2024 PLS-CADD Advanced Training and User Group

Developing Security Loads

by

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EPRI

Research Credit : Significant contributions by David Folk

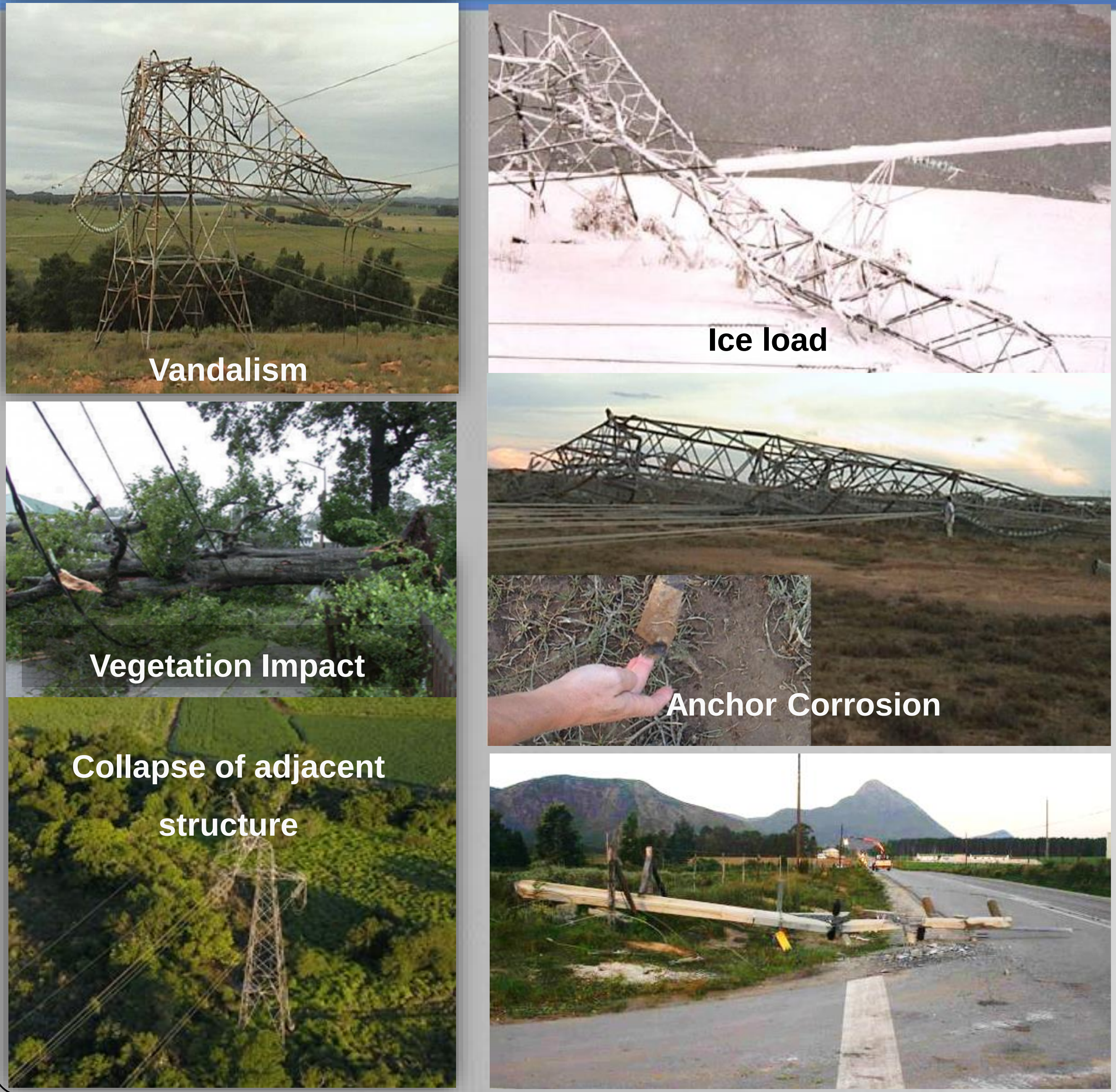
Session Overview

1. Should we care about security loads?
   - Nature & frequency of broken wire vs failure cascades
   - Dx vs. Tx considerations
2. Quantifying and modelling broken wire loads
   - Early and recent research findings
   - Modelling in PLS CADD
3. Avoiding longitudinal cascades
   - Key design features to avoid longitudinal failures
   - Modelling in PLS CADD
   - Case study

Should we care about security loads?

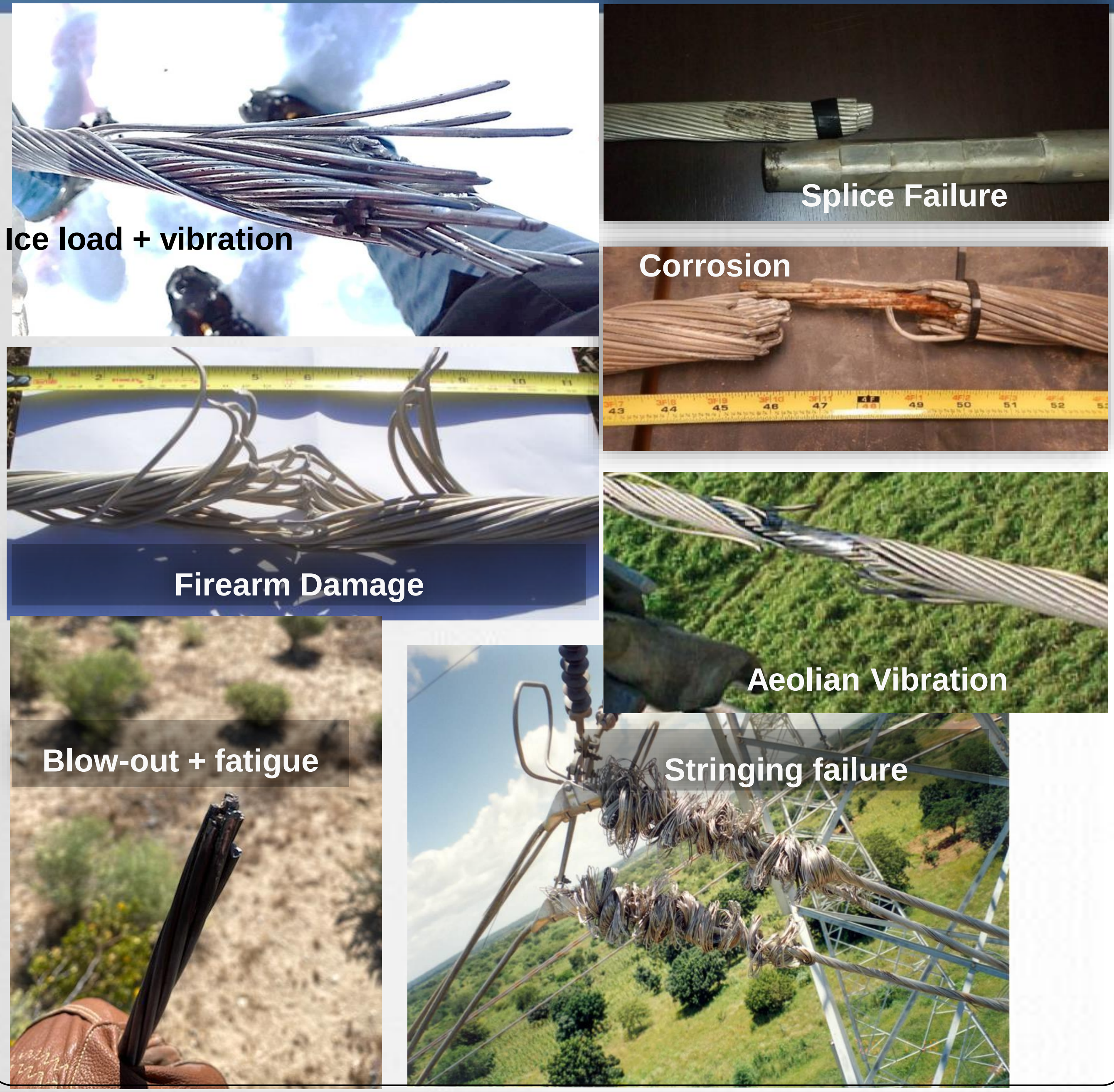
Longitudinal Load Sources & frequency

Longitudinal Cascades



On average, EPRI is notified of a cascade every second year

Broken Wires



On average, EPRI is aware of multiple broken wire events every year

Failure Containment vs. Broken Wire Events

Cascading Event

https://www.youtube.com/shorts/u2ES5TdT_Vo

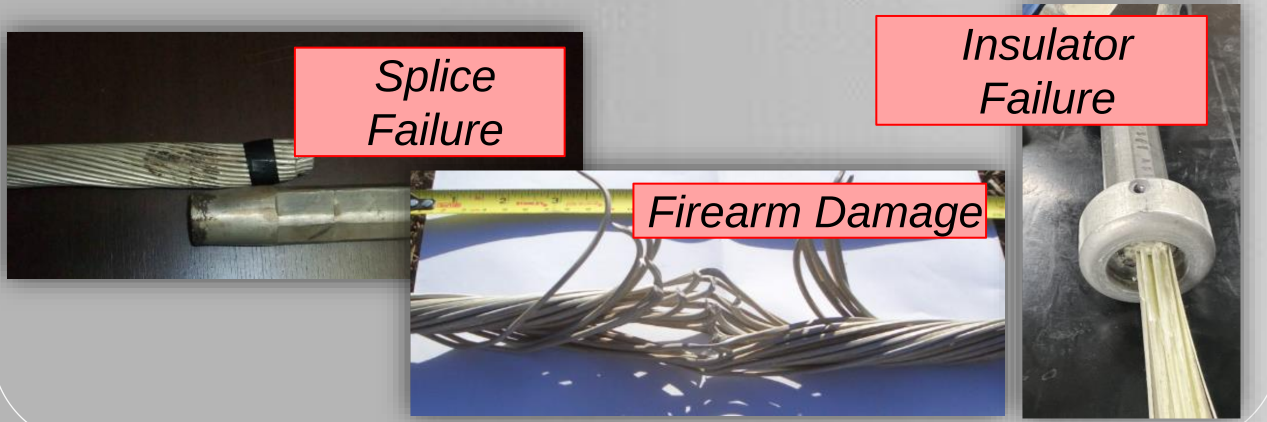
Broken Wire Tests

Failure Containment vs. Broken Wire Events

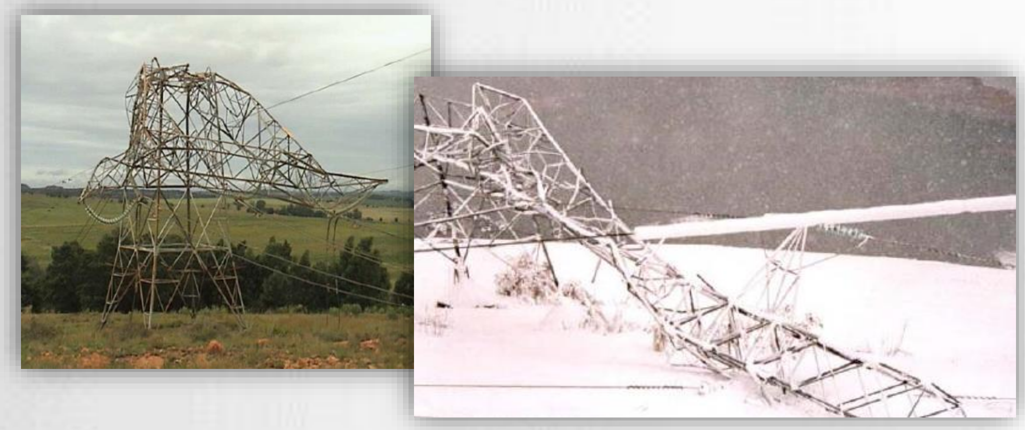
	Failure Containment / Anti-Cascading Loads	**Broken Wire / Dynamic Impact Loads**
Design Objective:	Extinguish cascading failure within a few structures	Contain broken wire event, prevent total structure failure
Nature of loads:	Mostly quasi – dynamic - residual static loading dominates	Dynamic, inertial loads
Number of affected phases & timing:	All phases / Sets of phases simultaneously load structure	Peak loads often do not occur simultaneously
Conductor State:	Wires may be intact	One or more phases broken
Possible design philosophy:	Apply residual static load on all phases / sets of phases **OR** include anti – cascade towers at intervals	Apply peak dynamic loads on individual phases, with everyday loads on remaining phases
EPRI Research	**CASE Method & Software**	**Dynamic Impact Test Line**

