Power Line Systems

IT'S ALL ABOUT YOUR POWER LINES

2019 PLS-CADD Advanced Training and User Group

Understanding Load Capacity of Post and Braced Post Insulators

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POWER LINE SYSTEMS

IT'S THE SOLUTION

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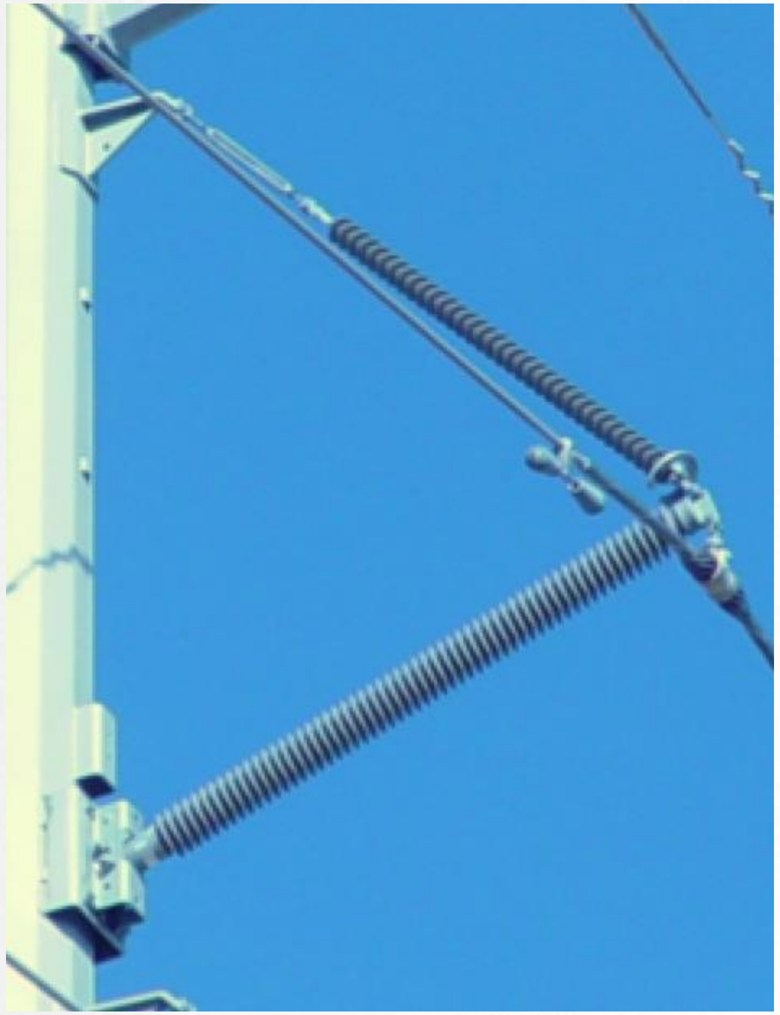
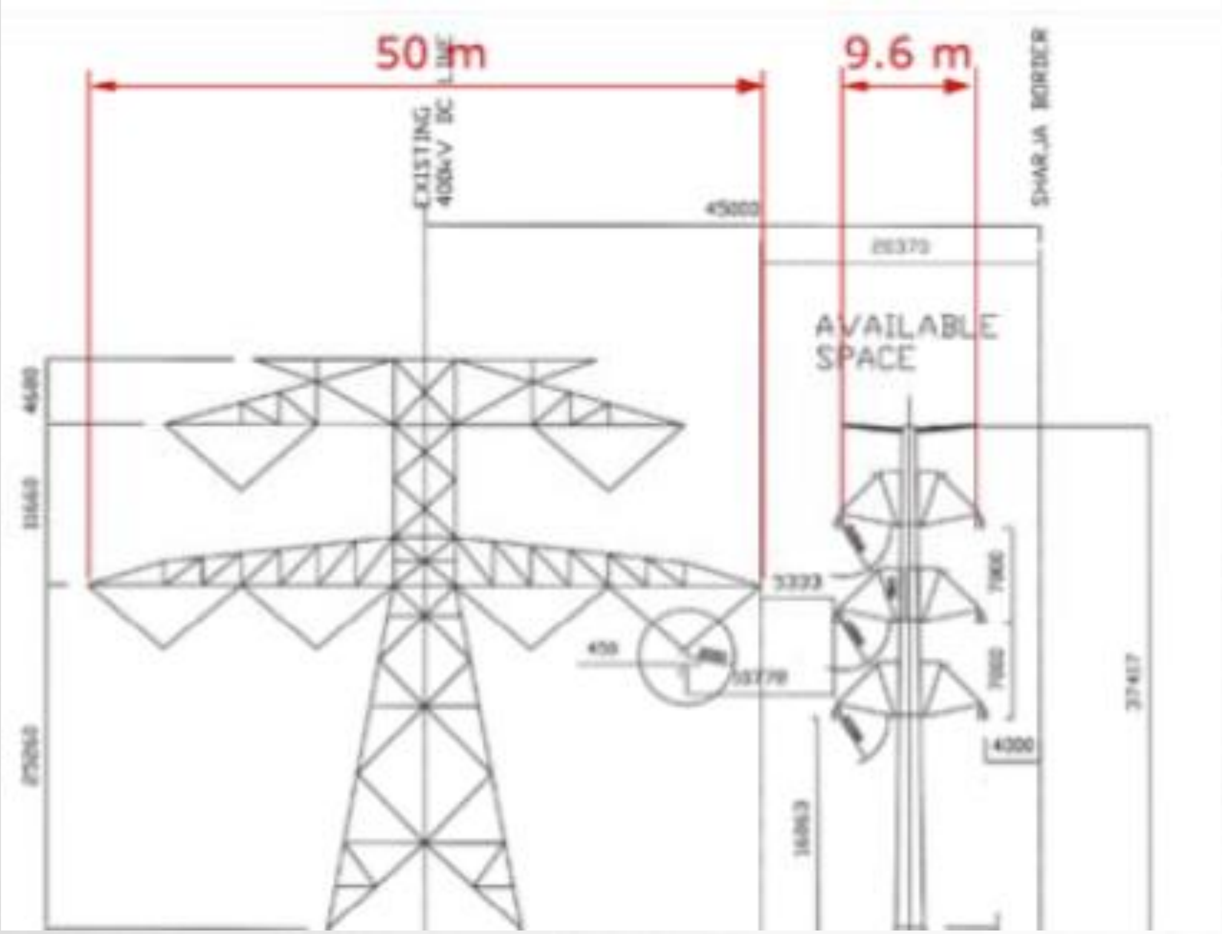
7. 220kV Braced Post Insulator Tests
8. FEM Modelling
9. Key Findings to date



Applications of Transmission Line Post Insulators

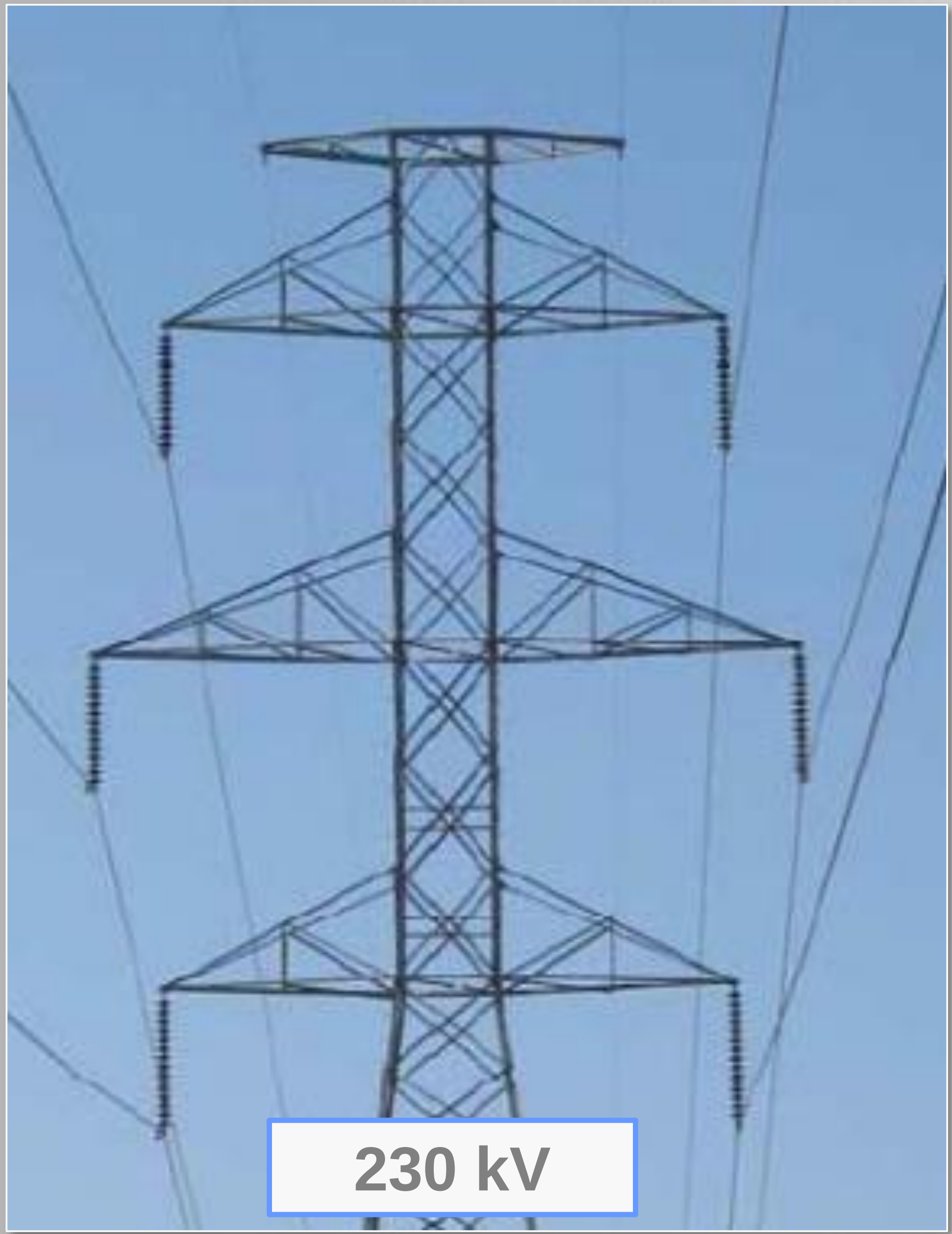
Applications of Transmission Line Post Insulators
420 kV – Horizontal (pivoting) Vee

- Numerous Case Studies have demonstrated that compact lines can be more cost effective than traditional, large format structures
- Transmission line post insulators often a key component of compact line designs



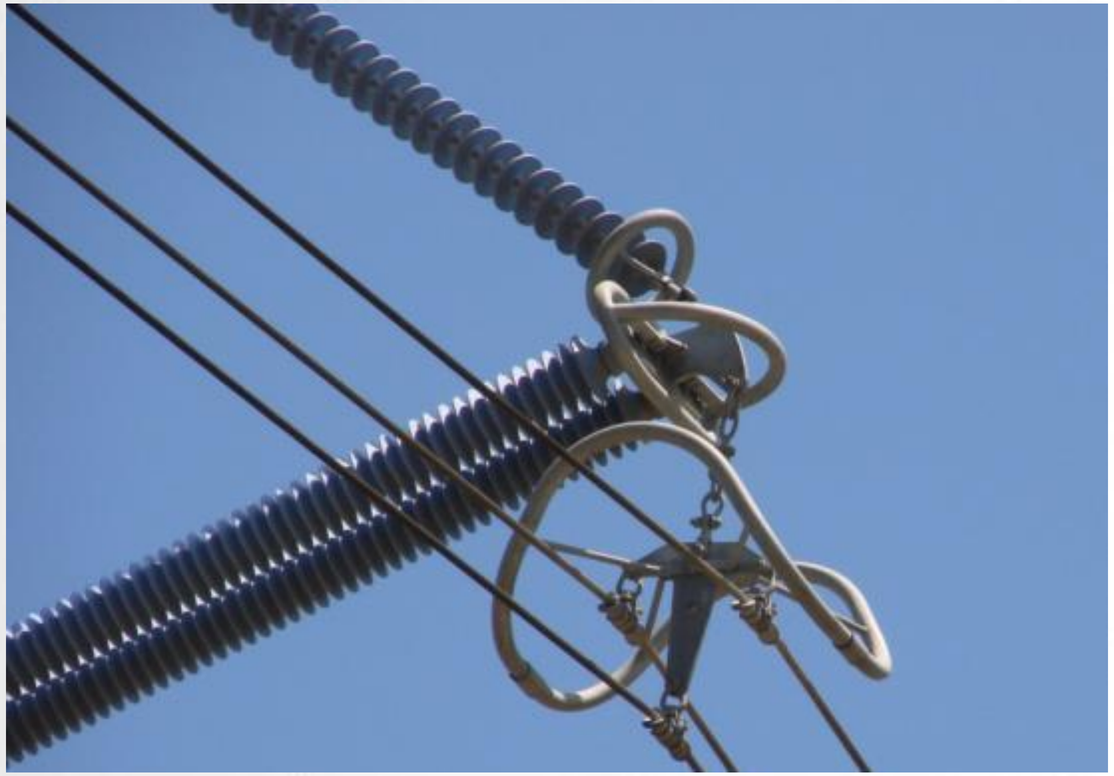
Traditional vs Compact Double circuit 420 kV lines in Dubai.

Applications of Transmission Line Post Insulators Line Upgrade using Horizontal (pivoting) Vee



Double circuit 230 kV line upgraded to double circuit 345 kV line - PacifiCorp Utility USA

Applications of Transmission Line Post Insulators
400 kV – Hybrid Braced Post



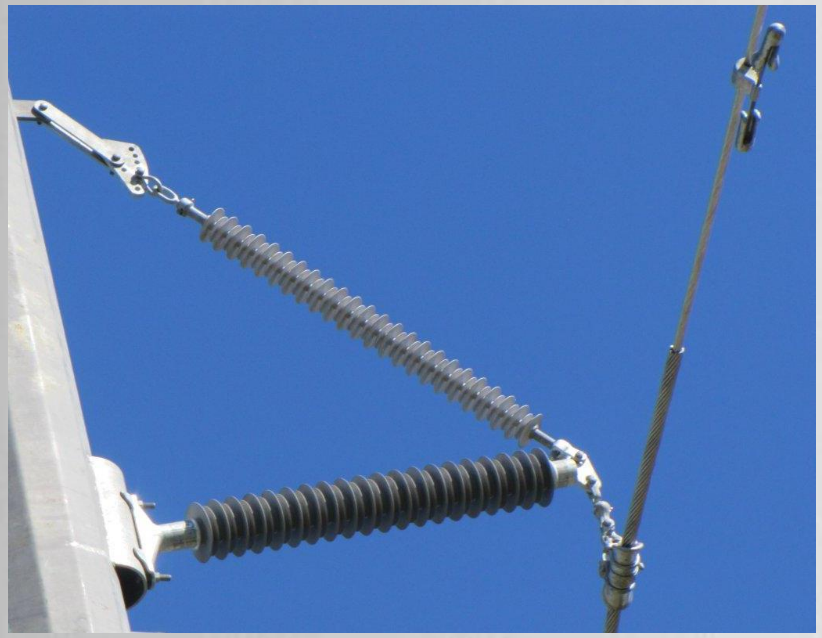
Applications of Transmission Line Post Insulators

