Incab

Sag and Tension Theory 102

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President

August 29, 2024

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PURPOSE AND LEARNING OBJECTIVES

This course will teach you the basics of sag and tension theory.

After this class, you will be able to:

1. Explain what a sag chart is
2. Explain what inputs go into generating a sag chart
3. Explain what outputs are included on a sag chart
4. Explain the Ruling Span concept and when it applies to sag and tension calculations
5. State how to calculate the actual sag or tension in a particular span in a ruling span segment
6. Explain the differences between spans that are “mechanically coupled” versus spans that are “mechanically independent” and how this affects sag and tension calculations
7. State why and how MRDT/MRCL and ZFSM should be checked as part of the sag and tension data generation process

Incab University "School of Excellence in Fiber Optics"
Agenda

- Introduction
- Learning Objectives
- Presentation
- Q&A (Technical questions only)
- Let's start!

An Acknowledgement

You likely have heard it said that “We stand on the shoulders of giants”

This is especially true for today’s presentation

I want to thank **Joe Renowden** for most of today’s material

Joe is still active, and he consults, most notably on what could be called “CSI: Failed Stuff”

So, if you are dealing with a problem with any cable, fitting, or just about anything else that has broken/failed when it should not have, reach out to him at:

Joe Renowden, P.E.
561-371-2744
joe_renowden@ieee.org

Now let’s get to today’s presentation…

Sag and Tension
Foundational Concepts Review

This presentation builds on concepts presented in “Sag and Tension Theory 101”

Let’s recall four fundamental concepts we learned in that earlier presentation:

1. Aerial cables expand and contract with **changes in temperature**
    - “**Elongation**” is the term we use for these changes
    - Metallic cables change a lot, relatively
    - Non-metallic cables (such as ADSS) change a little, relatively
    - Cables with mixed construction are somewhere in between
    - Elongation changes caused by temperature changes are **elastic** (= reversable) within the normal operating temperature range of aerial cables

Sag and Tension

Foundational Concepts Review

Continuing our recollection…

2. Aerial cables undergo “**creep**” which is a permanent, “**plastic**” (= irreversible) increase in elongation
    - You can think of creep as the cable being stretched over time by the tension on it
    - The tension comes from the cable’s own weight
    - Creep is one cause of the difference between “**initial**” sag and tension (at installation) and “**final**” sag and tension (taken as 10 years later)
        - The other cause is plastic elongation due to wind and/or ice loading

Comment: If there were no plastic elongation in a cable over time, then there would be no difference between initial and final sag and tension

Sag and Tension

Foundational Concepts Review

Concluding recollections…

3. The effects of 1 and 2 taken together with design conditions (assumed “loading conditions”) plus any applied limits on sag or tension will determine the final sag and tension values for a cable

4. The values that result from 3 make up a sag chart

Let’s look at the inputs, the calculation process, and then the sag charts that result

Sag and Tension

Inputs - Context

Two programs commonly used in the USA (apologies to rest of world) are:

- Southwire®'s Sag10® - This software traces its roots back to Alcoa software written for mainframe computers (remember those?) in the 1950's
  - The original version was a computerized implementation of the classical graphic method of producing sag chart data on a "light table"
  - Southwire maintains today's version, and you can find information about it at their website www.southwire.com/sag10

- Power Line Systems®'s PLS-CADD – In addition to generating sag and tension data, PLS-CADD performs functions such as spotting structures and checking clearances
  - Information about PLS-CADD at https://www.powerlinesystems.com/plscadd

➔ These two programs have (hugely) **different human user interfaces** (HUI), but the **sag and tension calculations** are **done using the same (basic) methodology**!

Sag and Tension

Inputs - Context

If both Sag10® and PLS-CADD are making sag and tension calculations using the same (basic) methodology, then that leads to two questions:

1. How do we know that is true?
    - Related question: Why the "basic" caveat?

2. Assuming it is true, what is the shared methodology?

Let's look at each question…

Sag and Tension

Inputs – Sag Coefficients

Question 1 – How do we know that both Sag10® and PLS-CADD are making sag and tension calculations using the same (basic) methodology?

Answer: Because both are using at least two sets of coefficients that describe

1. A 4th order polynomial that models the initial stress-strain curve for a cable, and
2. A 4th order polynomial that models the final stress-strain curve for a cable

Follow up question: How do we know this?

Sag and Tension

Inputs – Sag Coefficients in Sag10®

In Sag10, the polynomial coefficients are part of a "Chart"

For "Drake" (795.0 kcm 26/7 ACSR), the chart is 1-537

Sag and Tension

Inputs – Sag Coefficients in Sag10®

Here is what chart 1-537 looks like:

```
CHART # 1-537      TEST TEMP= 70. DEG F
  -1213.0   44308.1  -14007.0   -37618.     30676.     64000.00000
   -544.8   21426.8  -18842.0     5495.         0.          .00128
    -69.3   38629.0    3998.1   -45713.0    27892.     37000.00000
     47.1   36211.3   12201.4   -72392.0    46338.          .00064
```

Yikes! What does this all mean?

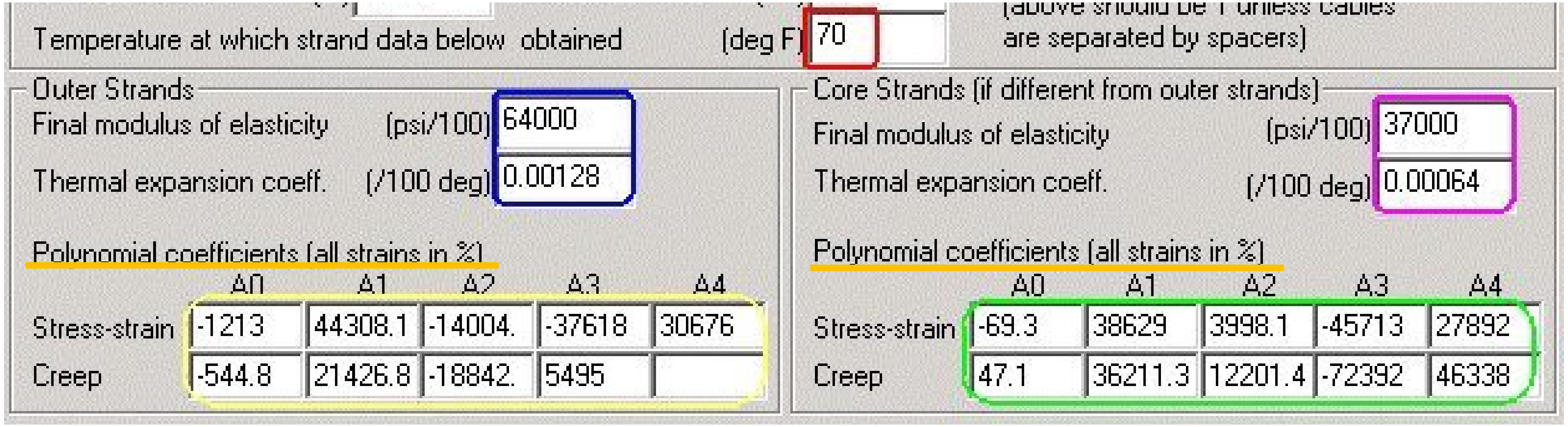
Sag and Tension

Inputs – Sag Coefficients in Sag10®

Here is what the data means:

CHART # 1-537 TEST TEMP= 70. DEG F

-1213.0	44308.1	-14007.0	-37618.	30676.	64000.00000
-544.8	21426.8	-18842.0	5495.	0.	.00128
-69.3	38629.0	3998.1	-45713.0	27892.	37000.00000
47.1	36211.3	12201.4	-72392.0	46338.	.00064



Sag and Tension

Inputs – Sag Coefficients in PLS-CADD

In PLS-CADD, the polynomial coefficients are part of a "wire file" (file type = .WIR). Here's one:

```
TYPE='CABLE FILE' VERSION='4' UNITS='US' SOURCE='DATABASE' USER='NextEra Energy Resources' FILENAME='539737 InSky OPGW S 48U
(2x24) 13.5mm 65kA2·s 88kN 1-1450'
Incab InSky OPGW S 48U (2x24) 13.5mm 65kA2·s 88kN(0.530, 48f max, 65.1kA2s@210C,) - Data by ETS 05/2024
0.154
0.530
0.362
19814
DATA ON THIS LINE IS NOT USED (Chart 1-1450)(MRDL = 16639)
172.7 167351.0 -24582.8 -91415.0 78623.0
404.5 102518.6 119106.6 -225839.0 90157.0
174000.0
.00082
.0 .0 .0 0. 0.
.0 .0 .0 0. 0.
.00000
.00000
76
0 ; num_pts
1 ; cable_file_type
0.0 0.0 0 0 0.5 0.5 0.0 0.0 0
```

So, the concept is the same, but the presentation/HUI is different in the two programs

Sag and Tension

Inputs – Sag Coefficients in PLS-CADD

And notice that…

```
TYPE='CABLE FILE' VERSION='4' UNITS='US' SOURCE='DATABASE' USER='NextEra Energy Resources' FILENAME='539737 InSky OPGW S 48U
(2x24) 13.5mm 65kA2·s 88kN 1-1450'
Incab InSky OPGW S 48U (2x24) 13.5mm 65kA2·s 88kN(0.530, 48f max, 65.1kA2s@210C,) - Data by ETS 05/2024
0.154
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174000.0
.00082
.0 .0 .0 0. 0.
.0 .0 .0 0. 0.
.00000
.00000
76
0 ; num_pts
1 ; cable_file_type
0.0 0.0 0 0 0.5 0.5 0.0 0.0 0
```

So, the concept is the same, but the presentation/HUI is different in the two programs

Sag and Tension

Inputs – Sag Coefficients Observations

You may have noticed two details and be wondering about those:

1. We said that there are two (2) sets of polynomial coefficients, but chart 1-537 seems to show four (4). Why?

2. In the PLS-CADD wire file using chart 1-1450, there are a bunch of zeroes where there are values in the 1-537 chart. Why?

Glad you noticed! Here's why....

Sag and Tension

Inputs – Sag Coefficients Observations Explained

Why does chart 1-537 seem to have four sets of coefficients, not just two?