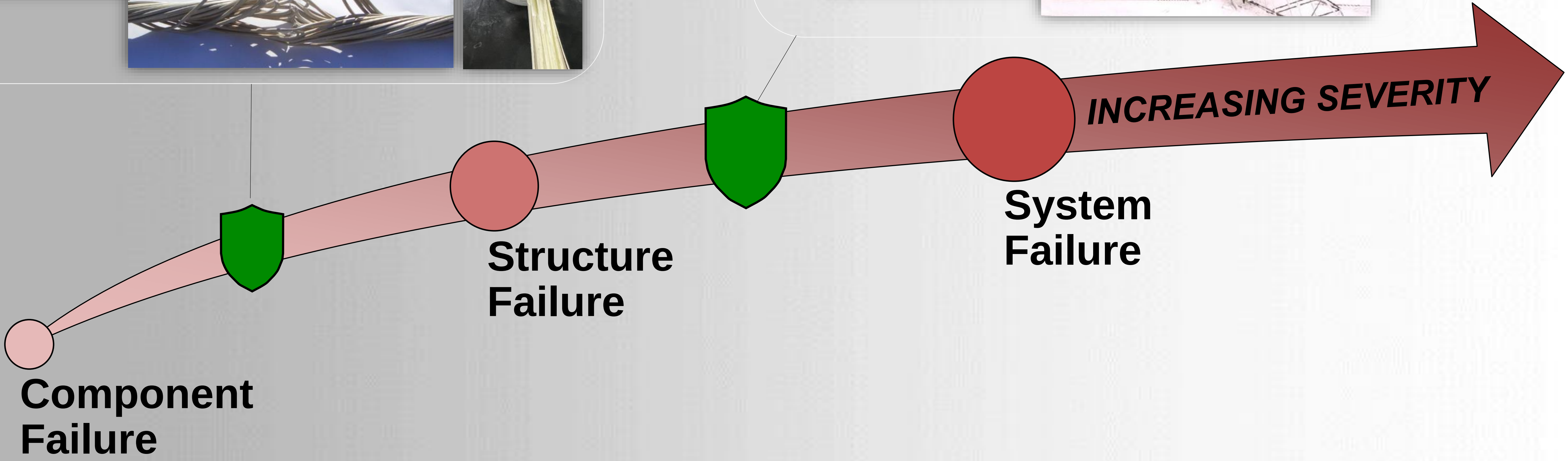
Security Load Design

Design for broken wire loads



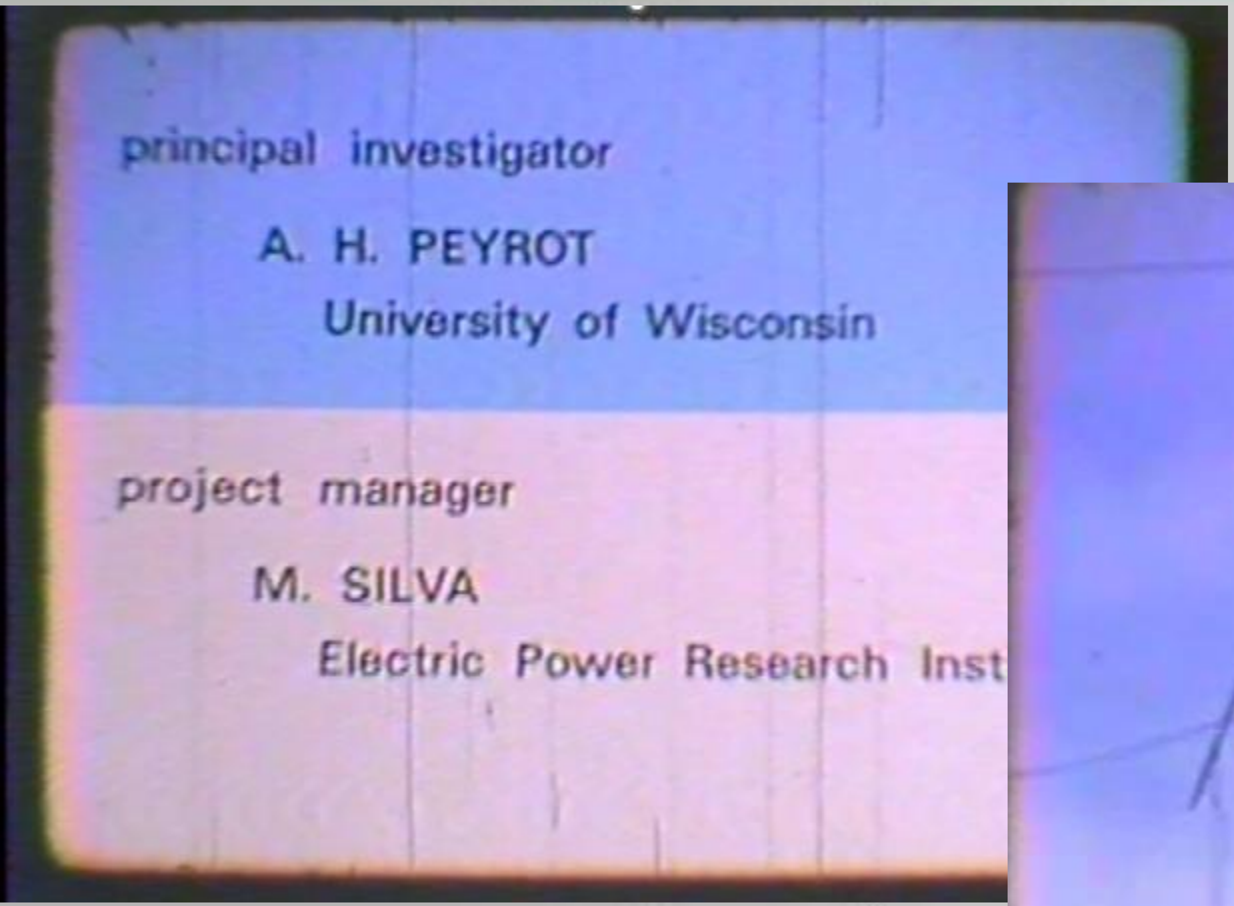
Design for residual static loads

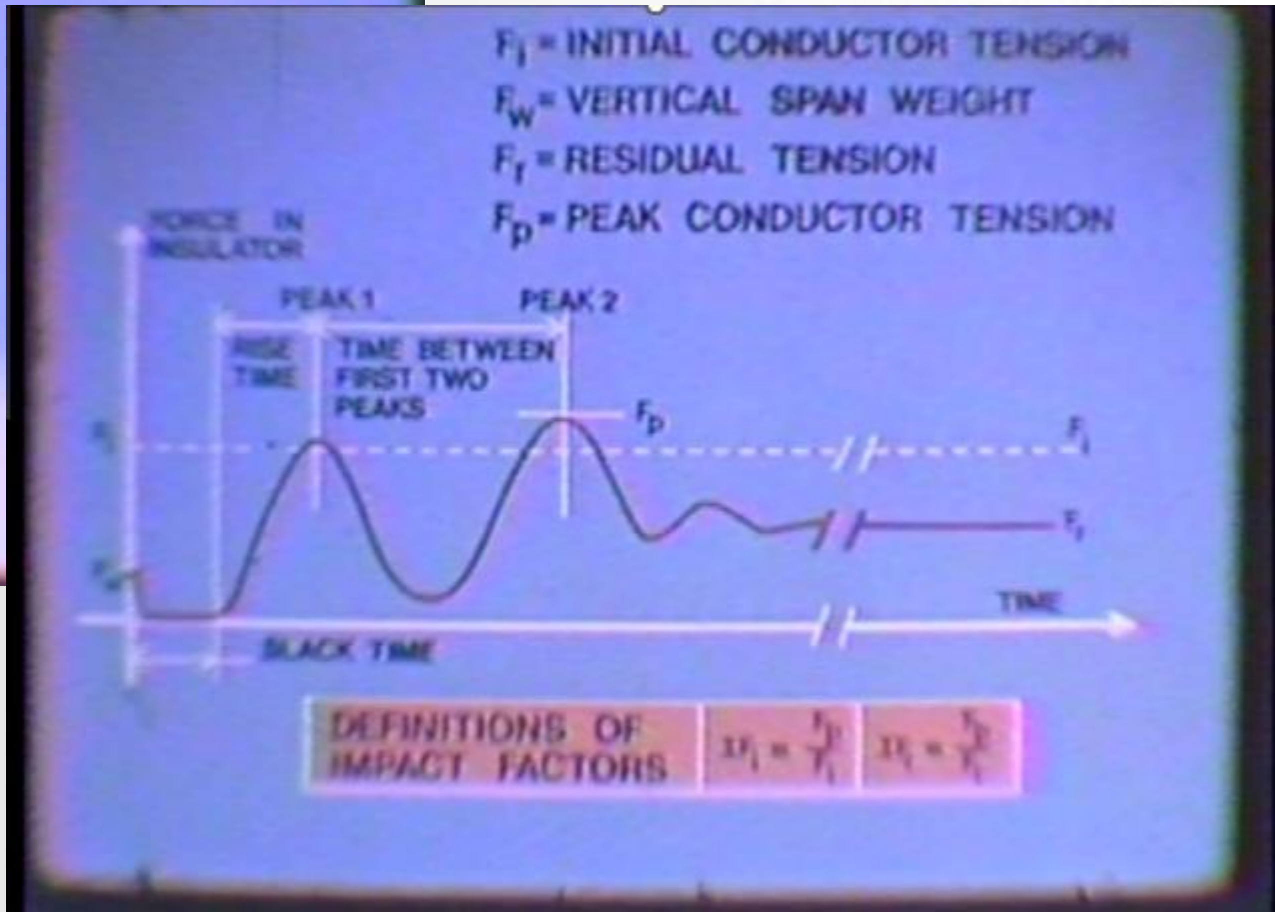




Broken Wire Loads

Early research into broken wires





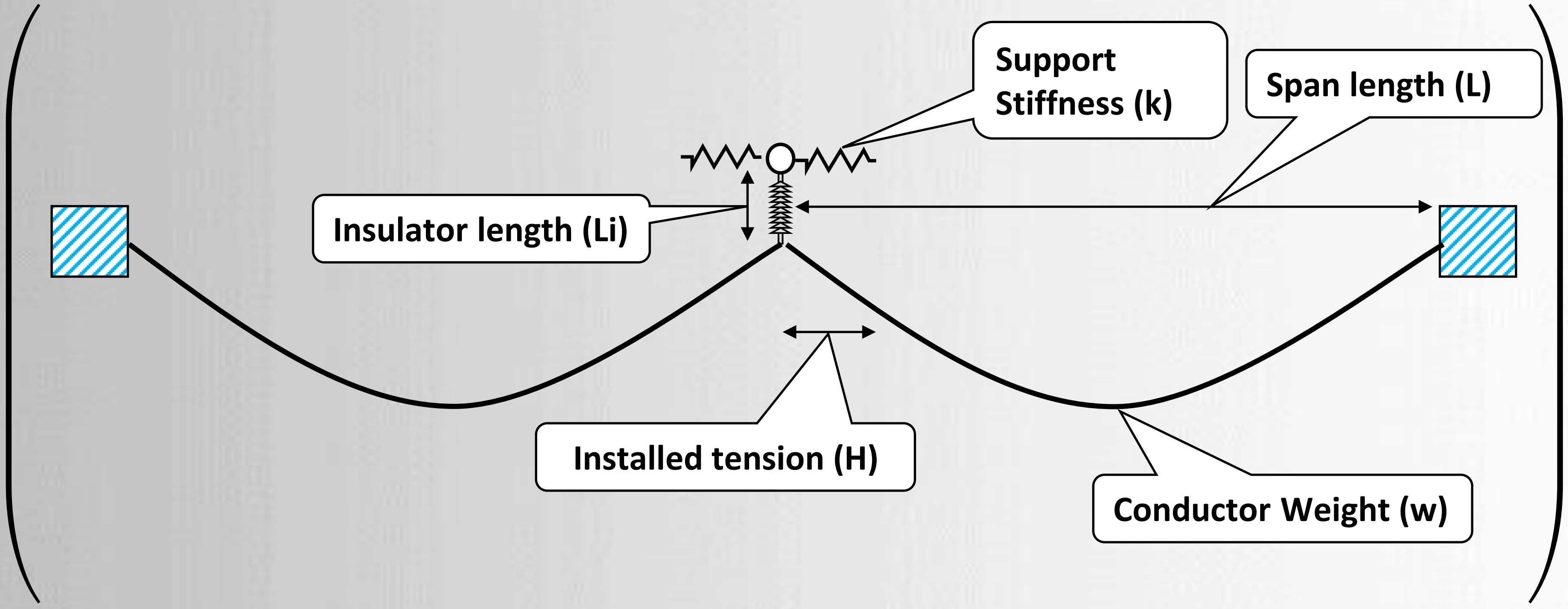
EPRI's Dynamic Impact Test Line -Research Objectives

- Develop confidence in broken wire load prediction though full-scale test results
- Include the impact of true conductor rupture
- Verify and calibrate accuracy of FEM models simulating broken wire
- Develop a simple, easy to use, empirically based formula for calculation of broken wire events

Leading Parameters

$$Dynamic\ Impact\ Factor = \frac{Peak\ Dynamic\ Load}{Everyday\ tension}$$

$$Dynamic\ Impact\ Factor = fn$$

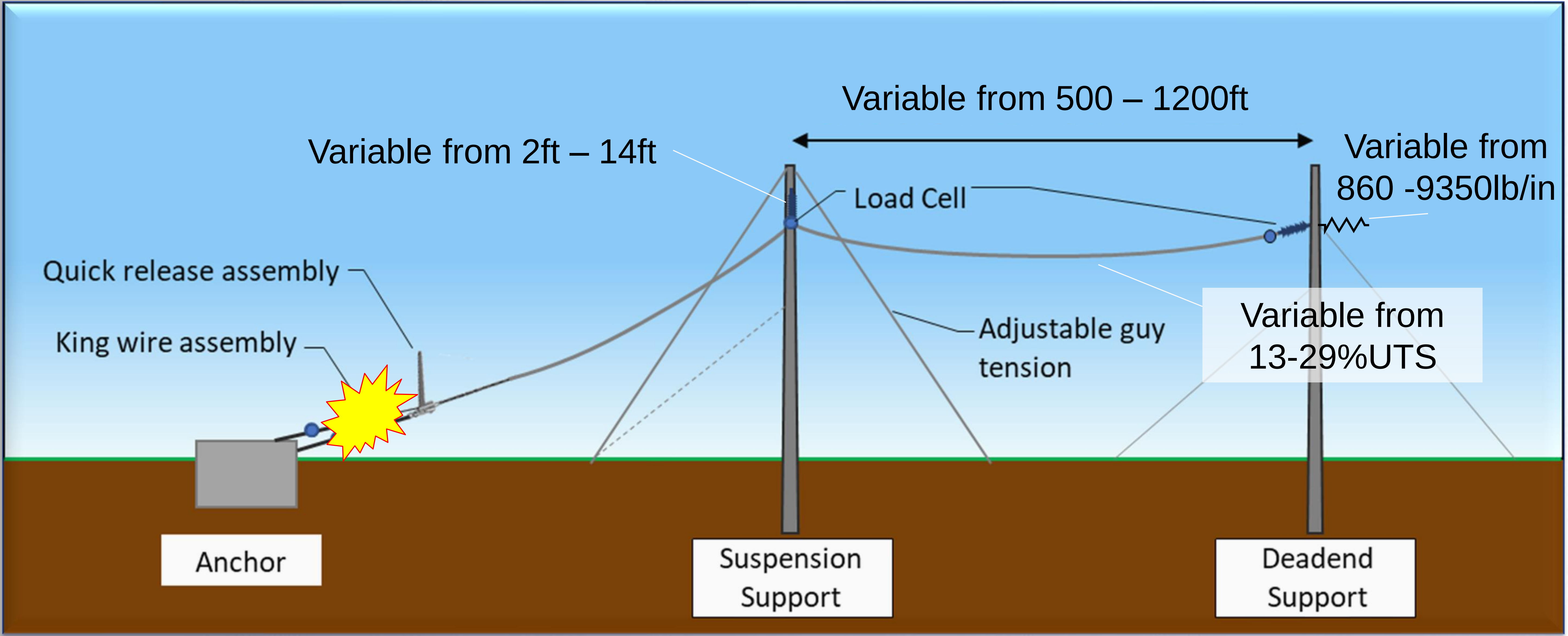


Past results range from 0.6 (*EPRI* 1997) *to* 2.4 *(Hydro Quebec 1997)*
Current results range from 0.70 to 2.0 (EPRI 2021-23)