Not your Grandpa's Post Insulators

1100kV AC single line circuit – China 2018

Typical Applications of post insulators

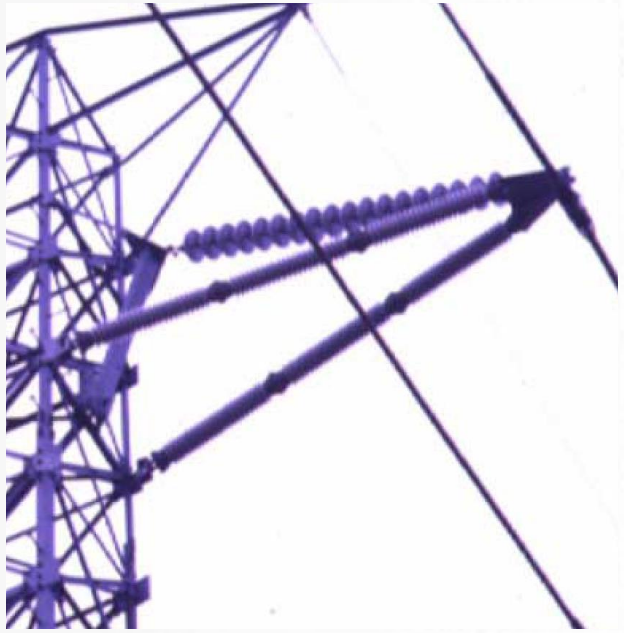
EPRI RESEARCH FOCUS



Post insulator

Braced Post insulator

Horizontal (pivoting) Vee



Insulated cross -arm

11-138 kV

Stability control

66-220 kV

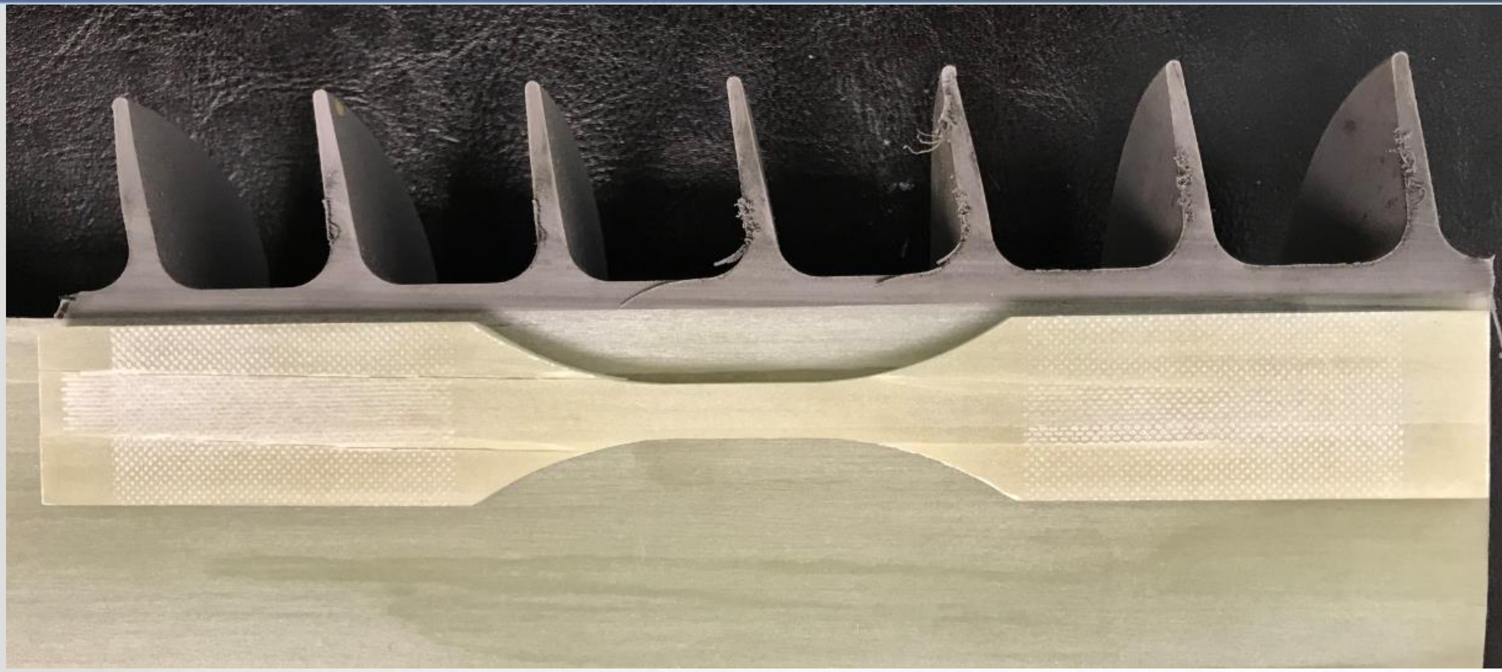
220-500 kV

300-1000 kV+

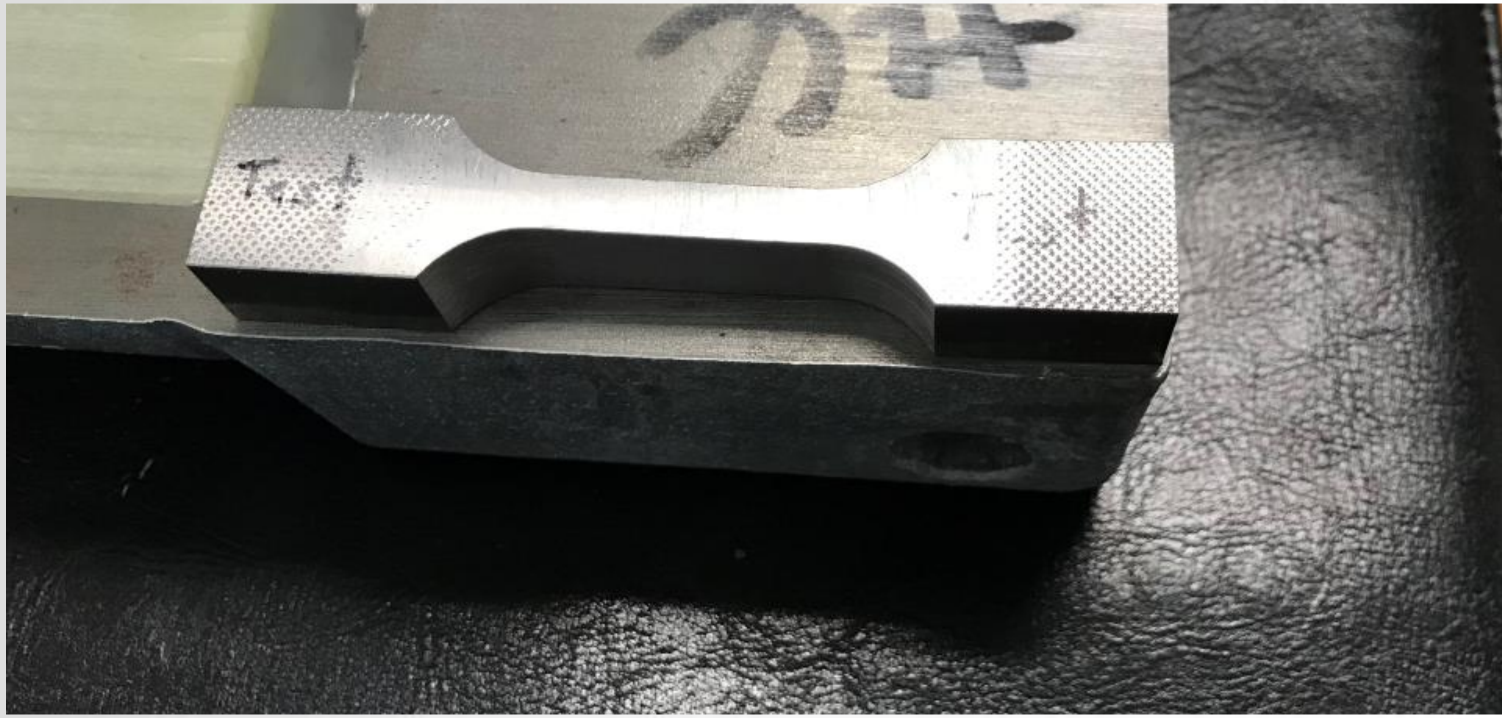
Small Scale Material Tests

Small scale coupon tests

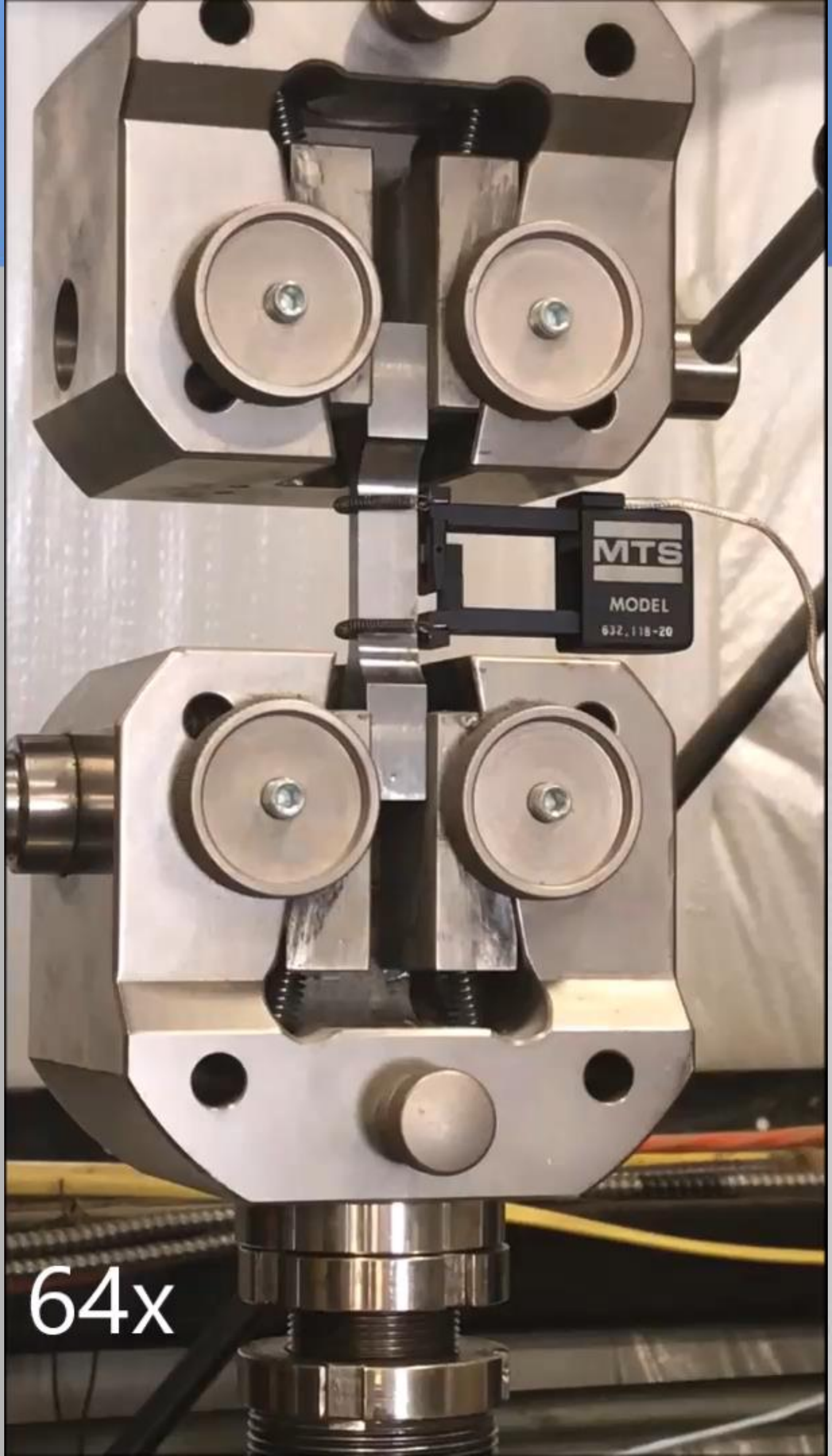
- Samples cut from post core (parallel to axis)

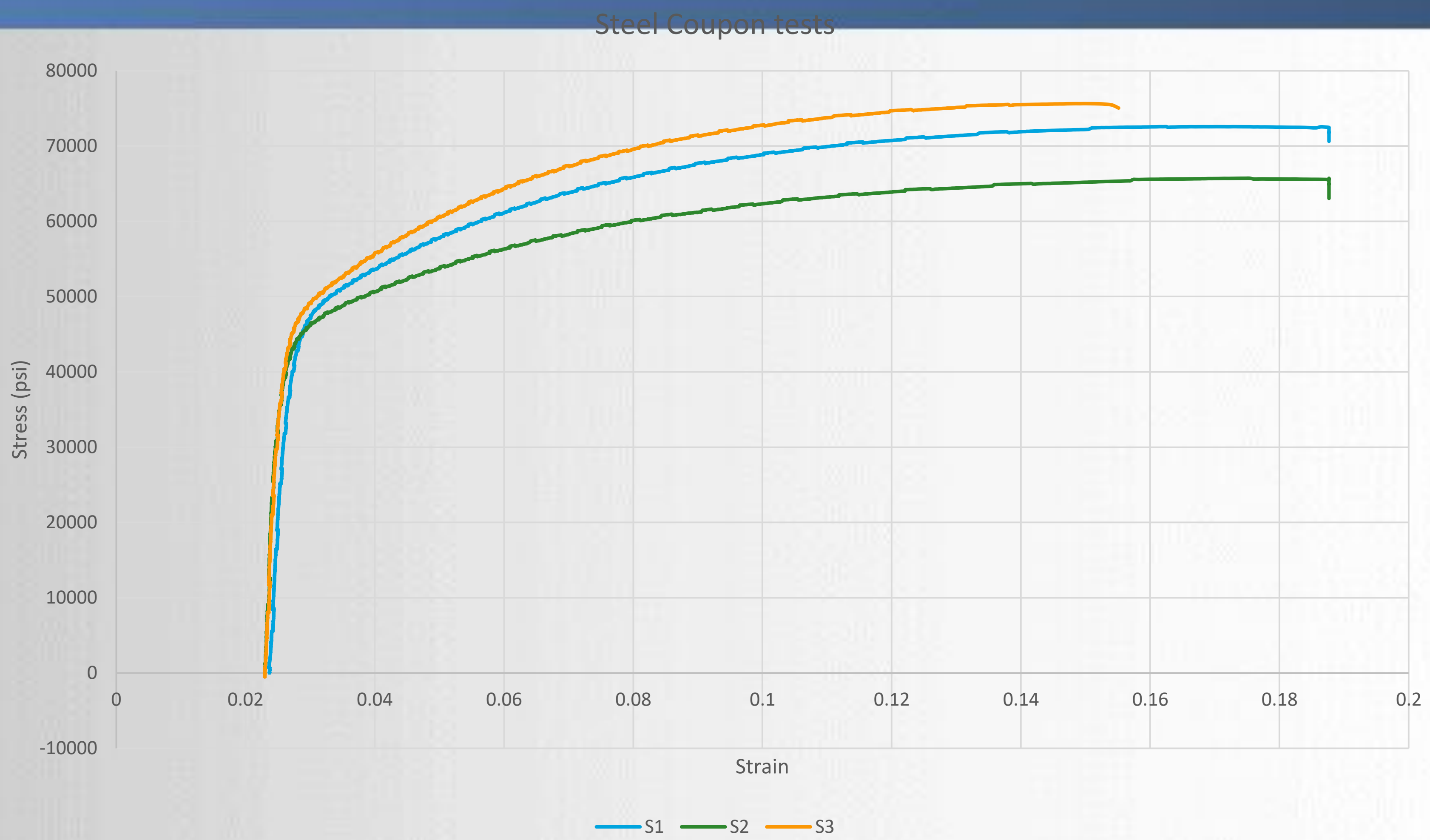


- Steel samples machined from base



Steel coupon from cast end fittings





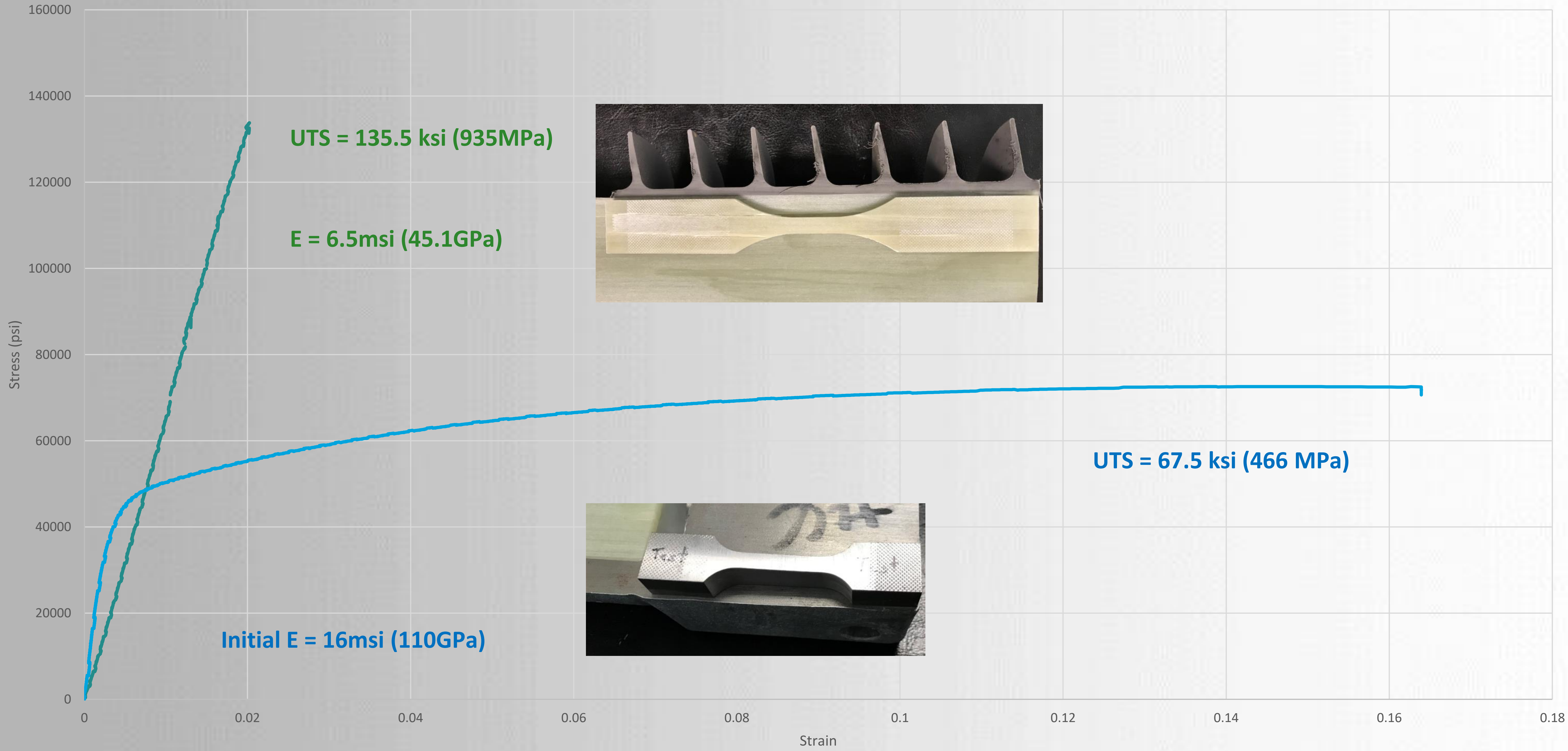
Average of 3 samples				
Ult. Stress	72.3	ksi	498	MPa
Yield stress	46.1	ksi	318	MPa
	64%	of ultimate		
Young's Modulus	16	msi	110	GPa

Note low E

Composite coupon test

- E important to determine buckling capacity $\frac{\pi^2 EI}{4L^2}$
  - 45 GPa measured based on coupon tests
  - Values much larger than those found in literature (37GPa)
- Ultimate tensile capacity significantly higher than published results
  - 930MPa measured vs. 800MPa published
- See ASTM D3039-17 for procedure

Small Scale Test results
Composite Core vs. Cast End Fittings

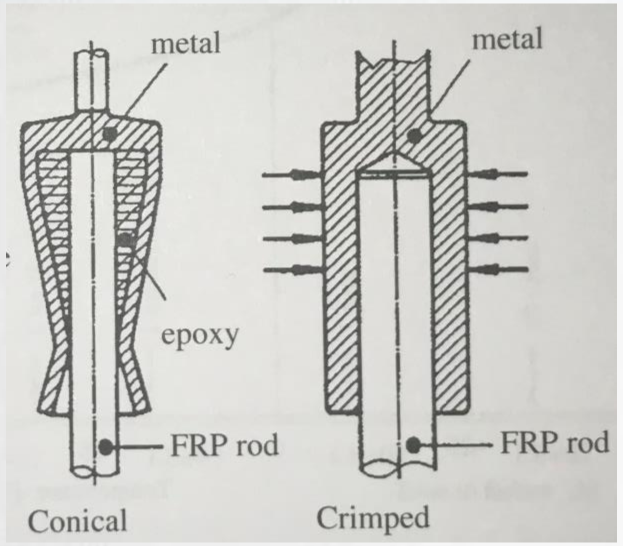


Appropriate Strength Factors

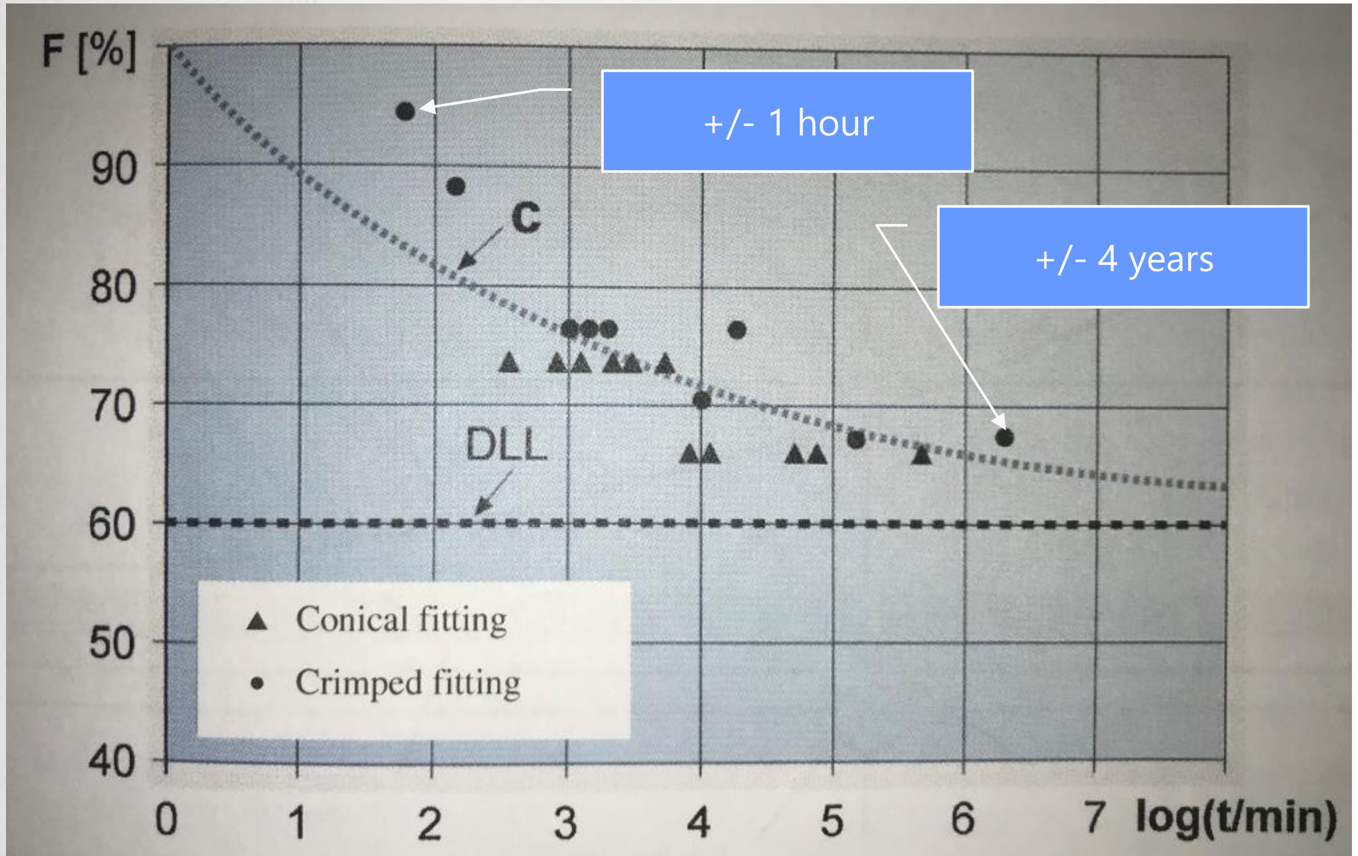
Failure Mode of Pultruded Composite Posts

Early Tensile Tests on long rod composites

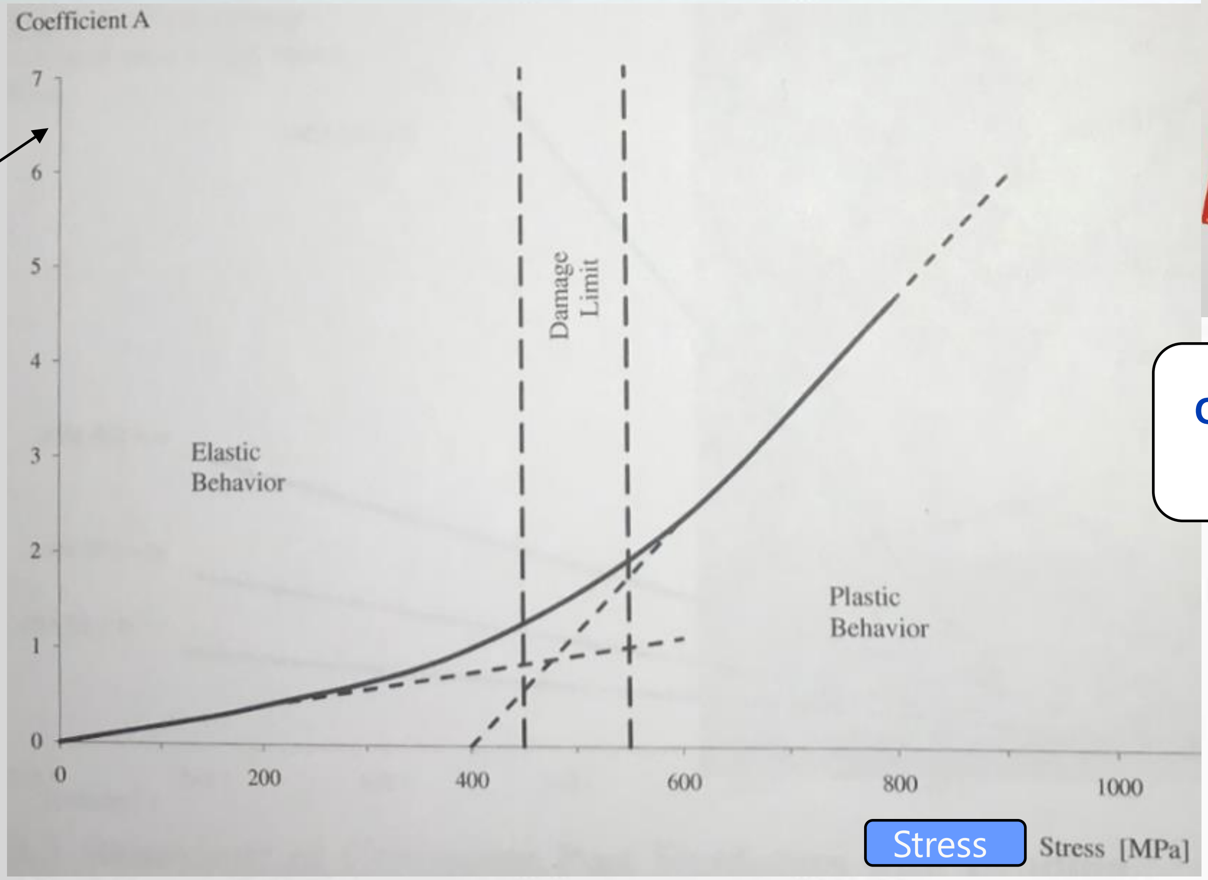
- Failure in pultruded composites largely creep dependent (failure after time under sustained tensile load)
- Failures of long term sustained load can occur at 0.65 ultimate strength
- Crimped fittings performed better that conical fittings



Source: Silicon Composite Insulators – Papailiou & Schmuck



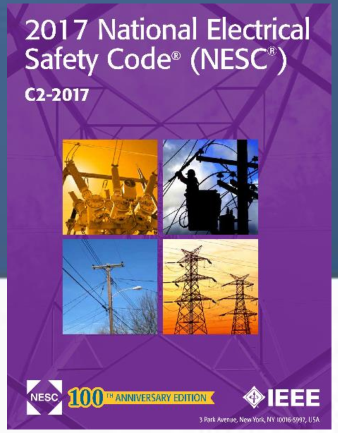
Failure Mode of Pultruded Composite Posts
Cantilever Tests on Composite Posts



Source: Silicon Composite Insulators – Papailiou & Schmuck

- Tip deflection of cantilever posts increase linearly with the log of time
- The deflection rate increases with increased stress levels
- A knee point in the deflection rates was used to establish damage limit
- For long post insulators, damage limits vary from 0.6-0.75 ultimate strength

NESC Strength Factors



- Strength factor for post insulators is 0.5 of ultimate capacity (SCL /SML) per Table 277.1
  - For tension and cantilever loads
  - No value for compression (0.5 assumed)
- Different strength factors may be used based on qualified engineering studies per Cl. 277

277. Mechanical strength of insulators

Insulators shall withstand all applicable loads specified in Rules 250, 251, and 252 without exceeding the percentages of their strength rating for the respective insulator type shown in Table 277-1.

EXCEPTION: Strength rating percentages other than those in Table 277-1 may be used if supported by a qualified engineering study, operating experience for local conditions, or recommendations of manufacturers.