Answer: Because it was common practice a long time ago for coefficients for ACSR conductor to be separated into those for the aluminum outer layer(s) and those for the steel core

- This permitted “scaling” an ACSR conductor design up or down (to better meet specific ampacity requirements, for example) without having to do a new set of stress-strain and creep tests

- The scaling was done by keeping the %steel relative to the %aluminum constant
    - Note that for OPGW “matching” %steel content to that of an existing chart is how a chart is usually assigned to one of these cables

Sag and Tension

Inputs – Sag Coefficients Observations Explained

Why does chart 1-1450 have a bunch of zeros where 1-537 has coefficients?

Answer: Because the second pair of coefficients would only be needed if the aluminum and steel were considered separately

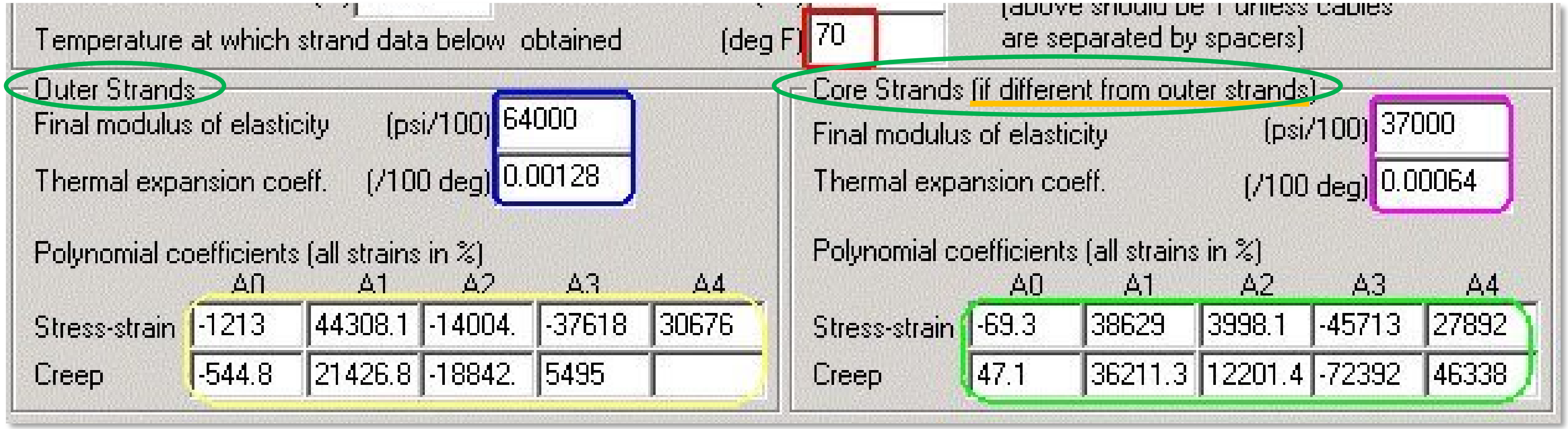
- Homogenous cables (only one material) do not need the second pair of coefficients – AAC, AAAC, ACS, galvanized steel cables, etc.

- "Composite" cables (two or more materials) tested as a complete cable do not need the second pair of coefficients – Notably OPGW (sometimes)

Sag and Tension

Inputs – Sag Coefficients Observations Explained

You can see the distinction on the Sag10® input screen we have already seen:



Sag and Tension

Inputs – Sources of Sag Coefficients

Both Sag10® and PLS-CADD have libraries of charts available

- In Sag10®, you can enter a chart number for a cable, plus a chart number will automatically come up for many standard conductors
- PLS-CADD has a library of wire files by cable type and manufacturer on their website – Each wire file has the sag coefficients included in it

Now we know about sag coefficients, what other inputs are needed?

Sag and Tension

Inputs – Besides Sag Coefficients

Both programs also need basic cable information:

1. Cross-sectional area (square inches or mm^2) – Sometimes aluminum and steel are separated

2. Outside diameter (inches or mm)

3. Unit weight (lb/ft or kg/km) – Also sometimes separated

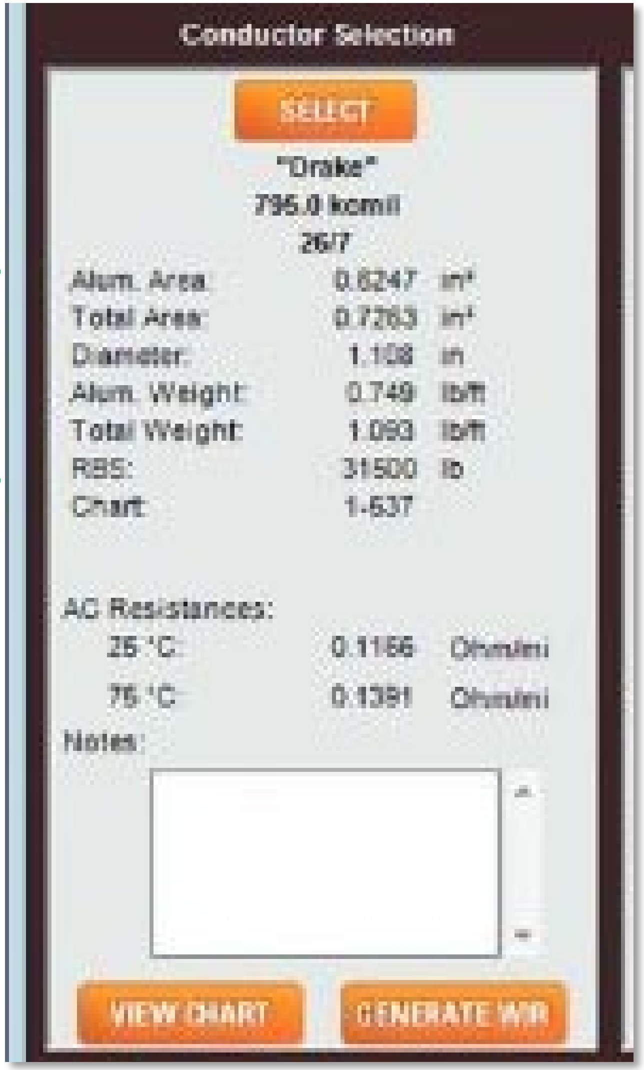
4. Rated Breaking Strength (lb or kN)

Let's quickly look at these in each program…

Sag and Tension

Inputs – Basic Cable Data in Sag10®

Basic cable data



Notice that steel and aluminum are effectively separated

(If you enter data for the aluminum and for the total, then the program can calculate the data for the steel)

Sag and Tension

Inputs – Basic Cable Data in a PLS-CADD wire file

Basic cable data

```
TYPE='CABLE FILE' VERSION='4' UNITS='US' SOURCE='DATABASE' USER='NextEra Energy Resources' FILENAME='539737 InSky OPGW S 48U
(2x24) 13.5mm 65kA2·s 88kN 1-1450'
Incab InSky OPGW S 48U (2x24) 13.5mm 65kA2·s 88kN(0.530, 48f max, 65.1kA2s@210C,) - Data by ETS 05/2024
0.154 ← Cross-sectional area (inch²)
0.530 ← Diameter (inch)
0.362 ← Weight (lb/ft)
19814 ← RBS (lb)
DATA ON THIS LINE IS NOT USED (Chart 1-1450)(MRDL = 16639)
172.7 167351.0 -24582.8 -91415.0 78623.0
404.5 102518.6 119106.6 -225839.0 90157.0
174000.0
.00082
.0 .0 .0 0. 0.
.0 .0 .0 0. 0.
.00000
.00000
76
0 ; num_pts
1 ; cable_file_type
0.0 0.0 0 0 0.5 0.5 0.0 0.0 0
```

Sag and Tension

Inputs – Loading Criteria

Next you will need to consider **added loads** to the cable – Four (4) are possible:

- **Wind** – Wind blowing across a cable will impart a load which, if strong enough, will elongate the cable

- **Ice** – Ice that accumulates on a cable will add weight which will elongate the cable

- **NESC "K factor"** – Specific to the US, this is an added load that varies by loading district

- **Other loads** – Anything that adds weight potentially can elongate the cable

Generally, the **most important** are the **wind and ice** loadings because they usually are the greatest – in other words, they cause the most elongation

Let's look at each of these four in turn…

Sag and Tension

Inputs – Loading Criteria - Wind

Wind blowing across a cable will impart a load which, if strong enough, will elongate the cable

- Expressed as a pressure in lb/ft^2 (Pascal (Pa) or N/m^2)
- Can convert wind speed to pressure:

$$P_W = 0.00256 \cdot V_W^2$$

where P_W = wind pressure (lb/ft^2) , and V_W = wind velocity (mph)

- The total wind load will be:

$$W_W = P_W \cdot \frac{(D_c+2t)}{12}$$

where W_W = wind load (lb/ft), D_c = diameter of cable (inch), t = thickness of ice (if any) (inch)

Notice that the presence of ice effectively helps increase the total wind load

(Note: I apologize to international listeners for not converting these equations to metric units)

Sag and Tension

Inputs – Loading Criteria - Ice

Ice – Ice that accumulates on a cable will add weight which will elongate the cable

- Expressed as a load in lb/ft (N/m)

- Ice loading will vary depending upon its density:
  - Glaze ice, rime ice, wet snow, and other forms of ice have different densities
  - Typically, glaze ice with an assumed density of 57 lbs/ft^3 is used

- The total ice load assuming glaze ice will be:

$$W_I = 1.244 \cdot t \cdot (D_c + t)$$

where W_I = ice load (lb/ft), D_c = diameter of cable (inch), t = thickness of ice (inch)

(Note: I again apologize to international listeners for not converting these equations to metric units)

Sag and Tension

Inputs – Loading Criteria – Combined Wind and Ice Loading

When there is **both wind and ice** loading, you combine the loading using this formula

$$W_{W+I} = \sqrt{(W_c + W_I)^2 + W_W^2}$$

where:

W_{W+I} = Resultant combined wind and ice load (lb/ft),

W_c = Cable's (bare) unit weight (lb/ft),

W_I = Weight of ice per unit length (lb/ft),

W_W = Wind load per unit length (lb/ft),

Sag and Tension

Inputs – Loading Criteria – NESC K Factor

Unique to the USA, the NESC adds this **"K factor"** often called a "safety factor" to the resultant of any wind, ice, or combined wind and ice loading

