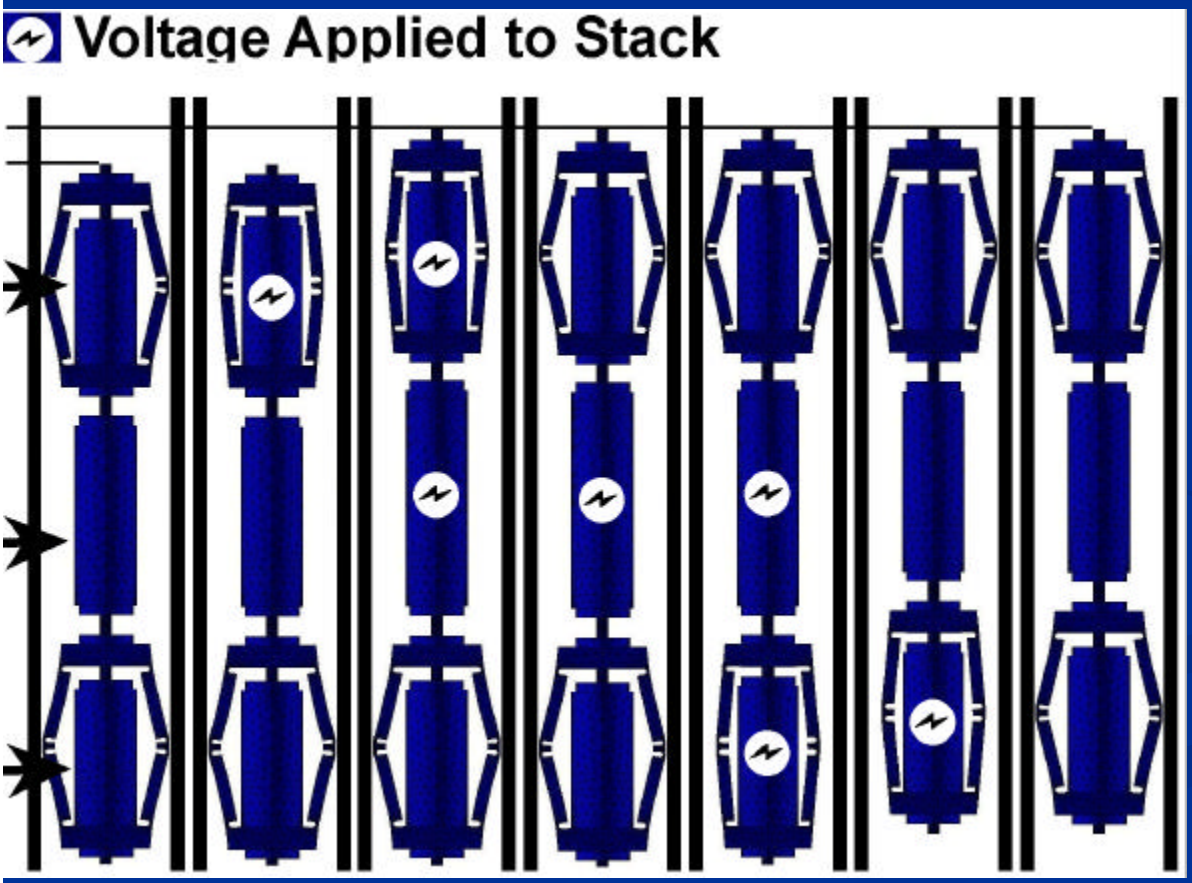
- Locked position
- Few parts
- Adjustability
- Pre-stressing

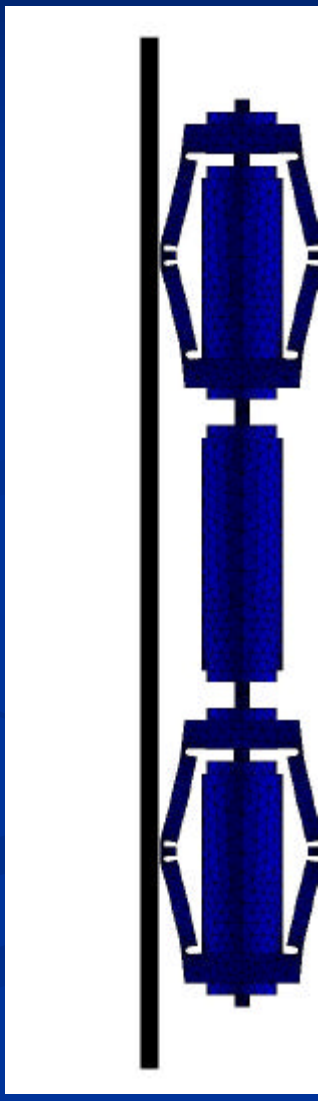


Final design

Inchworm Firing Sequence

- Firing Sequence



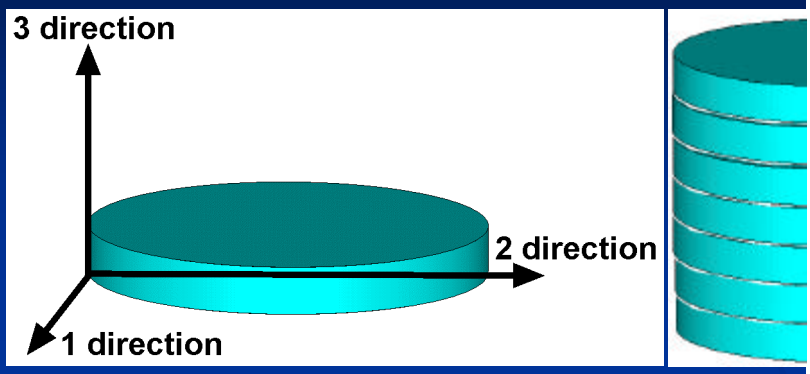


Actuator Modeling

ck modeling

Ansys-FEA software

- No electrostrictive materials



rostrictive effect

$$M_{33} E_3^{\,2}$$

Electric Field

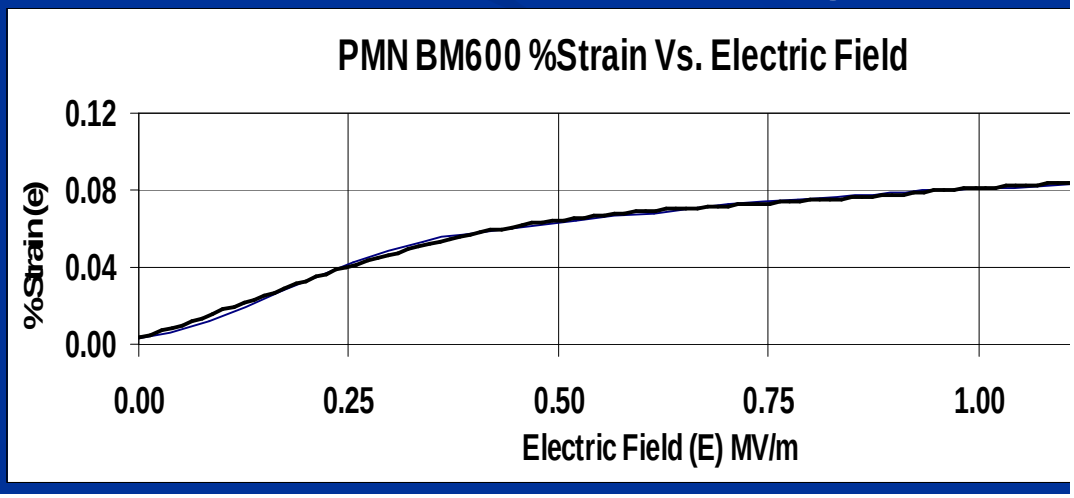
strictive Coeff.

Piezoelectric effect

$$e_3 = d_{33} E_3$$

Piezo Charge Coeff.

$$valent\ "d_{33} = \frac{e_3}{E_3}$$

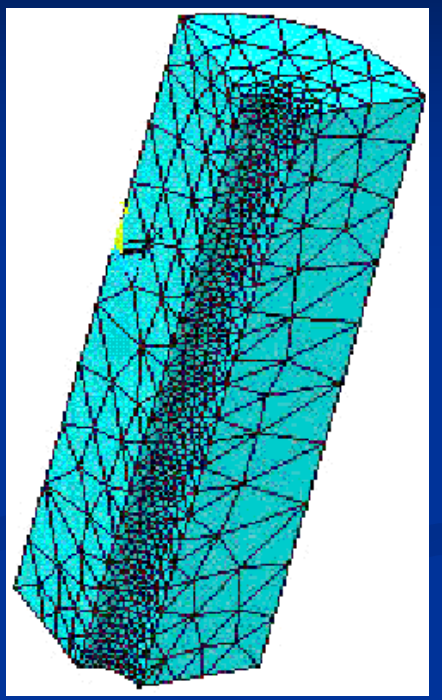


Stack Modeling

ke stack

tack free displacement (at 200V)

	Ansys	SensorTech
ree Displacement (um)	30.0	28.8



Brake stack

Brake stack properties

	Braking Stacks Ansys Design Model
er Thickness (mm)	0.381
nber of Layers	100
l Stack Height (mm)	57.15
imum Voltage (V)	200
ivalent d33 (pC/N)	1440

- Ansys data

Ansys Data	
Element Type	Solid 98 (x,
Number of Nodes	597
Number of Elements	364
Active Degrees of Freedom	2248

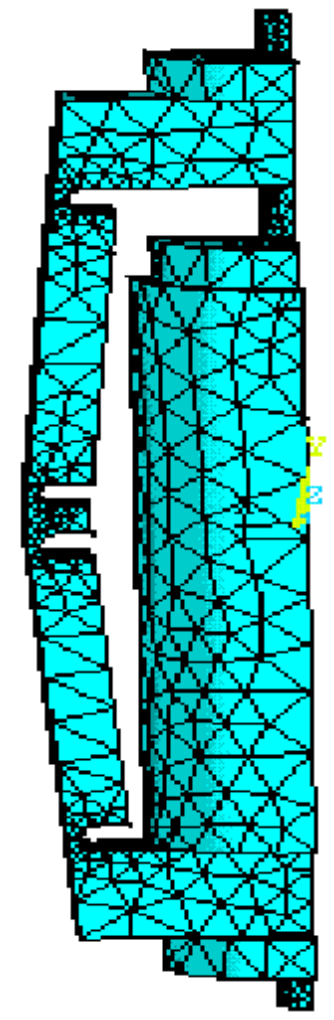
Brake Assembly Modeling

Modeling of the brake assembly

- Model was made parametrically to facilitate dimension changes
- All parts were made from Ti (6%Al, 4%V) to reduce thermal expansion between dissimilar metals

