POWER LINE® SYSTEMS

5400 King James Way, Suite 300
Madison, WI 53719, U.S.A.
Phone: 608.238.2171 **Fax:** 608.238.9241
Email: info@powerlinesystems.com
URL: https://www.powerlinesystems.com/

Finite Element Analysis In PLS-CADD

Introduction

While ruling span (RS) analysis is a simple way to calculate sag-tension and structure loading based on simplified assumptions, the reality is that overhead lines operate in the real world where span interaction and structure flexibility matter. Conductor is typically sagged with the wire in blocks, but then is quickly clipped in fixing the wire length and creating a complex relationship between wire sag, structure deflection, and longitudinal imbalances. PLS-CADD, with its Finite Element (FE) sag tension module SAPS, makes it easy to incorporate the concepts of finite element analysis for more accurate results. This tech note will address the concepts of FE analysis and how to utilize the FE capabilities in PLS-CADD.

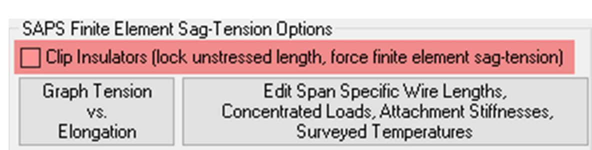
Wire System in FE

Ruling Span vs Finite Element

The major difference between a wire system in RS and FE is longitudinal loading. Ruling span sag tension assumes a constant horizontal tension across a section such that there is no longitudinal imbalance allowed at a structure for different weather cases or span configurations, similar to being in blocks. In reality, when wire is clipped in to the insulator there is a fixed length of wire between the attachment points, and the spans will interact with one another. Wire loading from items such as partial span icing, marker balls, or wind along the wire can result in loads on a structure that are in the direction of the wire. This longitudinal imbalance that occurs is not accounted for in RS based on the assumption that the section has a constant horizontal tension. When working in FE the fixed length of wire depends on the baseline wire length calculated from the sagging condition which is normally taken at 60 degree F under the initial condition but may be changed in the **Sections /Modify** dialog box to be a different temperature or cable condition if required. These sagging conditions are then used to calculate the unstressed cable length, which is the length of the wire at 0°C without mechanical loading deformation.

The second difference between RS and FE is insulator weight. In RS strain insulators are depicted, but are not taken into account for weight and clearances to survey points or ground. Typically this is not noticeable, but situations like short slack spans where the wire tension is low and the weight of the strain insulators are high compared to the wire can cause a different clearance result due to the varying span geometry between RS and FE.

Something to consider when working in FE cable conditions is that the wire system can be displayed in FE without having the wires clipped in. This will go through the fixed wire length calculations and determine insulator and wire positions for finite element and still give you the ability to quickly move structures without having to unclip the wires or equalize the tension. If FE is chosen for the cable condition for a load case in the **Criteria /Structure Loads (methods 3,4)** menu then the program will calculate the loads as if the wires are clipped. The advantage of clipping the insulators and locking in a fixed length of wire is that all clearances and structure loads

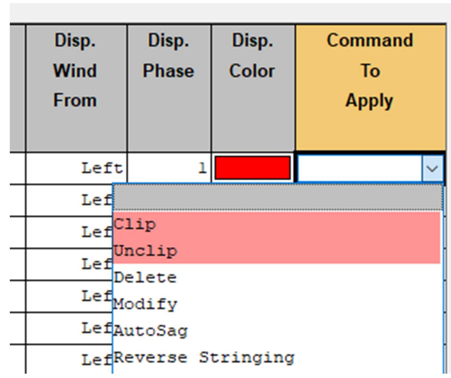


cable conditions will be automatically promoted to FE whether RS is selected in the criteria or not. You will receive a message confirming this if working with clipped insulators.

Working in Finite Element

Clipping in wires

When wires are initially strung, rollers are used to allow tension to equalize across the section. Once stringing operations are complete and wires are “clipped in” to each structure and the fixed length of wire can create longitudinal imbalances. In PLS-CADD users clip wires in by using the check box in the **Sections/Modify** dialog or applying the command in the **Sections/Table** dialog. Unchecking this box or using the Unclip command will revert the section back to a non-clipped configuration and you will lose any adjustments that were made to the fixed length of conductor.