- Expressed as a load in lb/ft (N/m)
- Varies by loading district (Heavy, Medium, and Light) – Will show in a moment
- What exactly does this K factor represent? That is, what is the basis for its added loads?
  - Exact answer seems to be lost in time
  - Calling it a "safety factor" seems to be just a means of trying to categorize it
  - I understood it to have been a "correction factor" that resulted when converting from the graphical method of generating sag and tension data (based on parabolas) to the computational method (computers crunching out the catenary formulas)
    - This explanation sounds good, but I cannot verify if it is true or not
    - So, **NESC K factors are what they are**

Sag and Tension

Inputs – Loading Criteria – Other Loads

Anything put on a cable with **significant weight** should be factored into the sag and tension calculations:

- Marker balls
- PLP airflow spoilers which help prevent galloping
- Other cable or cables that the cable will support
  - A cable that is being used as a messenger cable
  - The Hendrix spacer system

We will not consider these in detail today

➔ Just keep in mind that added loads = added sag and increased tension

➔ Plus, know that both Sag10® and PLS-CADD give you the option of including added loads such as these

Sag and Tension

Inputs – Standardized Loading Criteria

The USA has several sets of standardized loading criteria

The most widely used are:

- **NESC** Heavy, Medium, and Light
- **RUS** – Variation of the NESC
- **California GO 96** ("General Order")

Other countries and provinces have their own standardized sets of criteria

➔ Standardized loading criteria give you a starting point for determining what wind and ice loading to use when generating sag and tension data for a given geographical location

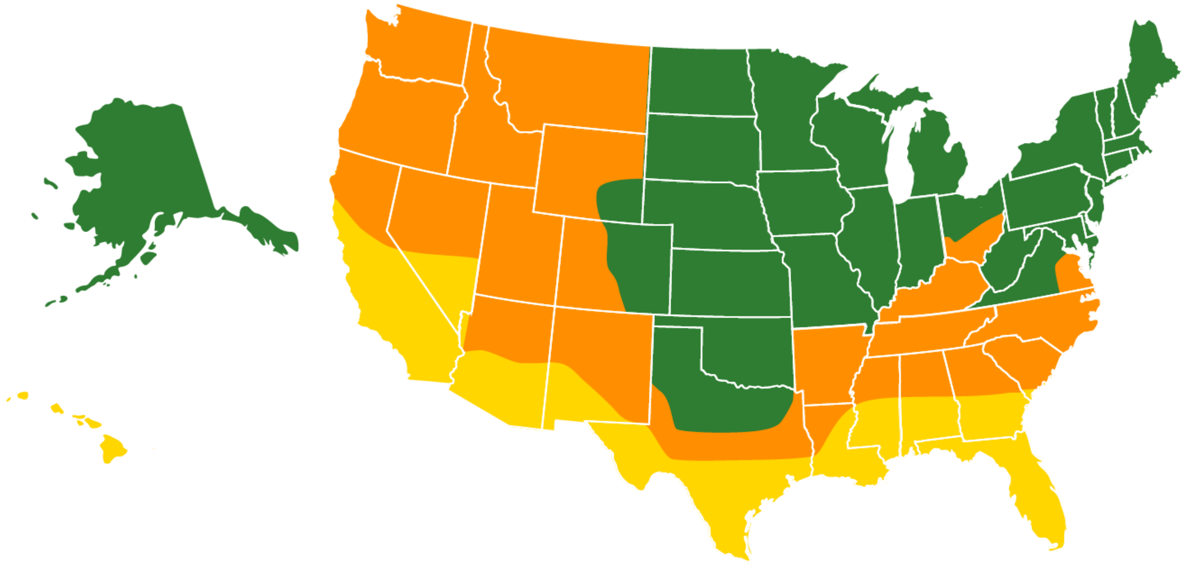
Sag and Tension

Inputs – Standardized Loading Criteria

Let's look at the NESC's sets:

District	Ice	Wind	Temp.	K
Heavy	**0.5 in.** 12.5 mm	**4 lb/ft²** 190 Pa	**0°F** -20°C	**0.3 lb/ft** 4.4 N/m
Medium	**0.25 in.** 6.5 mm	**4 lb/ft²** 190 Pa	**15°F** -10°C	**0.2 lb/ft** 2.5 N/m
Light	**0.0 in.** 0.0 mm	**9 lb/ft²** 430 Pa	**30°F** -1°C	**0.05 lb/ft** 0.7 N/m

NESC Loadings Table



NESC Loading Districts Map

Notice that these standardized loadings are applied at a specific temperature

- This is important
- Recall (Theory 101) that metallic cables change elongation significantly in response to changes in temperature
    - In contrast: Recall too that temperature effects are typically ignored for ADSS because it is non-metallic

Sag and Tension

Inputs – Standardized Loading Criteria

Standardized loading criteria also are applied with specific tension limits…For example:

- NESC Districts per Rule 250B
  - Initial tension at full load must be ≤ 60% RBS of the cable at 0°F (-20°C)
  - Initial tension with no load must be ≤ 35% RBS of the cable at 60°F (16°C)
  - Final tension with no load must be ≤ 25% RBS of the cable at 60°F (16°C)

- NESC Extreme Wind per Rule 250C
  - Wind load = 29.7 lb/ft^2 (1422 N/m^2) which corresponds to 90 mph (145 km/hr)
  - Initial tension at this load must be ≤ 80% RBS of the cable at 60°F (16°C)

- NESC Concurrent Ice and Wind per Rule 250D
  - Ice Load = 1 inch (25.4 mm) "glaze ice" (56 lb/ft^3 = 8797 N/m^3)
  - Wind load = 4.1 lb/ft^2 (196 N/m^2) which corresponds to 40 mph (64 km/hr)
  - Initial tension at this load must be ≤ 80% RBS of the cable at 15°F (-9°C)

Sag and Tension

Inputs – Elements of All Loading Criteria

Notice the pattern of the preceding standardized loading criteria:

- All have these four (4) elements:
  - An ice and/or wind **load**
  - Applied at a **specific temperature**
  - Up to a specific **tension limit** expressed in %RBS of the cable
  - Indication of whether the tension limit applies at "**initial** condition" (immediately after installation) or at "**final** condition" (taken as being after 10 years)
- Any other standardized criteria (for your state or country) plus any other unique criteria that you formulate must also have these four elements
  - Example: You live in Hawaii (lucky you) and want to consider a 120-mph (193 km/hr) wind (to allow for the occasional hurricane)
    - Wind load = $0.00256 \cdot (120^2) = 36.9$ lb/ft^2 (1767 N/m^2)
    - You must also decide at what temperature (perhaps 70°F = 21°C), a tension limit (maybe 80% RBS), and whether the limit will apply at initial or final condition

Sag and Tension

Inputs – Tension Limits

OK. But, why are those specific tension limits used in the NESC code?

- Answer: Because they work well… To illustrate this point:
  - If final tension at 60°F (16°C) below 10% RBS, then the sag will be quite large = structures must be taller = structures will cost more
  - If final tension at 60°F (16°C) above 25% RBS, then the cable will be highly susceptible to aeolian vibration damage
    - In fact, limiting final tension at 60°F (16°C) to 20% RBS is better and has been incorporated into both Sag10 and PLS-CADD
  - The NESC rule 250B limit of 60% RBS initial tension for its highest load cases allowed a "margin for error" for more severe weather conditions to happen but also yielded a reasonable tension at the final "everyday" (no load) condition of 60°F (16°C)
  - Metallic cables subjected to prolonged tension ≥ 80% RBS can begin to deteriorate structurally

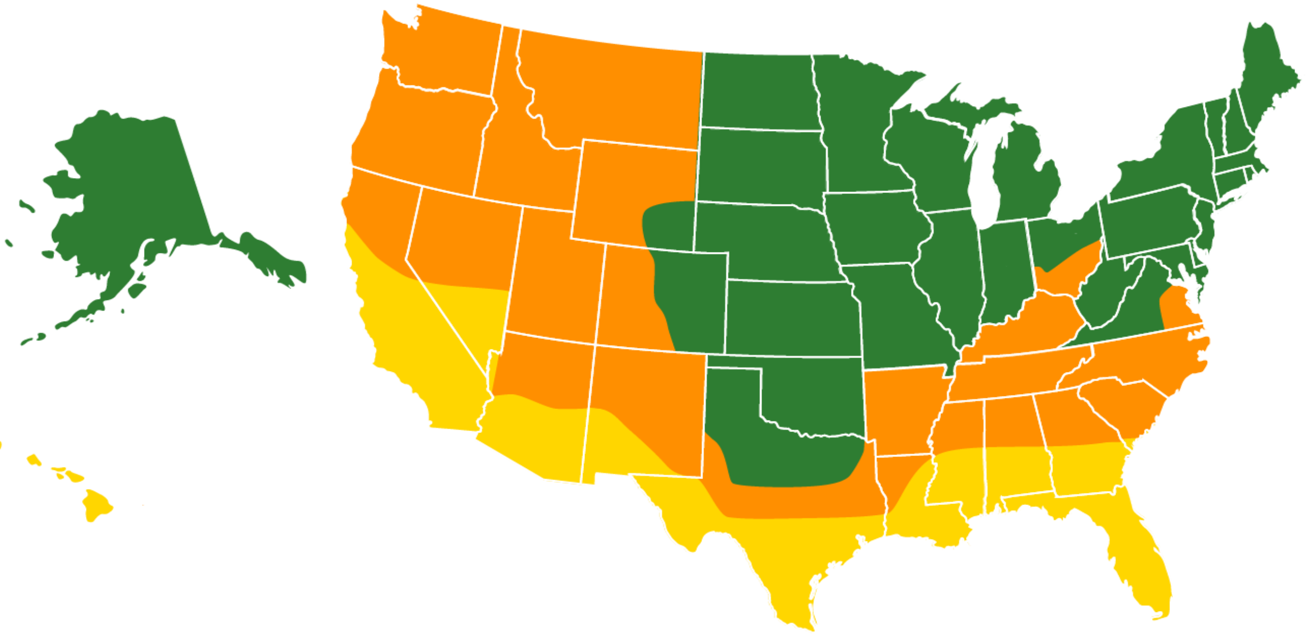
- So, while the NESC limits are specific to the USA, you find similar limits used throughout the world

Sag and Tension

Inputs – Recap Selecting Loading Criteria

Here is an overview of what you must do:

- Determine your base loading criteria
  - NESC Rule 250B loading zone (USA)
  - Or as per your state, province, or country
- Add any "extreme ice" or "concurrent wind and ice" conditions if you have them
  - NESC Rule 250C and D
  - Additional criteria as per your state, province, or country
- Add any criteria unique to your utility or project
  - Tension limits?
  - Sag limits?