Ansys data

Ansys Data	
Element Type (stack)	Solid 98 (x,y,z,volts)
Element Type (frame, nuts, rod)	Solid 92 (x,y,z)
Number of Nodes	12,455
Number of Elements	6,512
Active Degrees of Freedom	38,063



Brake assembly

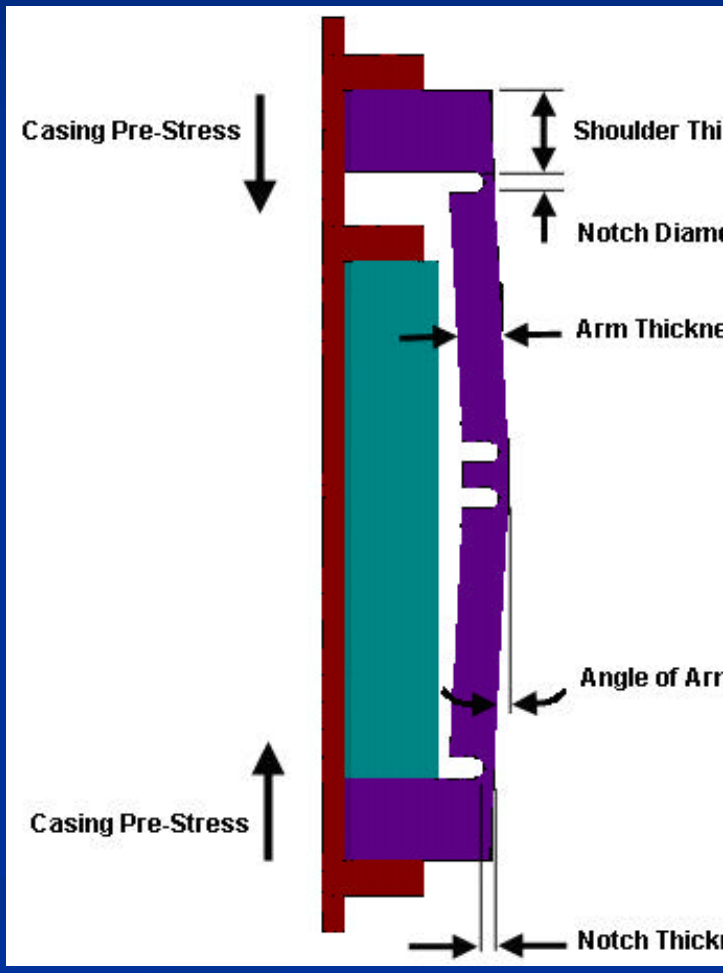
Parametric Optimization

esign Parameters

- Notch Thickness (NT)
- Shoulder Thickness (ST)
- Arm Thickness (AT)
- Arm Angle (AA)
- Notch Diameter (ND)
- Casing Pre-stress (CP)

erformance Criteria

- Range
- Blocked force
- Fatigue safety factor



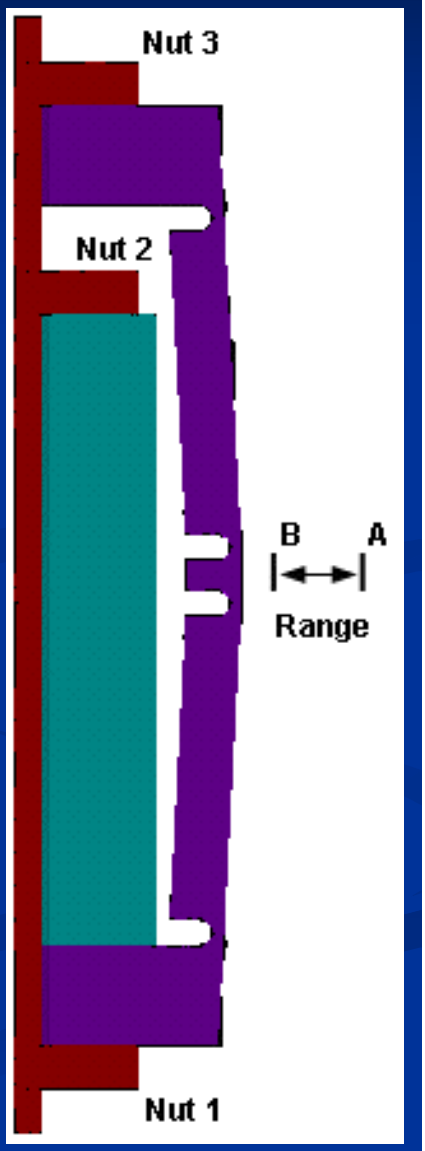
The Range

When Nut 3 is tightened the brake pad bows outward to position “A”

Now energizing the stack forces the threaded rod to lengthen allowing the brake pad to move to position “B”

A-B = Range, and is important because it is a measure of the pad motion during actuation

The design aims for a range >90um



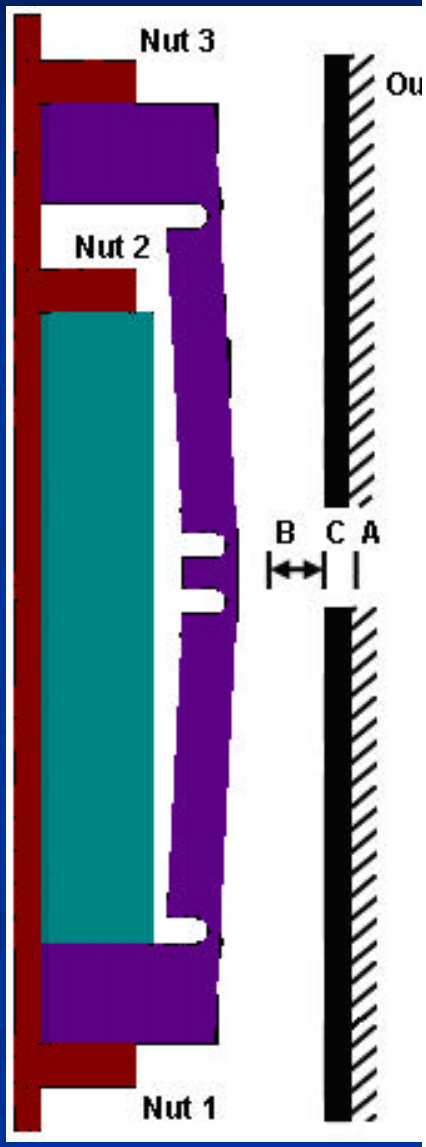
The Blocked Force

e outer casing (“C”) must be located
ween A and B

en C is located at B the force exerted
outer casing is called the “zero
rance blocked force”

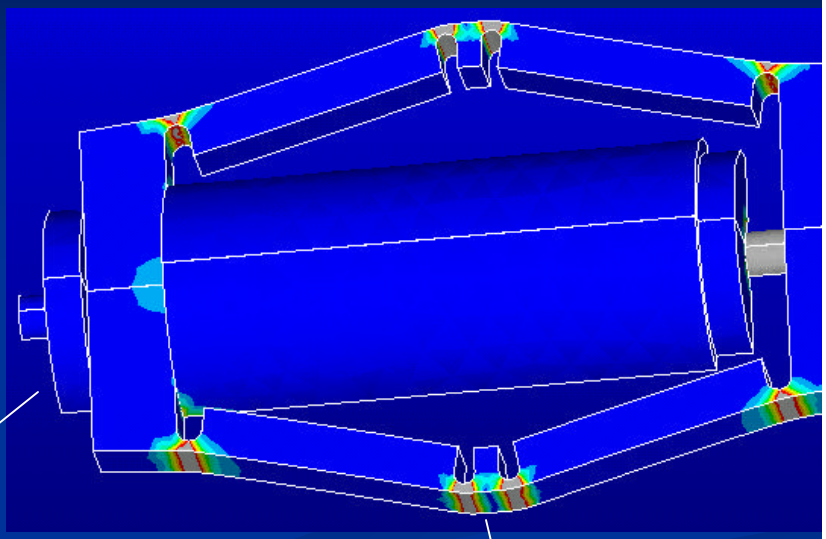
ensure the pads release the design
s for a clearance between 25.4um
01in) and 50.8um (0.002in)