EPRI's Dynamic Impact test line is designed to evaluate changes in all 5 parameters

Dynamic Impact Test Line Schematic

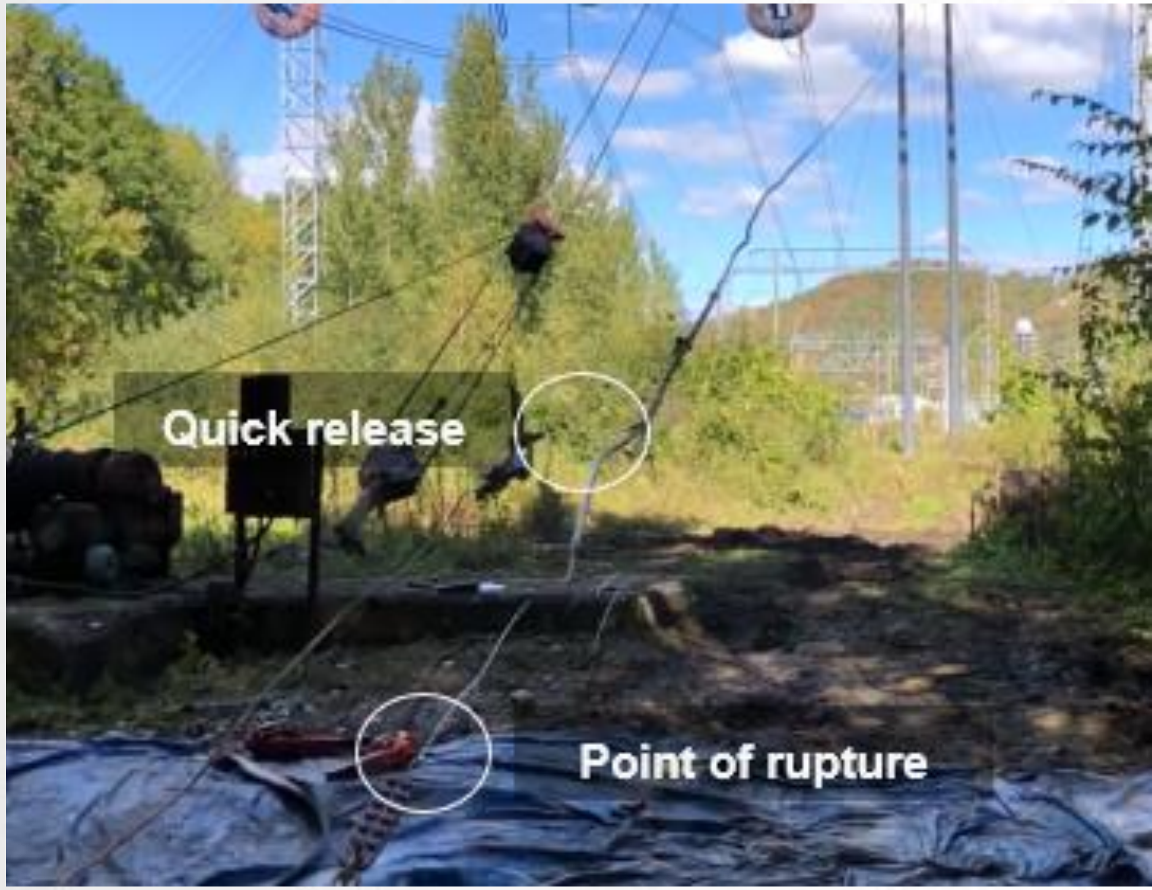
Critical Broken wire Scenario: Rupture one span away from strain structure



Impact of conductor rupture vs. quick release

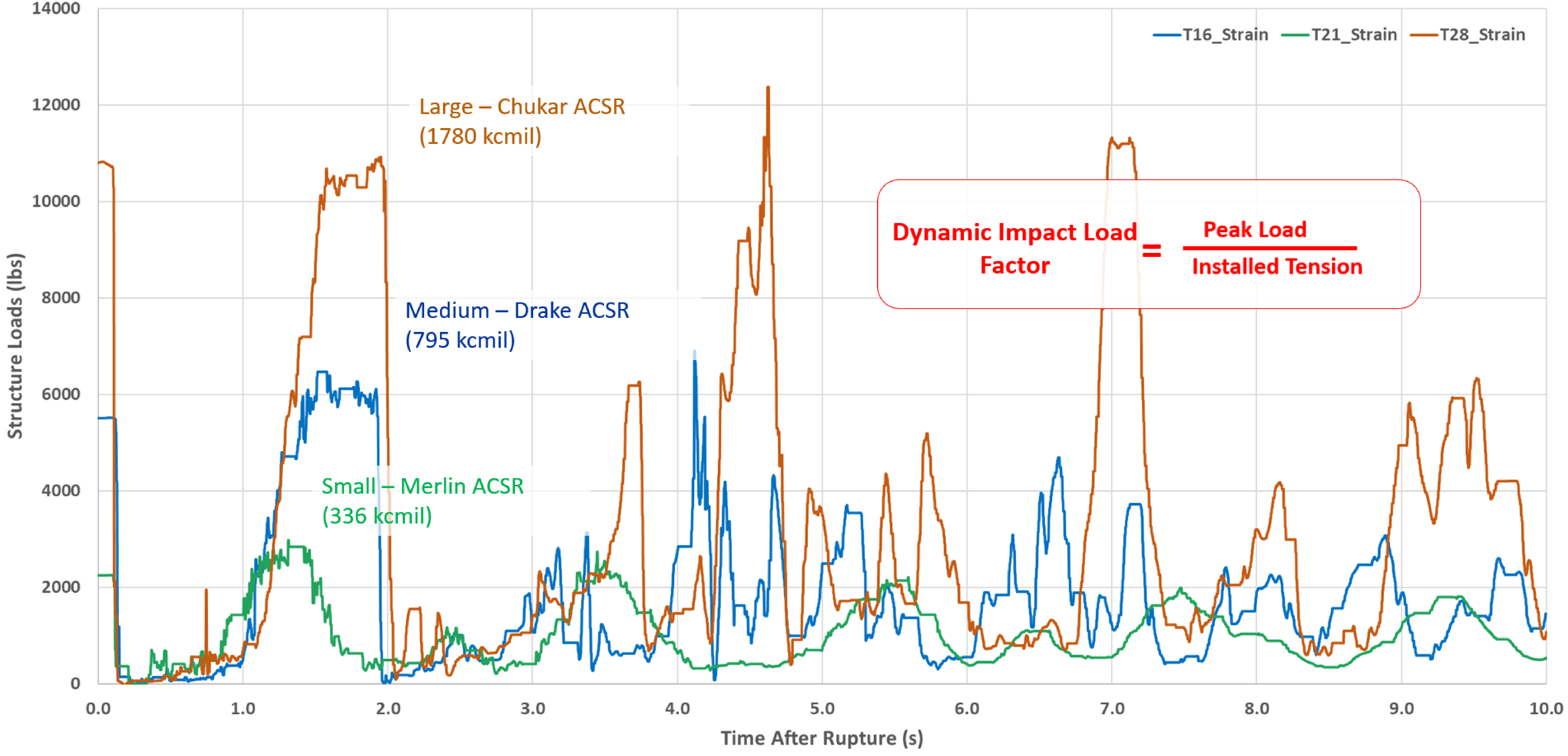
- Previous broken wire tests used quick release to simulated broken wires

Tests

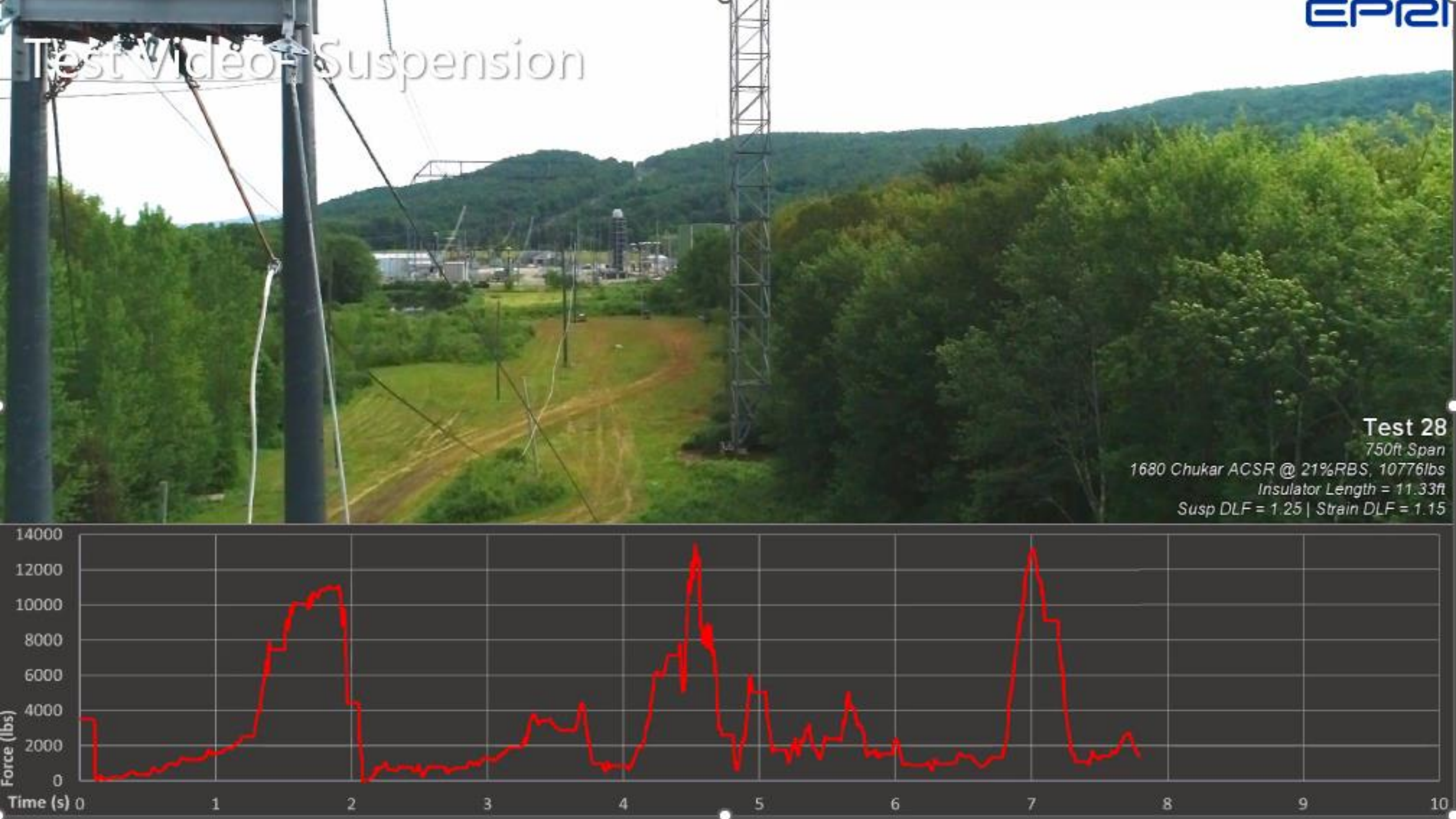


- Wire rupture has the potential to release additional axial shock load into conductor
- Wire rupture in tests achieved by 2 methods;
  - Rebar cutter – light conductors
  - Isolating king wire and allowing EDT to rupture it
- Conductor rupture compared to quick release results
  - Moderate increase (9%) in impact load at strain pole
  - No impact on suspension pole loads