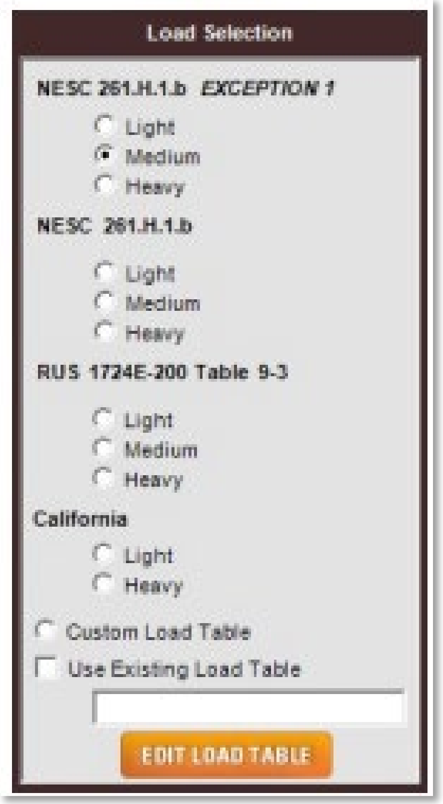


Sag and Tension

Inputs – Entering Loading Criteria and Tension Limits

Each program has its own way of entering these inputs…

Sag10®



PLS-CADD®

	Description	Wind Velocity (mph)	Wind Pressure (psf)	Wire Ice Thickness (in)	Wire Ice Density (lbs/ft^3)	Wire Ice Load (lbs/ft)	Wire Temp. (deg F)	Ambient Temp. (deg F)	NESC Constant (lbs/ft)	Wire Wind Height Adjust Model	W G Res Fa
1	NESC Heavy District	39.5395	4	0.5	56				0.3	None	1
2	NESC Extreme Wind (2	90.0251	20.736				60.0	60.0		NESC 2023	NESC
3	NESC Concurrent Ice	40.0112	4.096	1	56		15.0	15.0		None	1
4	Extreme Ice			0.5	56		30.0	30.0		None	1
5	Cold Uplift						-20.0	-20.0		None	1
6	Maximum Operating						212.0	90.0		None	1
7	NESC Tension Limit									None	1
8	NESC Blowout 6PSF	48.4258	6				60.0	60.0		None	1

- ➔ Both have commonly used standardized loading criteria, such as the NESC ones
- ➔ Plus, you can add and customize loading criteria
- ➔ Both have a second screen for adding and customizing tension limits

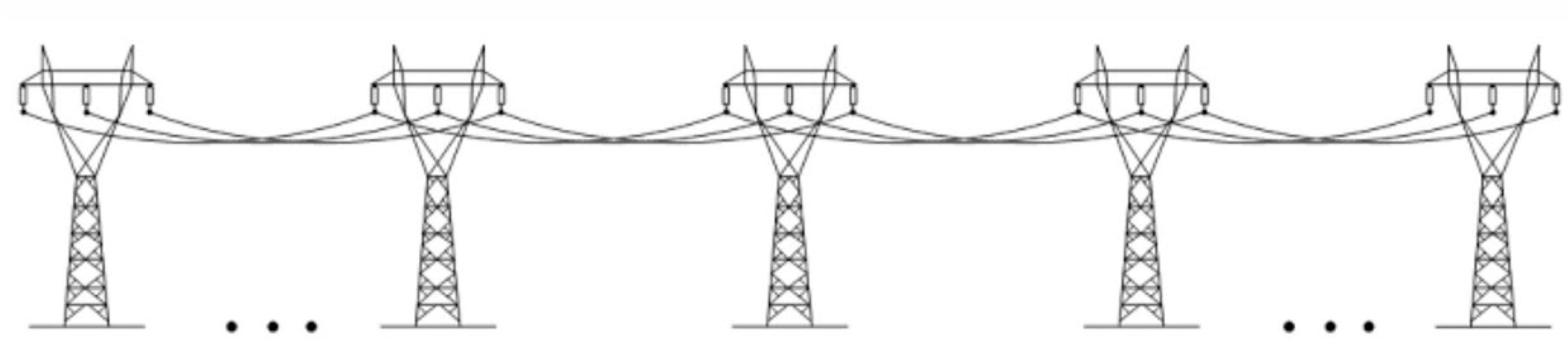
Sag and Tension

Inputs – Next Up: Span Data

OK, so we have our basic cable data and our loading criteria with tension limits

There is one more input that we need: **Span data**

Let's look at it…

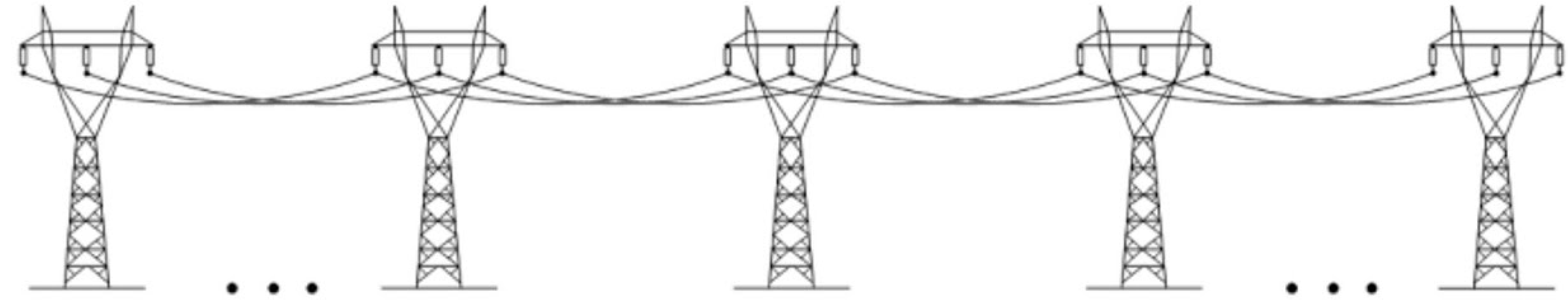


Sag and Tension

Inputs – Span Data

How we look at and treat the **span data** is going to **depend** upon **how the cable is installed** and **how it will operate** after installation

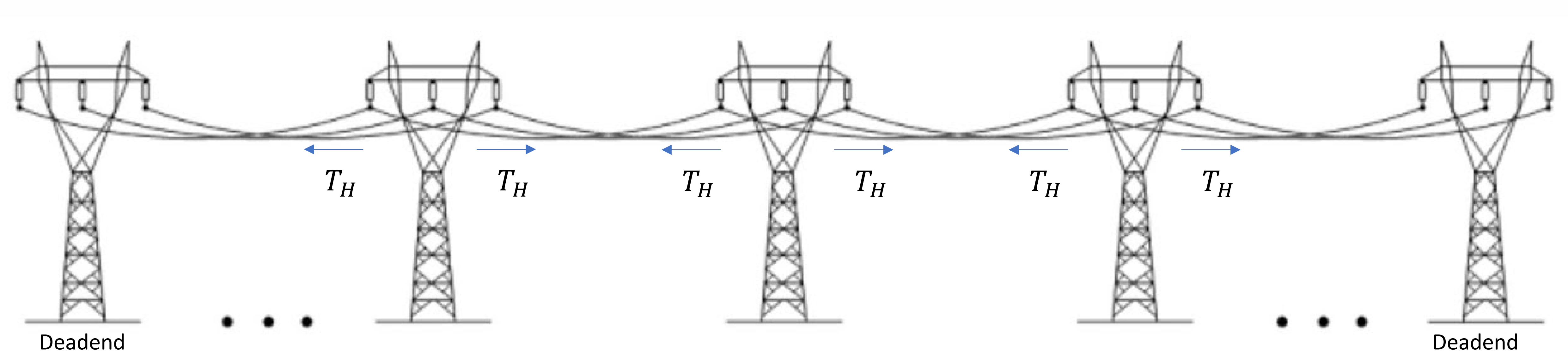
Consider a cable that was **pulled-in using stringing blocks** ("pulleys") (controlled tension stringing)



Sag and Tension

Inputs – Span Data

Because the cable is free to roll across the stringing blocks, the **horizontal tension (T_H) will equalize** at each structure across the line segment (from deadend to deadend)



OK. At what tension will it equalize?

Sag and Tension

Inputs – Span Data – Ruling Span

The tension will equalize at a value that is closer to that of the longer spans in the segment

In fact, there is a weighted average of the spans that will characterize precisely what the tension will equalize at

➔ We call this the "Ruling Span" (You could say there is "One span to rule them all!")