Table 277-1—Allowed percentages of strength ratings *(continued)*

Insulator type	Permitted stress (5) (allowed percentage of strength ratings)		Strength or load rating (1)	Reference standard
	Loading from Rule 250B	Loadings from Rules 250C and 250D		
Nonceramic				
Suspension type (2) Transmission class	50%	65%	Specified mechanical load (SML)	ANSI C29.12-2012
Suspension type (2) Distribution class	50%	65%	Specified mechanical load (SML)	ANSI C29.13-2013
Line post Transmission class	50%	50%	Specified cantilever load (SCL)	ANSI C29.17-2002
	50%	50%	Specified tensile load (STL)	
Line post Distribution class	50%	50%	Specified cantilever load (SCL)	ANSI C29.18-2013
	50%	50%	Specified tensile load (STL)	

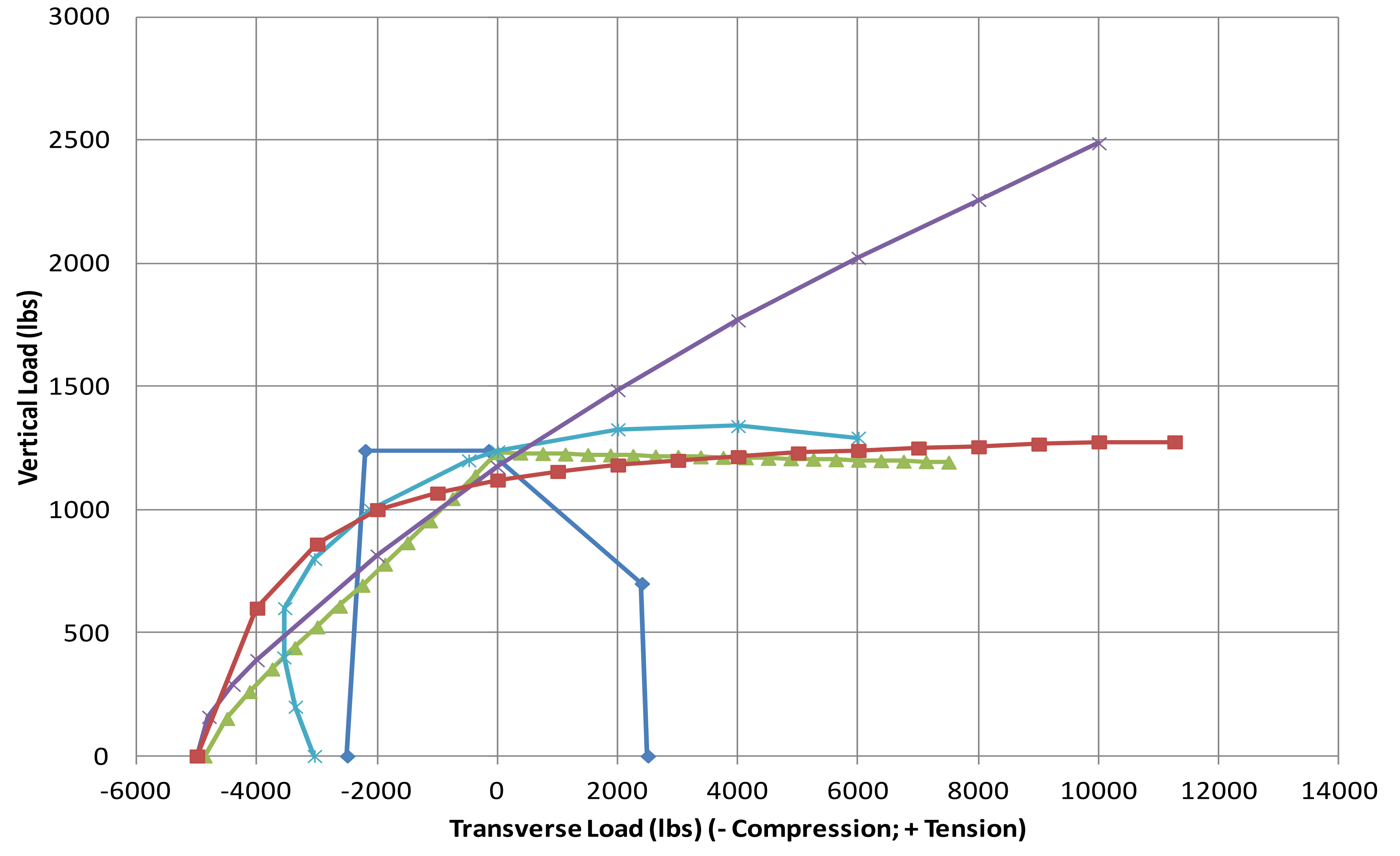
Some Comments on Strength Factors

- Experimental results support failure at 0.6 – 0.65 of ultimate loads over time under <u>sustained</u> tensile load
- Strength factors of 0.5 to permanent (continuous) service loads are valid
- Strength factor of 0.5 to ultimate transient loads possibly conservative
- Most ultimate loads (wind, ice, broken wires) are <u>transient</u>
- Strength factor of 0.5 may be influenced by
  - history of brittle fracture in earlier generation **<u>long rod composites</u>**
  - nature of failure mode (once a fiber breaks, strength is permanently reduced and remaining fibers carry increased stress)
- Field experience on post insulators indicate low incidence of in service failures under ultimate design loads

Post Insulator Capacity

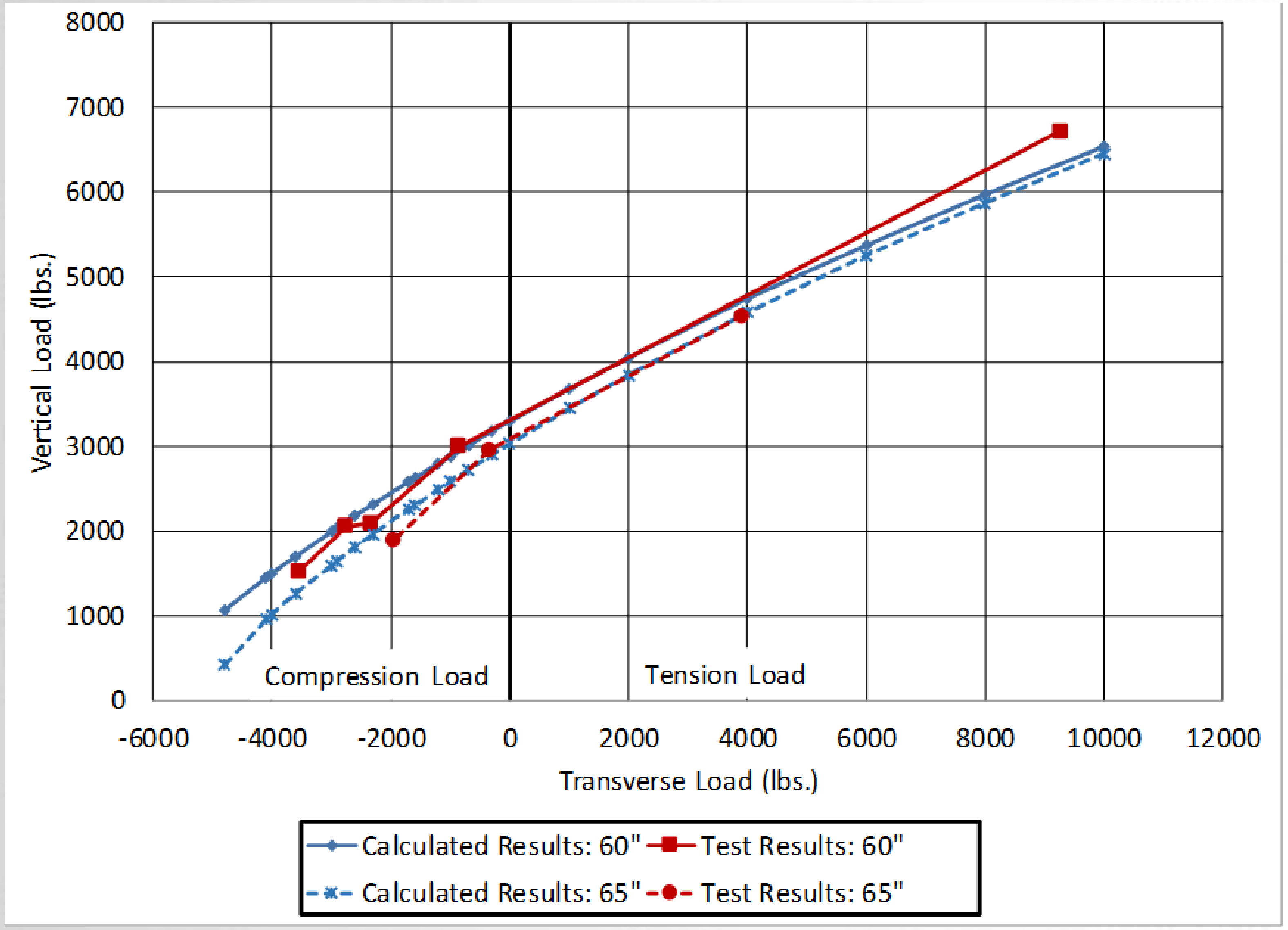
Disparities between load curves from different suppliers

- Significant disparities between load curves from different manufacturers evident from different product specifications
  - Despite similar generic composite material specification and base designs
- Can a generic calculator be developed?

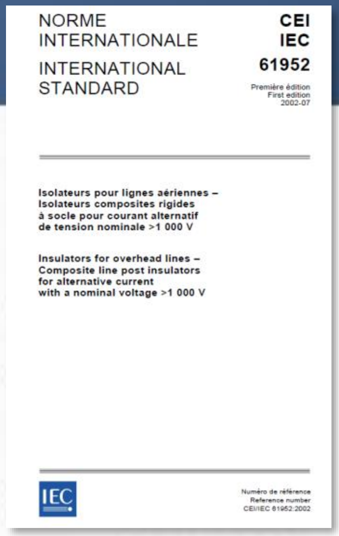


Combined Loading tests for Post Insulator

- EPRI Loading tests confirmed validity of IEC 61952 method



IEC 61952 – Determination of Post insulator capacity



- Combination of Vertical, Longitudinal and Compression / Tension loads converted to equivalent moment

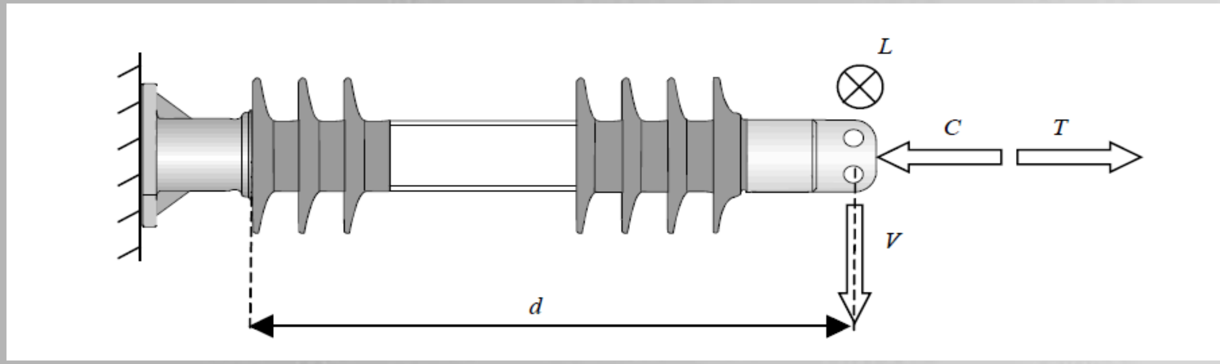
$$M_C = [(V^2+L^2)EI / C]^{1/2} \tan [d (C / EI)^{1/2}]$$

$$M_T = [(V^2+L^2)EI / T]^{1/2} \tanh [d (T / EI)^{1/2}]$$

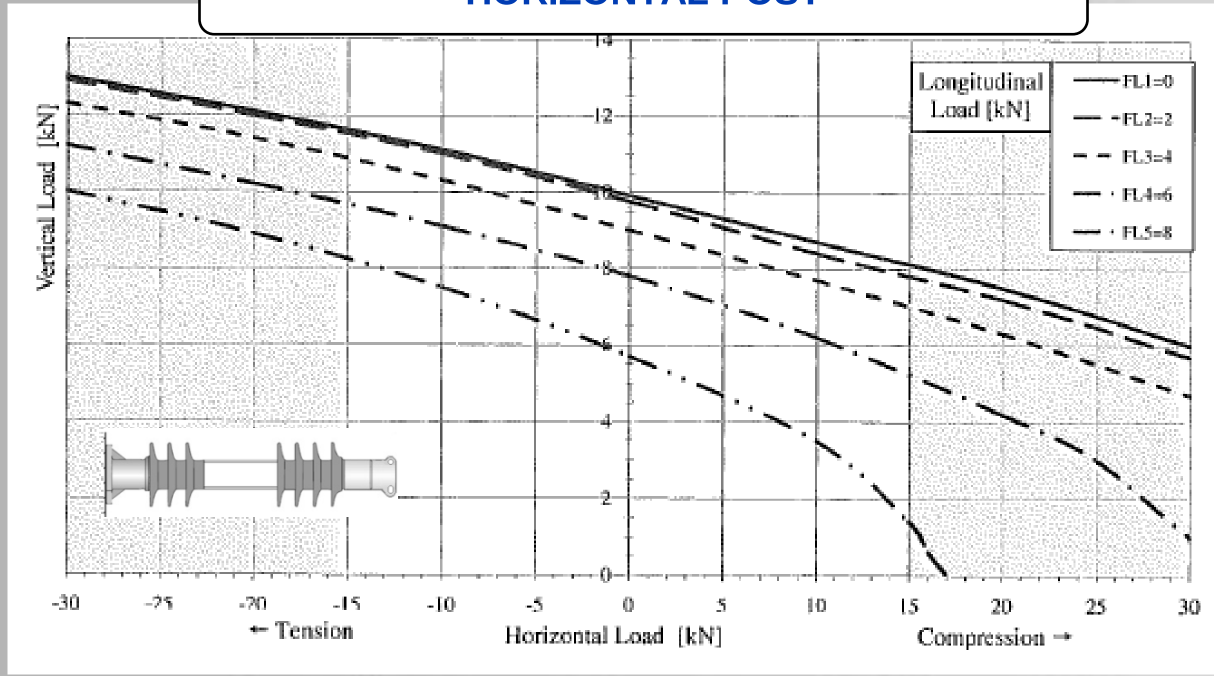
$$MDCL.d = M_c = M_T$$

$$= 0.5 \text{ SCL} = 0.5 \frac{\sigma_{max} \pi D^3}{32}$$

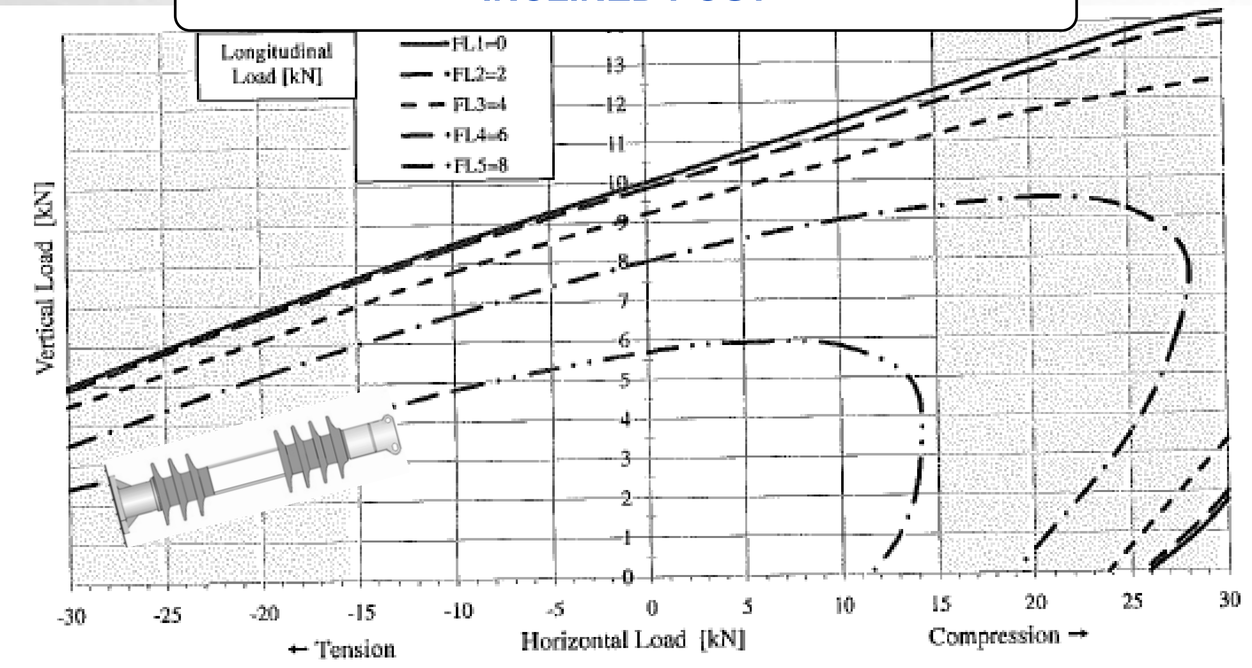
←NESC



HORIZONTAL POST



INCLINED POST



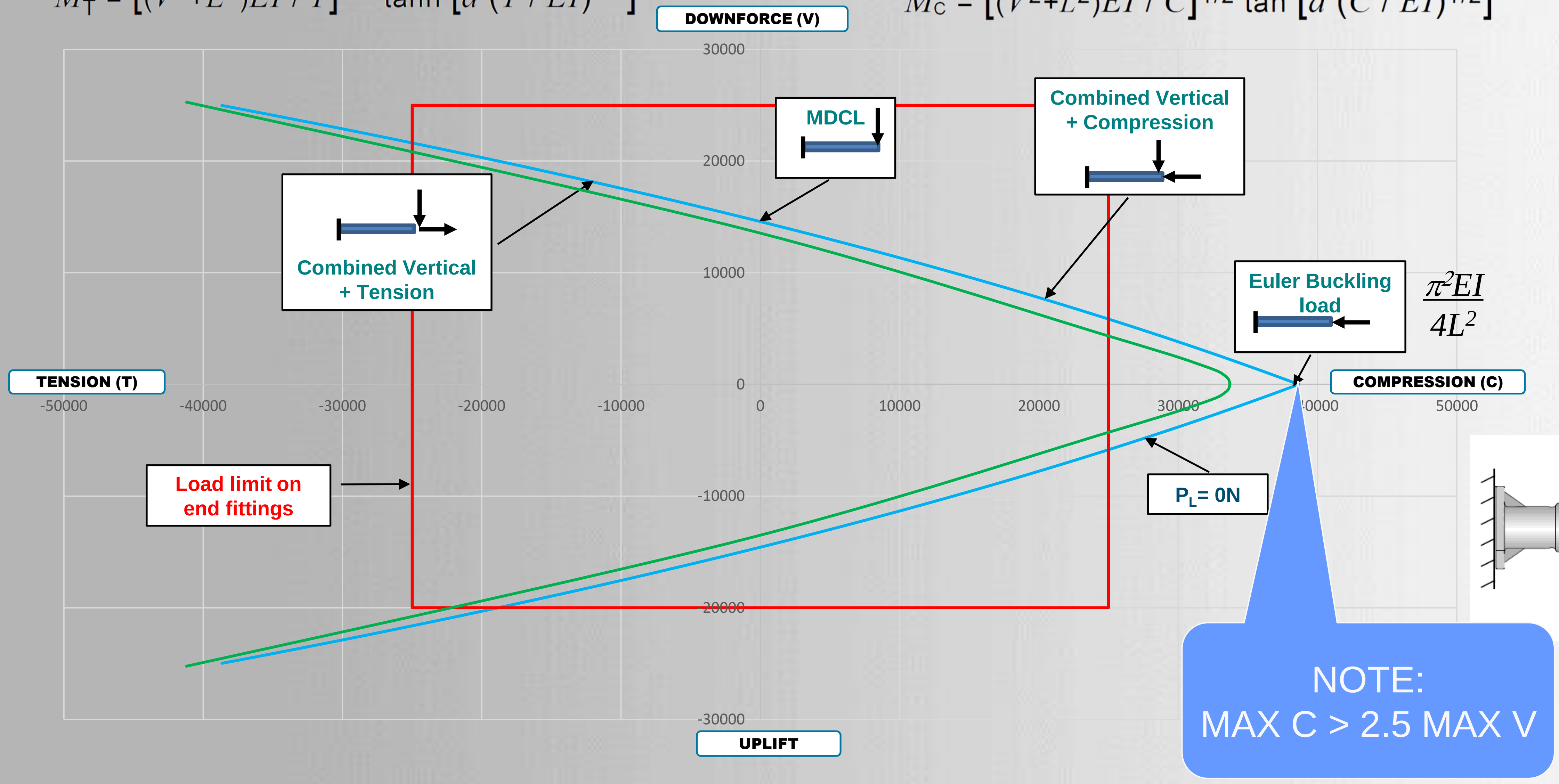
Anatomy of Post Insulator Capacity Curve – 2.5" Horizontal Post (Typical for 138kV)

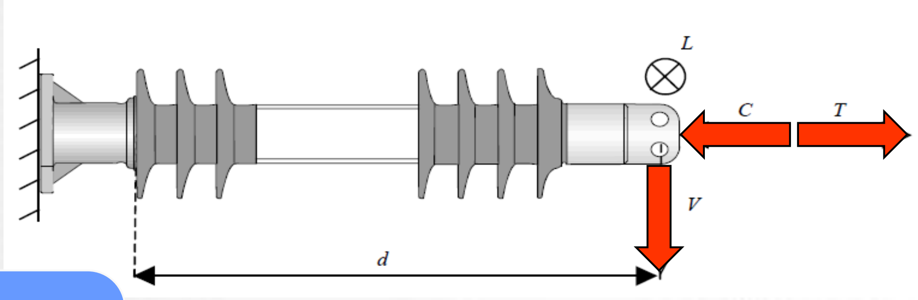
Combined Vertical + Tension Case:

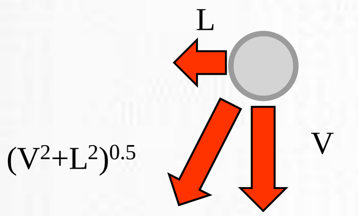
$$M_T = \left[(V^2+L^2)EI\ /\ T\right]^{1/2} \tanh \left[d\ (T\ /\ EI)^{1/2}\right]$$

Combined Vertical + Compression Case:

$$M_C = \left[(V^2+L^2)EI\ /\ C\right]^{1/2} \tan \left[d\ (C\ /\ EI)^{1/2}\right]$$