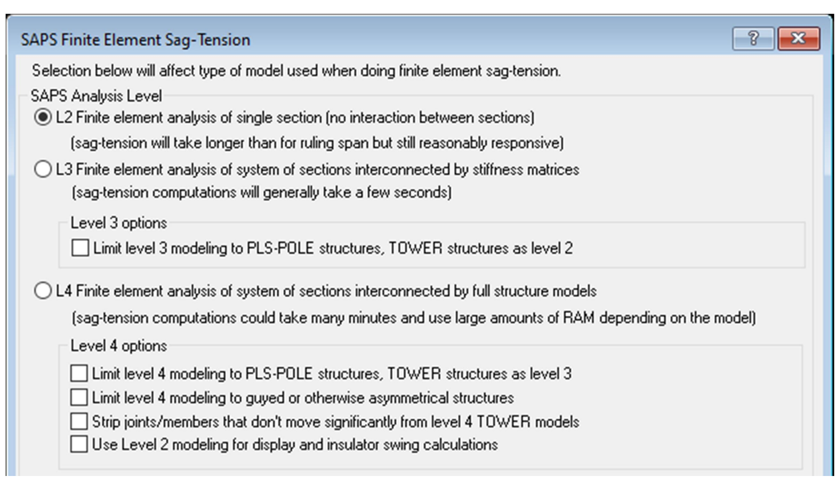
Levels of Analysis

PLS-CADD has four levels to choose from for performing sag-tension. To select the SAPS analysis level, navigate to **Criteria/SAPS Finite Element Sag-Tension**. Which level is chosen depends on a variety of factors. The size of the model, the design stage, and client requirements may dictate which level is used. The higher the SAPS level the greater the demand that is put on the computer to perform the analysis. With each increase in analysis level, the analysis becomes more expensive by one order of magnitude. That is to say that simply changing the analysis level from L1 to L2, or L2 to L3 requires 10 times more work out of the computer. It may make sense to only increase the SAPS level when necessary. Below is an overview of each of the analysis levels available.

Level 1 (L1) – Level 1 is ruling span analysis. For this reason you will not see this option under the SAPS Finite Element Sag-Tension dialog. In this level of analysis the horizontal tension in every span from one dead end to another is considered constant regardless of the weather case or span geometry, as if the wires were in rollers.

Level 2 (L2) – Level 2 is the first level of FE analysis. Allows for the interaction between spans such as a long span next to a short span while also taking into account the weight of the strain insulators as mentioned previously. Structures in L2 are fully rigid and do not deflect under load, but can experience longitudinal imbalances.

Level 3 (L3) – Similar to L2, L3 Allows for the interaction between spans while also taking into account structure deflection. Structure deflection in L3 is approximated using a stiffness matrix in the transverse and longitudinal directions for each wire attachment point. This stiffness matrix is derived from the full PLS-POLE or TOWER models. Note that no vertical deflection is allowed in the L3 method. The structure stiffness is purely linear so as the load on the structure increases, the deflection of the structure increases linearly. A simple example of linear deflection is a 1’ deflection with 1000lbs of load, and a 2’ deflection with 2000lbs of load.



Important Note: L3 is not recommended for asymmetrical, guyed structures, or structures with large deflections as the stiffness can be different depending on the direction of the load. For example, loading a guyed pole in the direction of the guy instead of against the guy will have different structure stiffness. Because of this the stiffness matrix may not accurately reflect the deflection and usage of these types of structures. L3 is also not recommended, or allowed for FRP poles due to the highly flexible nature of FRP structures. The linear stiffness matrix created would not give an accurate representation of these structures.

Level 4 (L4) – The most complete, but also most resource demanding analysis level is L4. L4 is similar to L3, but takes all structure properties into account when determining the deflection of the structures. The deflection and stiffness of a structure is based on a full finite element analysis of the structure. This level of SAPS analysis is suited for asymmetrical or guyed structures as it does not rely on stiffness matrix, but instead uses the structural properties of the structure to determine deflection and structure usage.

Limiting L3 and L4 Analysis

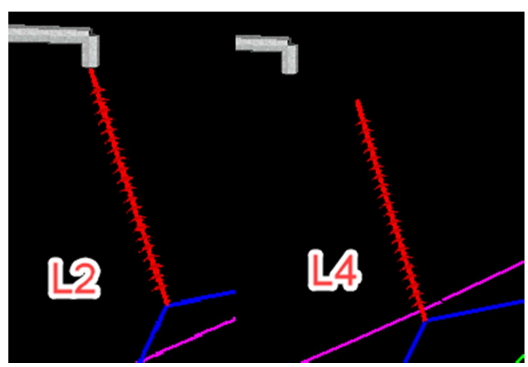
For options L3 and L4 the user has the option to further refine their analysis levels. The intent of these additional options is to limit what is being considered in the analysis. This can greatly decrease the time required to run an analysis depending on the model.

L3-1 – TOWER models are considered to be very stiff and typically have very little deflection when compared to a PLS-POLE model. It may not be necessary to calculate stiffness matrices and deflection for each TOWER model. By selecting this option the TOWER models are considered perfectly rigid as in L2.