Mathematically, we calculate the ruling span as:

$$S_{RS} = \text{Ruling Span} = \sqrt{\frac{sum\ of\ the\ spans^3}{sum\ of\ the\ spans}} = \sqrt{\frac{\sum S^3}{\sum S}} = \sqrt{\frac{S_1^3}{S_1} + \frac{S_2^3}{S_2} + \ ...\ \frac{S_n^3}{S_n}}$$

Where S_1 is Span 1, S_2 is Span 2, and so on with S_n being the last span in the segment

Credit: Equation developed by E.S. Thayer, published in *Electrical World*, July 12, 1924

Sag and Tension

Inputs – Span Data – Ruling Span Example

Span	Span (ft)	$Span^3$	Span
1	500	125,000,000	500
2	600	216,000,000	600
3	550	166,375,000	550
4	700	343,000,000	700
5	800	512,000,000	800
6	1,000	1,000,000,000	1,000
7	800	512,000,000	800
8	600	216,000,000	600
9	550	166,375,000	550
10	500	125,000,000	500
Sums		3,381,750,000	6,600

Average Span: 660

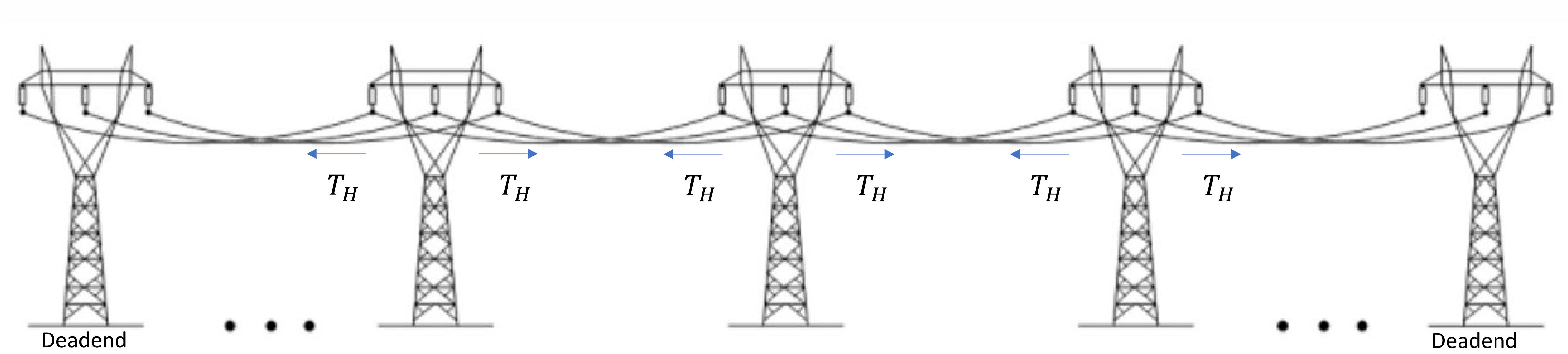
Ruling Span: 716

Sag and Tension

Inputs – Span Data – Ruling Span Close-Out

Two more important tidbits:

1. Because tension equalizes in a ruling span segment, we say that the segment is "**mechanically coupled**"
2. A segment will remain mechanically coupled *if* after "clipping-in" (installing clamps at structures in between the deadends) the attachment point can move in response to changes in horizontal tension (T_H)



Sag and Tension

Inputs – Span Data – Ruling Span Close-Out

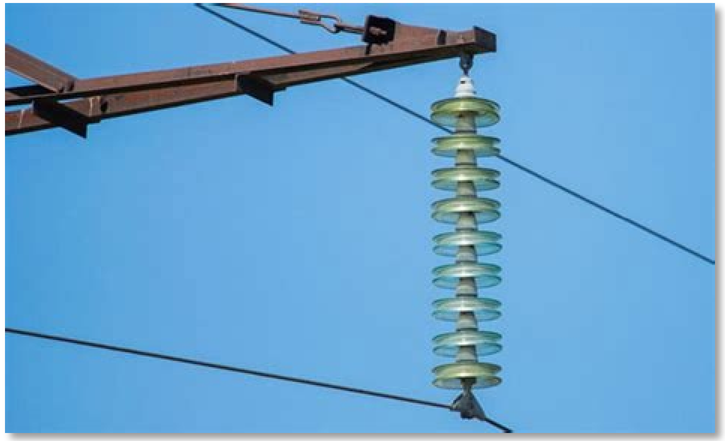
OK. But, how can a segment remain mechanically coupled after clipping-in?

Answer:

A. Insulator strings – Conductor is usually supported by insulator strings that can move thereby helping to equalize the horizontal tension in the spans on either side of the structure

B. Articulation – Other cables, such as OPGW, are usually supported by clamps using hardware that allows for movement again thereby helping to equalize the horizontal tension in the spans on either side

It only takes a little movement to maintain mechanical coupling!



Sag and Tension

Inputs – Span Data – The Anti-Ruling Span?

If the spans in line segment must be mechanically coupled for the Ruling Span concept to apply, then are there conditions where this is not the case?

Answer: You bet!

A. **Single spans** – A span that is deadended on both ends… But, in this situation the ruling span = span (you can check the math yourself), so you technically could say that the ruling span concept does still apply

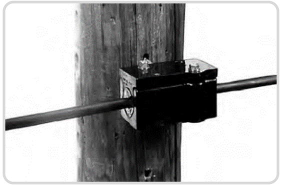
B. **Mechanically Independent Spans** – Each span acts independent of all others

- With conductor – Conductor supported on rigid post or pin insulators…even then, it is likely installation would still be governed by the ruling span concept
  - Not common on transmission lines, but common with distribution ones

- With ADSS – Very common with ADSS…One reason ADSS sag and tension calculations are often performed differently (separate webinar)…the other being that "moving reel" installation is used
  - See next slide

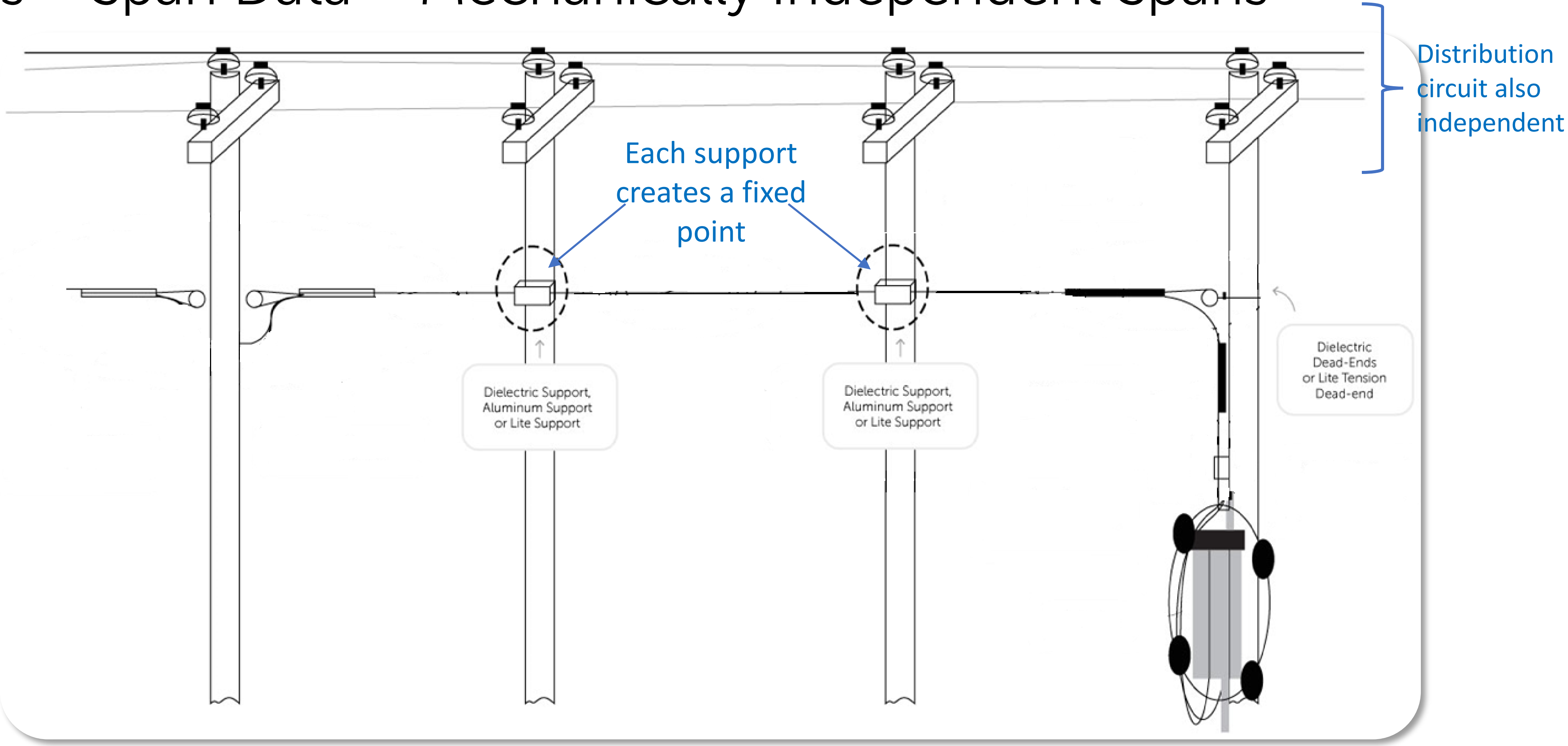
Sag and Tension

Inputs – Span Data – Mechanically Independent Spans



or

These types do *not* move to equalize tension



Supports create fixed points at each pole, so spans are mechanically <u>independent</u>

Sag and Tension

Inputs – Span Data – What Span(s) to Enter

So, what span information do I enter?

Straightforward answer:

A. If **Mechanically Coupled Spans** – Enter the ruling span(s)

B. If **Mechanically Independent Spans** – Enter each individual span

But, someone is likely to wonder, "What if we'll be stringing through blocks (coupled), but clipping with no swing or articulation (independent)?"

- Recommendation: Generate data using the ruling span(s), but then go back and check load imbalances in places where a "long" span is adjacent to a "short" one (suggest difference be > 50% of the short span)

Both Sag10® and PLS-CADD have a screen for entering (ruling) spans

- PLS-CADD will also calculate the ruling span from a series of spans

Sag and Tension

Inputs – Loading Criteria

Each program has its own way of entering loading criteria…

Sag10®

PLS-CADD®

	Description	Wind Velocity (mph)	Wind Pressure (psf)	Wire Ice Thickness (in)	Wire Ice Density (lbs/ft^3)	Wire Ice Load (lbs/ft)	Wire Temp. (deg F)	Ambient Temp. (deg F)	NESC Constant (lbs/ft)	Wire Wind Height Adjust Model	W G Res Fa
1	NESC Heavy District	39.5395	4	0.5	56				0.3	None	1
2	NESC Extreme Wind (2	90.0251	20.736				60.0	60.0		NESC 2023	NESC
3	NESC Concurrent Ice	40.0112	4.096	1	56		15.0	15.0		None	1
4	Extreme Ice			0.5	56		30.0	30.0		None	1
5	Cold Uplift						-20.0	-20.0		None	1
6	Maximum Operating						212.0	90.0		None	1
7	NESC Tension Limit									None	1
8	NESC Blowout 6PSF	48.4258	6				60.0	60.0		None	1

➔ Both have commonly used loading criteria, such as the NESC ones

➔ Plus, you can add and customize loading criteria

Plus plus, each has a second screen or input location for tension limits

Sag and Tension

Generating the Data

At long last, we have all the inputs we need!