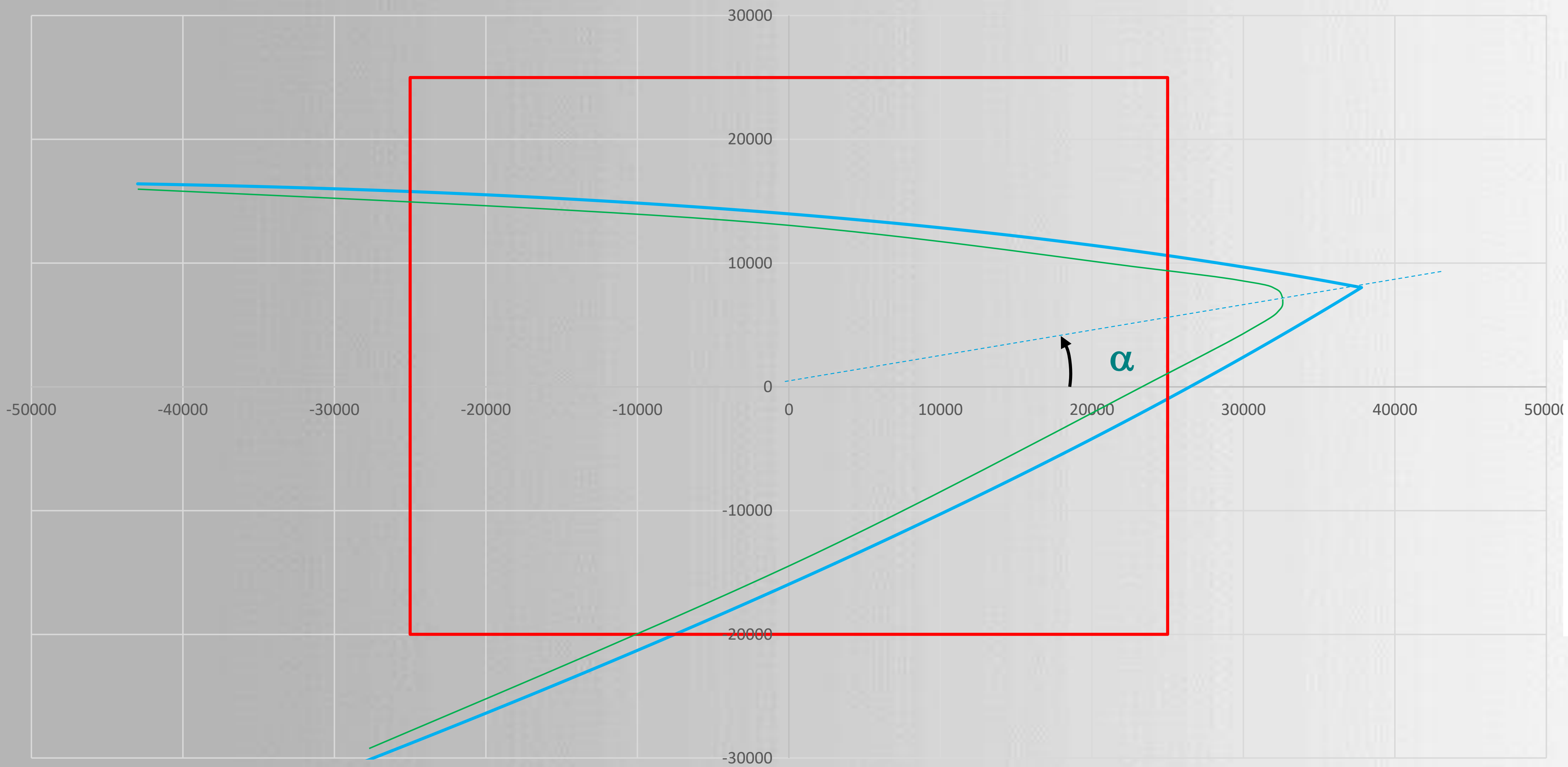


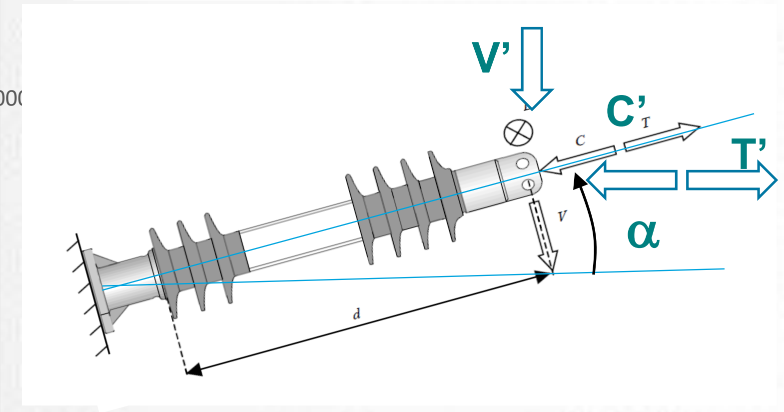




- Longitudinal loads incorporated as an additional vector to the cantilever load

Anatomy of Post Insulator Capacity Curve - Inclined Post





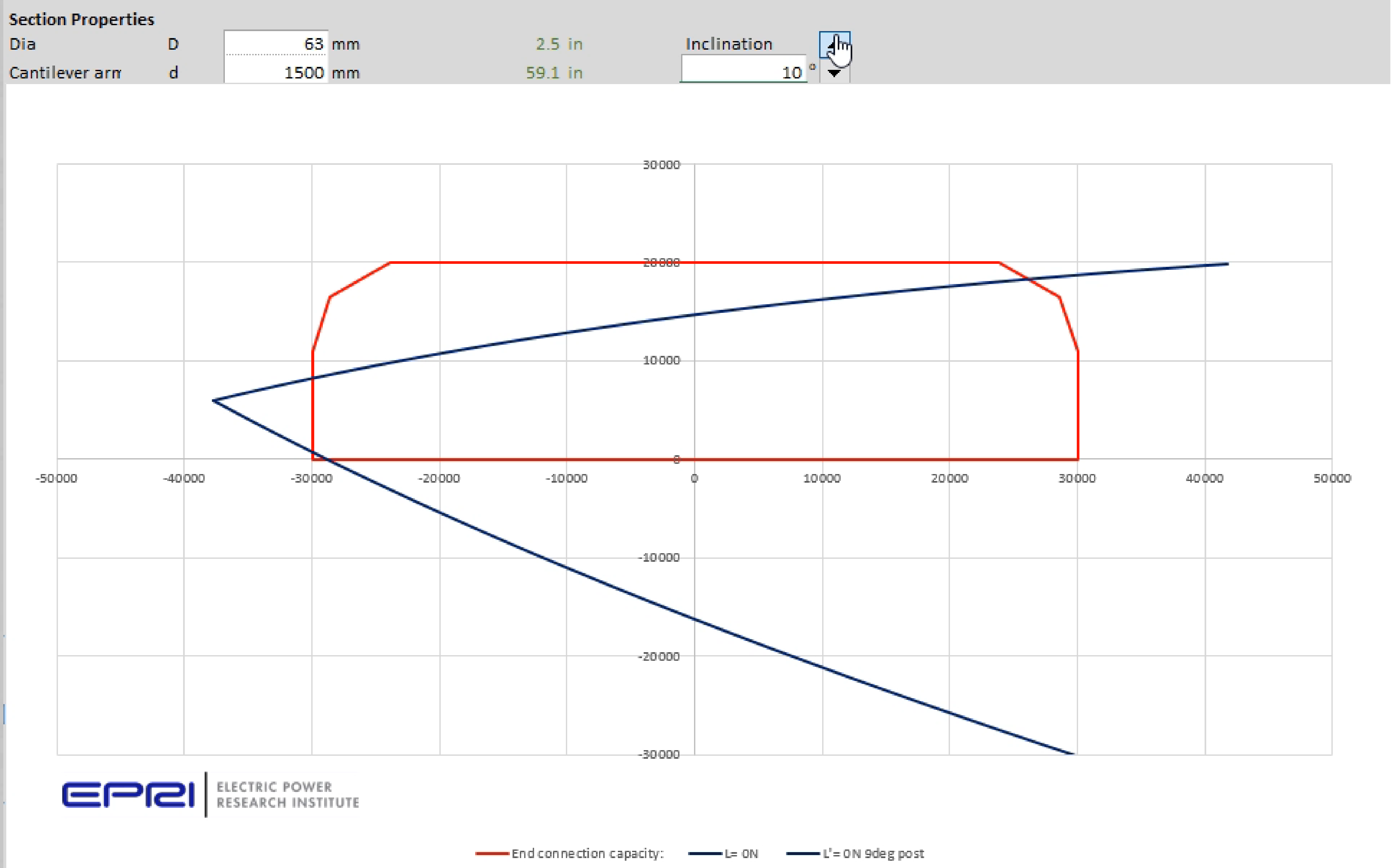
V = V'cosα + C'sinα

C = V'sinα + C'cosα

- Combined curve for inclined posts may be calculated by calculating local axis load vectors
- OR simply rotating the horizontal curve by the inclination angle α

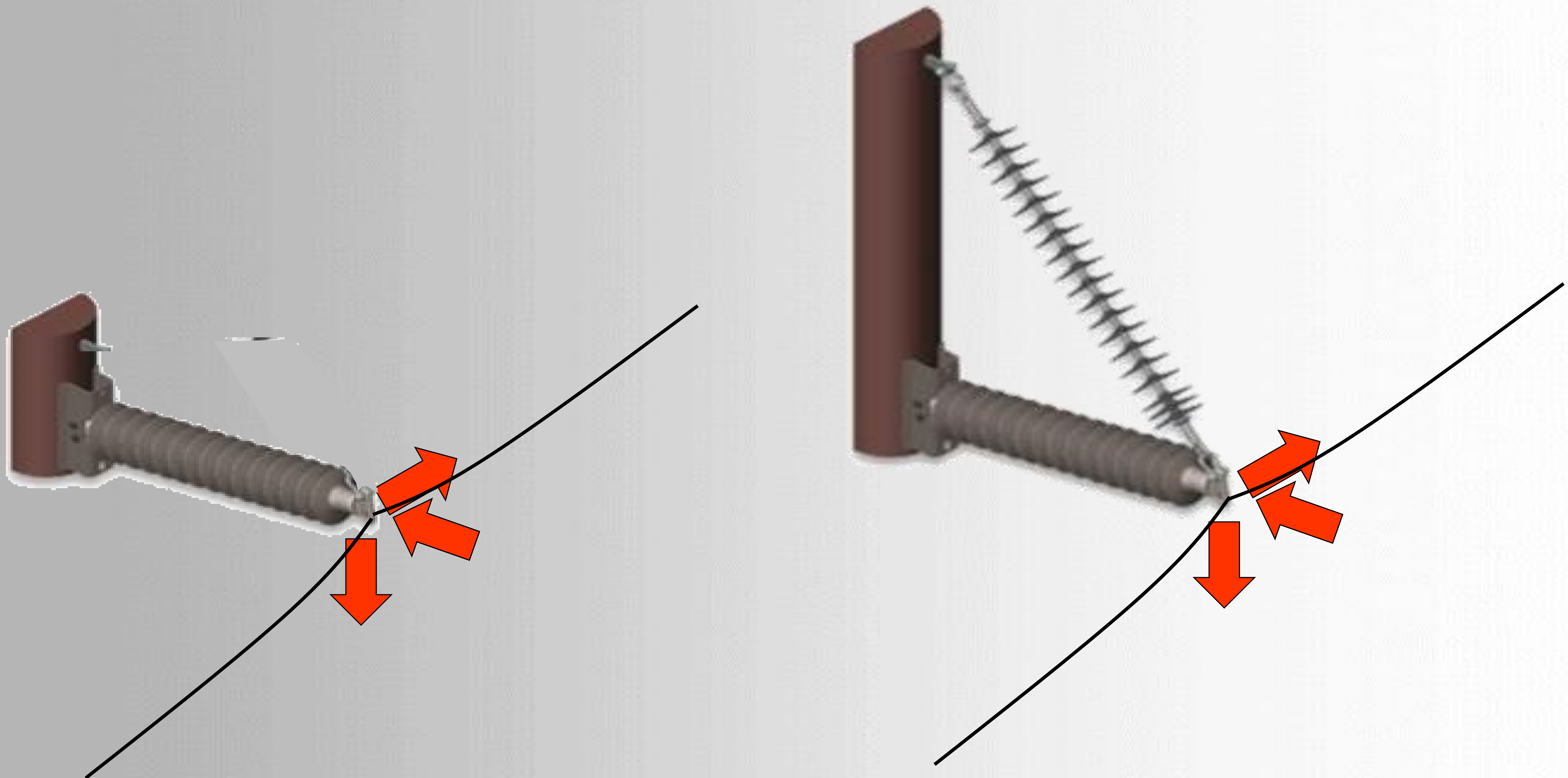
Optimizing Gain Base Angles - Inclined Post

- Post inclination (gain) angle α may be optimized for different length and diameter combinations
- Slender posts tend to benefit from higher gain angle
- Ability to optimize depends on supplier and base type connection
- Note: PLS & Conventional notation – Compression values are negative

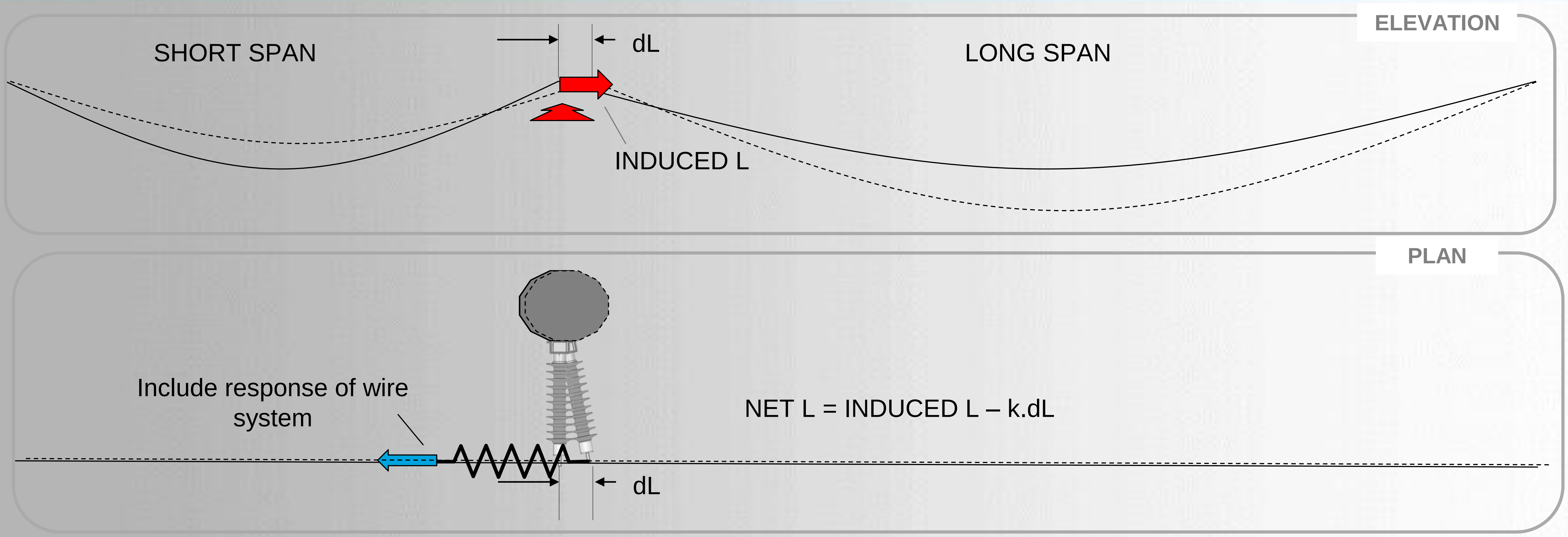


Braced Post Insulator Capacity

Braced vs. unbraced post failure modes



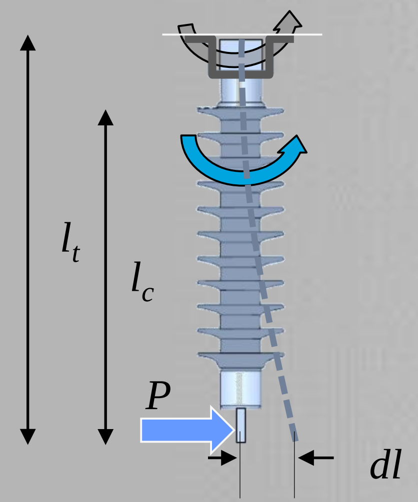
Impact of Insulator Deflection on Longitudinal Loads



- How much longitudinal strength do you need? (Probably less than you think)
- Longitudinal load can be induced from unequal adjacent spans
- Net longitudinal load **reduced substantially as insulator tip deflects** and tension redistributes
- Tip Deflection = pole deflection + rotation of base + flexure of post

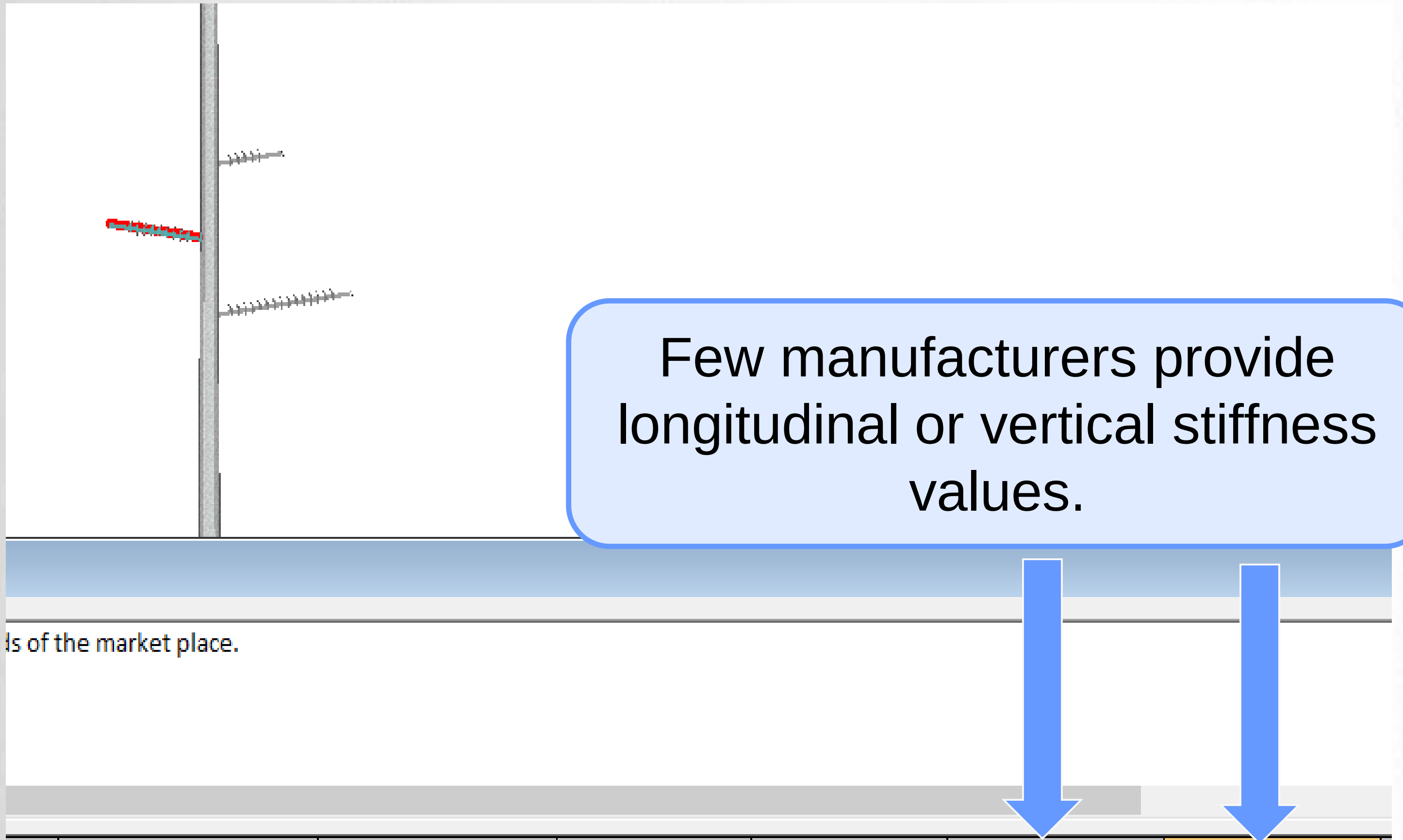
Determination of Longitudinal Stiffness
An Important Parameter both Capacity and Imposed Loads

- Very few manufacturers provide longitudinal or vertical stiffness values
- PLS Pole will default to 833lb/in (very stiff) where no input made
  - Vertical stiffness not critical – may be assumed stiff
  - Longitudinal stiffness measured values for varied from 30lb/in (220kV) to 150lb/in (138kV)
- Longitudinal Stiffness may be calculated from
  - Torsional stiffness (in lb-in/rad) of base
  - Flexural stiffness of composite post



~~$$\frac{P}{dl} = \frac{3EI}{l_c^3} + \frac{k_\theta}{l_t^2}$$~~

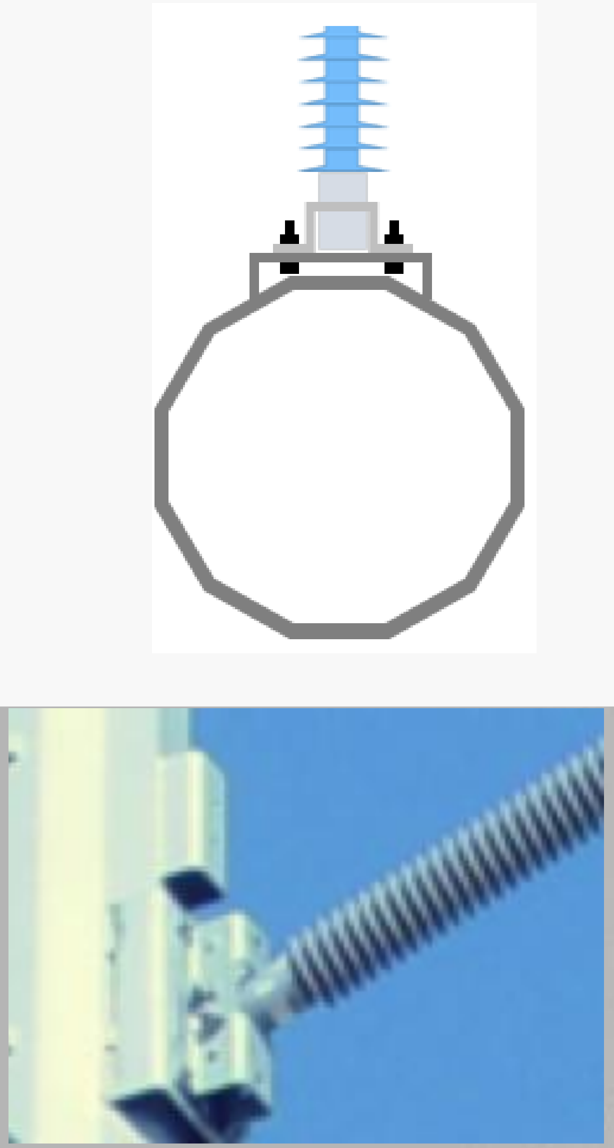
$$\frac{P}{dl} = 1/\left(\frac{l_c^3}{3EI} + \frac{l_t^2}{k_\theta}\right)$$



nt	Interaction Capacity	Cantilever Capacity (N)	Tension Capacity (N)	Comp. Capacity (N)	Long. Stiffness (N/m)	Vert. Stiffness (N/m)
.956	Edit (110 points)	0	0	0	0	0
.852	Edit (108 points)	0	0	0	0	0
.194	Edit (114 points)	0	0	0	0	0
7.09	Edit (114 points)	0	0	0	0	0
.538	Edit (114 points)	0	0	0	0	0

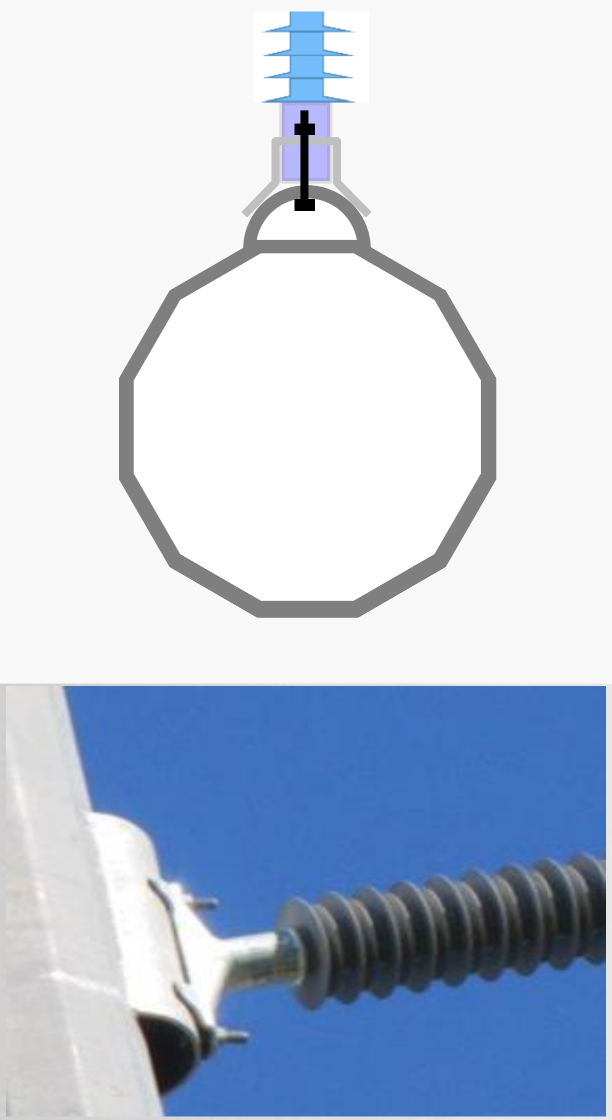
Few manufacturers provide longitudinal or vertical stiffness values.