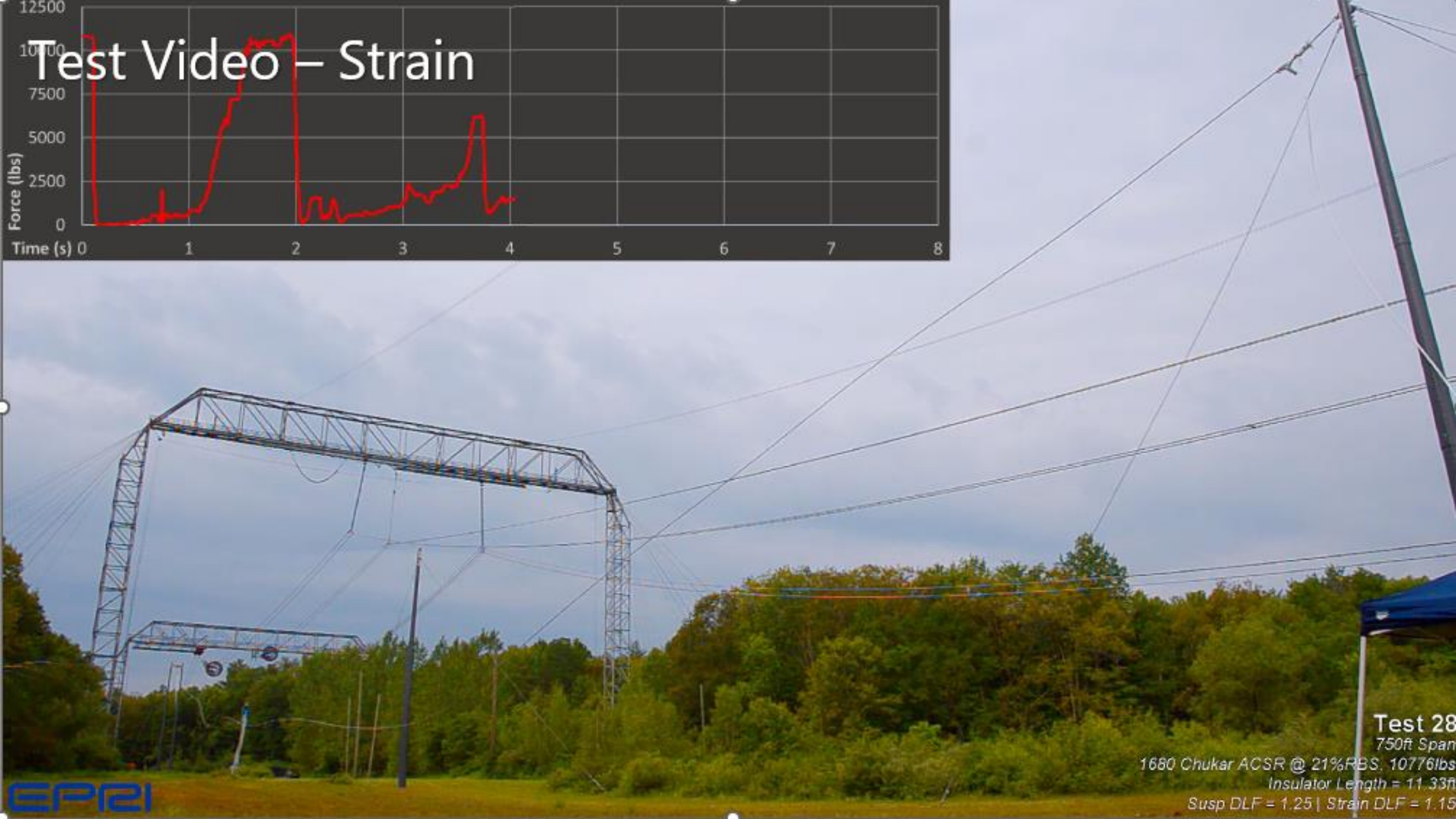
Broken Wire Test Time History



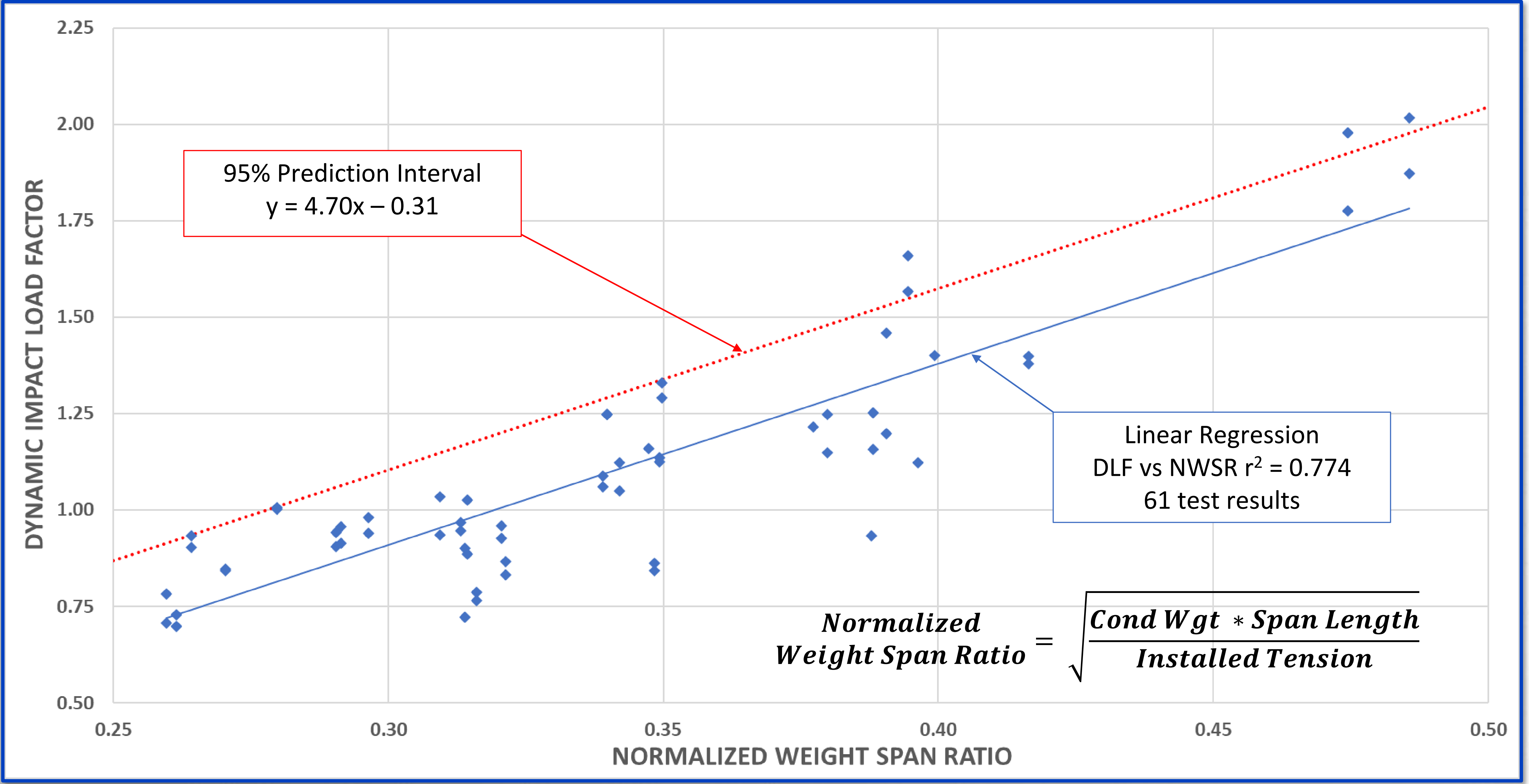
Test Video – Suspension



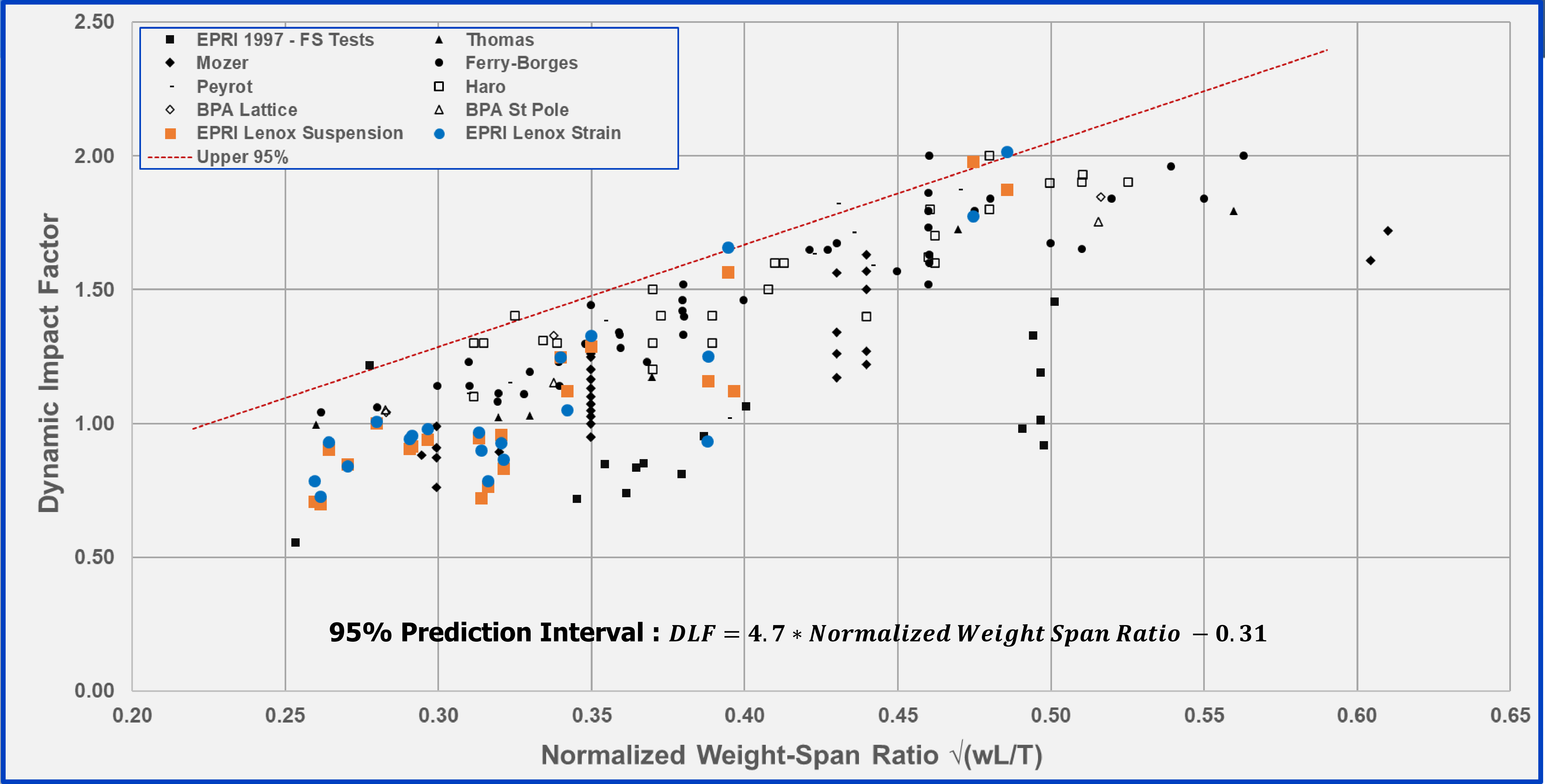
Test Video – Strain



Preliminary Results



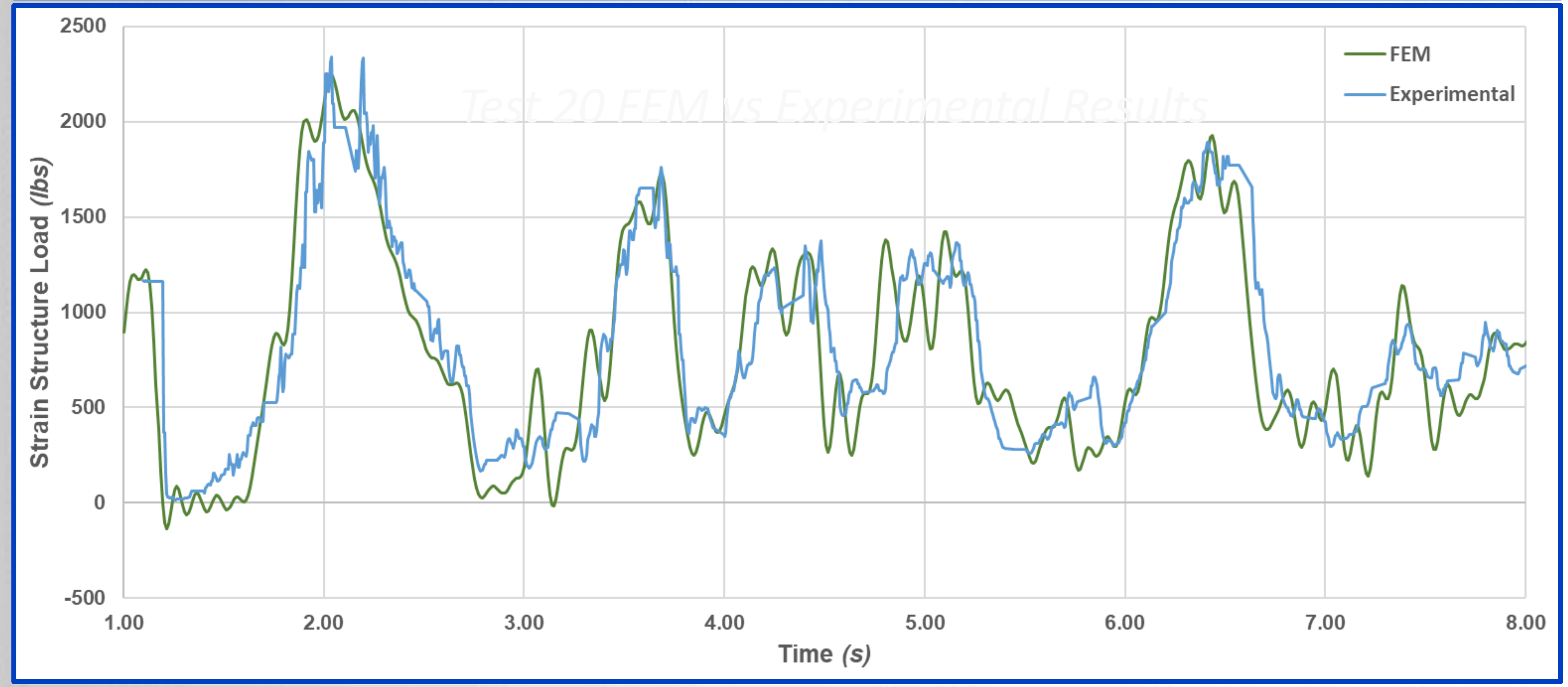
Preliminary Results vs Historical Results (full scale and model tests)



Calibrated Finite Element Modeling

- FEM is being completed in parallel with full scale testing
- Full scale testing is being used to calibrate an FEM model
- FEM will allow for extrapolation of line parameters beyond what is feasible at the Lenox site
- Initial results show strong correlation between FEM peak loads and experimental results
- Time histories of the FEM also show strong correlation with experimental results

Test Number	6	6_{FEM}	7	7_{FEM}	16	16_{FEM}	19	19_{FEM}	20	20_{FEM}
Suspension Structure Dynamic Load Factors	1.00	1.10	1.57	1.54	1.16	1.28	0.95	0.91	1.87	1.88
Strain Structure Dynamic Load Factors	-	-	-	-	1.25	1.18	0.97	0.90	2.02	1.92



Calibration of FEM model essential for accurate FEM predictions

Significant findings to date

- Strong correlation between Normalized Weight Span Ratio and Dynamic Load Factor
- Small ratio between strain and suspension tower loads (1.010)

L, w & H are the most significant variables

- Weak correlation between insulator length and DLF
- Varied (indeterminate) correlation between structure stiffness and DLF

Ongoing research to determine impact of Li & k

Ongoing research may produce refinements in empirically based DLF prediction

DLF - Empirically based Calculation

- 795 Drake ACSR Conductor – Unit Weight = 1.094 lb/ft
- Span Length = 1000ft
- Tension = 7934.5lb @ 32°F Initial (H/w = 7233.4ft / 2205m)
- Class H3, H-frame, FRP crossarm

$$\begin{matrix} Normalized \\ Weight\ Span\ Ratio \end{matrix} = \sqrt{\frac{Cond\ Wgt * Span\ Length}{Installed\ Tension}}$$

- Normalized Weight Span Ratio = $\sqrt{\frac{L * w}{H}}$ OR $\sqrt{\frac{L}{C}}$
- $= \sqrt{\frac{1000ft * 1.094\frac{lb}{ft}}{7935lb}} = 0.371$