- Sag coefficients + basic cable data + loading criteria + tension limits + span data

Now we can hit the Sag10® "Calculate Sag & Tension" or PLS-CADD "Sag-Tension" button!

Yay!

➔ Let's look at what the programs are doing to generate the data, and then look at the output

Sag and Tension

Generating the Data – Inside the "Black Box"

Two fundamental things are going on inside each both programs

1. Calculating the sags and tensions for each combination of loading conditions and tension limits

2. Finding which of those at (1) above is the "design condition" (controlling)
   ➔ Having found which condition controls, the programs then go back and re-calculate the other loading conditions based upon the design condition

By now you know that we are going to look at each of these in turn…

Sag and Tension

Generating the Data – Inside the "Black Box"

Task 1 - Calculating the sags and tensions for each combination of loading conditions and tension limits

Recall our sag coefficients… this is where those get used

It is easiest to explain this task using an example, so let's use chart 1-1450 that we saw earlier:

```
DATA ON THIS LINE IS NOT USED (Chart 1-1450)
172.7 167351.0 -24582.8 -91415.0 78623.0
404.5 102518.6 119106.6 -225839.0 90157.0
```

Remember that these coefficients are for a 4th order polynomial equation modeling the cable's stress-strain curve

Sag and Tension

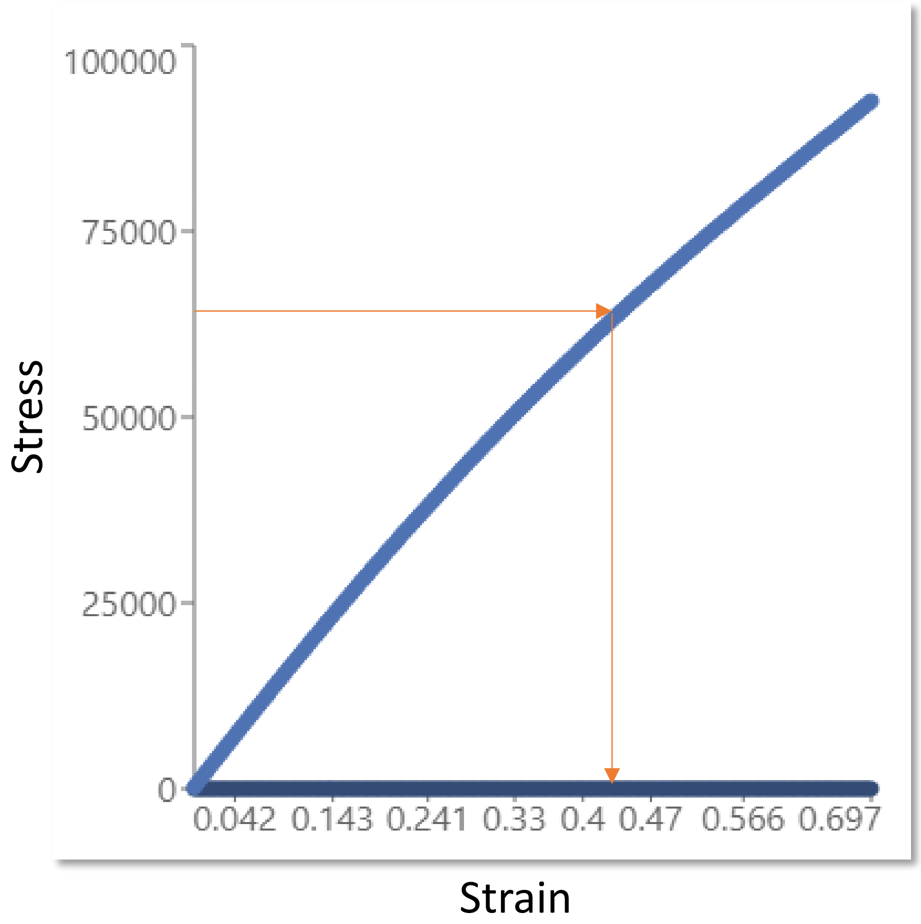
Generating the Data – Inside the "Black Box"

Task 1 – continued

You can use any graphing calculator to see the curve they generate....

So, the program will convert loads to stress (tension), and then use the curve to determine the corresponding strain (elongation) which then leads to sag and tension

We saw the corresponding formulas for this in the Theory 101 presentation



Sag and Tension

Generating the Data – Inside the “Black Box”

Task 1 – concluded

The program must do this process for each set of loading condition + tension limit that you enter

Notes:

A. Calculating for the initial condition is conceptually straightforward (“plug and chug” as engineers say)

B. Calculating for the final condition is less straightforward – You must make two assumptions (both could be challenged)
   1) Creep will finish in 10 years
   2) Whatever is the highest load does occur during the 10 years

Sag and Tension

Generating the Data – Inside the "Black Box"

Task 2 - Finding which of those at Task 1 is the "design condition" (controlling)

It is easiest to explain this task using an example

- Recall our earlier example with an engineer in Hawaii
- Let's say that he or she used the NESC Light conditions plus added two conditions:
  - ➢ Initial tension with a 36.9 lb/ft^2 (1767 N/m^2) wind load must not exceed 80% RBS at 70°F (21°C)
  - ➢ Final tension with no loading must not exceed 20% RBS at 60°F (16°C)
    - Keeps aeolian vibration manageable – now included in both Sag10 and PLS-CADD

Sag and Tension

Generating the Data – Inside the "Black Box"

Task 2 - continued

So, now we have these five (5) cases to check:

1. (NESC Light) Initial tension at full load must be ≤ 60% RBS of the cable at 0°F (-20°C)
2. (NESC Light) Initial tension with no load must be ≤ 35% RBS of the cable at 60°F (16°C)
3. (NESC Light) Final tension with no load must be ≤ 25% RBS of the cable at 60°F (16°C)
4. (HI Wind) Initial tension with a 36.9 lb/ft^2 (1767 N/m^2) wind load must not exceed 80% RBS at 70°F (21°C)
5. (Aeolian vibration) Final tension with no loading must not exceed 20% RBS at 60°F (16°C)

Sag and Tension

Generating the Data – Inside the "Black Box"

Task 2 – continued again

The programs will start with a condition, then use its results to check the others

Find solution for this → 1. (NESC Light) Initial tension at full load must be ≤ 60% RBS of the cable at 0°F (-20°C)

↓

Check: Does the solution at (1) also meet this? 2. (NESC Light) Initial tension with no load must be ≤ 35% RBS of the cable at 60°F (16°C)

↓

Check: If yes, does it also meet this? 3. (NESC Light) Final tension with no load must be ≤ 25% RBS of the cable at 60°F (16°C)

↓

Check: And this? 4. (HI Wind) Initial tension with a 36.9 lb/ft^2 (1767 N/m^2) wind load must not exceed 80% RBS at 70°F (21°C)

↓

Check: And this, too? 5. (Aeolian vibration) Final tension with no loading must not exceed 20% RBS at 60°F (16°C)

Sag and Tension

Generating the Data – Inside the “Black Box”

Task 2 – continued yet again

If a condition is *not* met, then that becomes the “new condition” and all others are checked again – Let’s say #4 was not met by the solution for #1… so now…

Check: And this? 1. (NESC Light) Initial tension at full load must be ≤ 60% RBS of the cable at 0°F (-20°C)

Check: If yes, does it also meet this? 2. (NESC Light) Initial tension with no load must be ≤ 35% RBS of the cable at 60°F (16°C)

Check: Does the solution at (1) also meet this? 3. (NESC Light) Final tension with no load must be ≤ 25% RBS of the cable at 60°F (16°C)

Find solution for this → 4. (HI Wind) Initial tension with a 36.9 lb/ft² (1767 N/m²) wind load must not exceed 80% RBS at 70°F (21°C)

Check: And this, too? 5. (Aeolian vibration) Final tension with no loading must not exceed 20% RBS at 60°F (16°C)

Sag and Tension

Generating the Data – Inside the "Black Box"

Task 2 – concluded (in part)

Conceptually, the process is as illustrated – The algorithms used by the two programs likely differ in their specifics (I don't know)

The **condition that controls** (also solves all others) is called the "**design condition**" and will be noted on the sag and tension data

Once there is a solution, the programs apply the **coefficient of thermal expansion** to calculation sag and tension for any other temperatures you indicated you wanted data for

Sag and Tension

Generating the Data – Inside the “Black Box”

Task 2 – concluded (really!)

Concluding notes:

A. It is possible to have so many conditions or conflicting conditions such that there is <u>not</u> a solution – You’ll get an error message and must change something

B. It is possible that two conditions reach the same solution – You’ll get an annotation that there is a “common point”

Sag and Tension

Working with the Output

So, we ran calculations in Sag10®, and here's what we got:

Cable Data:

```
Area = 0.1510 Sq. in     Diameter = 0.531 in     Weight = 0.293 lb/ft    RTS = 14136 lb
Data from Chart No. 1-1439
English  Units
Limits and Outputs in Horizontal Tensions.

Span = 450.0 Feet                    Customary Heavy Load Zone
Creep is NOT a Factor
```

Design Points

	Temp °F	Ice in	Wind psf	K lb/ft	Weight lb/ft	Final H-Sag Ft	Final V-Sag Ft	Final Tension lb	Initial H-Sag Ft	Initial V-Sag Ft	Initial Tension lb	
NESC Heavy →	0.0	0.50	4.00	0.30	1.364	5.38	9.85	3081	4.73	8.66	3500*	← Controlling (Note the *)
Extra ice + wind →	30.0	1.50	2.00	0.00	4.124	2.35	16.31	6345	2.35	16.31	6345	
Ice only →	32.0	0.50	0.00	0.00	0.934	0.00	10.78	2196	0.00	8.93	2648	
Other temperatures of interest to this utility	-20.0	0.00	0.00	0.00	0.293	0.00	6.29	1180	0.00	3.61	2055	
	0.0	0.00	0.00	0.00	0.293	0.00	7.04	1054	0.00	4.07	1821	
	30.0	0.00	0.00	0.00	0.293	0.00	8.14	911	0.00	4.90	1513	
	60.0	0.00	0.00	0.00	0.293	0.00	9.19	807	0.00	5.86	1266	
	90.0	0.00	0.00	0.00	0.293	0.00	10.18	729	0.00	6.89	1077	
	120.0	0.00	0.00	0.00	0.293	0.00	11.11	668	0.00	7.92	936	
	167.0	0.00	0.00	0.00	0.293	0.00	12.47	595	0.00	9.49	782	
	212.0	0.00	0.00	0.00	0.293	0.00	13.67	543	0.00	10.88	682	

* Design Condition

Note: 167°F and 212 °F not really needed for OPGW, but…

Comment: Output format can vary, and PLS-CADD data will look different, but the same kind of information is always there

Sag and Tension

Working with the Output

Assuming that the output on the last slide was for a ruling span (a good assumption), how can we apply it to a specific span?