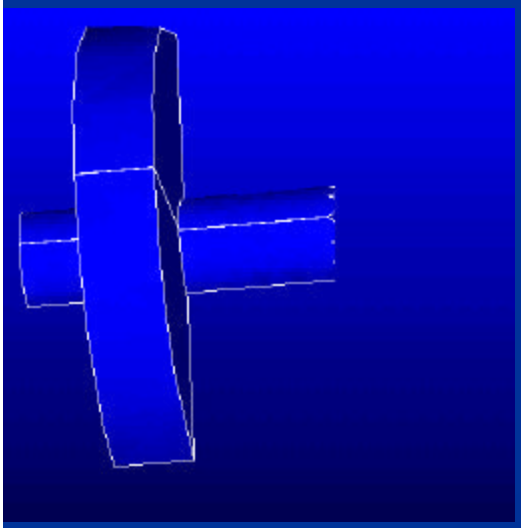
e design aims for a blocked force
5N

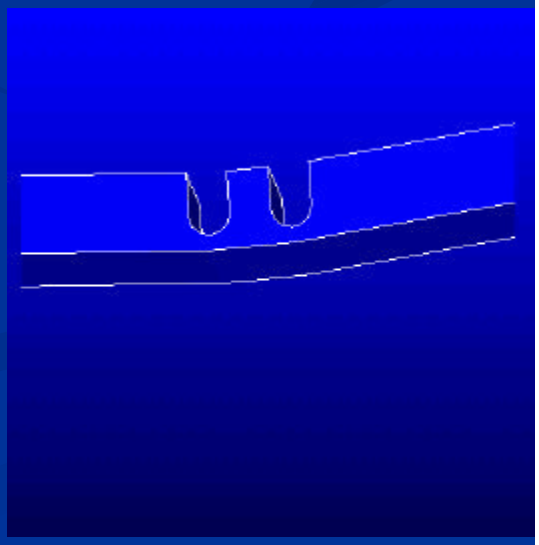


Critical Fatigue Locations

- rod
- center notches







Fatigue Safety Factor

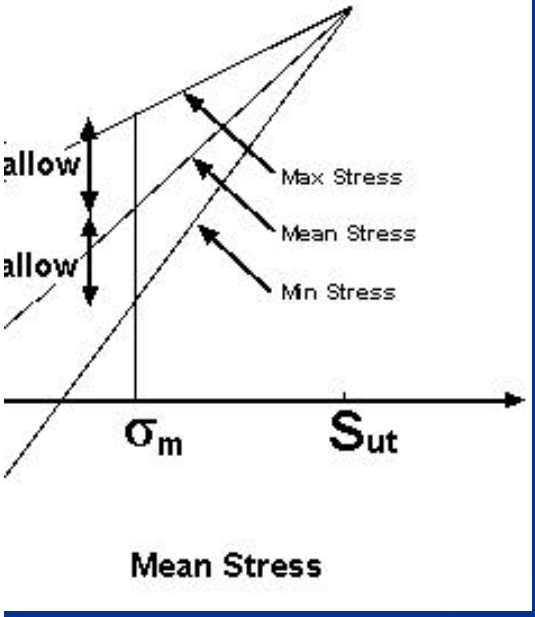
Mach

Se =

Sut =

e modified Goodman relation was used to ermine the allowable stress amplitude (σ_{allow})

fied Goodman Diagram



$$\frac{s_{allow}}{S_e} + \frac{s_m}{S_{ut}} = 1$$

Maximum allow stress amplitude

$$s_{allow} = S_e \left(1 \right.$$

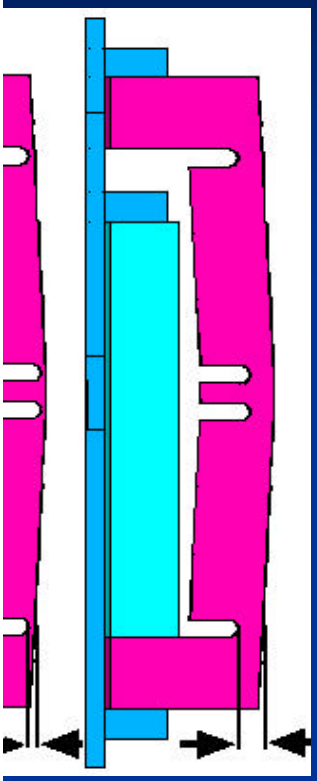
Fatigue safety factor

$$SF = \frac{s_{allow}}{s_a}$$

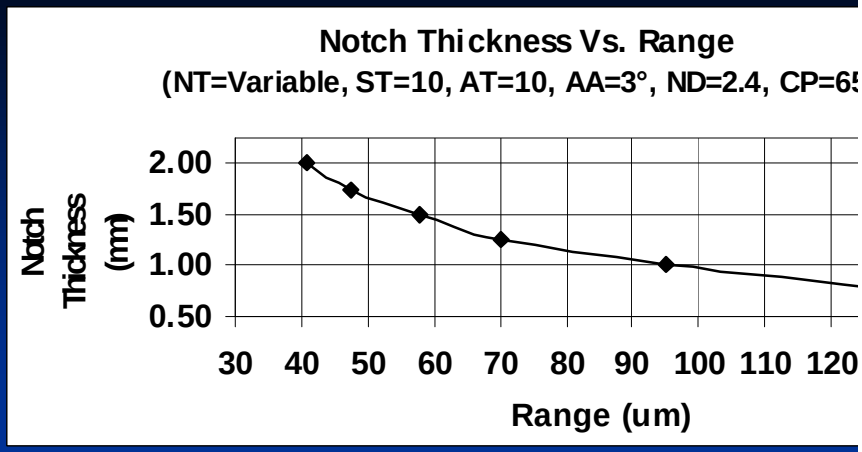
Actual stress amplitude

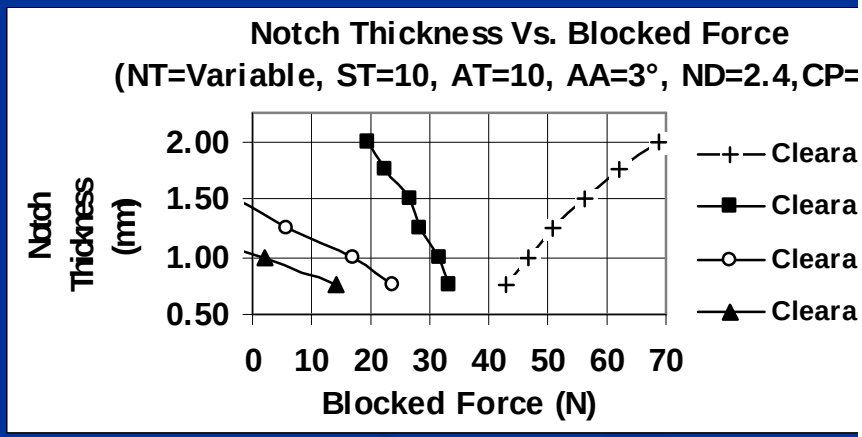
$$s_a = s_{max} - s$$

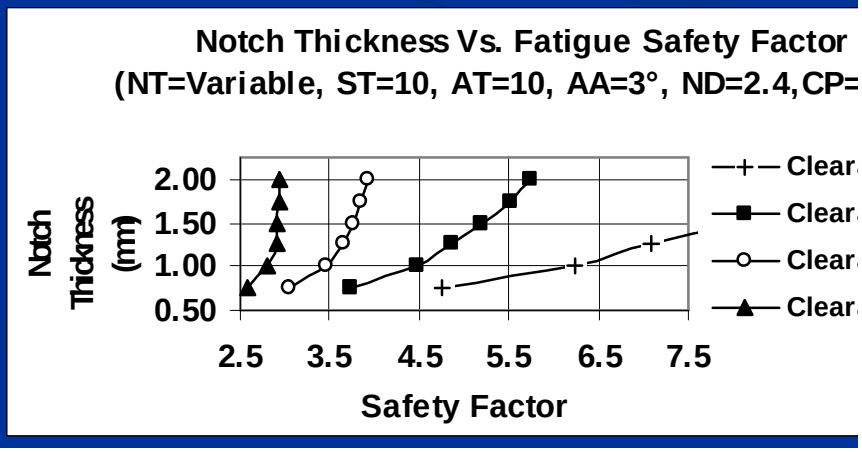
otch
ckness



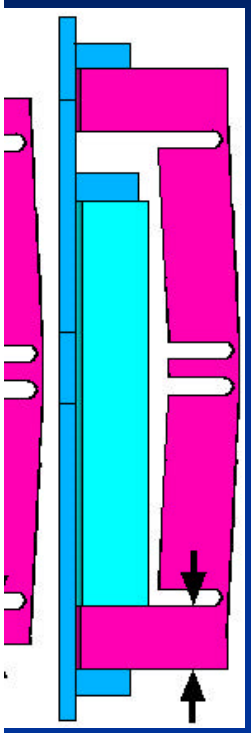
notch thickness was
ed between from
mm to 2mm
sen notch thickness =
n