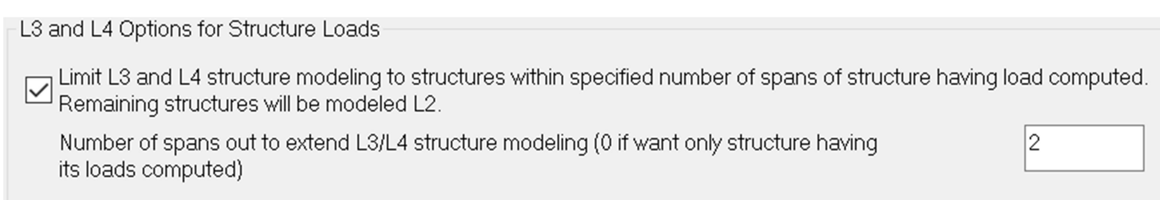
L4-1 – Like the above checkbox, this checkbox will only use L4 analysis for POLE models and TOWER models will be modeled as L3. This is again due to the greater flexibility of POLE models. It may not be necessary to perform such an intense level of analysis if a TOWER is deflecting only a small amount.

L4-2 – As mentioned in the L3 analysis overview, asymmetrical structures are not good candidates for L3 analysis. Checking this box will analyze all symmetrical structures using L3 analysis, but will promote asymmetrical and guyed structures to L4 which can speed up analysis time.

L4-3 – Another way to save time in L4 is to prevent the software from analyzing members that do not significantly move in TOWER models. This option will remove certain members from TOWER models simplifying their analysis and reducing run time.



L4-4 – Insulator swing calculations and display in 3D view can take structure deflection into account. This takes longer than L2 as the structure deflection under each weather case must be calculated. If you leave this option unchecked insulators will account for structure deflections and appear to disconnect from structures as shown in the figure to the right. This also speeds up the process of viewing the models since the wire display is shown in L2. It is a great way to quickly view the line but still have the results based on L4. Structure check times will also be decreased due to uplift calculations being performed in L2.



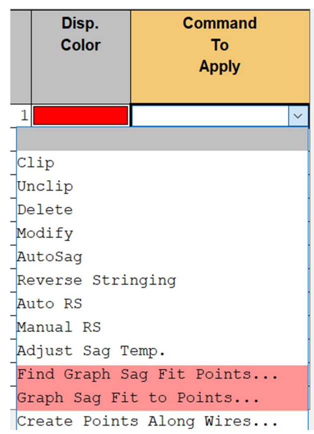
The final option for limiting L3 and L4 analysis is to reduce the number of structures included in the structure loads analysis. By default, the software will include the section the structure is in and the sections adjacent to those sections in the sag-tension analysis. This concept is described in more detail in Appendix N.3 of the PLS-CADD manual. Depending on the length of the sections and the number of other tap lines the analysis could get very large and take a long time. There may also be modeling errors in other structures that require further attention resulting in non-convergence of L4. To reduce the size of the model subject to L4 analysis, enter in the number of spans to include in the analysis. This will only consider the structures within this range as flexible and all other structures will be considered rigid. . The number of structures to choose is up to engineering judgement, but there appears to be a diminishing return on the accuracy of results when specifying more than two or three structures.

Impacts of FE Analysis

Structure Loads

Structure loading is a broad term that is the culmination of applied loads and span geometry. These different factors will be discussed in more detail, but as stated above finite element analysis gives the user the ability to take tension imbalances and structure deflection into account. In ruling span analysis the wire is assumed to have a constant horizontal tension throughout the section. FE locks the wire length in each span which can create imbalances and pull the structure or insulators in the direction of the load. Even without events causing a large tension imbalance, it is still typical to see a difference between loading from RS and FE analyses due to factors such as insulator weight, structure deflection, or span interactions.

Graphical Sagging

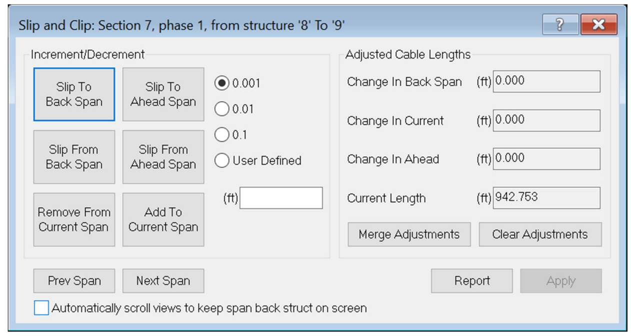


The difference between graphical sagging in ruling span or finite element can be small for flat areas where structures are evenly spaced without any external factors affecting a single span or portion of a section. As with most projects, there are likely to be differences between the idealized ruling span model and the more accurate finite element model. Construction tolerances, non-uniform wire elongation due to creep or load, and large differences in span geometry throughout the section are just a few examples of where sagging in FE will provide a better solution that RS.