Answer: Use this equation:

$$S_{AS} = S_{RS} \cdot \left(\frac{S_{AS}}{S_{RS}}\right)^2$$

where S_{AS} = the actual span of interest and S_{RS} = the ruling span

And, you can do the same for the horizontal tension

Sag and Tension

Working with the Output – Checking ZFSM and MRDT or MRCL

Before moving on, we need to look at two manual checks (neither Sag10® nor PLS-CADD do them for you) you need to make for OPGW and ADSS:

1. You should ensure that **under “everyday” conditions** [60°F (16°C), no load, both initial and final] that the **tension** on the cable **< ZFSM** (zero-fiber strain margin)
    - Fiber strain kills optical fiber in the long run! 🡐 especially if > 0.2%!
    - ZFSM is the point of onset for fiber strain
    - ZFSM should be on the cable manufacturer’s datasheet, but if not, then ask

Sag and Tension

Working with the Output – Checking ZFSM and MRDT or MRCL

And…

2. You should ensure that under **all loaded conditions** (both initial and final) that the **tension** on the cable **< MRDT** (an OPGW's "maximum rated design tension") *or* **MRCL** (an ADSS's "maximum rated cable load")

    - Exceeding MRDT or MRCL is asking for optical problems (and voiding the warranty)

    - Ideally, fiber strain would still be 0% at MRDT or MRCL (that is, ZFSM = MRDT or MRCL), but often there is strain at MRDT or MRCL

    - Check that if **strain at MRDT or MRCL** then it should be **< 0.2%**

    - Fiber strain is usually *not* shown on cable datasheets (but should be!), so usually you must ask!

Sag and Tension

Working with the Output – Checking ZFSM and MRDT or MRCL

Example based on cable data presented already –

- If ZFSM = MRDT = 11,309 lb (80% RBS) (Typical for a Type S OPGW)

```
Area = 0.1510 Sq. in    Diameter = 0.531 in    Weight = 0.293 lb/ft    RTS = 14136 lb
Data from Chart No. 1-1439
English  Units
Limits and Outputs in Horizontal Tensions.

Span = 450.0 Feet                 Customary Heavy Load Zone
Creep is NOT a Factor
```

Design Points					Final			Initial		
Temp °F	Ice in	Wind psf	K lb/ft	Weight lb/ft	H-Sag Ft	V-Sag Ft	Tension lb	H-Sag Ft	V-Sag Ft	Tension lb
0.0	0.50	4.00	0.30	1.364	5.38	9.85	3081	4.73	8.66	3500*
30.0	1.50	2.00	0.00	4.124	2.35	16.31	6345	2.35	16.31	6345
32.0	0.50	0.00	0.00	0.934	0.00	10.78	2196	0.00	8.93	2648
-20.0	0.00	0.00	0.00	0.293	0.00	6.29	1180	0.00	3.61	2055
0.0	0.00	0.00	0.00	0.293	0.00	7.04	1054	0.00	4.07	1821
30.0	0.00	0.00	0.00	0.293	0.00	8.14	911	0.00	4.90	1513
60.0	0.00	0.00	0.00	0.293	0.00	9.19	807	0.00	5.86	1266
90.0	0.00	0.00	0.00	0.293	0.00	10.18	729	0.00	6.89	1077
120.0	0.00	0.00	0.00	0.293	0.00	11.11	668	0.00	7.92	936
167.0	0.00	0.00	0.00	0.293	0.00	12.47	595	0.00	9.49	782
212.0	0.00	0.00	0.00	0.293	0.00	13.67	543	0.00	10.88	682

* Design Condition

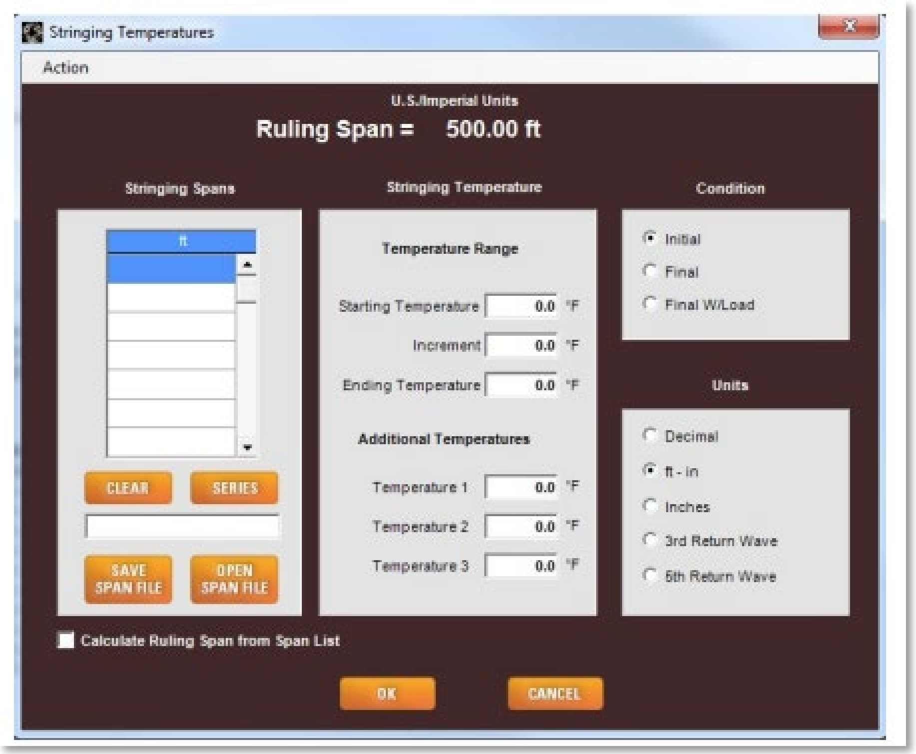
Both ZFSM and MRDT easily met at both initial and final conditions

Sag and Tension

Working with the Output – Stringing Charts (or Tables)

During installation, the line crews need to know what the sag should be in a specific span at a specific <u>cable</u> temperature

To facilitate providing them this information, both Sag10® and PLS-CADD will generate stringing charts (or tables) for a range of span lengths and temperatures



To generate a stringing chart in Sag10®

Sag and Tension

Working with the Output – Stringing Charts (or Tables)

Here's an example of one, in metric units no less!

OPGW Catalog #: 62003608 94/ 55 mm2/ 620

Ruling Span: 150.0 m
Special Load Zone

Stringing Sag Table Using Initial Sag
Max Tension = 24575 Nt

Design: 25.0 % Ult. @ -30 Deg °C, 0.00 mm Ice, 0.00 Ntsm Wind, Initial

H Tens (N)	24574	22817	21065	19326	17614	15944	14338	12822	11424	10171	9079	8149	7370	6722	6184	5734
Temp °C>	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
Sag / Span	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter	Meter
100.0	0.30	0.32	0.35	0.38	0.41	0.46	0.51	0.57	0.64	0.72	0.80	0.89	0.99	1.08	1.18	1.27
125.0	0.46	0.50	0.54	0.59	0.65	0.71	0.79	0.89	1.00	1.12	1.25	1.40	1.54	1.69	1.84	1.98
150.0	0.67	0.72	0.78	0.85	0.93	1.03	1.14	1.28	1.43	1.61	1.80	2.01	2.22	2.44	2.65	2.86
175.0	0.91	0.98	1.06	1.15	1.27	1.40	1.55	1.74	1.95	2.19	2.46	2.74	3.03	3.32	3.61	3.89
200.0	1.18	1.28	1.38	1.51	1.65	1.83	2.03	2.27	2.55	2.86	3.21	3.57	3.95	4.33	4.71	5.08
225.0	1.50	1.62	1.75	1.91	2.09	2.31	2.57	2.87	3.23	3.62	4.06	4.52	5.00	5.49	5.96	6.43
250.0	1.85	1.99	2.16	2.35	2.58	2.85	3.17	3.55	3.98	4.47	5.01	5.59	6.18	6.77	7.36	7.94

Both actual spans and cable temperatures can be interpolated ad infinitum!

Sag and Tension Theory 102 Recap

Today, we have learned:

1. What a sag chart is
2. What inputs go into generating a sag chart
3. What outputs are included on a sag chart
4. What the Ruling Span concept is and when it applies to sag and tension calculations
5. How to calculate the actual sag or tension in a particular span in a ruling span segment
6. The differences between spans that are “mechanically coupled” versus spans that are “mechanically independent” and how this affects sag and tension calculations
7. Why and how MRDT/MRCL and ZFSM should be checked as part of the sag and tension data generation process

For more information on this topic, get the *Southwire Overhead Conductor Manual* at their website

Sag and Tension

Optional Topic – Possibly Highly Disturbing!

We have completed today's topic, and you are free to go

- You are equipped to take the test to earn CE credits

But, there is a topic that I would like to broach, but I warn you now, you risk being "red pilled"

Last chance to go about your day…

Note: I absolve Joe Renowden of any responsibility for what follows

Sag and Tension

Optional Topic – **Most Sag Charts are Wrong!**

I'm sorry, but it is true… Recall from Theory 101 when we talked about putting parabolic error in context, there was this (seemingly innocuous) statement:

"There is error in stress-strain curves – There are several reasons for this which we do not have time to discuss today (we will next time)"

"Several" really distills down to two big ones:

1. Most charts are based on data from the 1950's – 1960's

2. Most charts do not cover the full range of elongation that a cable could experience in the field

You know the routine… Let's look at these…

Sag and Tension

Optional Topic – Most Sag Charts are Wrong!

Source of error #1 - Most charts are based on stress-strain and creep tests performed on conductors in the 1950's – 1960's (no OPGW yet!)