Torsional Stiffness of Base Connection Variants

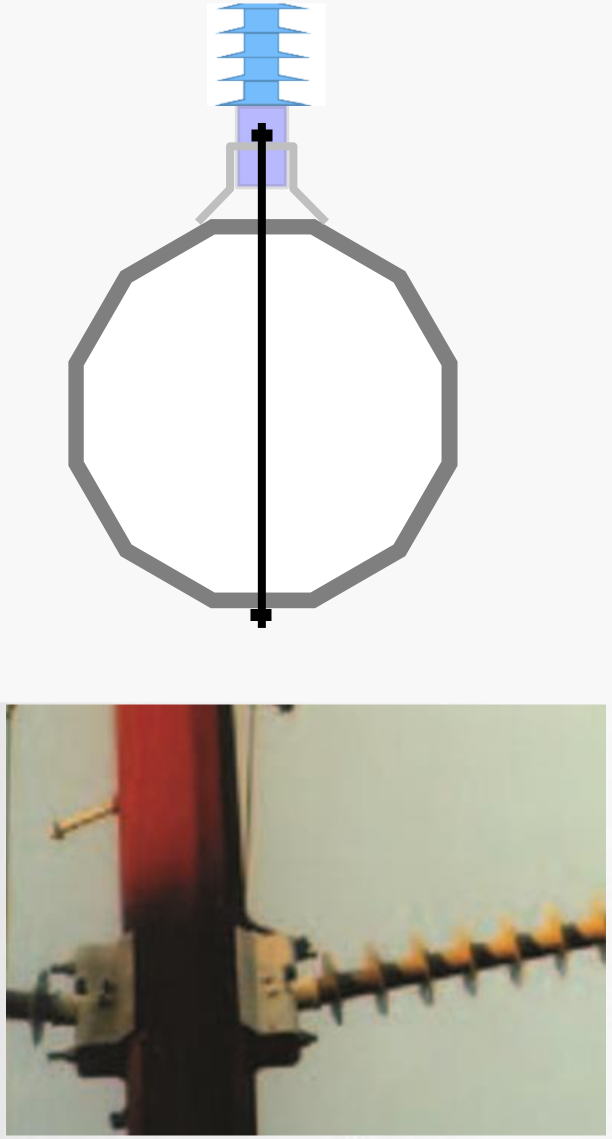


FALT BASE (4 BOLT CONNECTION)
1.2-3.5 105 Nm/rad

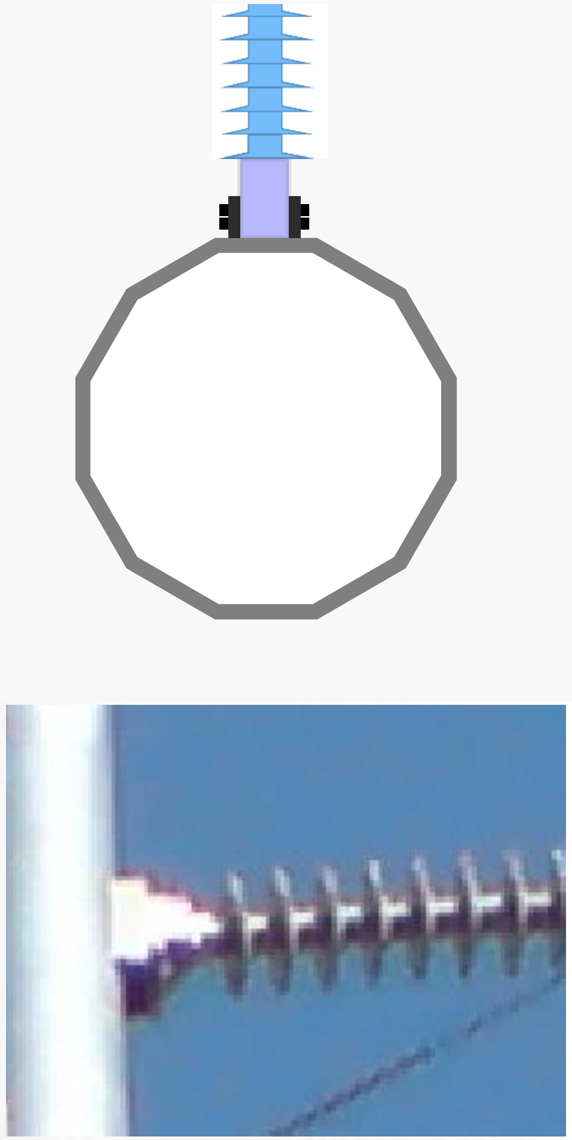
FLAT BASE (2 BOLT CONNECTION)
1.1-2.5 10^5 Nm/rad



BENDABLE BASE (FACE CONTACT)
1-2 105 Nm/rad



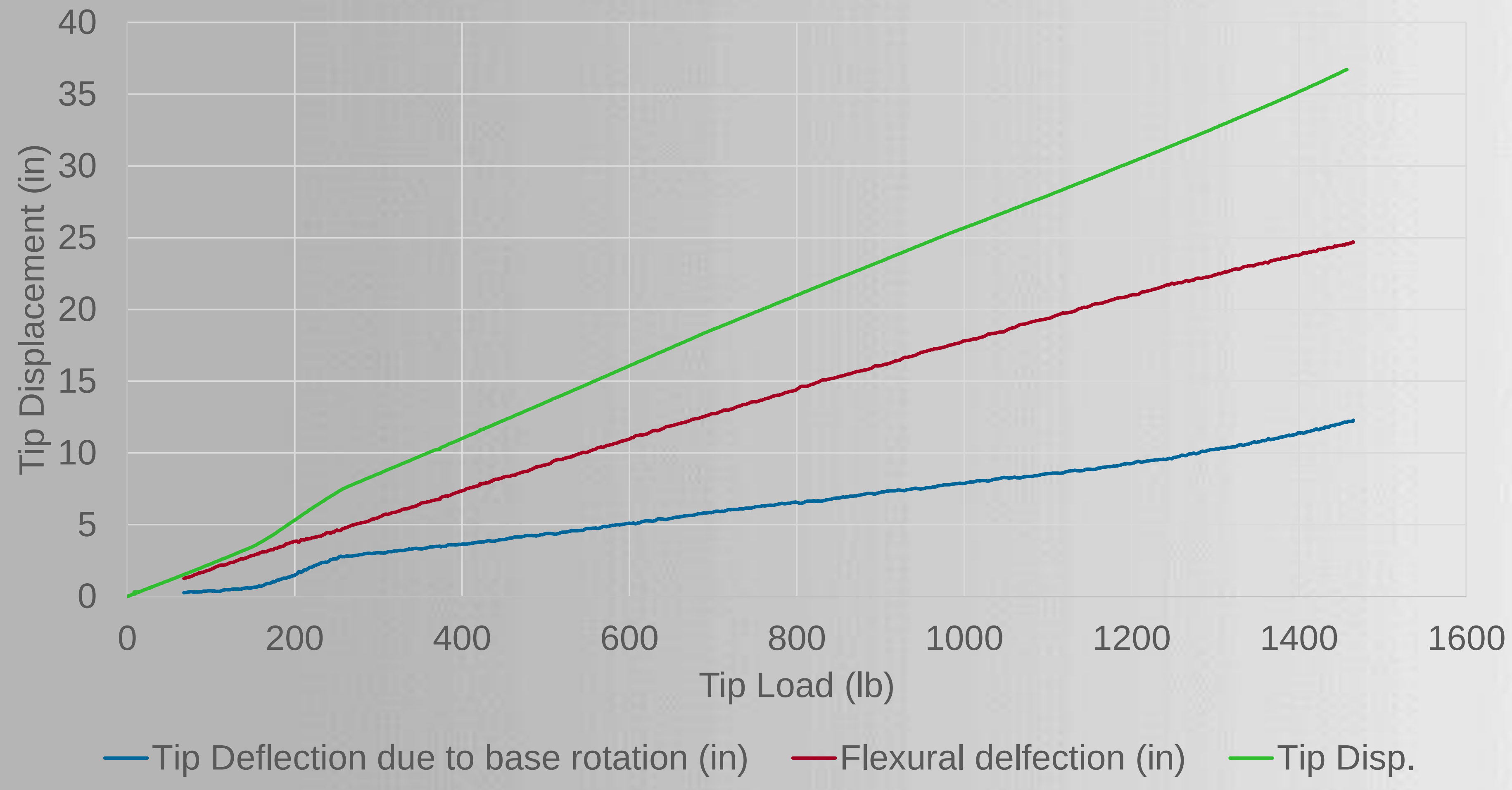
BENDABLE BASE (EDGE CONTACT)
0.7-1.4 105 Nm/rad

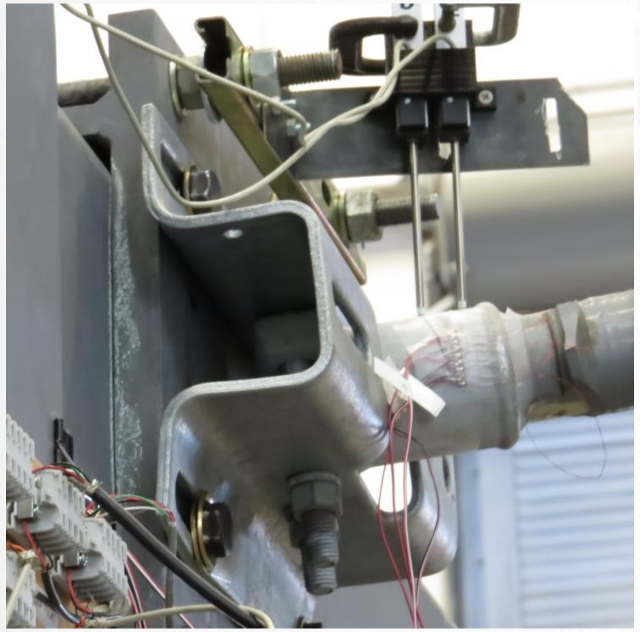


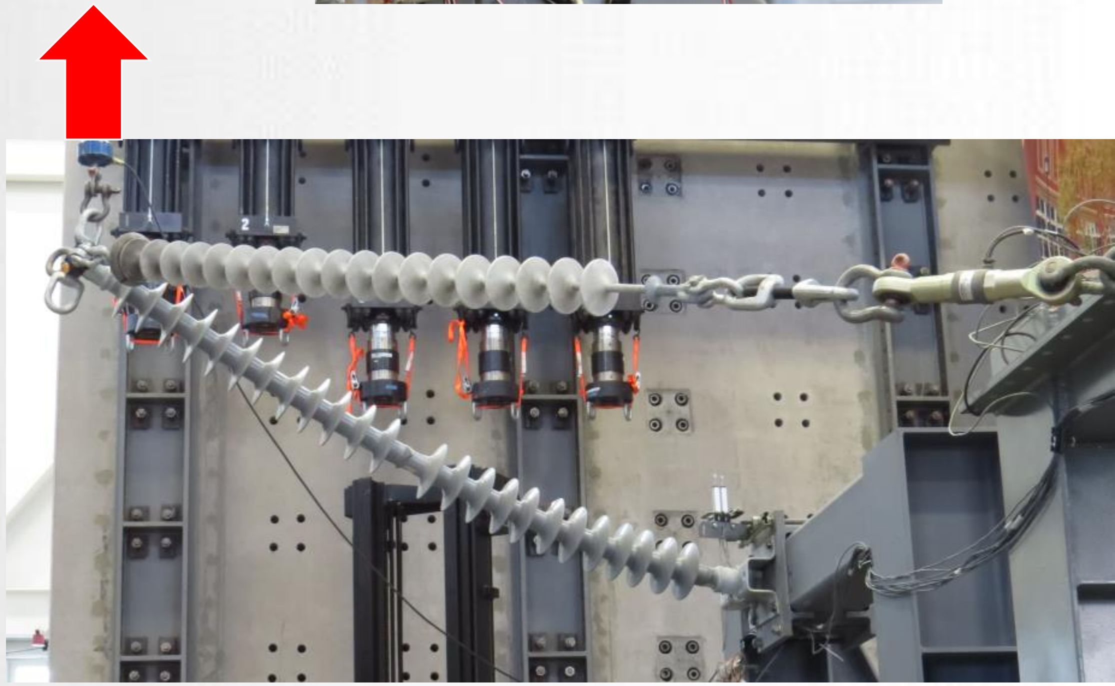
DIRECT POLE MOUNT
10-15. 10^5 Nm/rad

Longitudinal Stiffness tests
FLAT BASE (4 bolt connection)

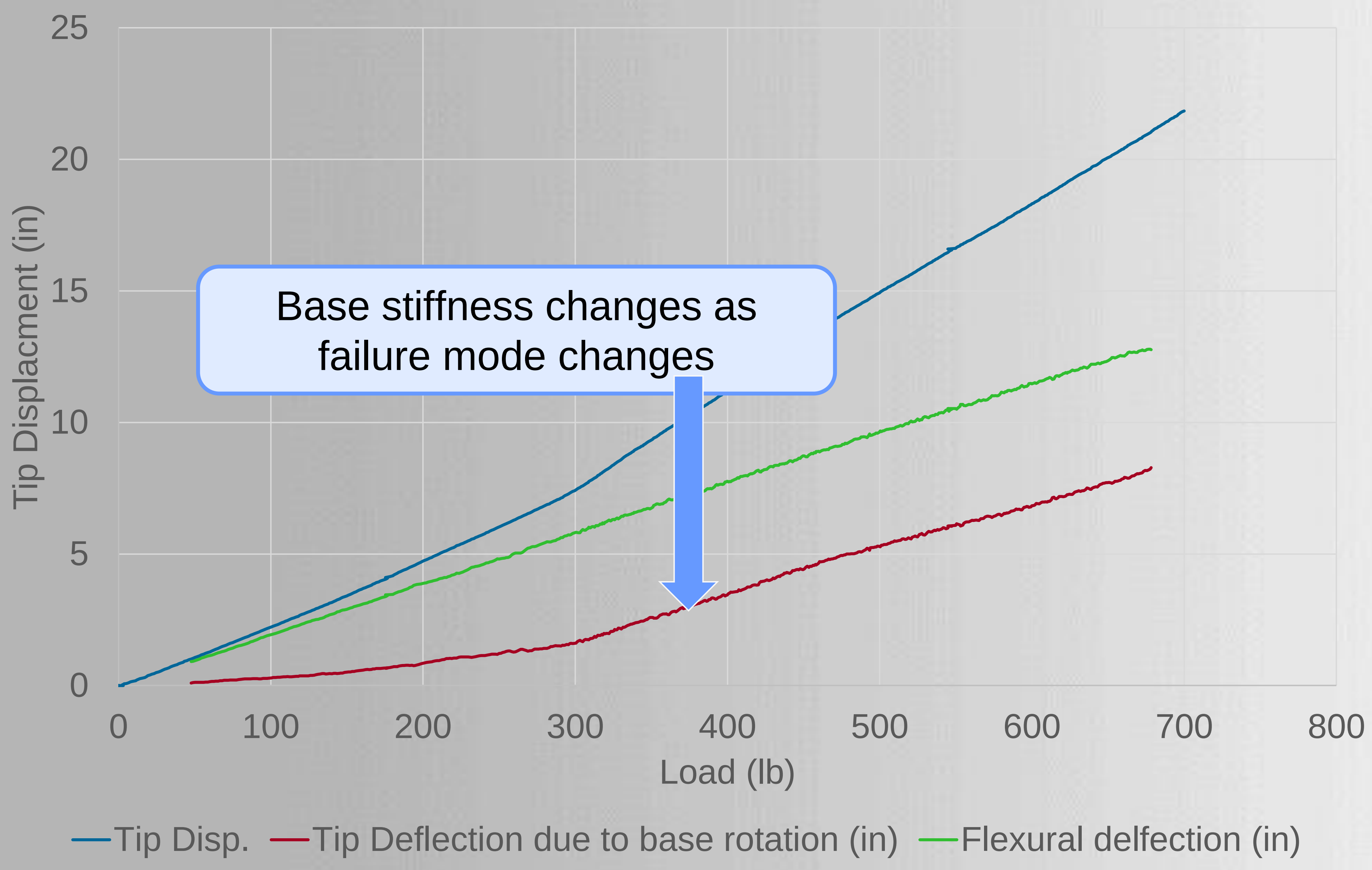
- Rotation of base measured with LVDT pair
- Elastic Modulus of composite post may be deduced from net tip deflection due to flexure

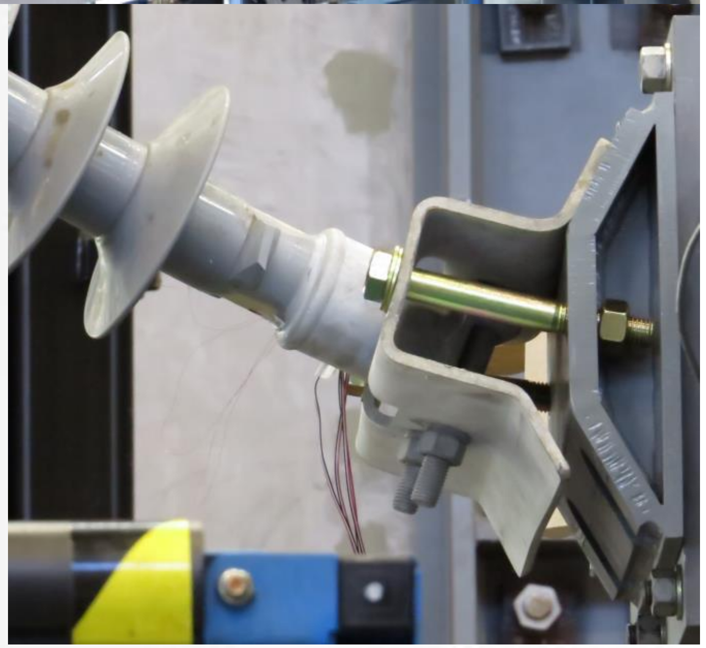






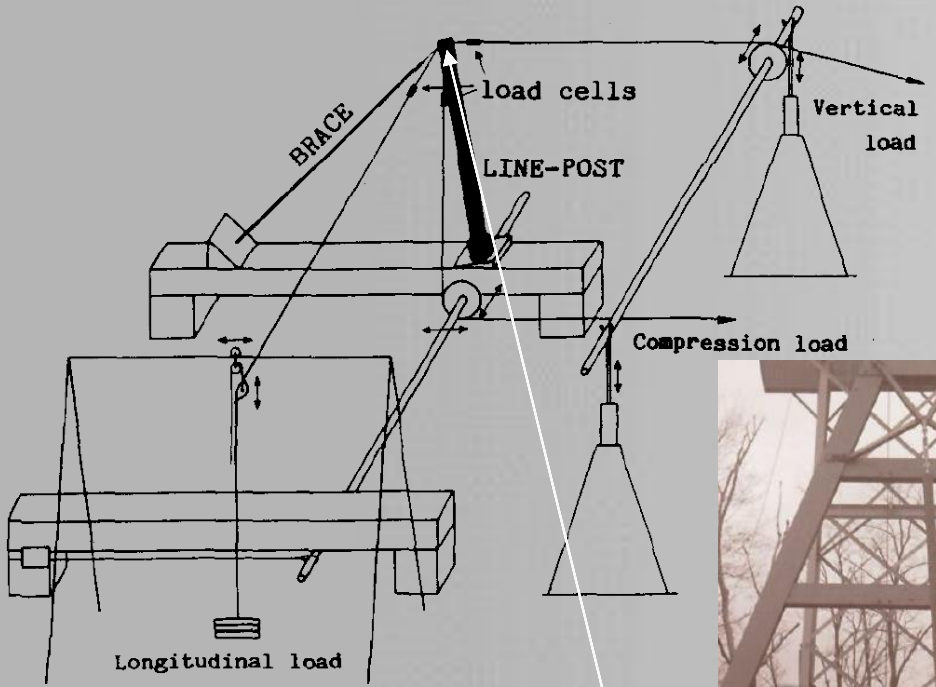
Longitudinal Stiffness tests
Bendable base with edge contact