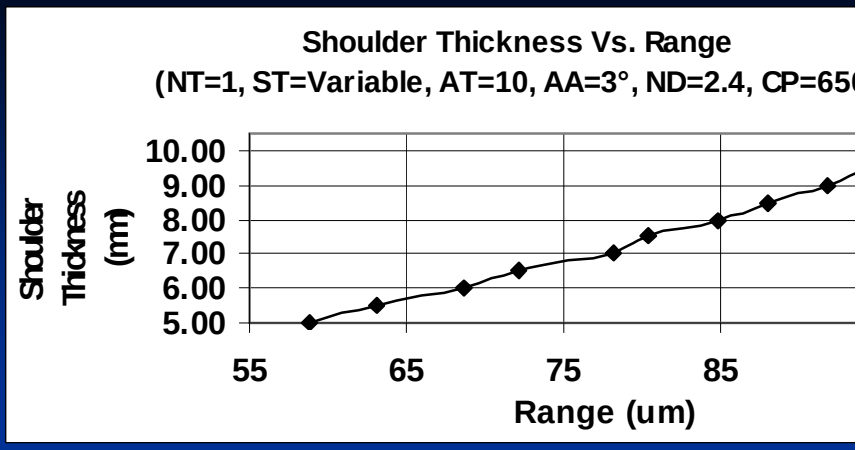


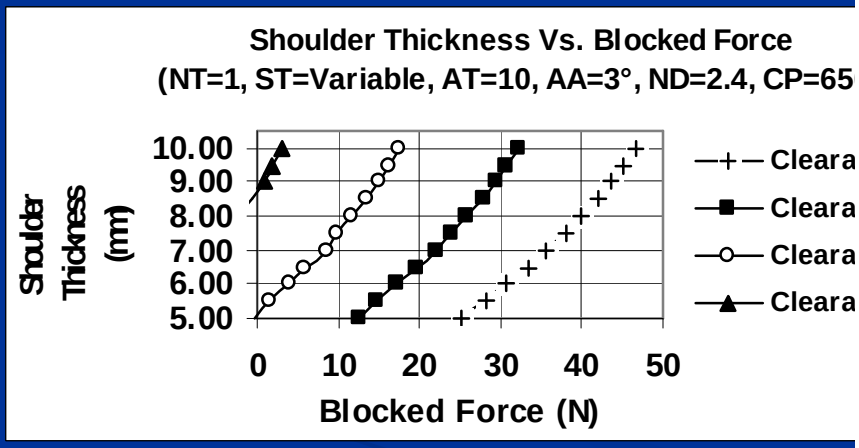


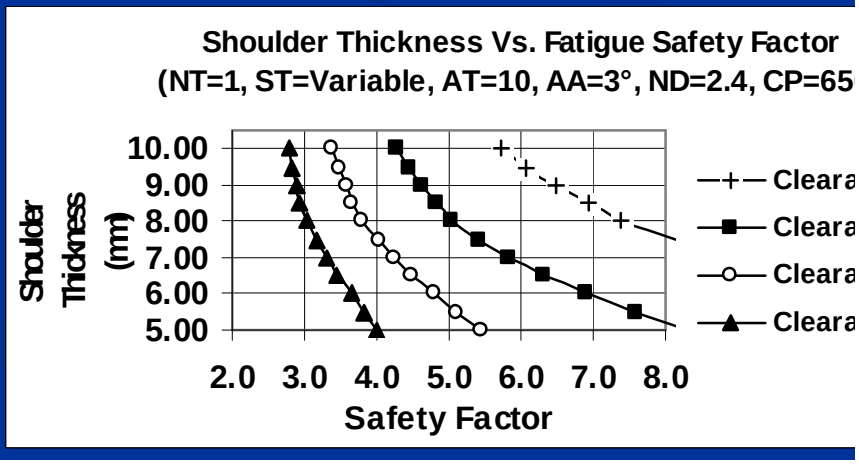
oulder
ckness



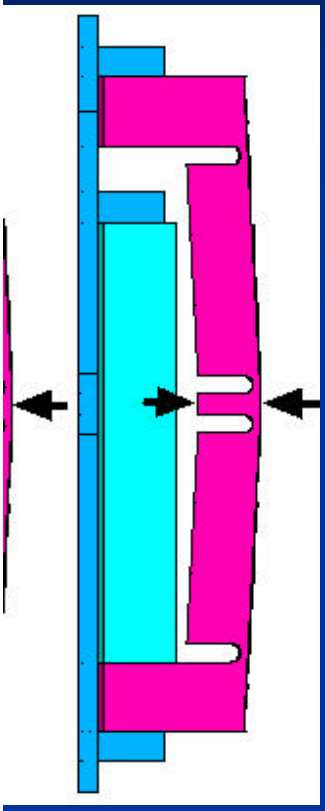
shoulder thickness was
ed between 5mm to
m
sen shoulder thickness =
n



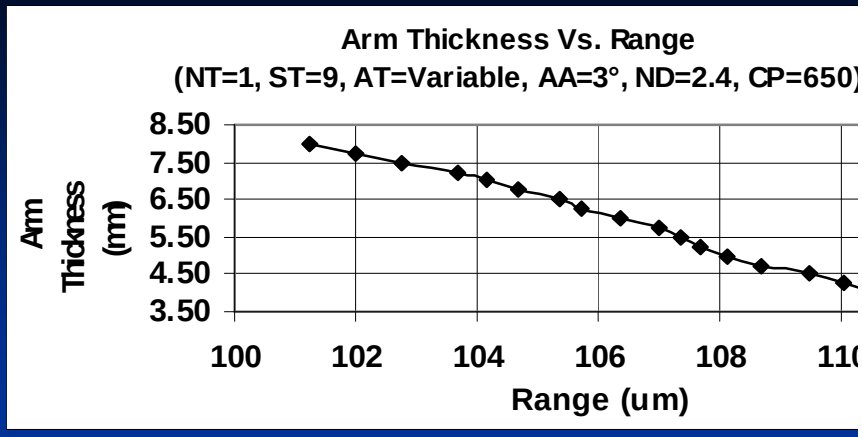


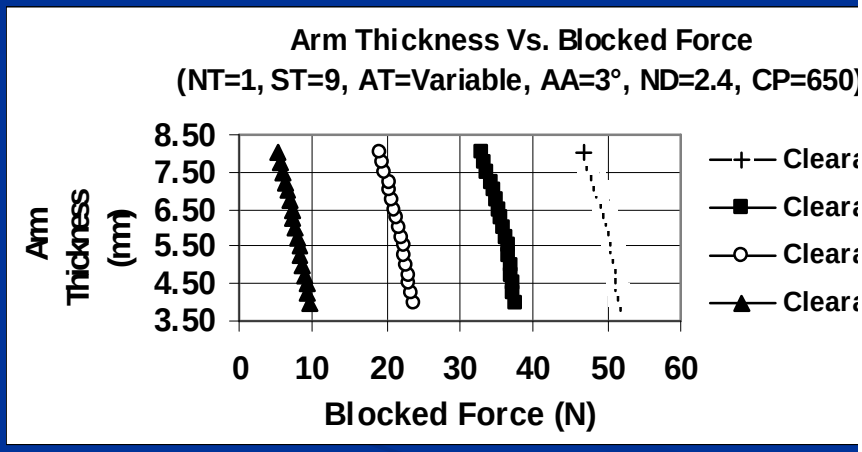


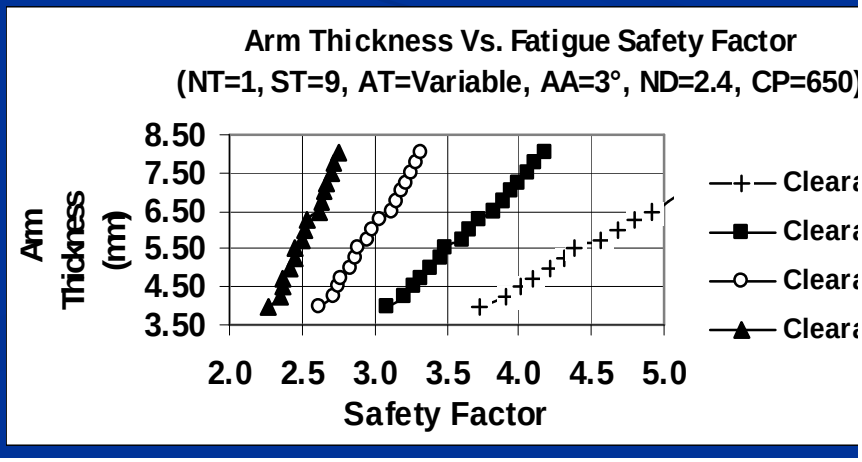
Arm
ckness



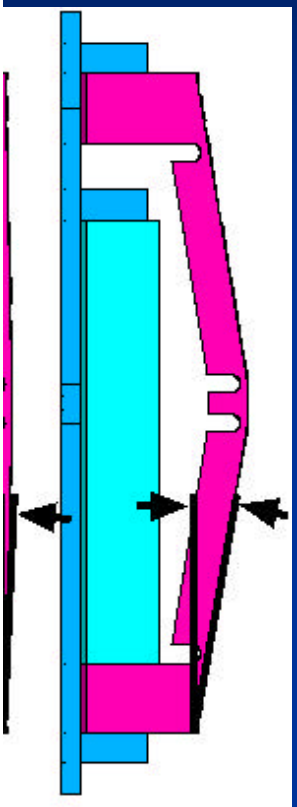
arm thickness was varied
veen 4mm to 8mm
sen arm thickness =
n