Example applied to PLS CADD

- WSR = $\sqrt{\dfrac{1000ft * 1.094\frac{lb}{ft}}{7935lb}} = 0.371$
- DLF Preliminary Equation = 4.7 * WSR – 0.31
- DLF = 4.7 * 0.371 – 0.31
- DLF = 1.44
- Point Load = Tension * DLF = 7934.5lb * 1.44 = 11388lb

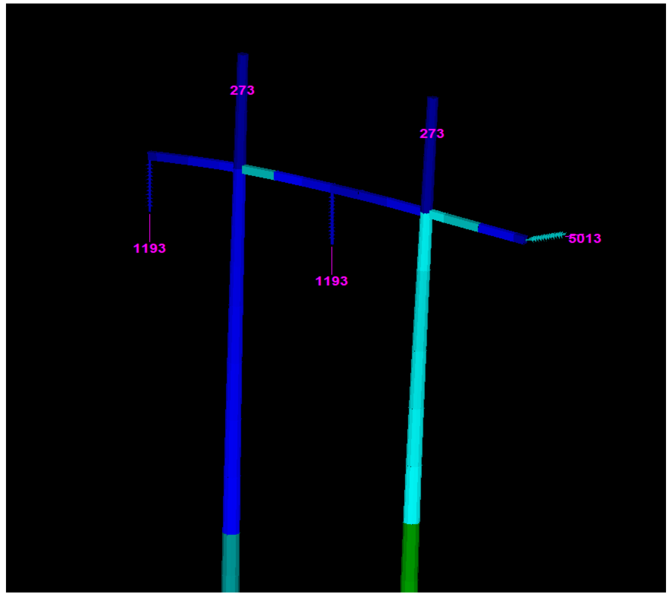
Note: This empirical prediction includes results for a range of insulator lengths and structure stiffnesses

DLF Modeling Method A – L2 Analysis – Adjust Tension %

1. Break line back conductors
2. Apply % Hor. Ten. Command, set target % = DLF

Description	Weather case	Cable condition	Wind Direction	Bisector Wind Dir (deg)	Wire Vert. Load Factor	Wire and Struct. Wind Load Factor	Wire Tension Load Factor
Broken Wire_Adjust Tension %	32 Deg F	Initial FE	NA+	NA	1	1	1

#1 Wire(s) Set Phase Span	#1 Command	#1 Value (%) (# subcond.) (lbs) (deg)	#2 Wire(s) Set Phase Span	#2 Command	#2 Value (%) (# subcond) (lbs) (deg)
2:3:Back	Broken Wire (# Broken Subconductors)	10	2:3:Ahead	% Hor. Ten. (changes V, T and L)	144



RESULT

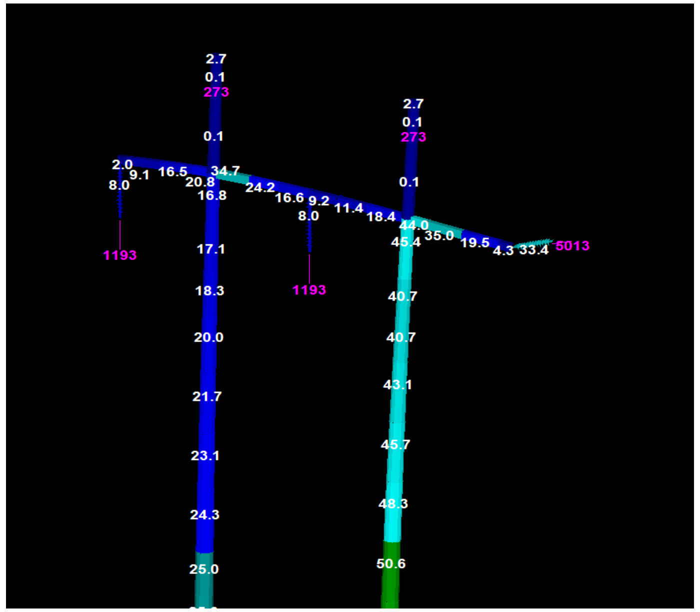
1. Warning Message
2. Resultant load = 5013lb

Warning

One or more of your load cases violates current requirements for finite element sag-tension. Currently finite-element sag-tension isn't compatible with '% Horiz. Tension' or '% Strands Broken' load adjustments. Results may be incorrect.

Continue displaying warning messages (click No to redirect this and future messages to a report window for remainder of this operation)?

Yes No



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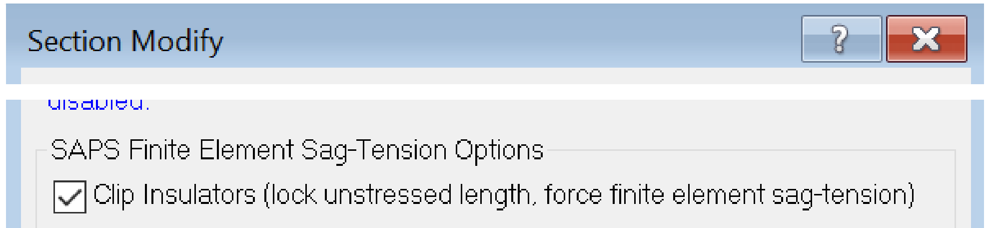
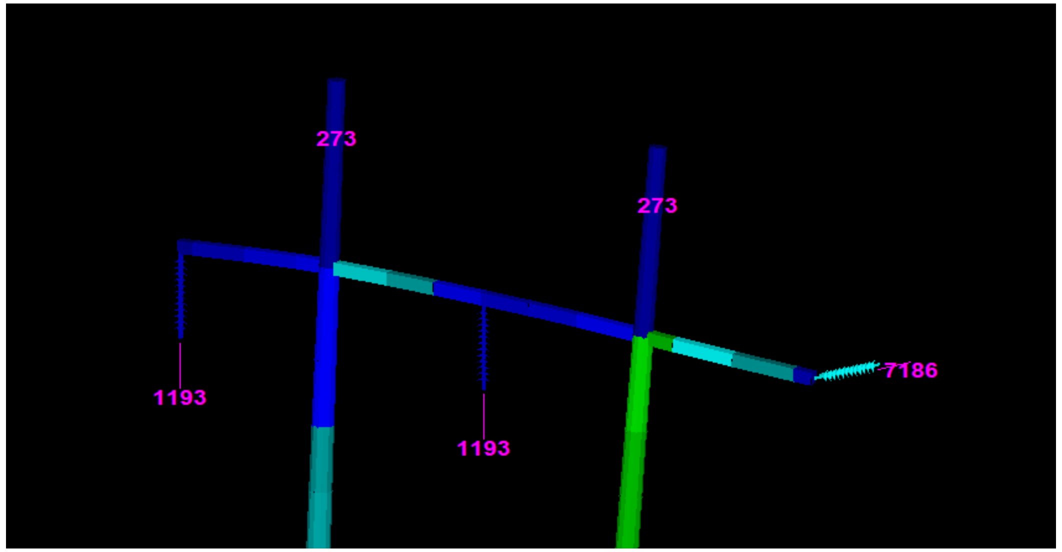
DLF Modeling Method B – L2 Analysis – Load Factor Application

1. Clip Insulators
2. Apply wire tension load factor = DLF
3. Break line back conductors

Description	Weather case	Cable condition	Wind Direction	Bisector Wind Dir (deg)	Wire Vert. Load Factor	Wire and Struct. Wind Load Factor	Wire Tension Load Factor
Broken Wire_LF	32 Deg F	Initial FE	NA+	NA	1	1	1.44

#1 Wire(s) Set Phase Span	#1 Command	#1 Value (%) (# subcond.) (lbs) (deg)
2:3:Back	Broken Wire (# Broken Subconductors)	10



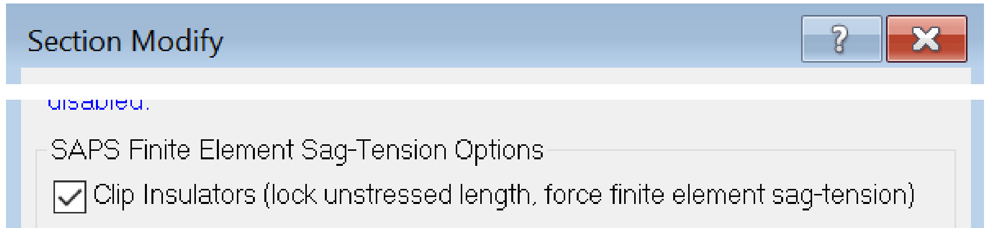


RESULT

Resultant load on Suspension = 7186lb (includes RSL after insulator swing out)

DLF Modeling Method C – L2 / L3 Analysis – Apply Point Load

1. Clip Insulators
2. Break line back conductors
3. Apply Add Long Load Command, set target load = Tension * DLF

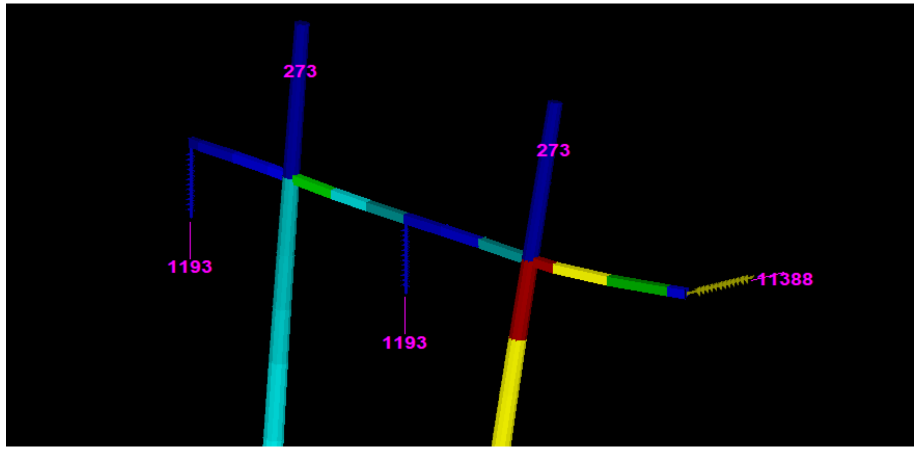


Description	Weather case	Cable condition	Wind Direction	Bisector Wind Dir (deg)	Wire Vert. Load Factor	Wire and Struct. Wind Load Factor	Wire Tension Load Factor
Broken Wire_Apply Point Load	32 Deg F	Initial FE	NA+	NA	1	1	1

#1 Wire(s) Set Phase Span	#1 Command	#1 Value (%) (# subcond.) (lbs) (deg)	#2 Wire(s) Set Phase Span	#2 Command	#2 Value (%) subcond (lbs) (deg)
2:3:Back+Ahead	Broken Wire (# Broken Subconductors)	10	2:3:Ahead	Add Long. Load (wire coord. system)	11388

RESULT

1. Resultant load = 11388lb
2. Xarm @ 122.9%
3. Pole at 143%



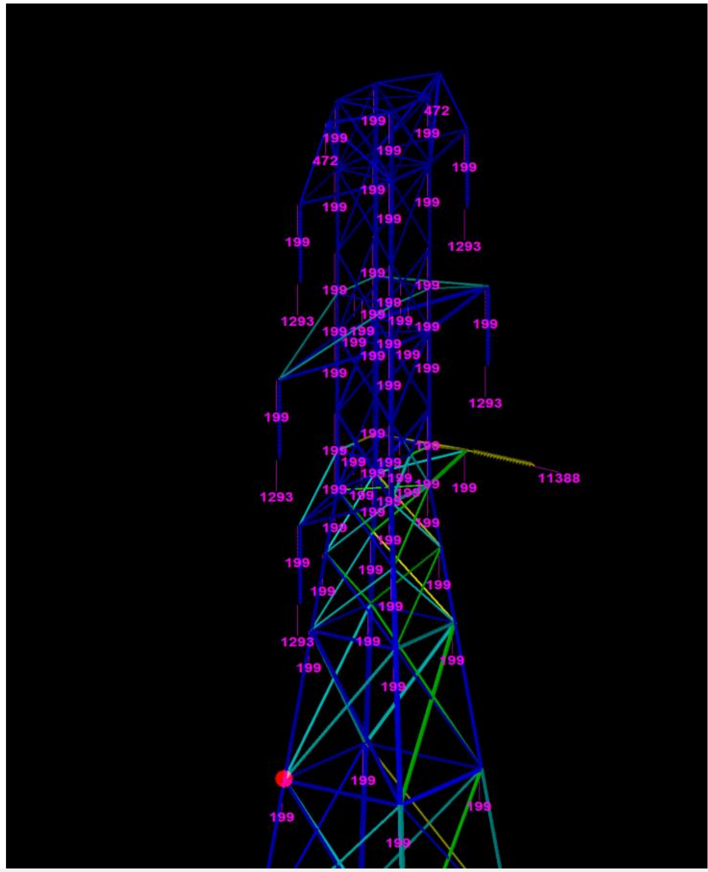
DLF Modeling Method C – L2 / L3 Analysis – Apply Point Load

~115kV DC Lattice Tower

1. Break line back conductors
2. Apply Add Long Load Command, set target load = Tension * DLF

Description	Weather case	Cable condition	Wind Direction	Bisector Wind Dir (deg)	Wire Vert. Load Factor	Wire and Struct. Wind Load Factor	Wire Tension Load Factor	Struct. Weight Load Factor	Struct. Wind Area Factor
Broken Wire_Apply Point Load	32 Deg F	Initial RS	NA+	NA	1	1	1	1	1

#1 Wire(s) Set Phase Span	#1 Command	#1 Value (%) (# subcond.) (lbs) (deg)	#2 Wire(s) Set Phase Span	#2 Command	#2 Value (%) subcond (lbs) (deg)
2:3:Back+Ahead	Broken Wire (# Broken Subconductors)	10	2:3:Ahead	Add Long. Load (wire coord. system)	11388



RESULT

1. Resultant load = 11388lb
2. Max Xarm Member @ 83.4%
3. Max Leg Member at 26.2%

PLS CADD modelling summary

- Method A (% Hor. Tension) – not appropriate for FE cables
- Method B (Wire Tension LF) – will include RSL of suspension insulators (strain structures will be accurate)
- Method C (specify load) – Will apply specified dynamic load irrespective of cable model