- Production and quality control processes for steel and aluminum wires have changed (improved) over the intervening decades ➔ so the wires themselves are different today

- Cable stranding has changed, especially for conductor, over the intervening decades
  - Back then: Planetary stranding for nearly everything
  - Today: Bow or rigid for conductor – Much higher production speeds with "good enough" stranding quality (more stress on the wires)
    - Planetary still used for OPGW – But, much better laylength and braking control, so better overall quality than stranders way back when

    ➔ So here too, today's cables are different

    Is "different" on balance, better, worse, or no net change in terms of sag?
    Hold this thought

Sag and Tension

Optional Topic – Most Sag Charts are Wrong!

Source of error #2 - Most charts do not cover the full range of elongation that a cable could experience in the field

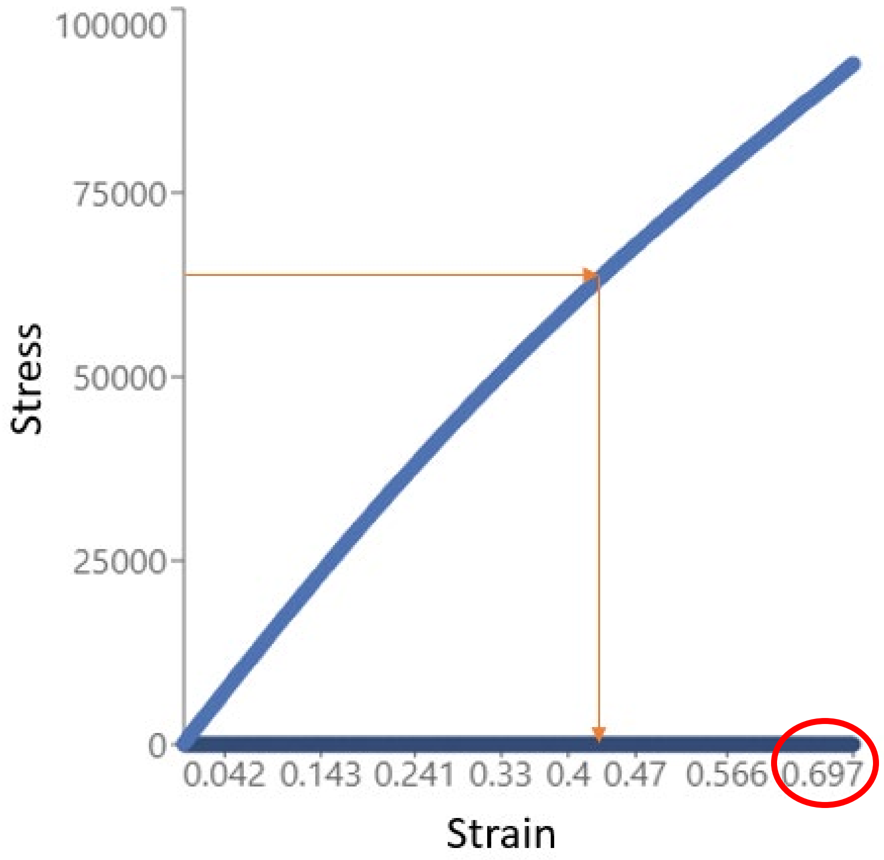
- That is because stress-strain testing "back then" was generally done to a strain of about 0.5% which roughly equates to 50% RBS (+/- 10% RBS)
    - We expect cables to perform to at least 60% RBS, plus with "extreme ice" and "concurrent ice and wind" loads, even up to 80% RBS
    - The two programs deal with this limitation by extrapolating the curve – But, extrapolation does imply error which begs the question, "How much?"
    - What's worse is that standard charts do not tell you to what limit they were performed – You can only make an educated guess if you plot the data (see next slide)

Sag and Tension

Optional Topic – Most Sag Charts are Wrong!

Source of error #2 – Example using chart 1-1450

- You likely did not notice that when I showed you this curve, that the strain went to 0.7%
- Why did I do that? Because it "looked about right"



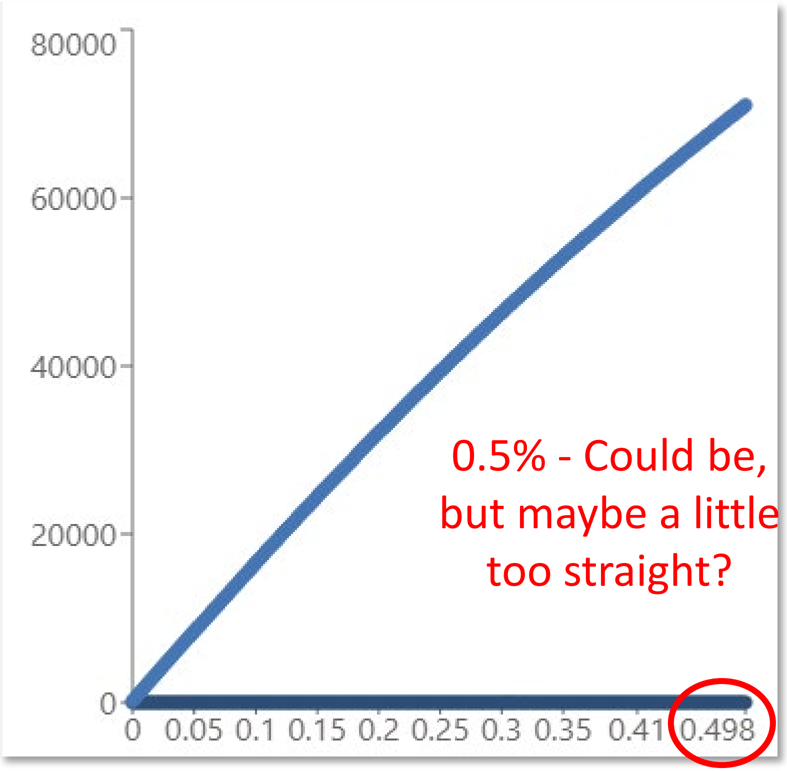
Sag and Tension

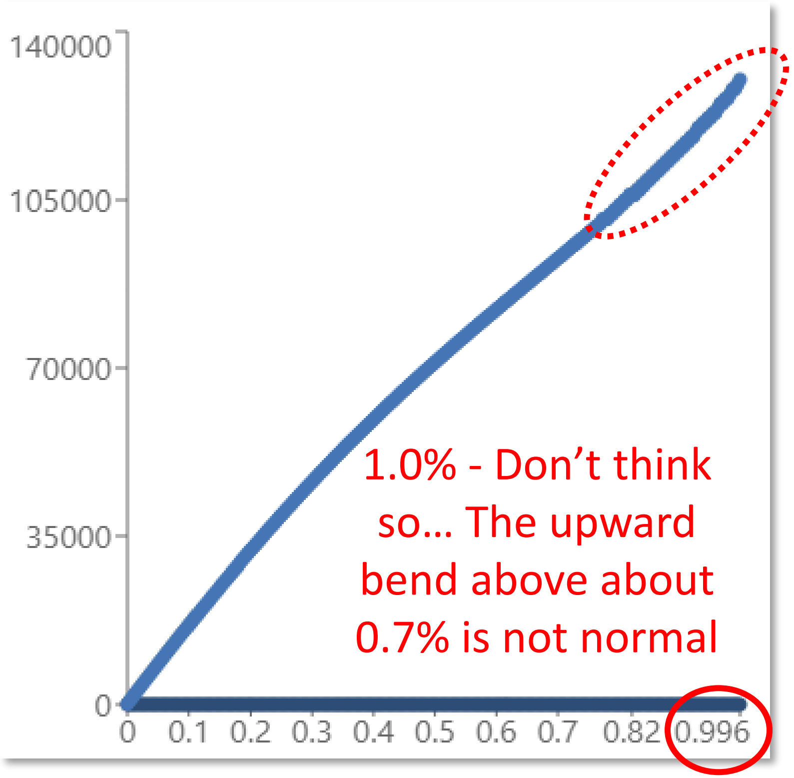
Optional Topic – Most Sag Charts are Wrong!

Source of error #2 – Example using chart 1-1450

The main take-away is that I do not know to what strain the test was taken to

- Let's look at 0.5% and 1.0% to compare….





Sag and Tension

Optional Topic – OMG! Are We Doomed?!

Given this shocking news, why are not transmission lines falling down all over the country?

- Recall the question: Is “different” on balance, better, worse, or no net change?
  - Best guess: Different is better on balance
    - Improved production and quality control of the wires likely means that it takes more stress on average to produce a given strain (less likely to break prematurely, too)
      - If so, then today’s cables likely sag less than the calculations if you measure the tension during sagging
      - Conversely, the tension is lower than the calculations if you measure the sag during sagging

      ➔ So, the errors can be considered “favorable”
      ➔ The preceding is consistent with my observations about OPGW in the field, but very limited data points

Sag and Tension

Optional Topic – Let's Fix This!

Can't we fix this by doing new testing?!

- In theory, yes… In reality, I don't think so…
  - IMHO, you cannot do just one stress-strain test and one creep test on a cable you made today and claim that you now have "confirmed" coefficients for it
    - You must do multiple such tests
    - Plus, you really need to do at least three (3!) creep tests on one cable to confirm that parameter
    - So, likely economically and temporally (time it would take) not practical

  - Also, especially not practical for OPGW
    - Each company has 100's of designs
    - Many are never purchased for one reason or another
    - So, if test, then when? At proposal? What if not bought? Who pays? Later? But, engineering must continue along with production itself!

    ➔ Again, not practical – That's why the "matching" mentioned earlier is used

Sag and Tension

Optional Topic – Let's Choose to Be Happy

So, let's pretend we never had this optional part of the presentation

Current practice with sag charts is clearly not perfect, but it works "good enough"

- Best guess is the error is < 10% (and favorable)
- Plus, best guess is the error in sagging is at least this much, too

As an old song put it, let's

"**Don't worry! Be Happy!**"

Follow-Up Information

Follow-up email contains:

Link to Video & Presentation Download

Link to Quiz for PDH Credits

Survey to give us feedback, including suggestions for topics we ought to cover

To receive PDH Credits:

Pass the quiz with 70% or higher

Please allow one business day for credits to be submitted to RCEP

Any questions, reach out to:

marketing@incabamerica.com

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Thank you!
Questions?

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