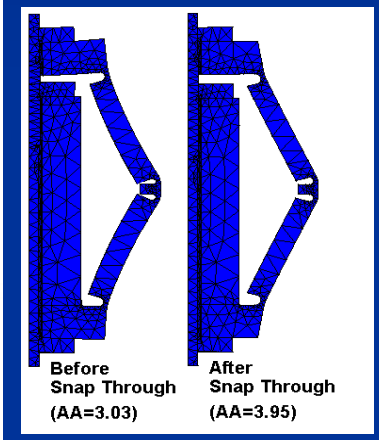


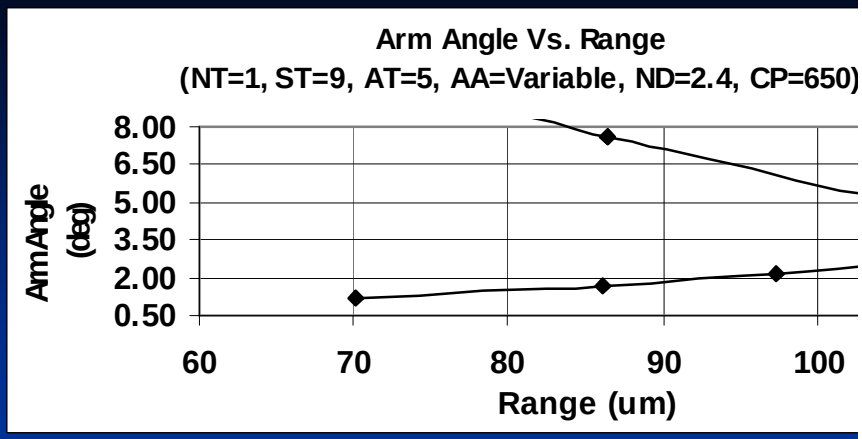


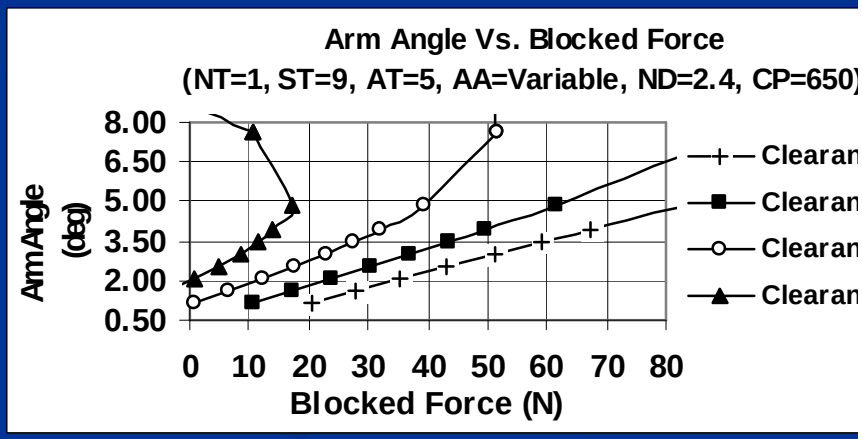


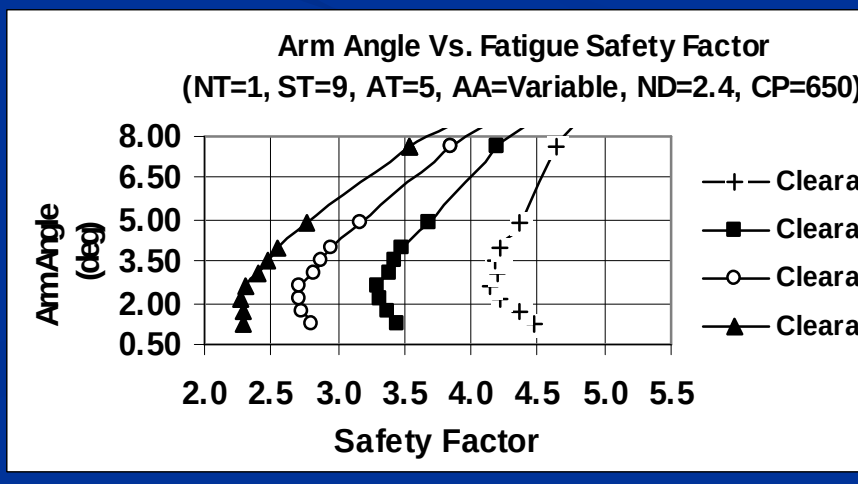
m
gle





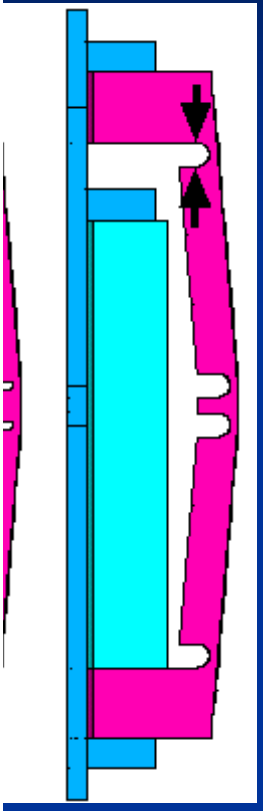




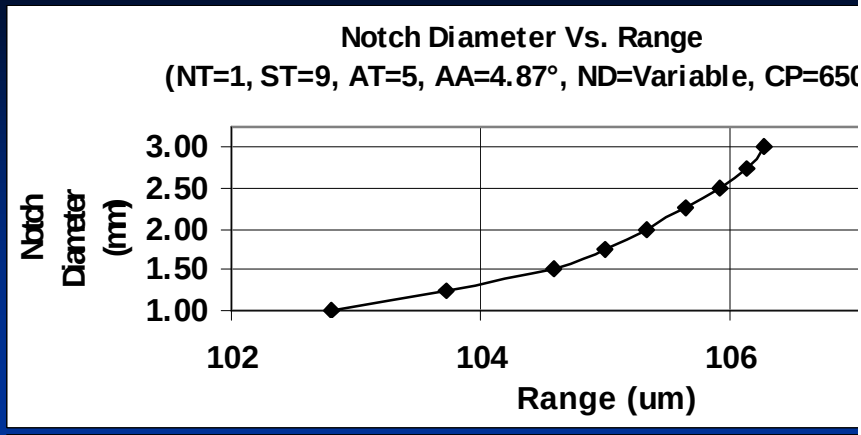


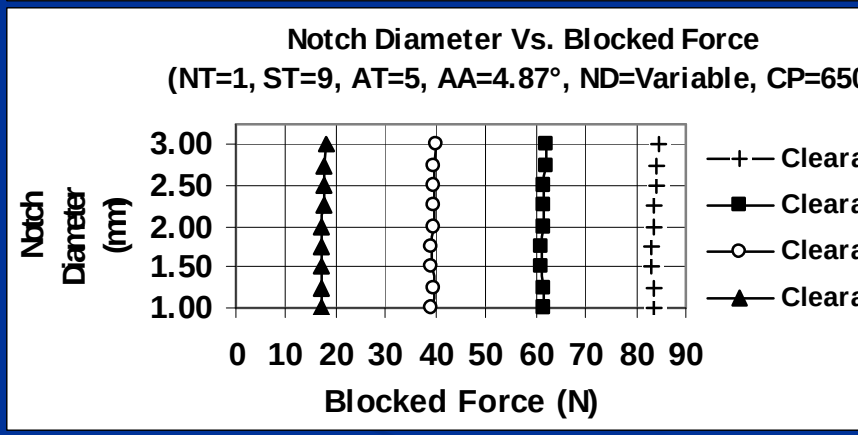
arm thickness was varied
veen 1.2º to 9.4º
sen arm angle = 4.9º