Impact of Wire System on Insulator Buckling Capacity

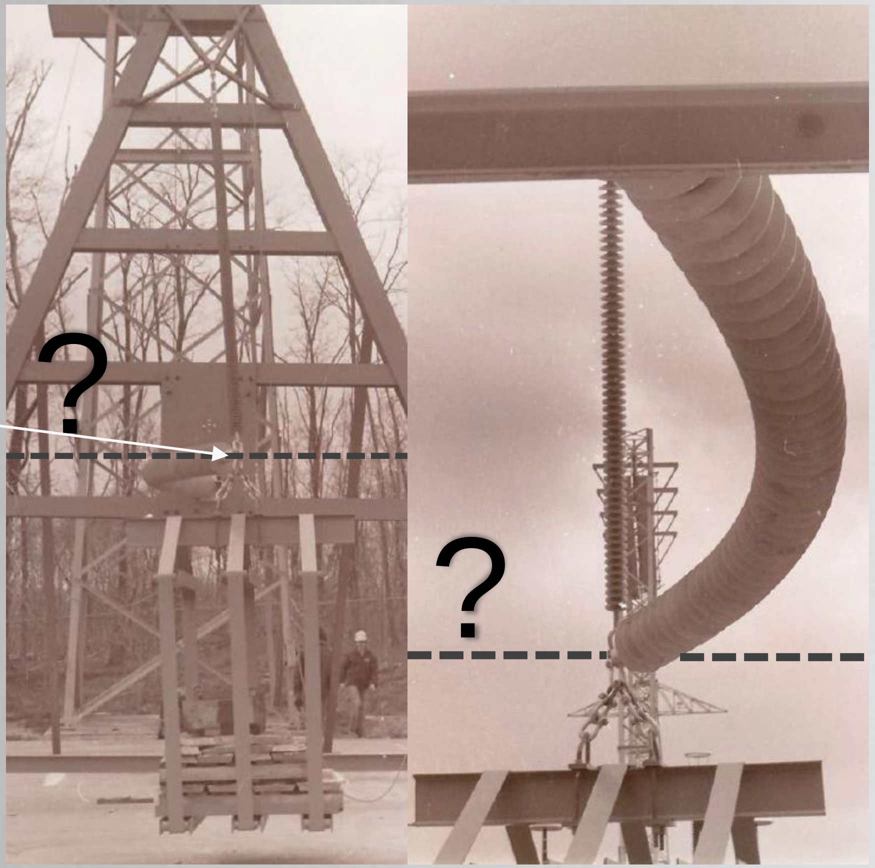
- Previous testing has not always included the effect of end restraint provided by the wire system

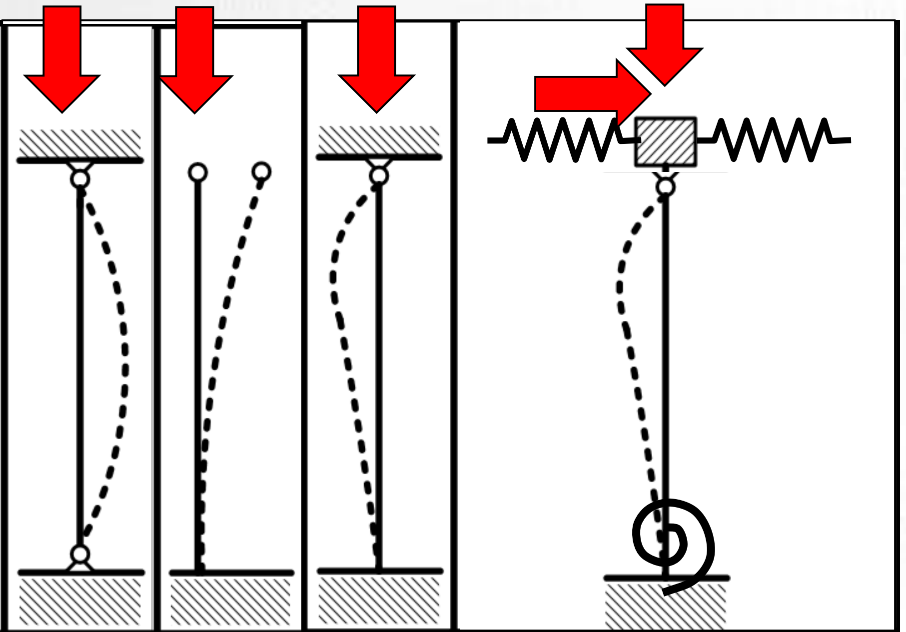
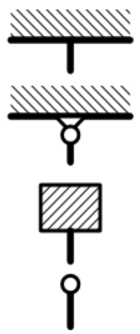


$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{\pi^2 E}{\left(K\frac{L}{r}\right)^2}$$

NO RESTRAINT ON END

- Buckling coefficient on Braced Posts is complex and depends on
  - Torsional stiffness of base
  - Stiffness of wire system

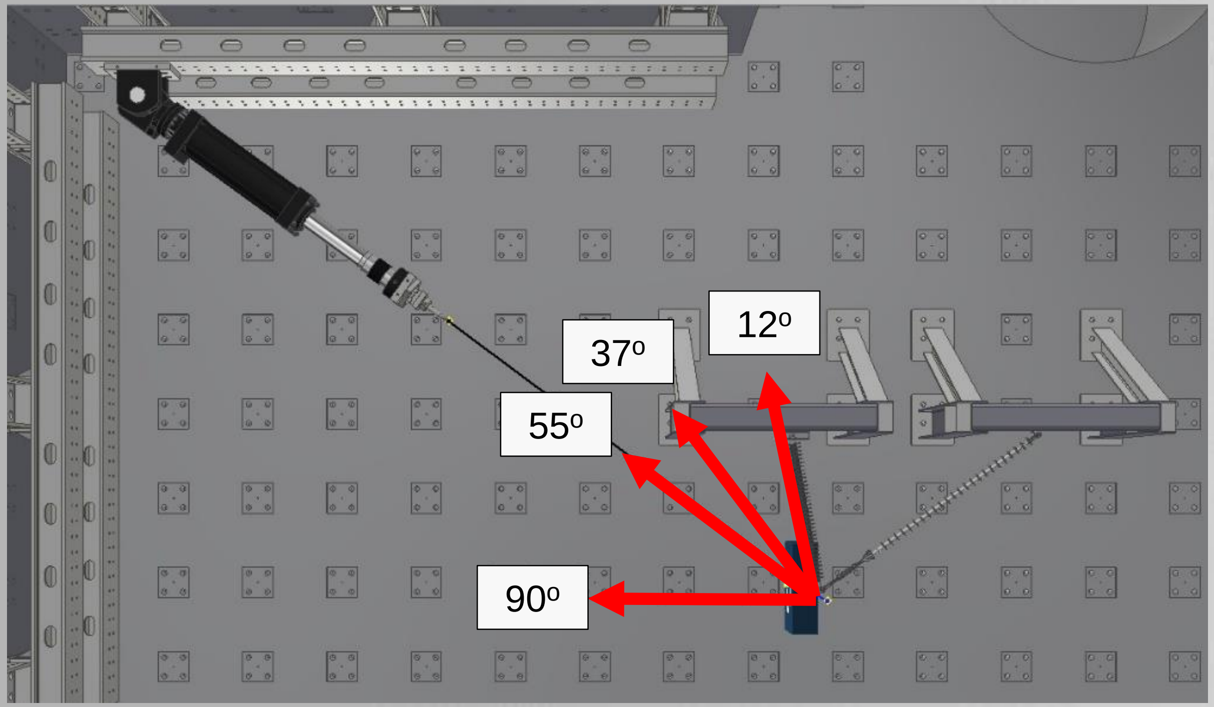


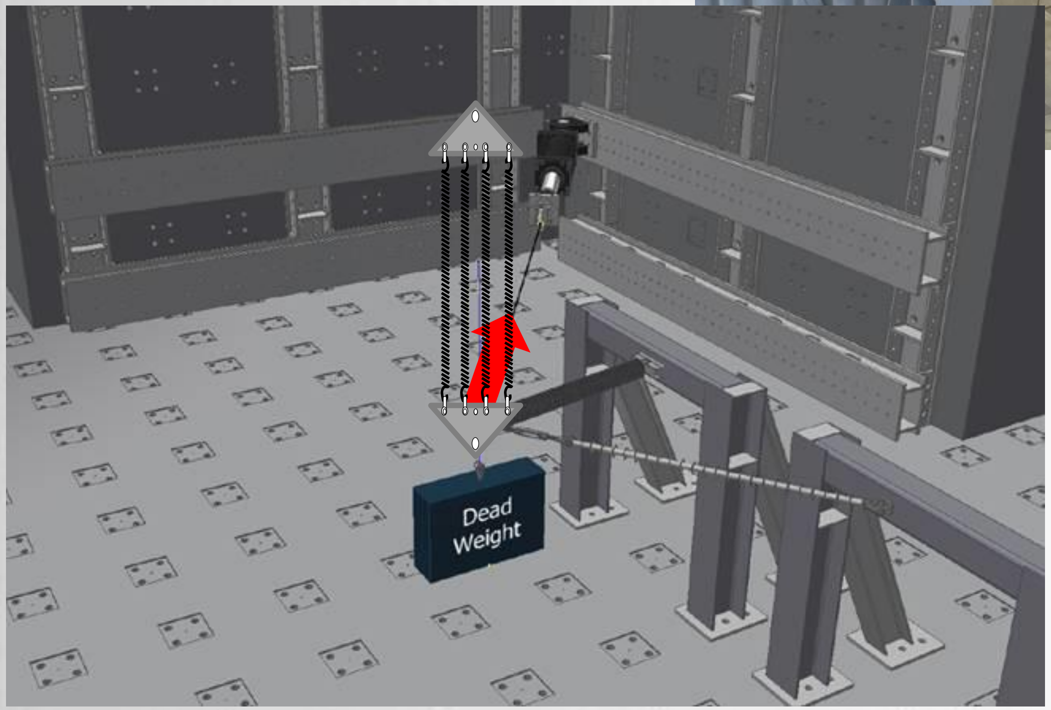
Buckled shape of column shown by dashed line				
Theoretical K value	1.0	2.0	0.7	?
Recommended design value K	1.0	2.10	0.80	
End condition key		Rotation fixed and translation fixed Rotation free and translation fixed Rotation fixed and translation free Rotation free and translation free		

138kV Braced Post Insulator Tests

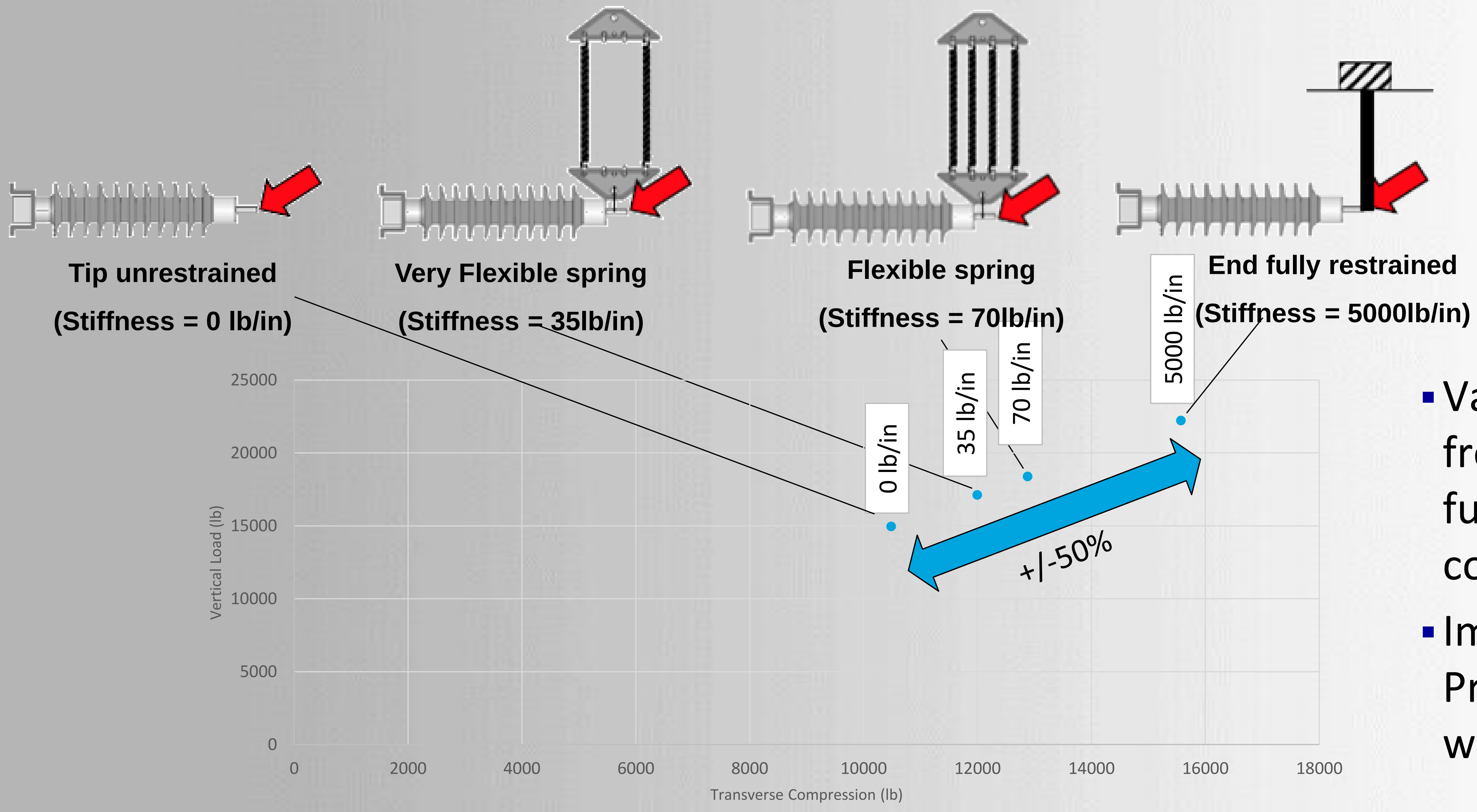
138kV Braced Post Test setup

- Arrangement rotated 90 degrees to facilitate testing
- Predominant load applied with load ram at various vectors to impose different combinations of transverse and vertical load
- Dead weights apply longitudinal load
- Spring assembly to verify effect of conductor support





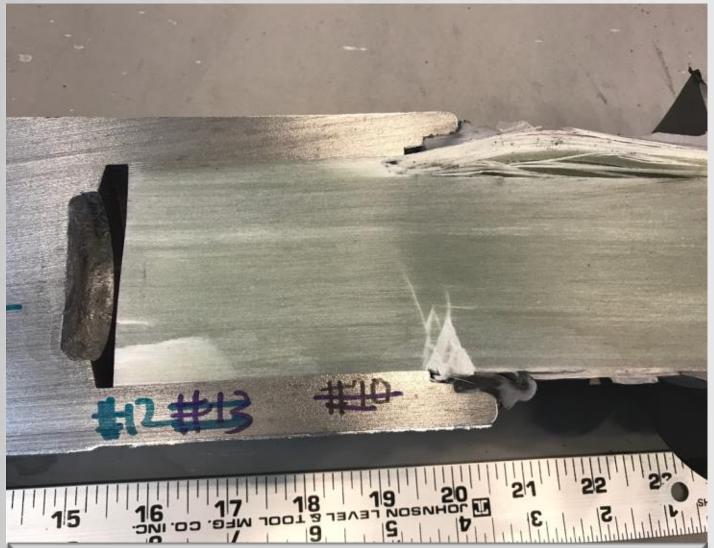
Effect of end restraint on insulator capacity



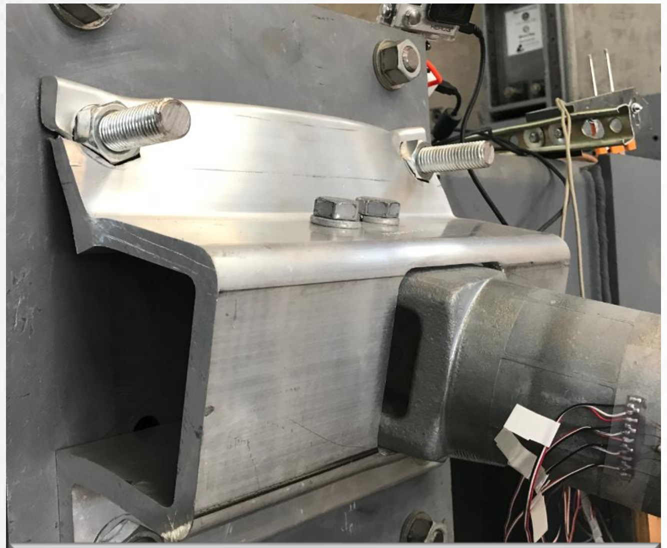
- Variation = +/-50% from unrestrained to fully restrained conditions
- Impact on capacity Proportional to log of wire stiffness

138kV Braced Post testing - Different modes of failure

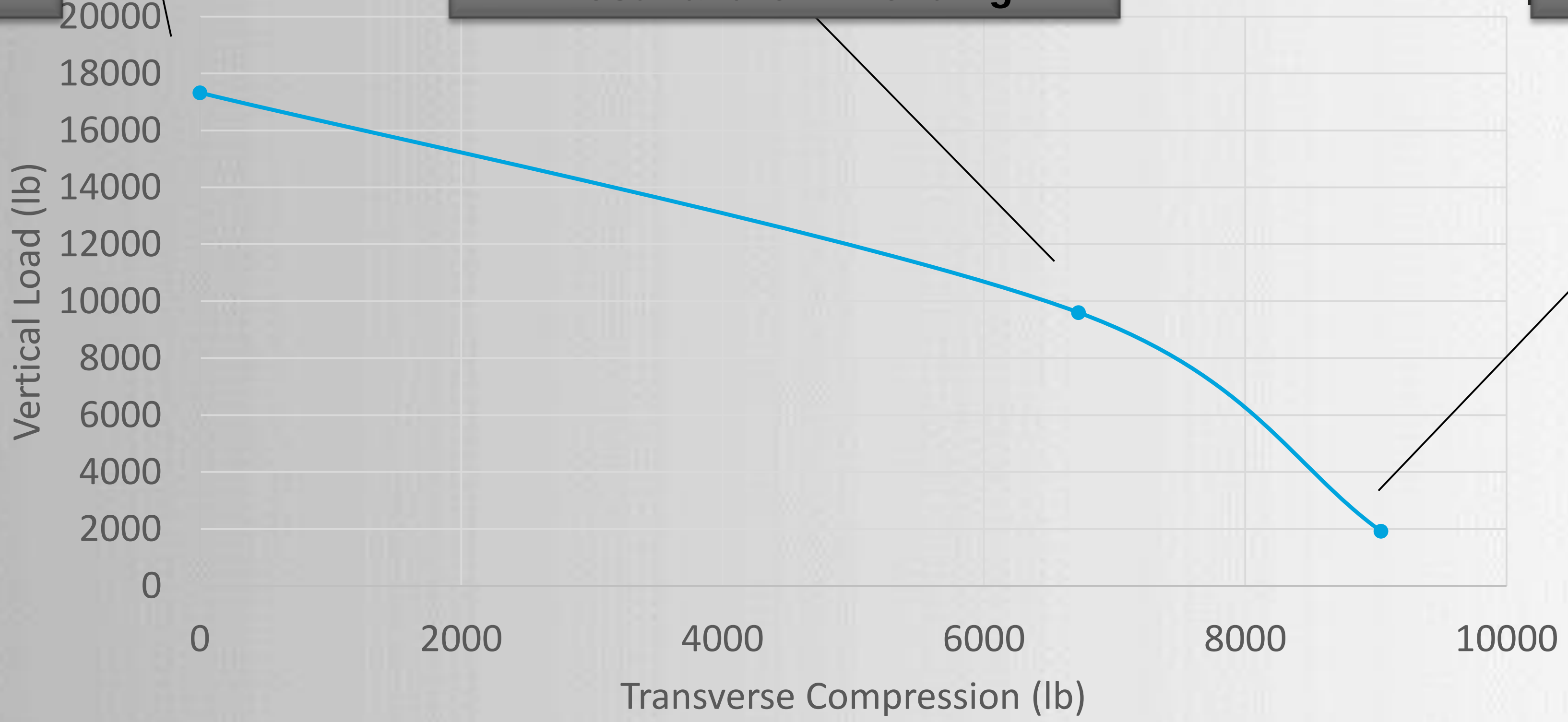
End fitting failure



Post Failure in Bending



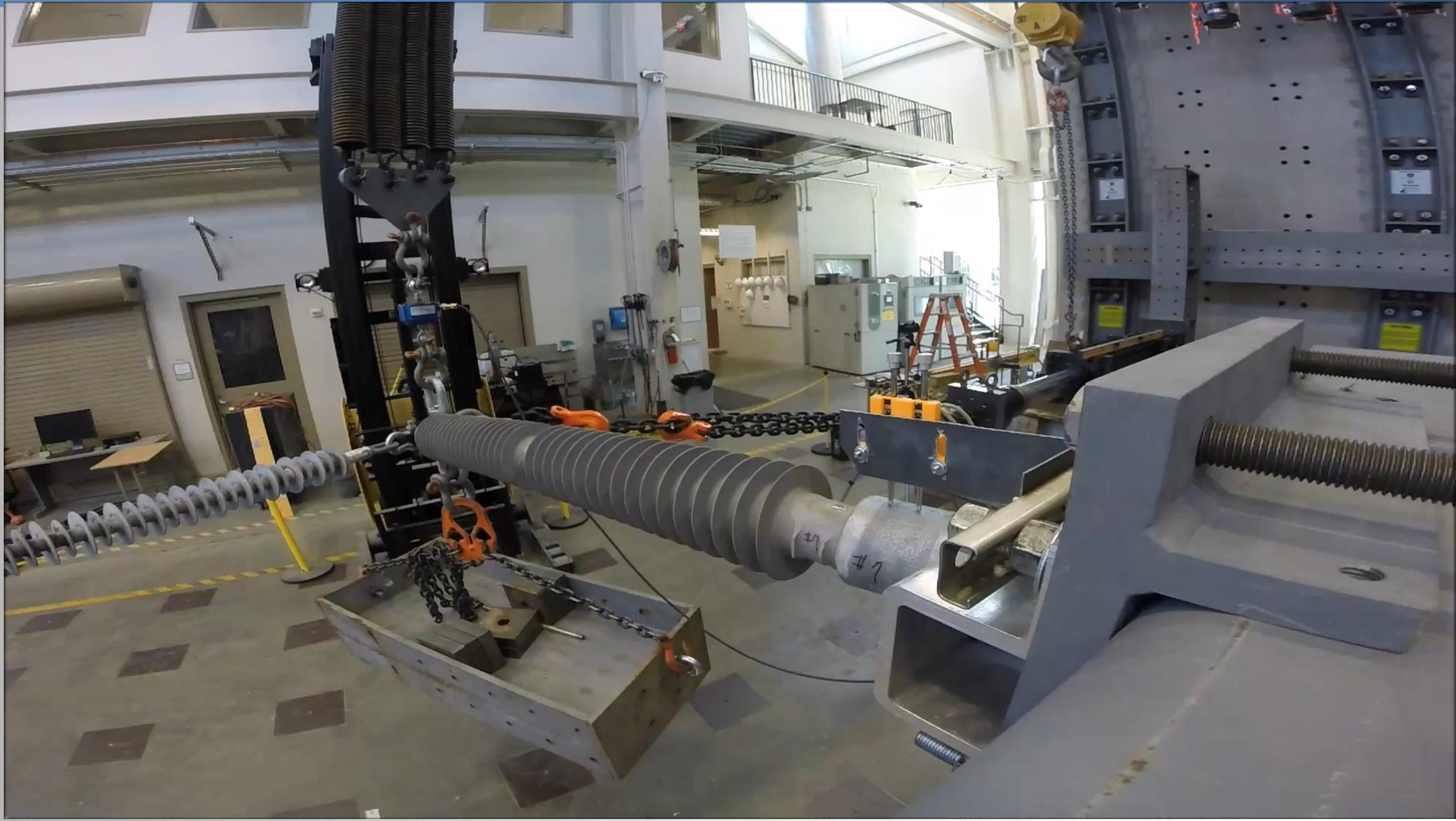
Base Plate Failure



- No buckling failures in 138kV Posts (!)