Cascading Failure Loads

Resiliency and longitudinal cascades

- <u>All</u> conductors connected to the structure are affected

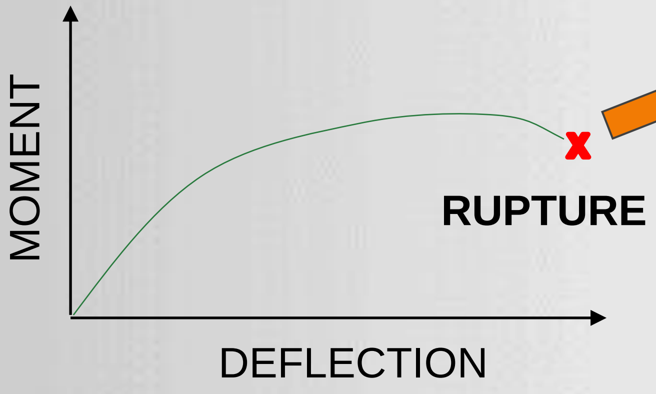
Structure Types that are sensitive to cascades

- Structures not designed without specific consideration for longitudinal loads
- Structures that rely on longitudinal support of shieldwire
- Self-supporting structures with reduced longitudinal capacity
- Planar structures are at risk for longitudinal cascades
  - H-frames, especially wood & lattice frames





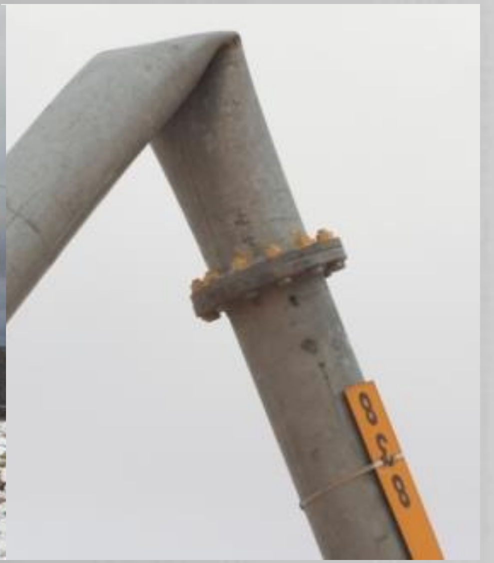
Consider Impact of Material Type

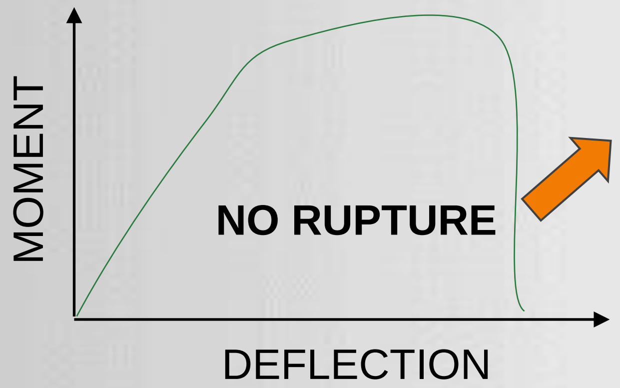


LARGE AMOUNT OF ENERGY RELEASED

CASCADE CONTINUES

- Wood poles fail suddenly upon rupture



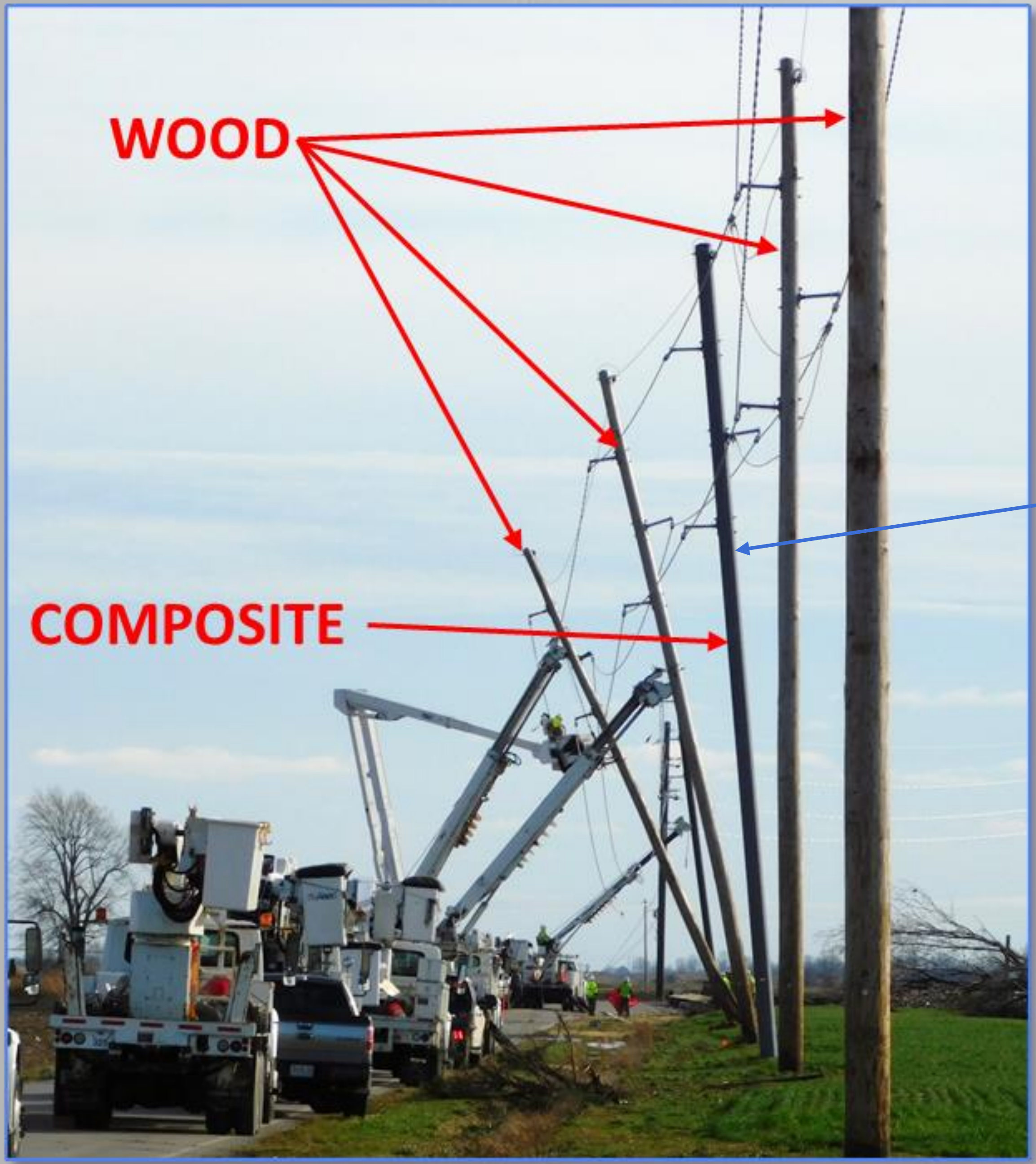


DAMPING OF DYNAMIC LOAD

CASCADE EXTINGUISHED MORE READILY

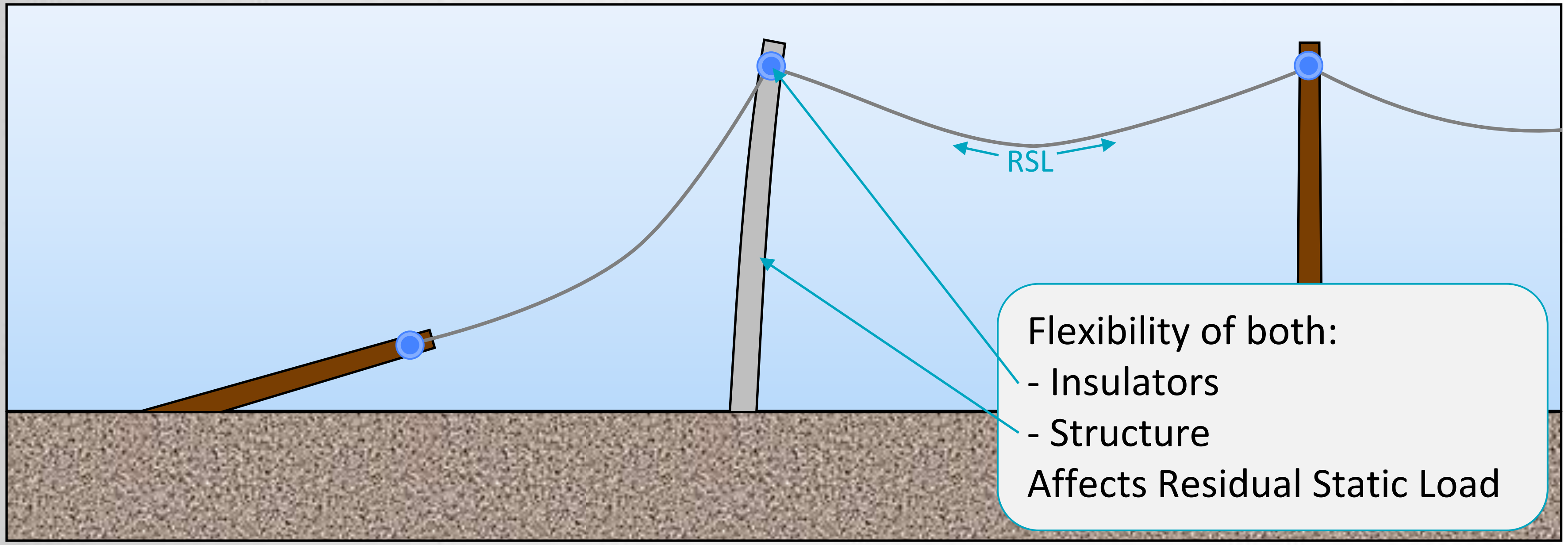
- Steel and lattice structures absorb energy

Use of Composite poles in wood pole lines to increase resiliency



- Some utilities are using composite structures to arrest cascades in wood pole lines
  - What loads should the composite pole resist?
  - Can it be too flexible (allowing too much deflection on next wood pole)

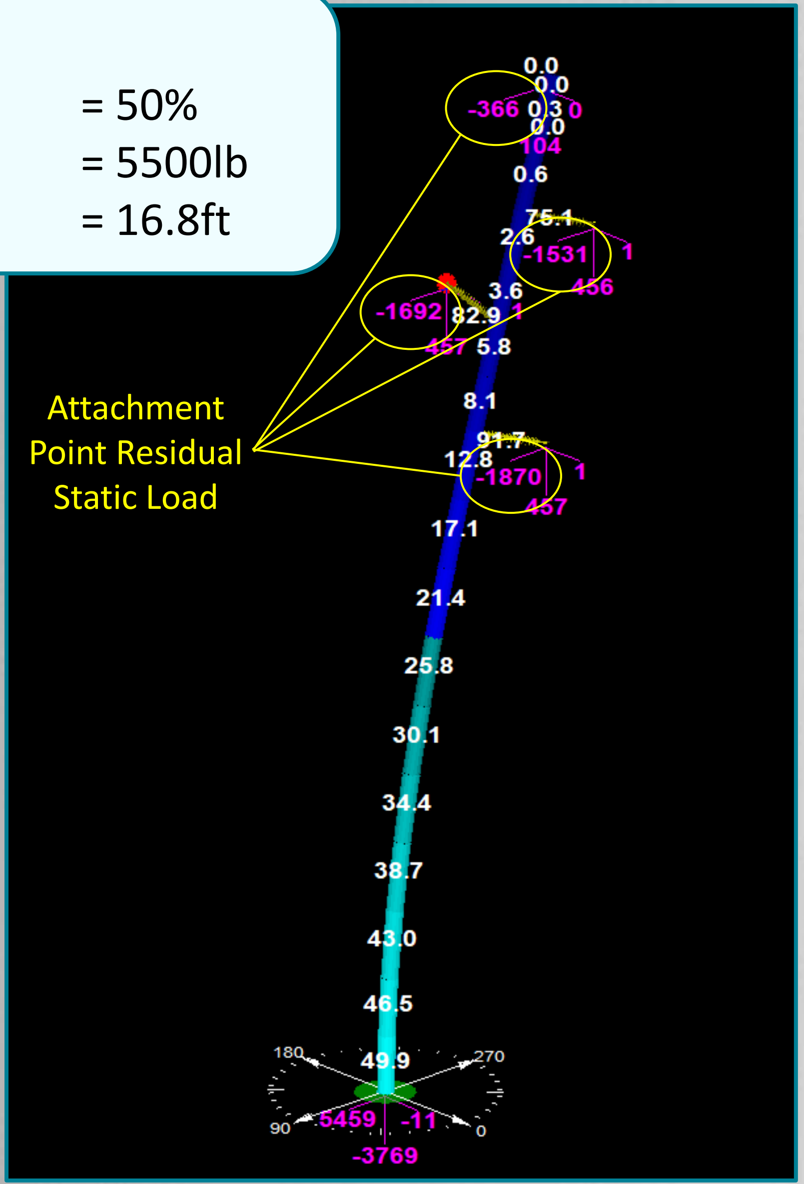
Note: Anti – cascade composite pole is a tangent structure with standard post insulators