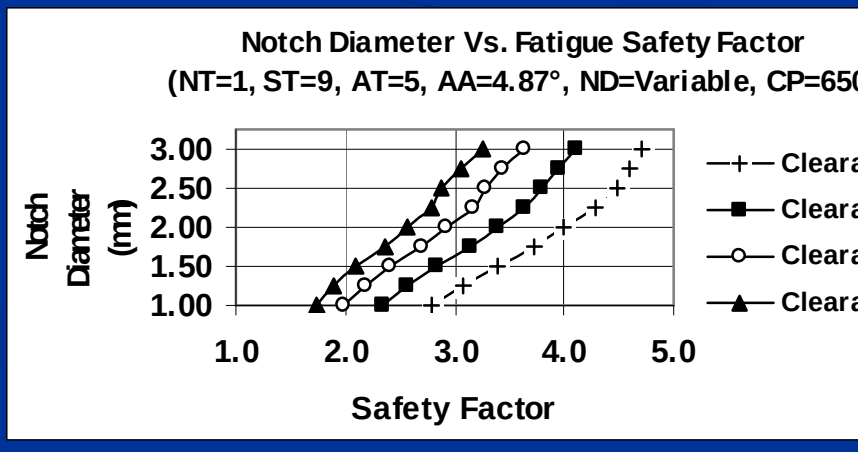
otch
meter



notch diameter was
ed between 1mm to 3mm
sen notch diameter =
nm

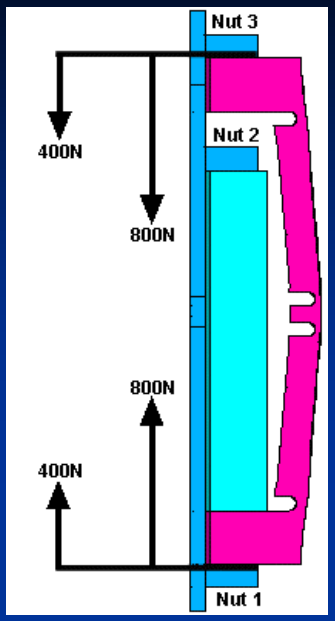


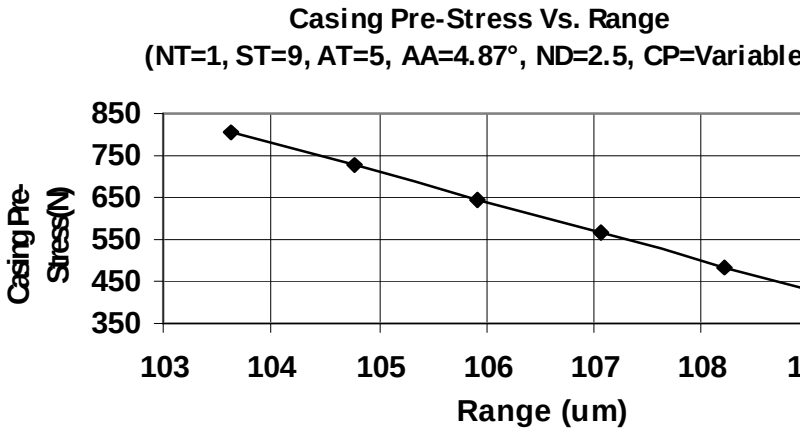


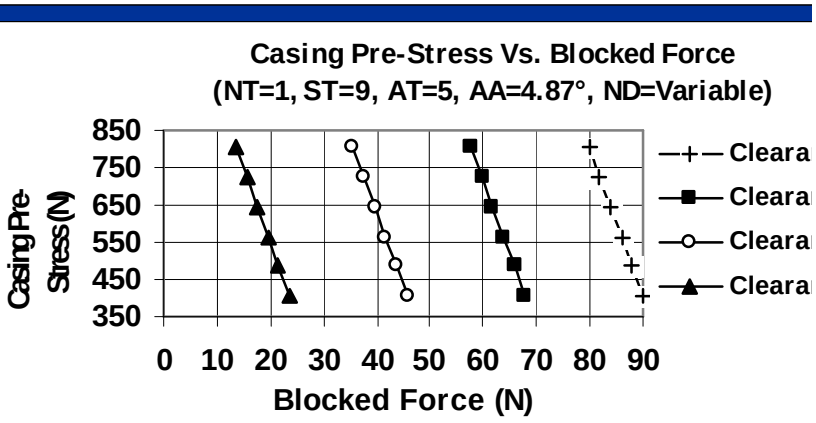


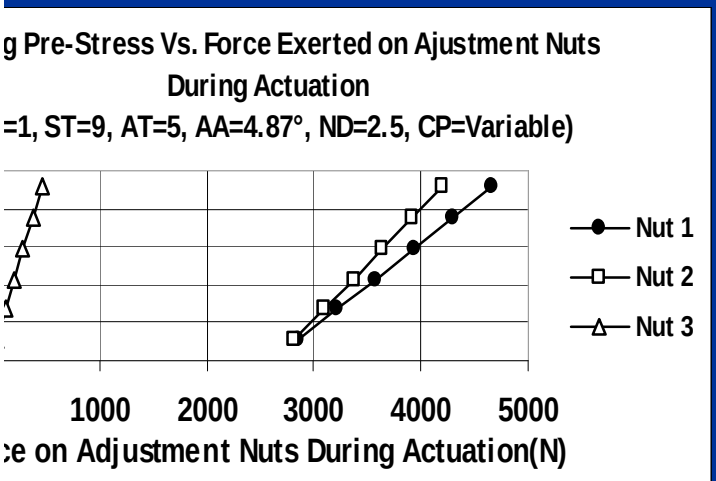
asing
-Stress

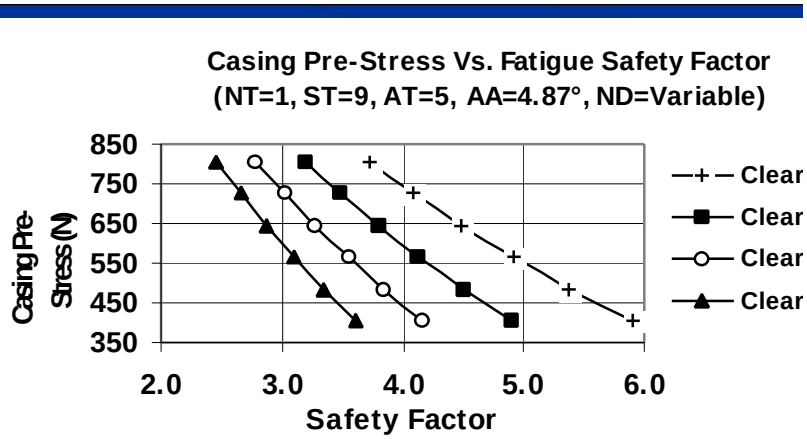
casing pre-
was varied
een 400N
0N





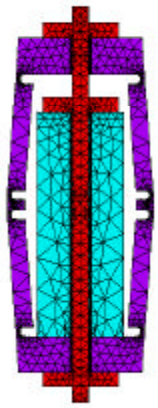






sen casing pre-stress =
N

Final Design



Notch Thickness (NT)= 1mm

Shoulder Thickness(ST)= 9mm

Arm Thickness(AT) = 5mm

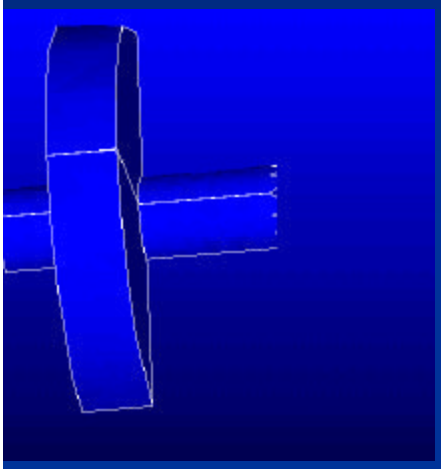
Arm Angle(AA) = 4.87°

Notch Diameter(ND) = 2.5mm

Casing Pre-Stress(CP) = 565N

Inchworm Actuator Results
Brake Stack Free Disp. (um) 
Brake Pad Disp. (um) 
Extending Stack Free Disp. (um) 
Brake Pad Blocked Force (N): 25.4 Clearance 50.8 Clearance
Actuator Output Force (N): 25.4 Clearance 50.8 Clearance
Max. Operating Freq. (Hz) Actuator Speed (mm/min)

Final Design Fatigue Analysis



Rod

$s_{min} = 238\,MPa$

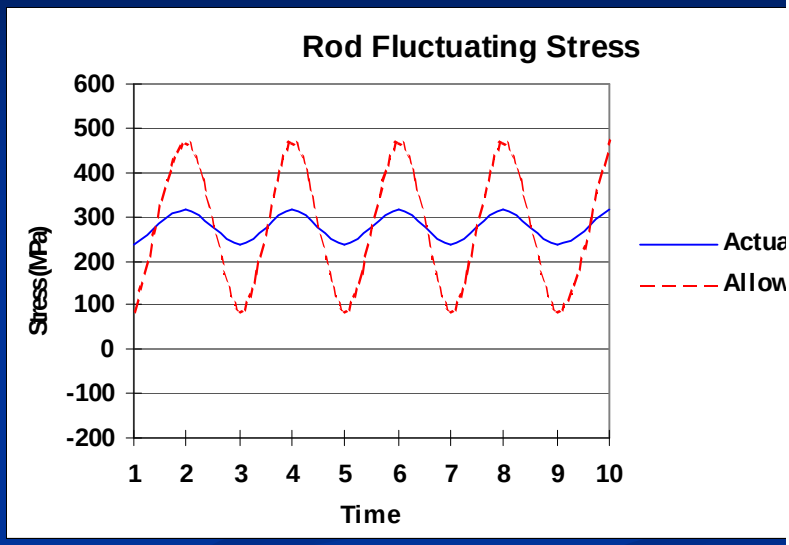
$s_{max} = 318\,MPa$

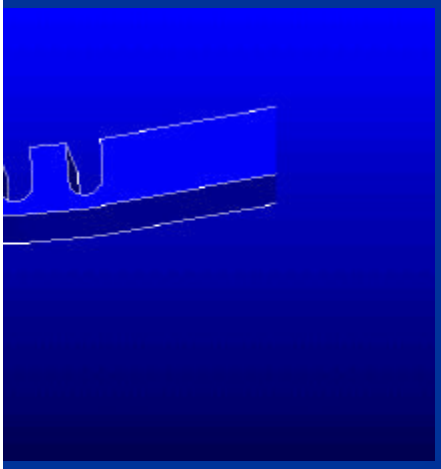
$s_{m} = 278\,MPa$

$s_{a} = 40\,MPa$

$s_{allow} = 193\,MPa$

$SF = 4.8$





Center Notches

$s_{min} = 77\,MPa$

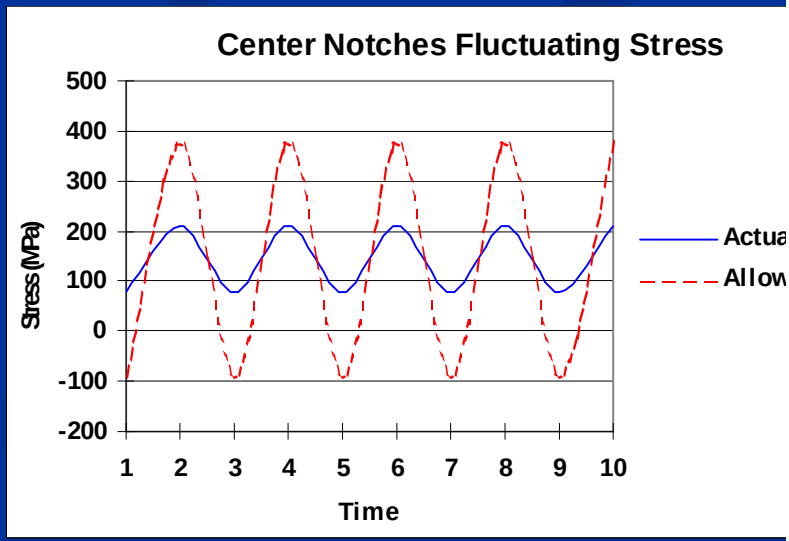
$s_{max} = 209\,MPa$

$s_{m} = 143\,MPa$

$s_{a} = 66\,MPa$

$s_{allow} = 244\,MPa$

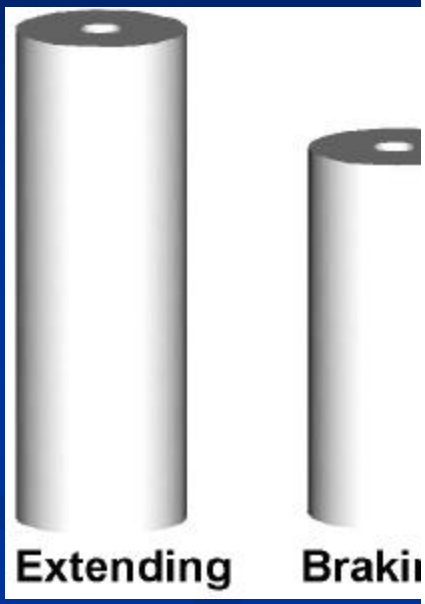
$SF = 3.6$



Actuator Prototyping

nsys model based on quoted stacks

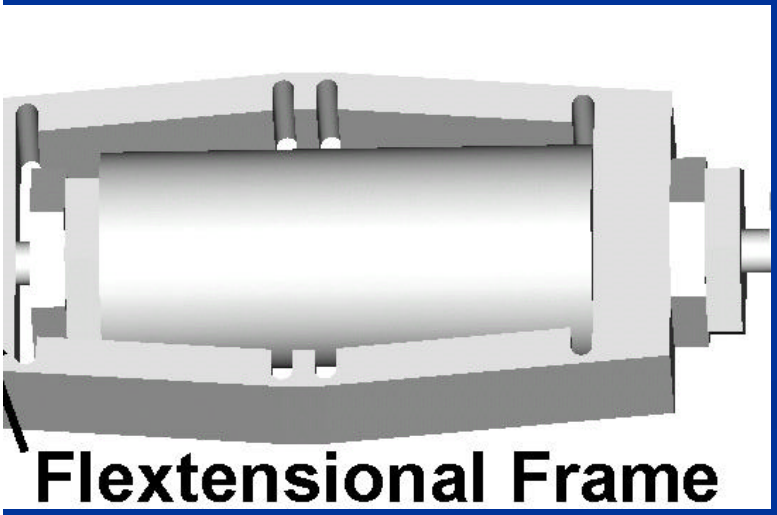
ne quoted stacks were manufactured
t had shorting problems



	Braking Stacks		Extending Stacks	
	Ansys Design Model	Supplied Prototype Stacks	Ansys Design Model	Supplied Prototype Stacks
ickness (mm)	0.381	0.500	0.381	0.760
of Layers	100	70	133	40
ack Height (mm)	57.15	57.15	76.20	50.80
n Voltage (V)	200	285	200	285
nt d33 (pC/N)	1440	1187	1440	1465