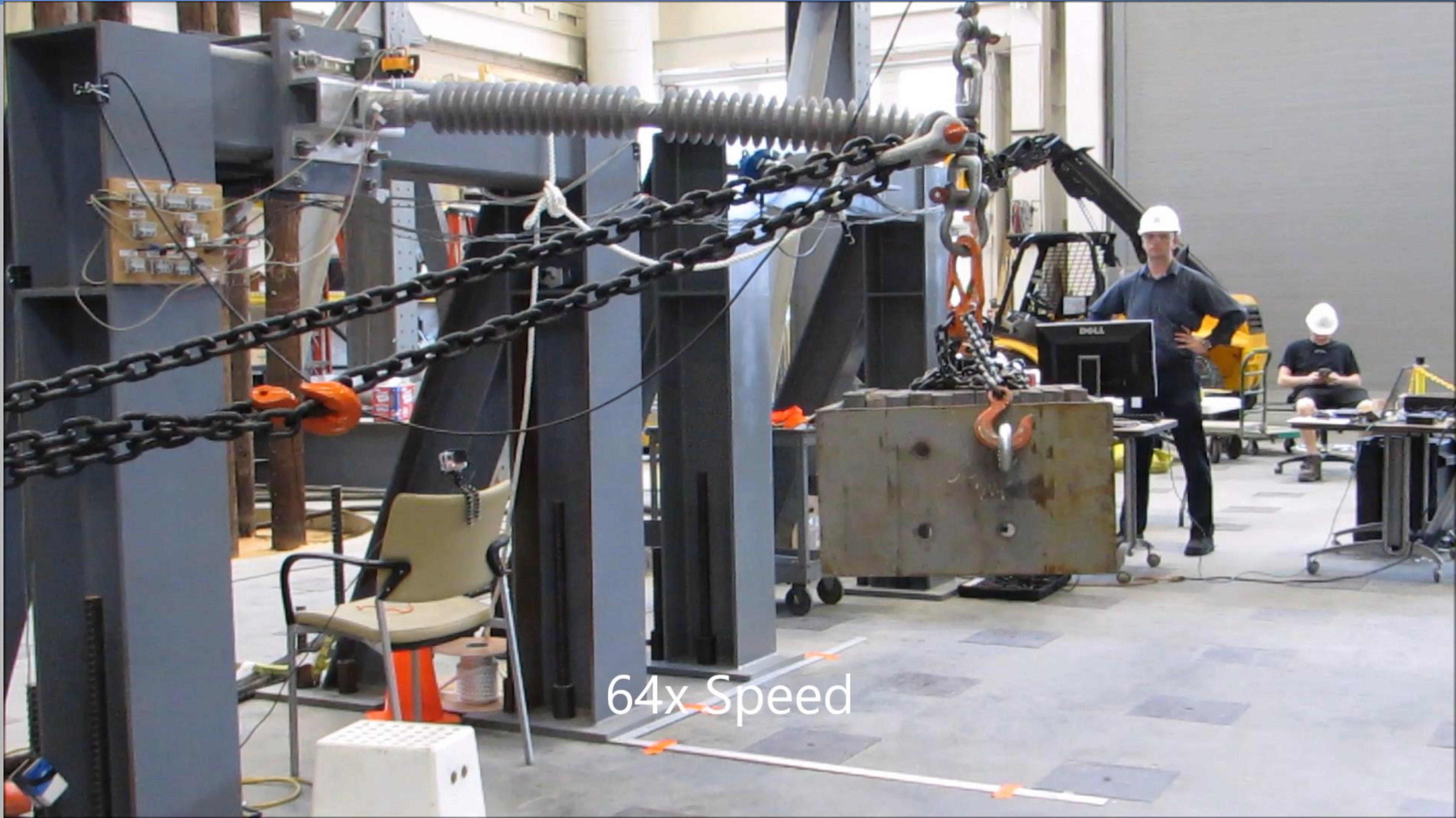
138kV Braced Post Test - End fitting failure

- End fitting failures can induce impact loads on other parts of the system

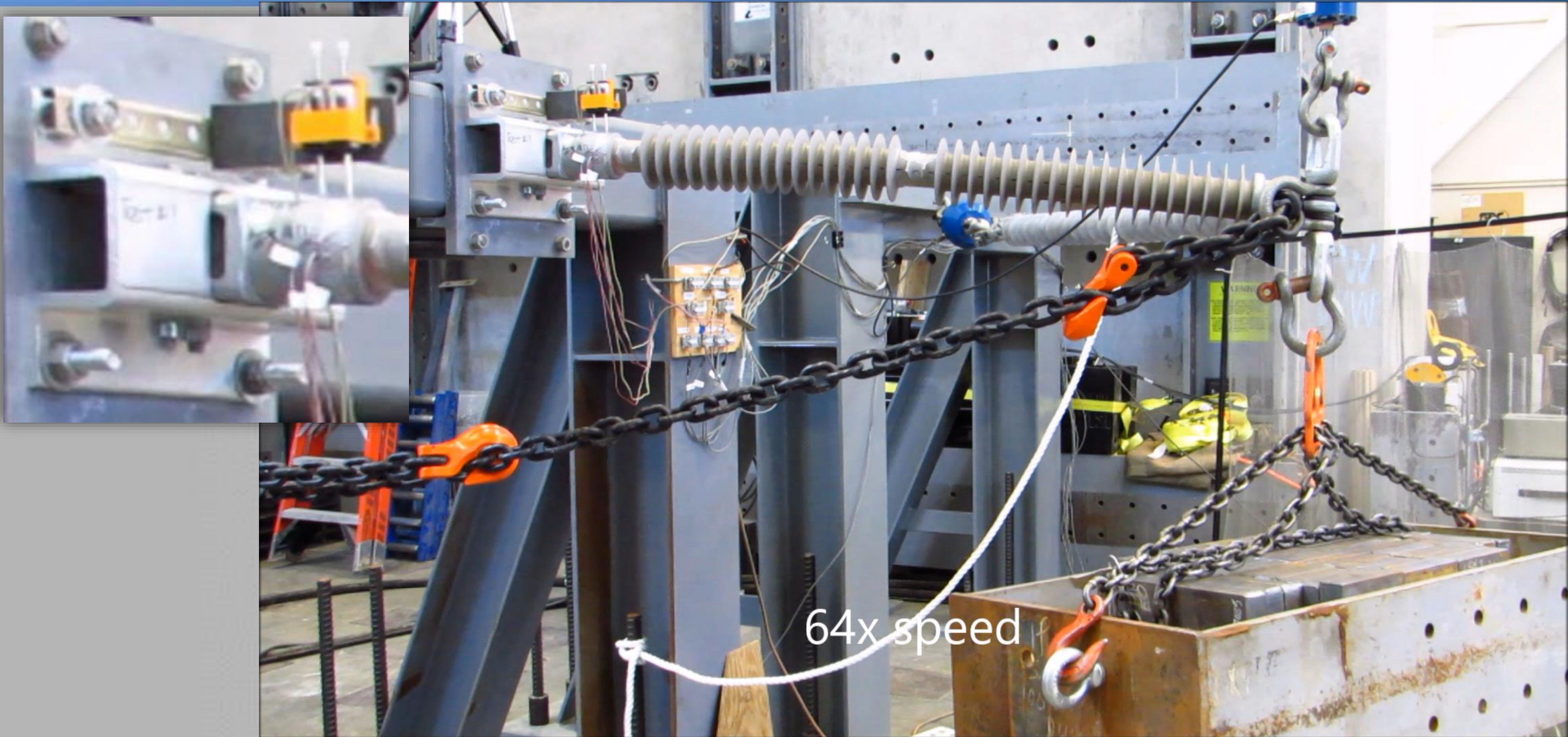


138kV Braced Post Test - Post failure in bending

- Post failures in bending are gradual (no dynamic loads induced into system)

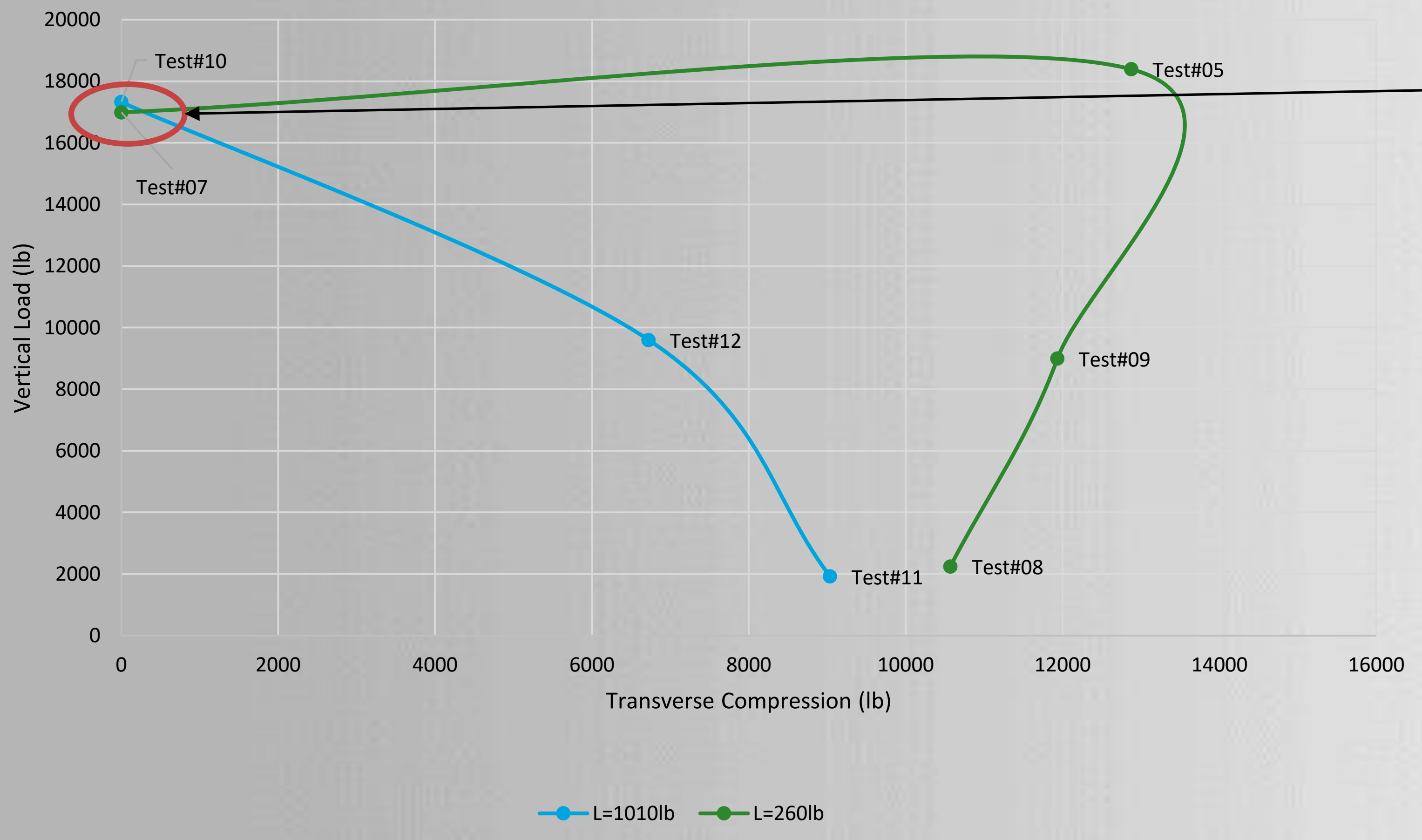


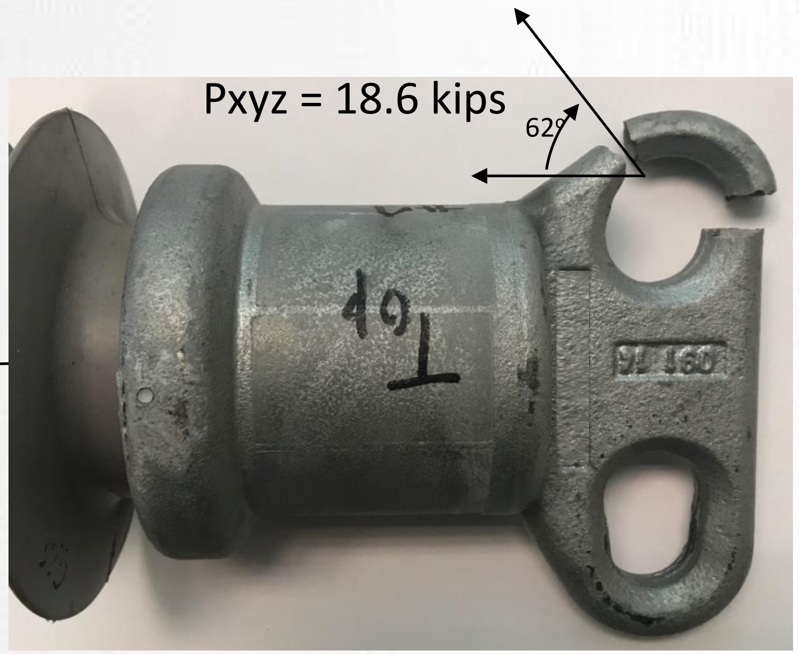
138kV Braced Post Test - Base failure

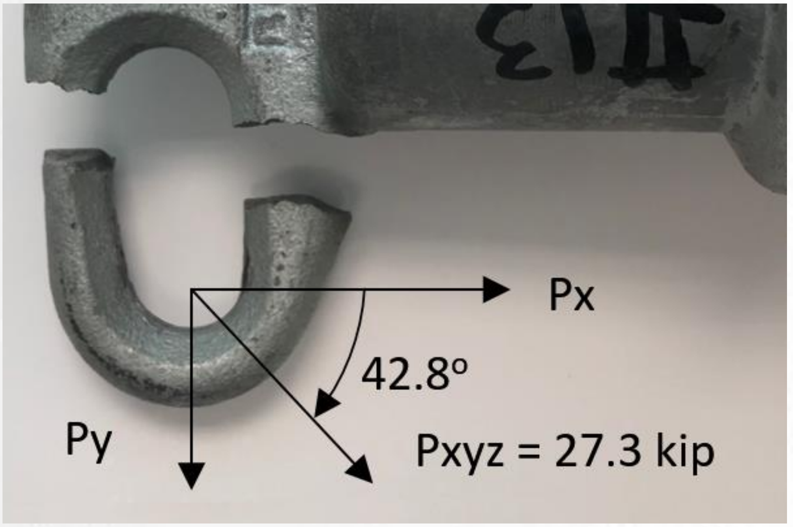


End connection design can be critical

- End fittings have failed prematurely under some combination loads
- NESC Strength factors do not distinguish between composite components and metal components



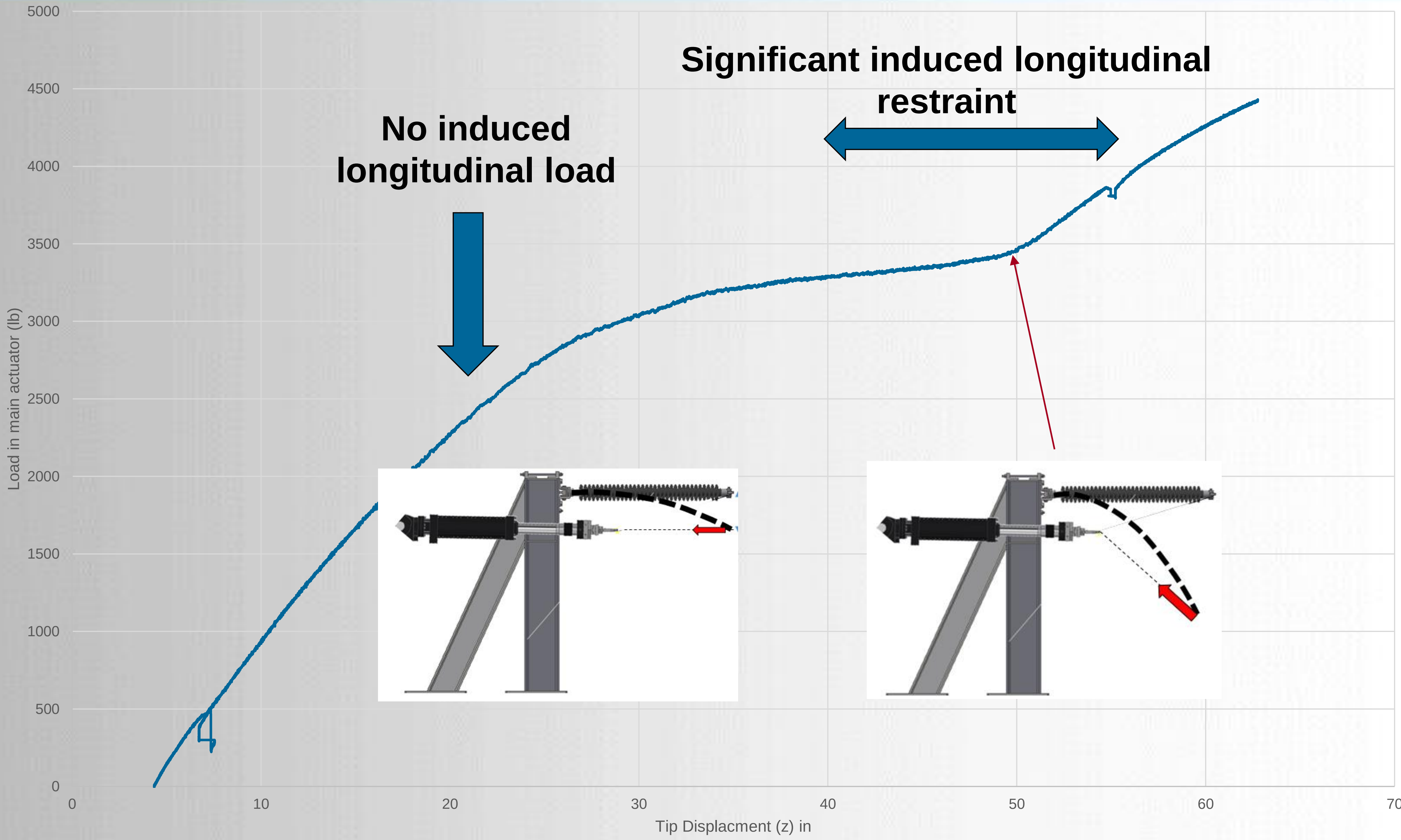




220kV Braced Post Insulator Tests

Phase 2 – 220kV braced post insulator tests
Accommodating large tip deflections

- 138kV tests conducted with hydraulic actuator positioned at level close to peak loads
- 220kV tip deflections too large to allow fixed position of actuator



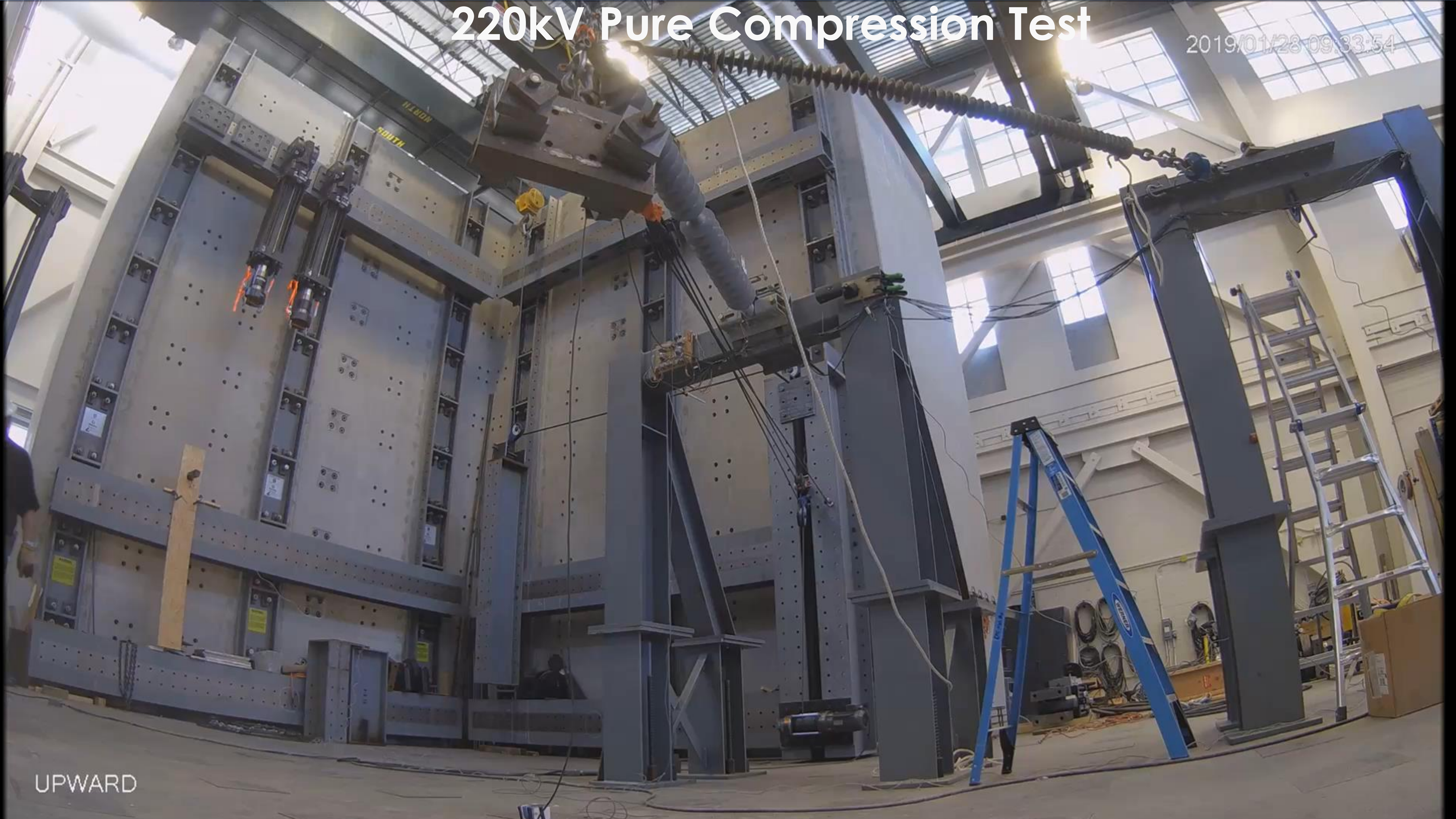
Phase 2 – 220kV braced post insulator tests
Accommodating large tip deflections

- Increased reaction frame size
- Load application by winch

Phase 2 – 220kV braced post insulator tests
Keeping loads orthogonal

- Load maintained at -3º to -3º from horizontal
  - Wireless digital inclinometer