Equivalent Composite vs. steel pole - cascade resistance

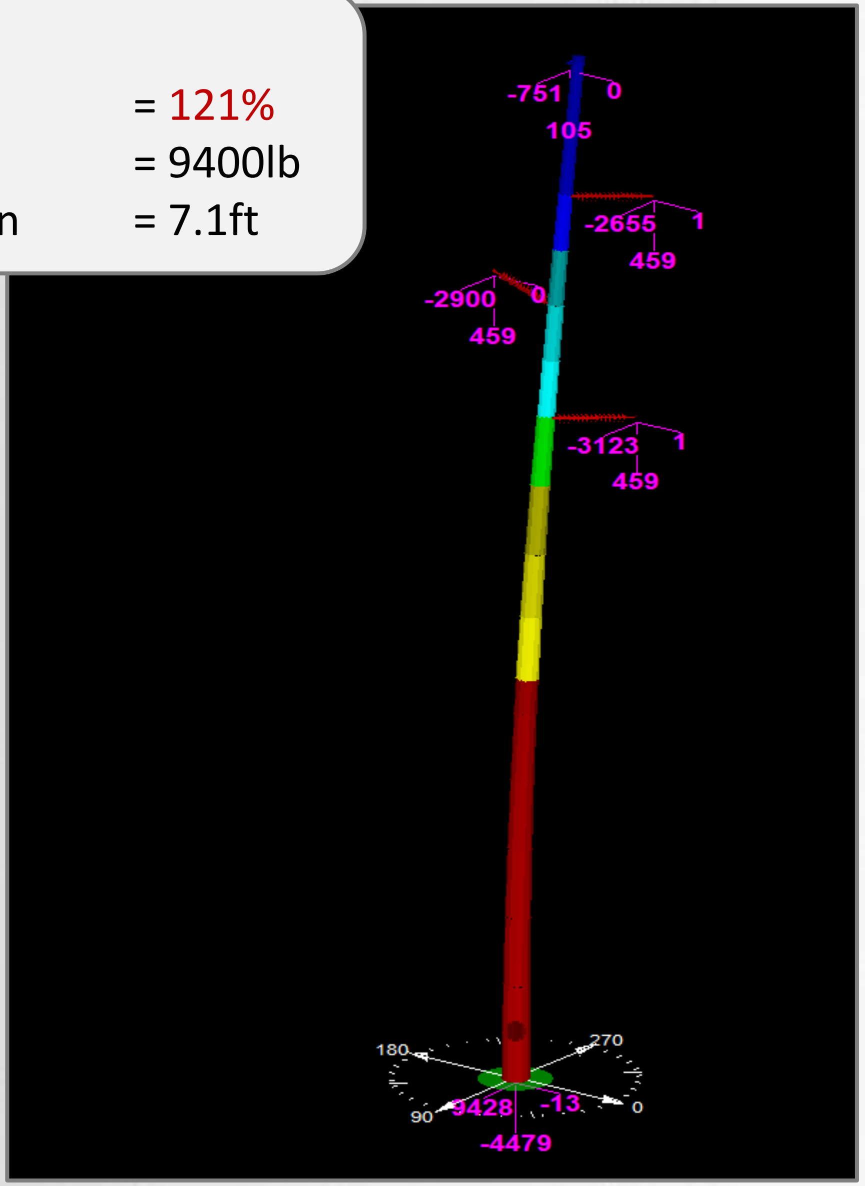
FRP Pole

Utilization	= 50%
RSL	= 5500lb
Tip Deflection	= 16.8ft



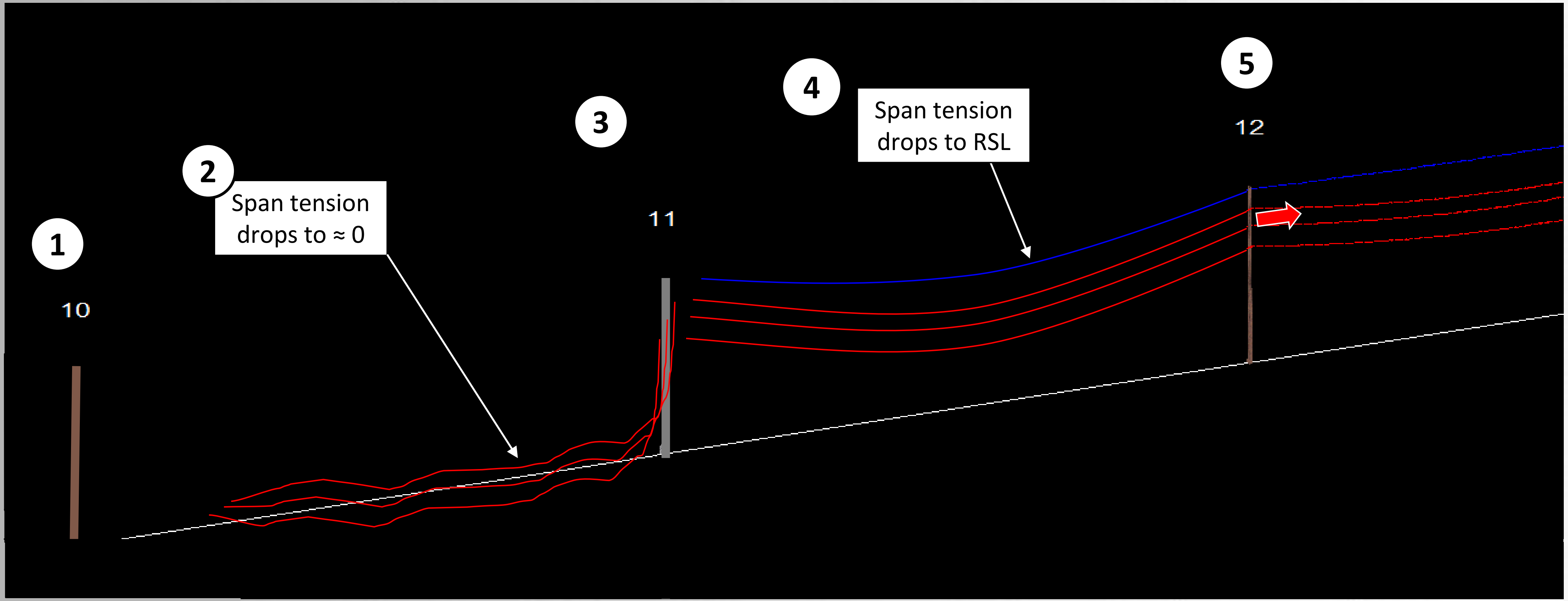
Steel Pole

Utilization	= 121%
RSL	= 9400lb
Tip Deflection	= 7.1ft



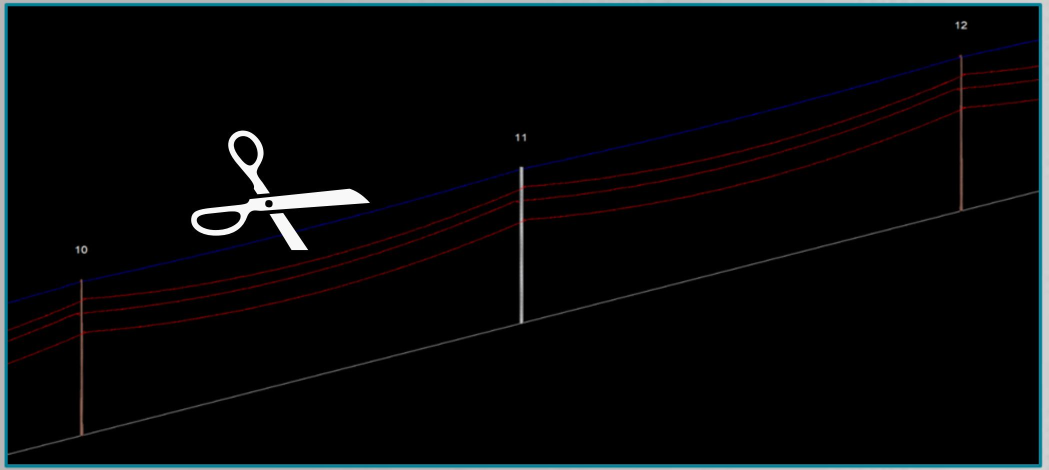
Composite + Wood pole line: Longitudinal Cascade Sequence

1. Structure fails longitudinally
2. Loss of tension in all wires of compromised span
3. Adjacent structure & insulators deflect due to unbalanced load
4. Intact span loses tension, settles at residual static load (RSL)
5. Tension imbalance on next wood pole



RSL Modeling – Loads on Composite structure (traditional method)

1. Model Transmission Line using all M4 models (level 4 cable, clipped in)



Setup Notes				Anti-Cascading Pole Results			
Notes	Test #	Case	Weather	Pole Usage *%*	Insulator Usage *%*	Combined RSL *lb*	Tip Δ *ft*
Adjacent structures modeled as M4 models	35	3	30° F | 0mph Wind | 0" Ice	49.9	91.7	***5459***	16.79

2. Create Load Case

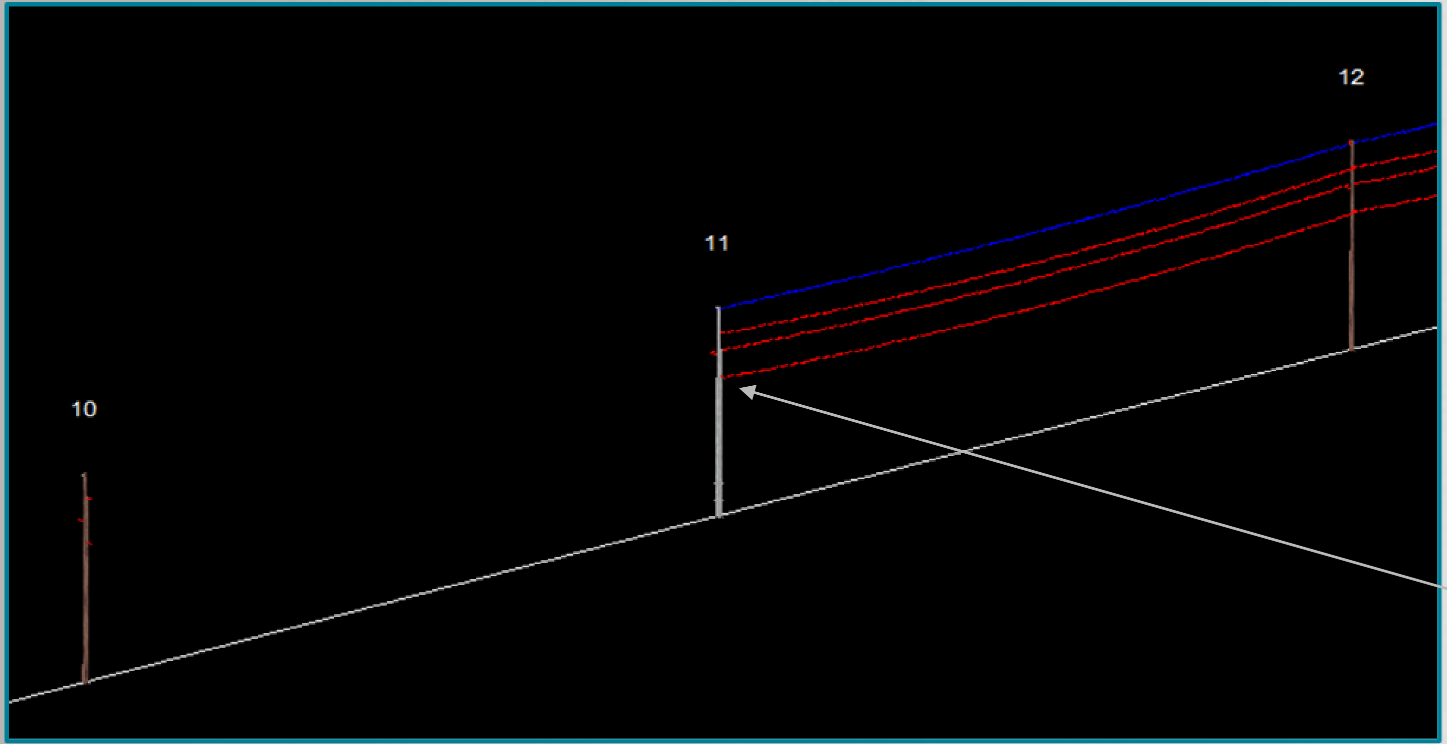
Description	Weather case	Cable condition	Wind Direction	Bisector Wind Dir (deg)	Wire Vert. Load Factor	Wire and Struct. Wind Load Factor	Wire Tension Load Factor
All Wires Broken_30 deg F_comp pole iteration_r0	30 Deg F	Initial FE	NA+	NA	1	1	1

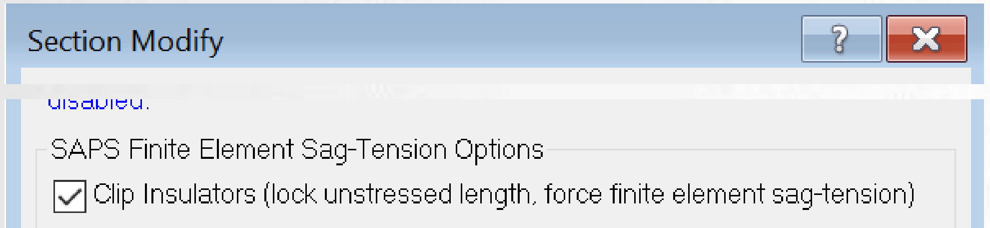
Structure Loads Criteria

	Adjust Cable Loads	#1 Wire(s) Set Phase Span	#1 Command	#1 Value (%) (# subcond.) (lbs) (deg)
25	Yes	Back Spans	Broken Wire (# Broken Subconductors)	10

RSL Modeling - Loads on composite pole and first wood pole (revised method)

1. Model Transmission Line using all M4 models (L4 cable , clipped in).
2. One-way stringing applied to anti-cascading structure