Flextensional Frame

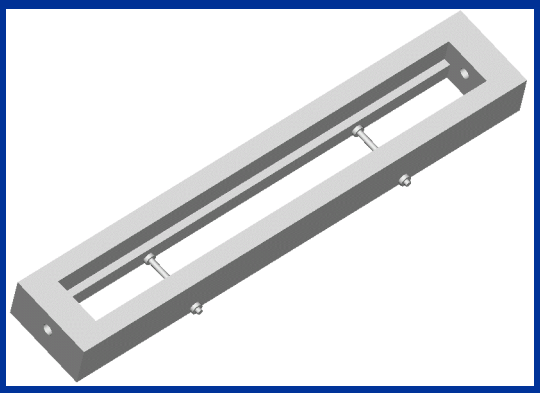
- Frames were manufactured by the wire EDM process



Outer Casing

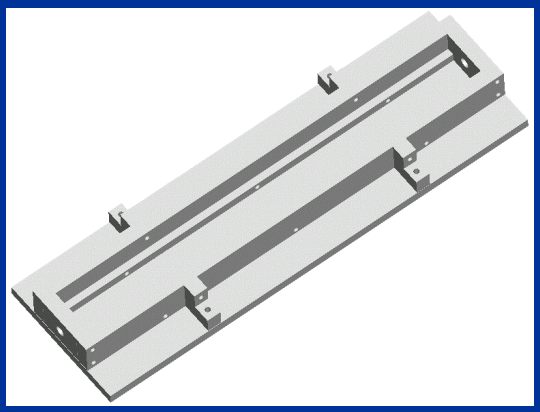
uter channel

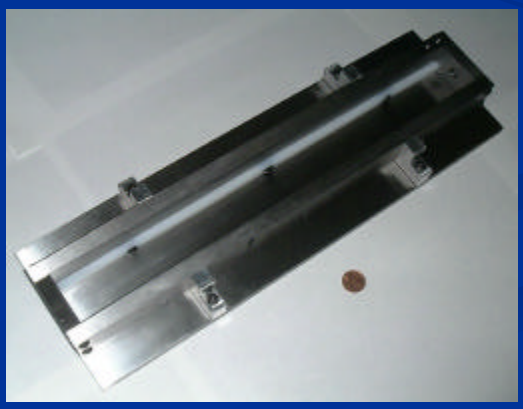
- First option (Ti)
  - Channel cut from one solid piece of Ti using the EDM process



Very expensive

- Second option (Oil hardened ground tool steel)

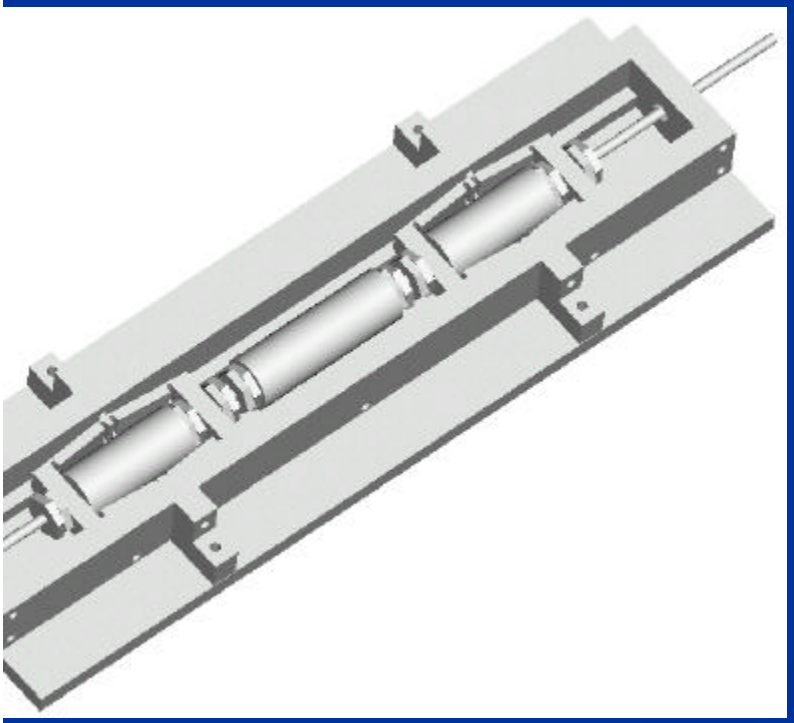


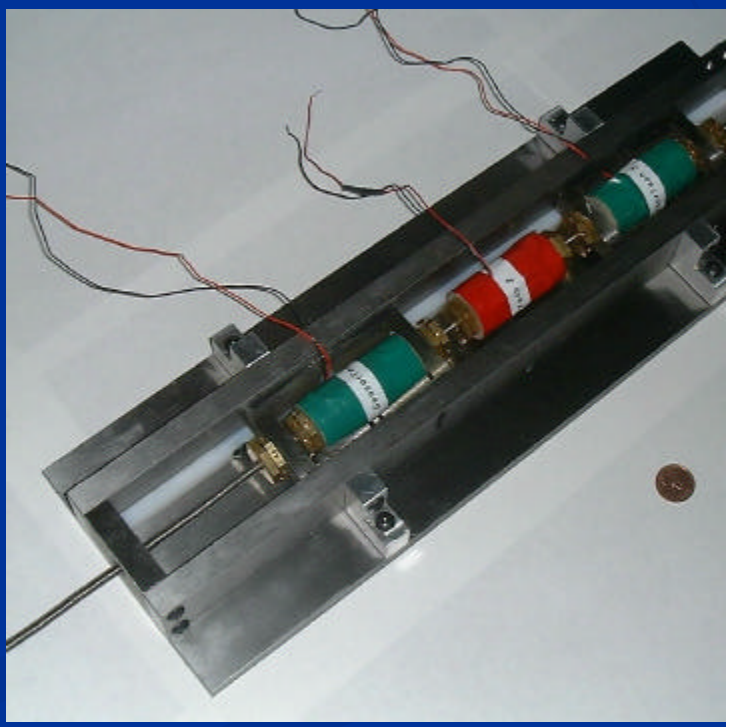


Made in
machine

Actuator Assembly

Assembling all the components the inchworm actuato
was made

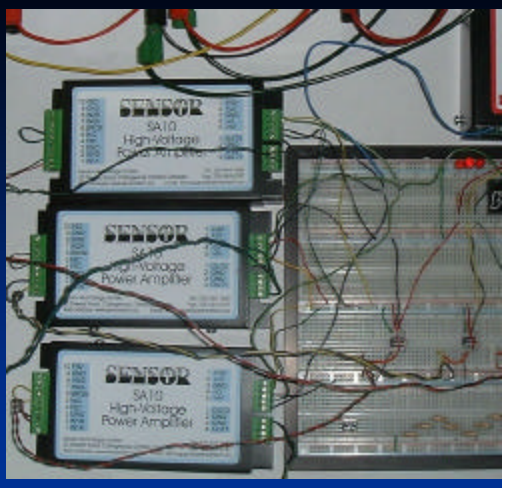


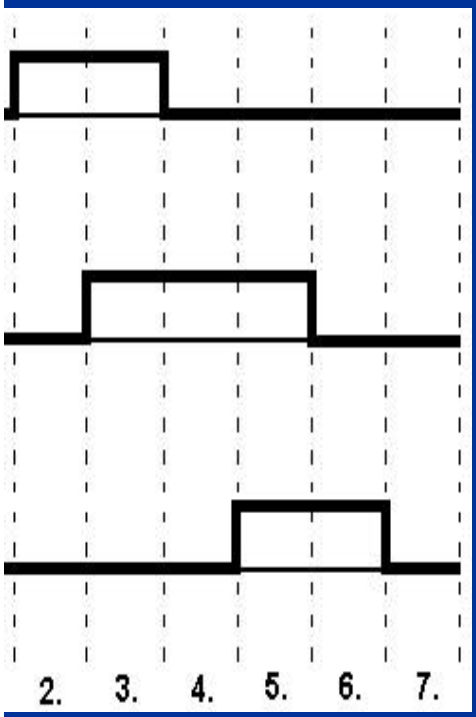


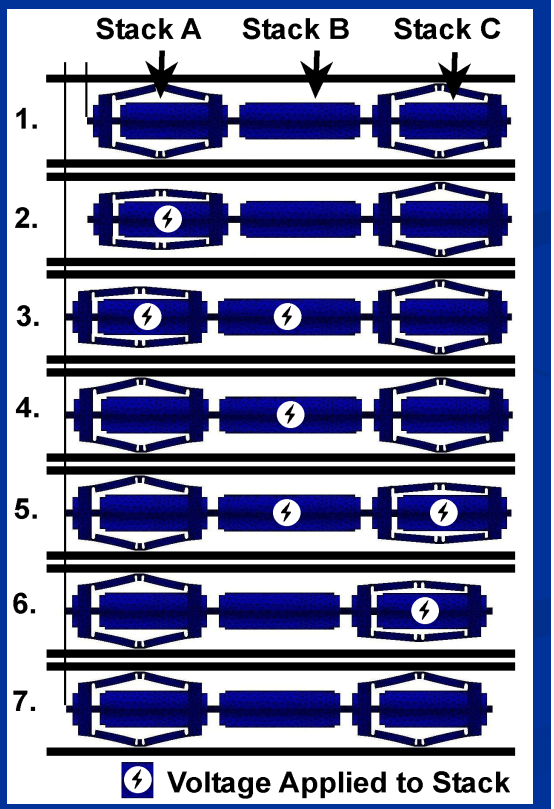
Controller

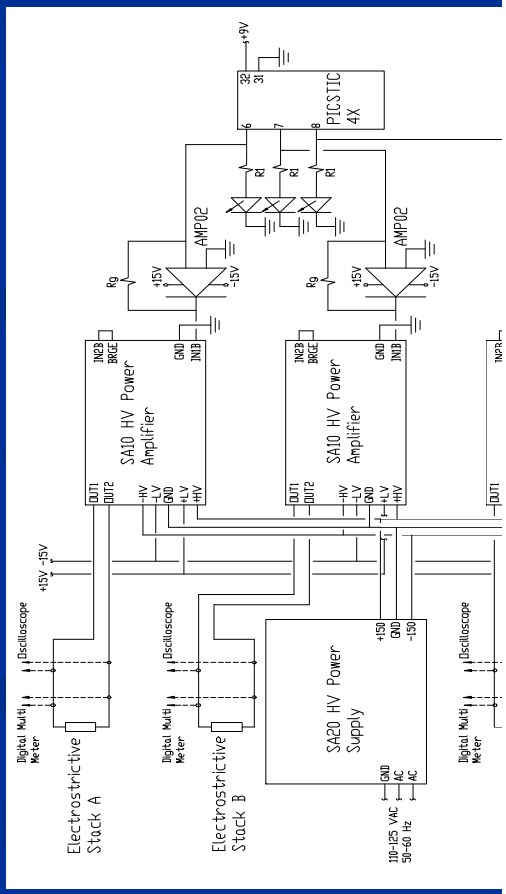
Activation sequence to create motion.