220kV Pure Compression Test




11/30/2018 11:49:14 AM
Load Angle: 3 Vert : 4 Trans
ANGLE

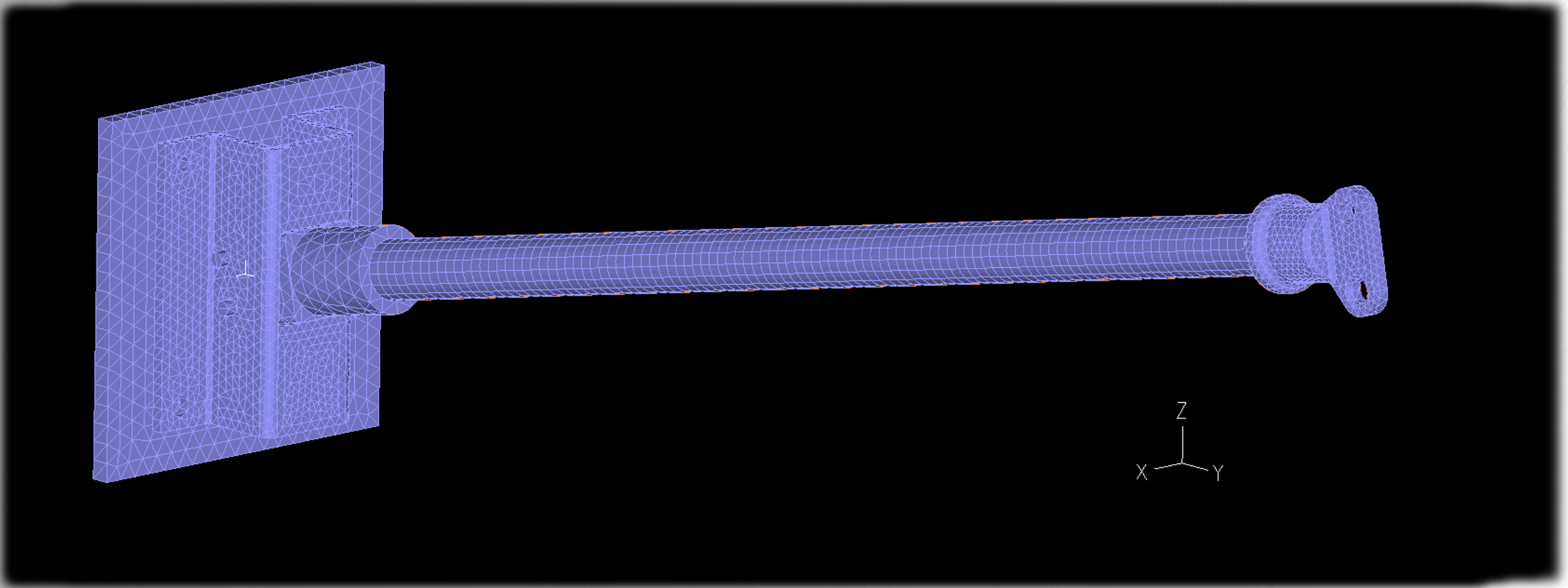

11/13/2018 09:10:48 AM
ANGLE


12/19/2018 09:07:07 AM
HYUNDAI
15BRP-7 AC
WERNER
UPWARD

FEM Modelling

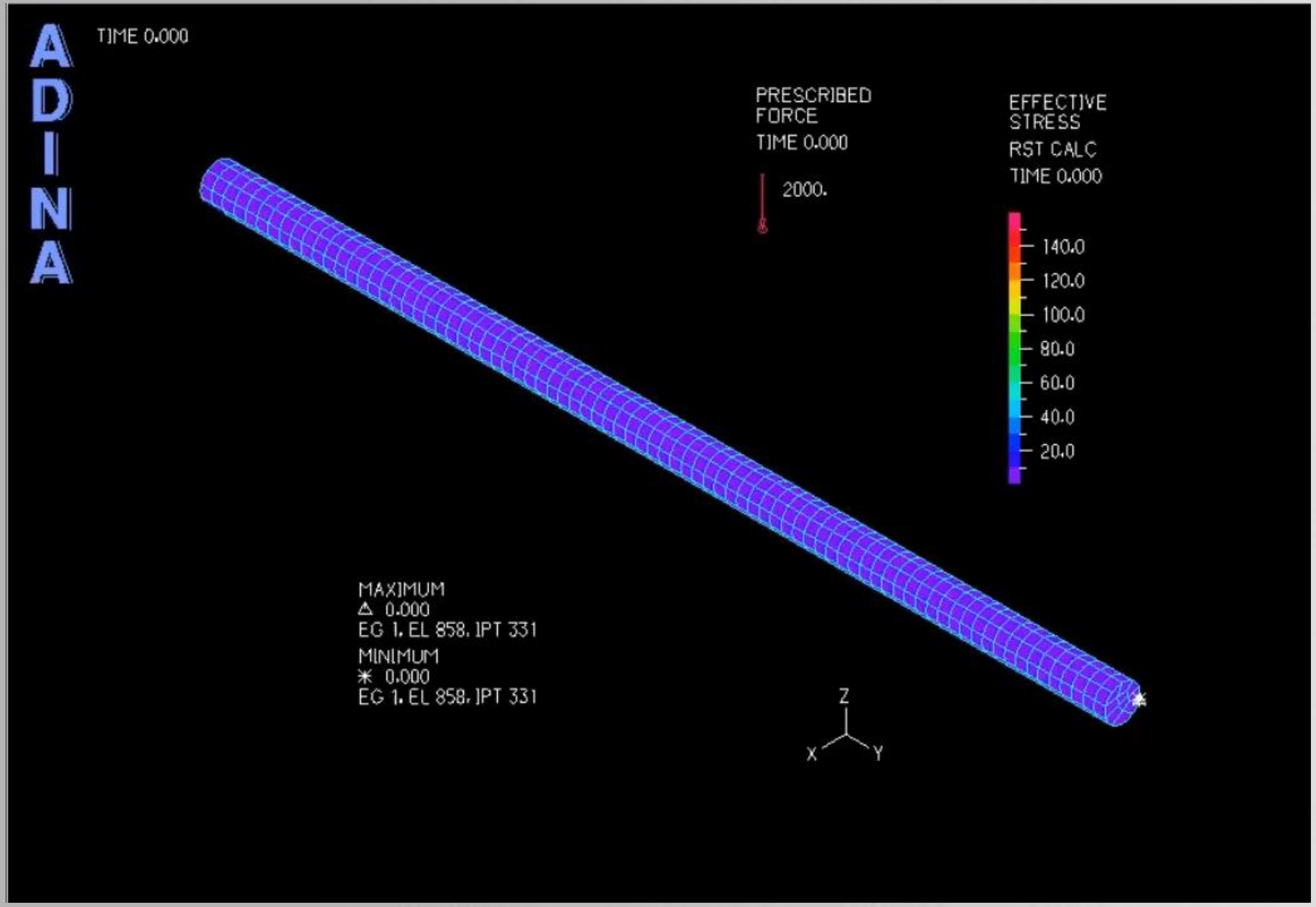
Initial FEM modelling

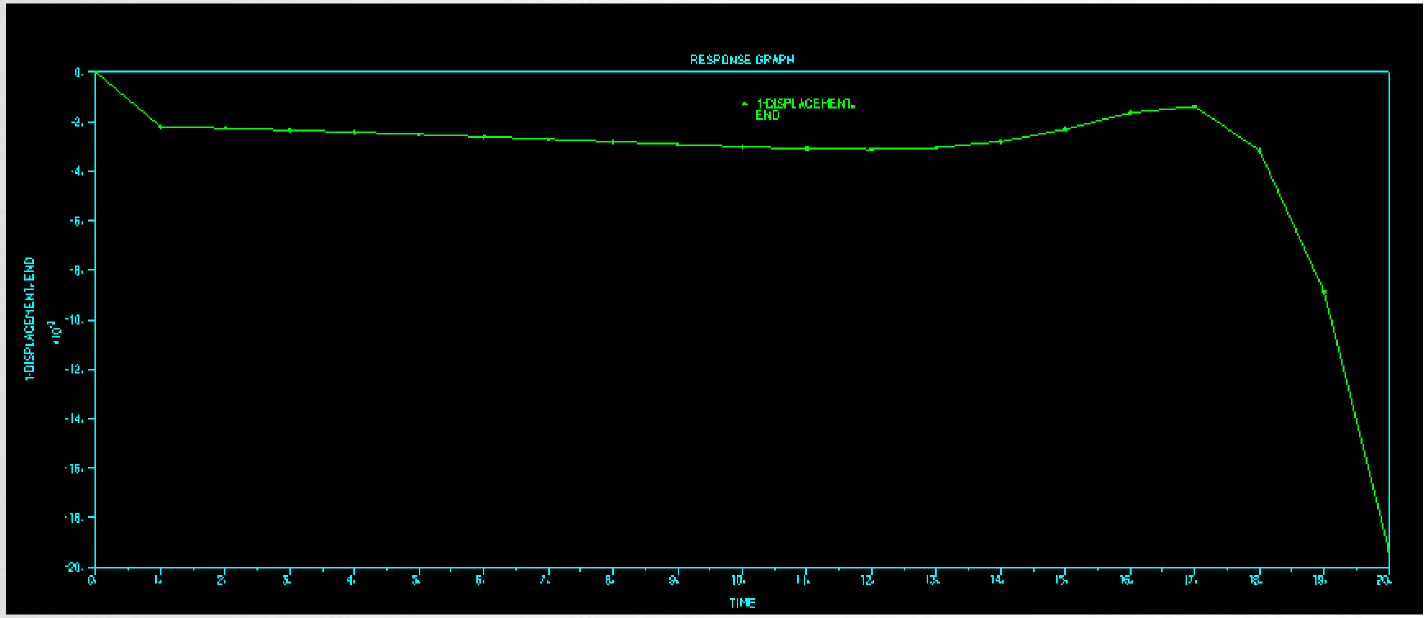
- FEM Modelling performed in ADINA
- Incorporating different materials joined by “glue mesh”



	Youngs Modulus		Ultimate stress		Poissons Ratio
	E (Mpa)	E (ksi)	fy (Mpa)		
Composite ECR Glass Core	37000	5370	800	120	0.45
A36 steel	200000	29010	470	70	0.26
6063 T5 Aluminum	68900	9990	140	20	0.33

Initial FEM modelling

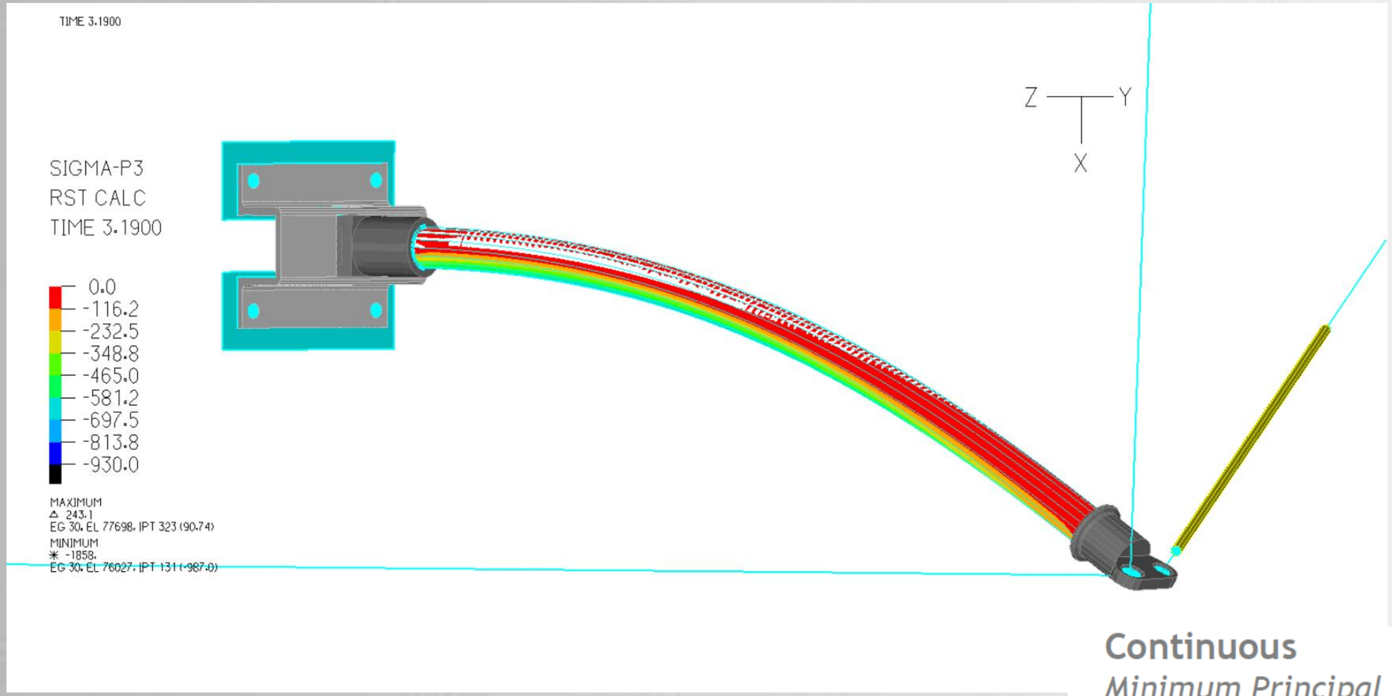


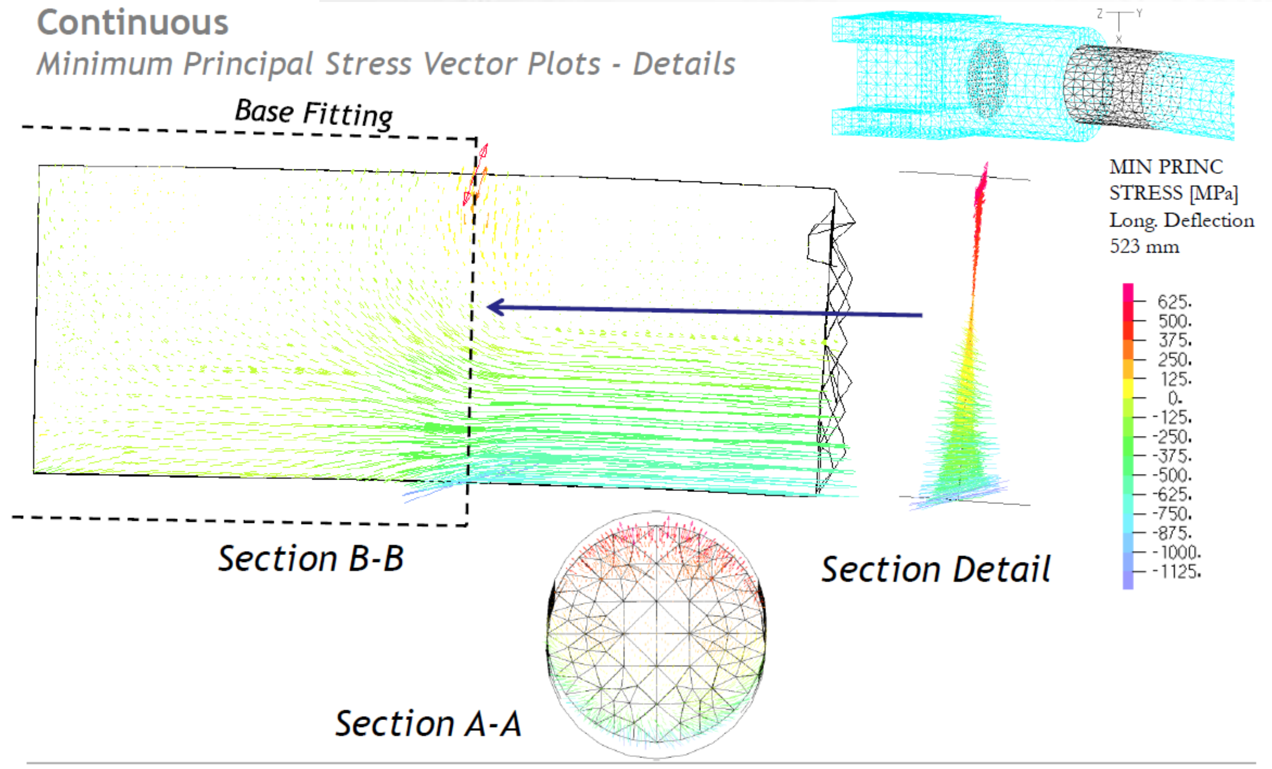


- Loads applied with time function to determine
  - Displacement
  - Non-linear deflection
  - Buckling capacity

Later FEM modelling

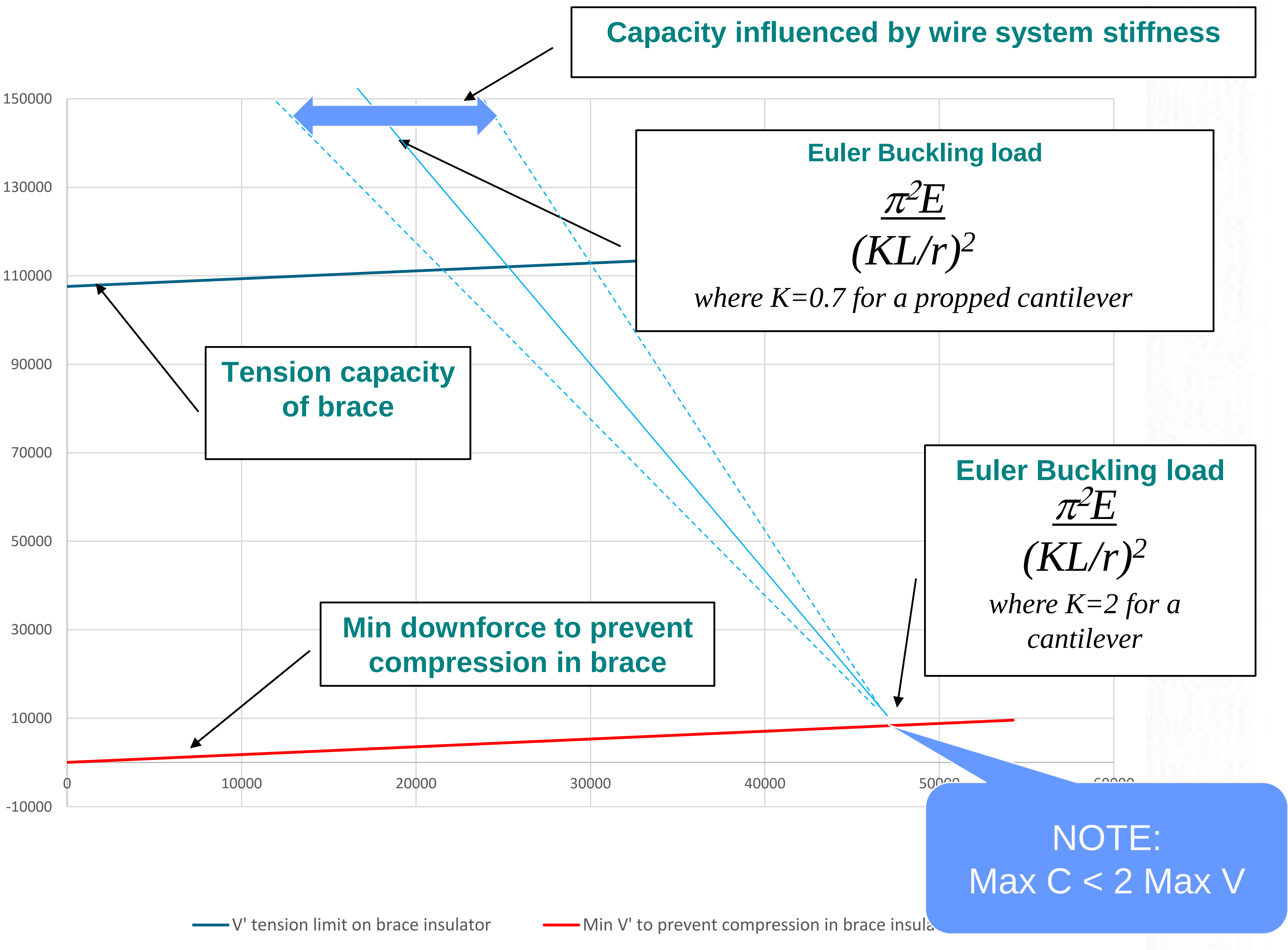
- Good correlation between FEM model and displacement
- Prediction of failure load more challenging
- Interference model used to simulate stress between housing and composite post



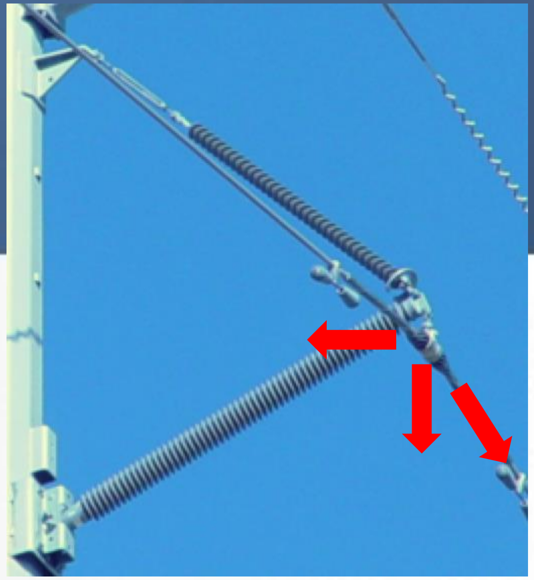


Anatomy of a Braced Post Insulator Capacity Curve

- Capacity of braced post highly dependent on direction of load
  - “weakest” point: pure compression load - = buckling load on post insulator
  - “strongest” point = pure vertical load – allows compression loads in post +/- 4 x higher
- Capacity varies based on restraint from wire and rigidity of base

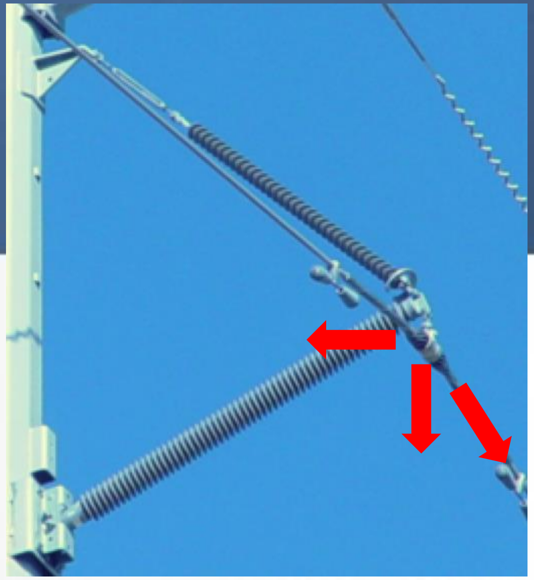


Key Findings to date



- Large disparities between published load curves for similar insulators
  - Some don’t publish interaction capacities (only max horizontal and vertical loads)
- Longitudinal stiffness of braced post system impacts net longitudinal load, and determines P-delta moments induced
  - Very few suppliers publish longitudinal stiffness
- Different testing techniques employed by manufacturers
  - No published or industry standard for testing braced posts
- It pays to test – ability to use own, verified test data and strength factors

Key Findings to date (contd.)



- Impact of the wire system has a significant impact on insulator capacity
- No manufacturers attempt to quantify the impact of wire system on capacity
- Many different modes failure types observed on tests to date
  - “Good” failure modes: bending, base failure, buckling
  - “Bad” failure modes: end connection rupture, brace failure – induce dynamic loads
- Base connection types have a large impact on compression capacity for longer (220kV) posts

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Thank you for your attention

Questions/ Comments?

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