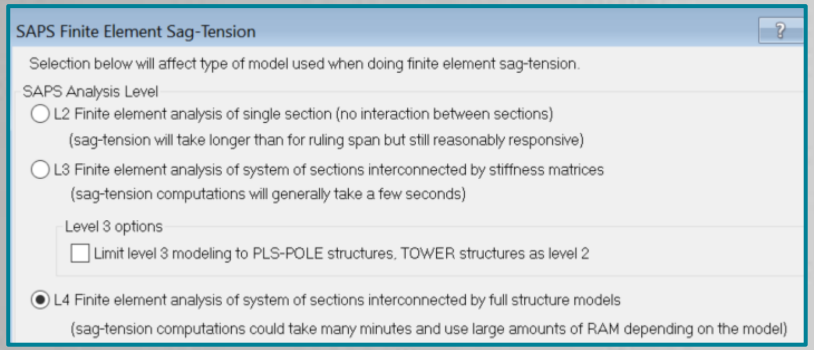
Dead end - section starts here

3. Create Load Case
   – No “Adjust Cable Loads” modifications are required

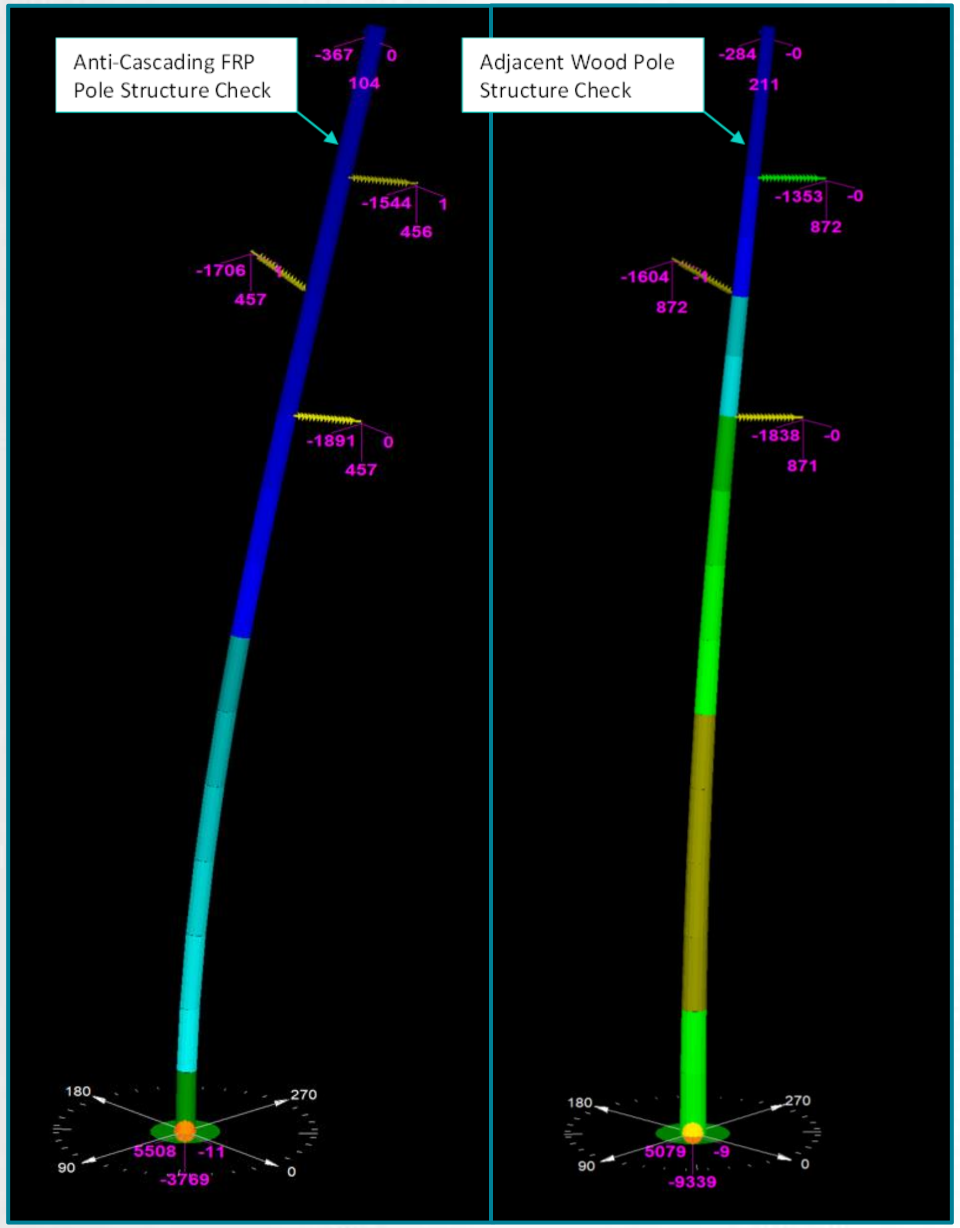
RSL Modeling - Loads on composite pole and first wood pole (revised method)

3. Change Modeling Settings to assume FE analysis

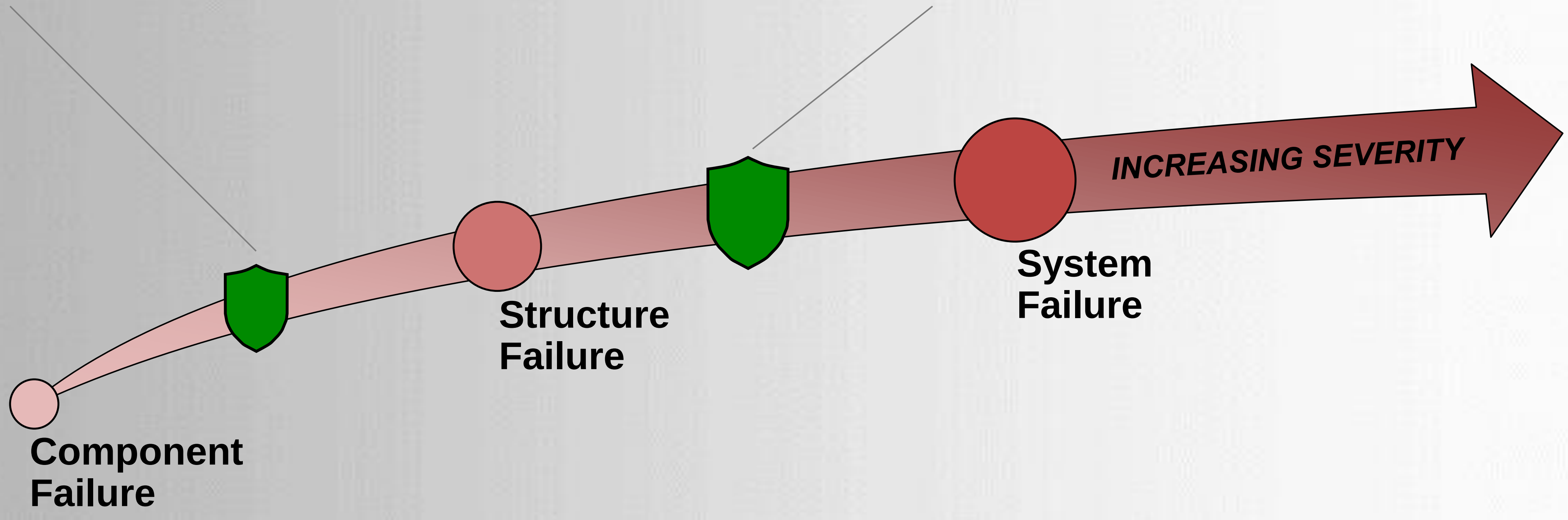
4. Conduct Structure Check on anti-cascading and adjacent structure



Case Study Result: Composite structure not too flexible

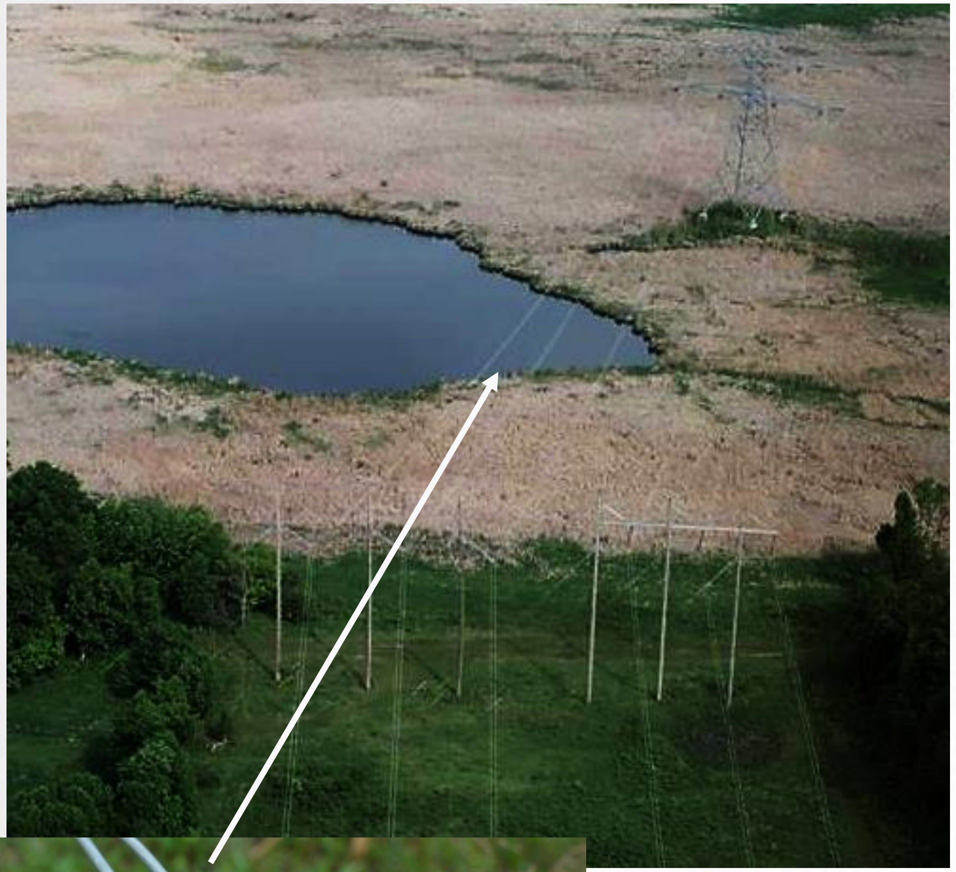


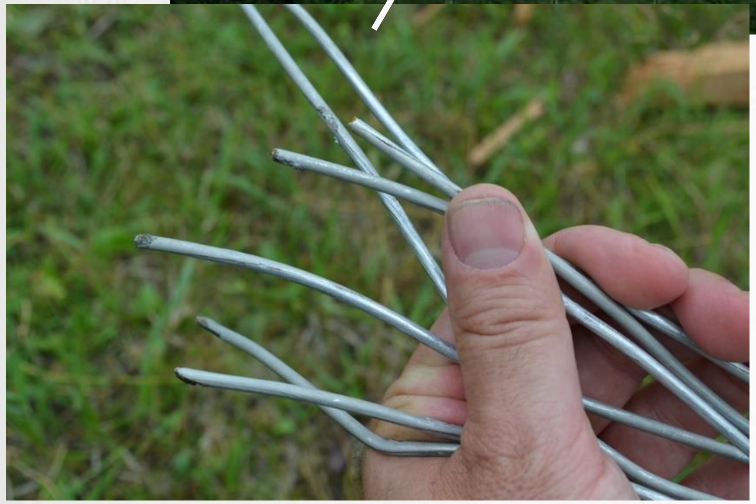
CASE STUDY INVOLVING BOTH BROKEN WIRE AND CASCADE



Event Sequence

- Broken wire event on damaged shield wire during wind storm
- Damage from lightning suspected or conductor contact (galloping)
  - Of 7 strands, only 2 were fully intact
  - 2 strands were burned through
  - 3 strands were compromised





Event Sequence

- Excessive deflection resulted in failure of wood pole
- Guy failure on a stay from slippage with corroded internal springs in guy grip locking mechanism

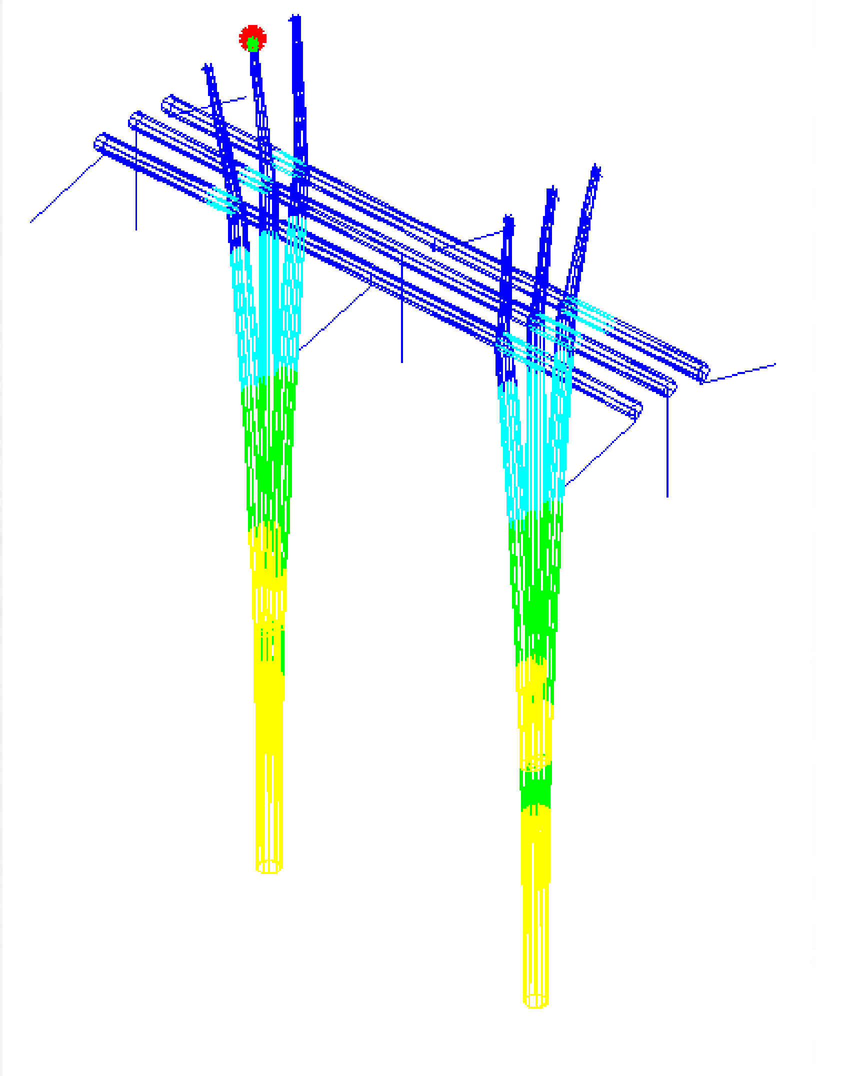
Event Sequence

- Dead end insulator assemblies failed on strain structure
- Cascade continued until next anti-cascade tower

Application of residual static load (RSL) on all phases

RSL = Net longitudinal load following removal of conductor tension in adjacent span, considering both insulator and structure deflection

- Application of RSL is elementary in PLS CADD
  - Provided that, as a minimum -
  - Level 2 cable model is used for rigid (self- supporting lattice) structures
  - Level 3 cable model is used for flexible structures (e.g. steel, wood & composite poles)
  - Additional reductions from purpose designed load reduction techniques may be relevant
- NOTE: Application of RSL to all phases may well not dominate many axisymmetric structures
  - i.e. Overturning from extreme wind > overturning from RSL
- Additional reduction factor for back – tension of intact wires may be applicable to suspension / tangent structures (0.8?)



RSL LOADING DID NOT CONTROL THIS 230kV STEEL POLE

Advanced Sag & Tension
IEC
FAC 008/009
Materials Management
NESC
PLS-CADD®
LiDAR Modeling
Structural Analysis
CSA
Distribution
Pole Analysis
CENELEC
Transmission
NERC Ratings
Line Optimization
Project Estimating
FAC 003
ASCE
Joint Use
PLS-POLE
GO95
Vegetation Management
1000+ Users in 100+ Countries
Storm Hardening
IEEE
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Thank you for your attention

Questions/ Comments?

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