Jeff Schoenfeld









Results

mpare "apples to apples" an
sys model of the prototype
s developed

e results differ by less than 9%

equency limitation
Still in research phase

Inchworm Actuator Results	Ansys Design Model	Ansys Prototype Model
Brake Stack Free Disp. (um) 	30.0	27.1
Brake Pad Disp. (um) 	107.4	78.2
Extending Stack Free Disp. (um) 	39.9	16.7
Brake Pad Blocked Force (N):		
25.4 Clearance	64.2	18.6
50.8 Clearance	41.6	7.5
Actuator Output Force (N):		
25.4 Clearance	83.5	24.2
50.8 Clearance	54.0	10.0
Max. Operating Freq. (Hz)	---	2.22
Actuator Speed (mm/min)	---	1.0

Applications

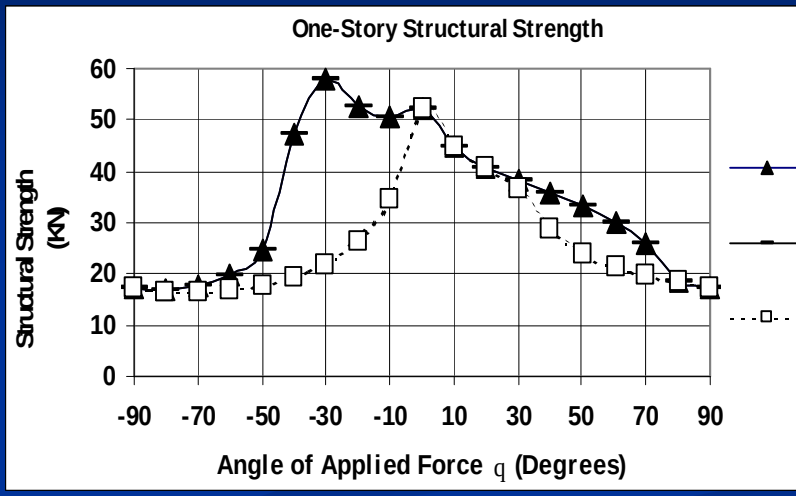
-story adaptive truss

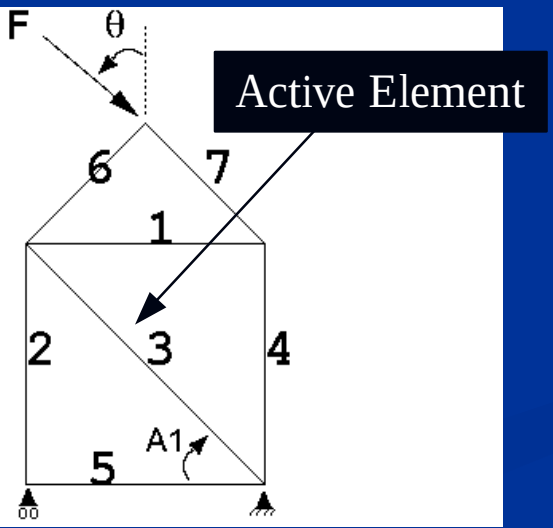
Concept

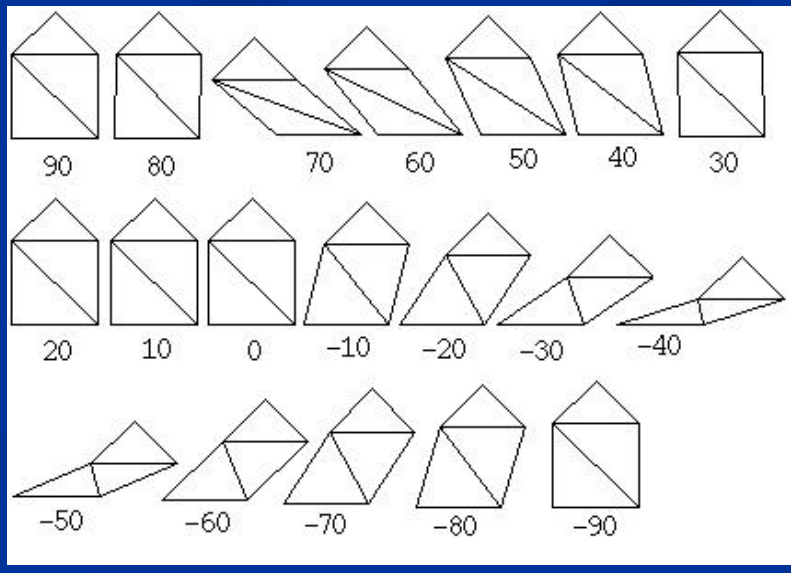
- Satellite docking

lts confirmed by:

- Paper by Shao (1990)
- Ansys
- MatLab

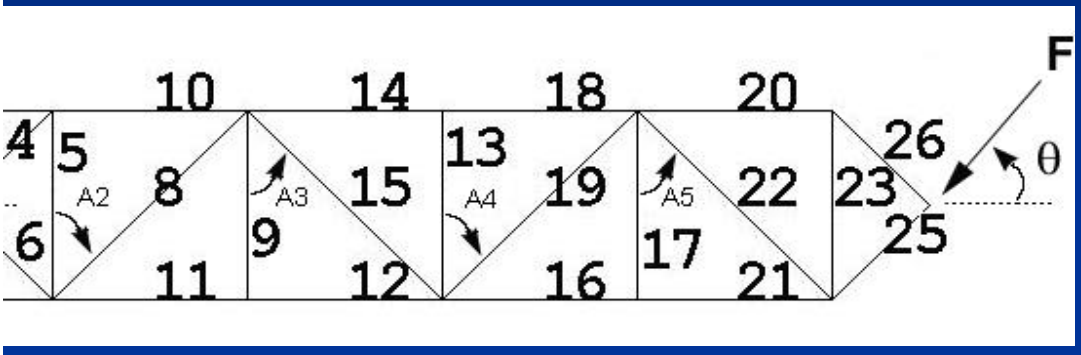


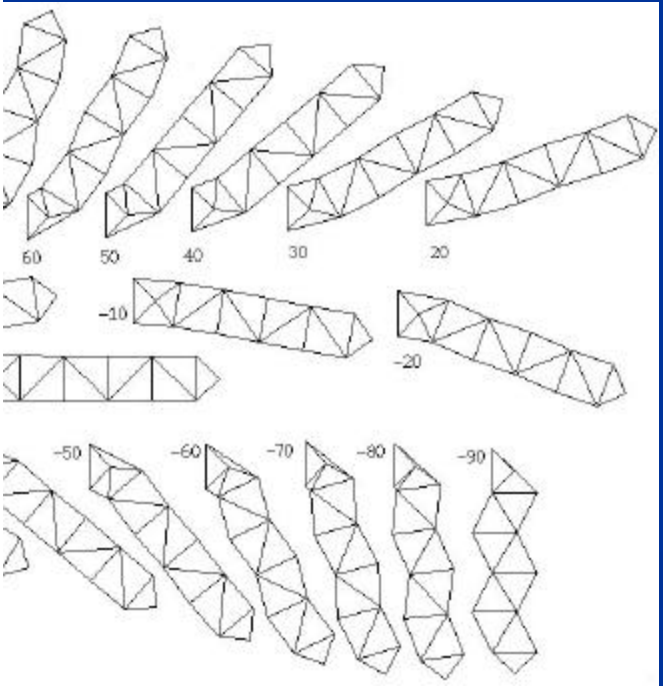


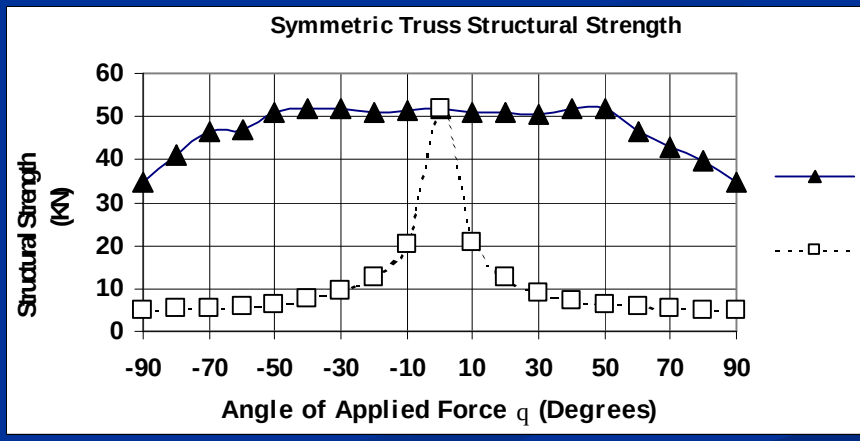


ymmetric truss structure

ults







Conclusions

- Ansys model was developed
- Dimensions were optimized
- The design was prototyped
  - 9% difference against computer simulations
- Numerical results show adaptive structures hav
  increased structural strength
- Further work
  - Increasing the frequency of the stacks
  - Dynamic analysis of adaptive structures