Graphical Sagging can be performed through two different commands. The first is by using the **Sections/ Graphical Sag** command from the PLS-CADD toolbar. The second and easier way is to apply the graphical sagging command through the **Sections/ Table**. Using the **Sections/ Graphical Sag** option gives the users the ability to choose between six different sagging options. Two of these options will use ruling span theory to determine the sagging tension. The remaining four will allow for individual spans to be adjusted to match survey points. The six options are covered in more detail in Appendix N.8 and section 10.3.2.1.4 of the PLS-CADD manual. When using the **Sections/ Table** option the user will first have the software find the point in each span that the wire will be fit to. The user then graphically sags to these fit points using either RS (Fit mode A) or FE (Fit mode B). It is always recommended that RS be used as a starting point, but the best fit will likely always come from performing an FE fit. This graphical sagging method is discussed in the Graphical Sag Tech Note, and in section 10.3.5. There is also a webinar titled "Graphical Sagging & FE Cable Adjustments" available through the software in the **Help/Register for Training Classes** dialog.

Slip and Clip

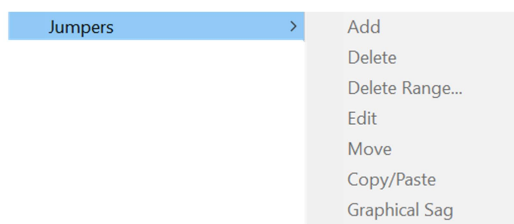
Given that span lengths are fixed in a finite element wire system, it can be very useful to change the length of the wire in each span. This is similar to graphical sagging, but involves making the adjustment in a different way. With graphical sagging, the user chooses a point for the wire to pass through, and the unstressed wire length is adjusted to match that point. While this will often be the most useful solution, tasks like adding a dead end in an existing section or shifting wire from one span to another may be more accurately accomplished by adjusting the length of wire in that span. Enter Slip and Clip, which gives users a dialog for adding, removing, or transferring wire between spans in an easy and incremental manner.

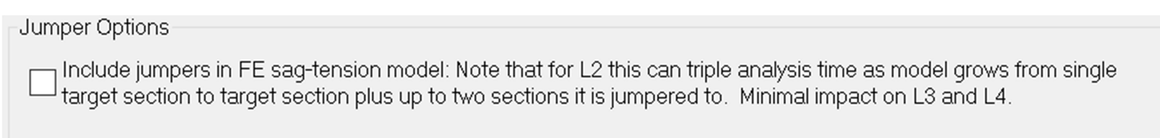


Sections/ Slip and Clip, is a user-friendly version of the table to "Edit Span Specific Wire Lengths, Concentrated Loads… found in the **Sections/Modify** dialog. Slip and clip changes are more easily applied and the effect of these changes is seen immediately. The Adjusted Cable Lengths field also shows what adjustments have been made to the span and allows the user to merge the current span length with the change. Keep in mind that changing the length is changing the *unstressed wire length*. As discussed above, this is not the wire length in the span but rather the wire with no stress at 0 degC, i.e. laying the conductor on the ground. Normally a user is not making large adjustments so the stressed length versus unstressed length is negligible however if making large changes you will want to consider if the difference is large enough to cause any issues. Slip and Clip is covered in section 10.3.6 of the PLS-CADD manual, but more detail and a feature demonstration are available in the Slip and Clip YouTube video.

Jumpers

PLS-CADD gives users the ability to model jumpers between an ahead and back span. This aids in checking clearances to the jumper, how the jumper influences structure loading, and designating circuits and phases. In order to use jumpers the option to include jumpers in the FE sag-tension model must be selected from the **Criteria/ SAPS Finite Element Sag-Tension** dialog. Without this option selected, the **Structures/ Jumpers** dialog will be inaccessible. For a more in-depth look at how to use jumpers see our YouTube video on modeling jumpers, or refer to section 10.3.8 of the PLS-CADD manual.





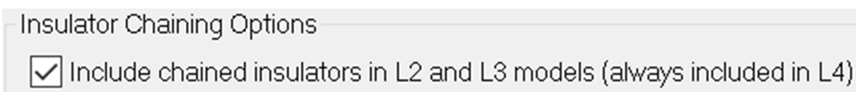
Concentrated Loads/Partial Span Icing

Like jumpers, concentrated loads require that a section use FE sag-tension. Concentrated loads like marker balls, bird flight diverters, and detuning pendulums increase the tension in the span in which they are installed and also influence adjacent spans as well. Because of this difference in tension on a span by span basis, ruling span methodology no longer applies. In the presence of concentrated cable loads PLS-CADD will auto-promote the section to finite element if the span is not already clipped in and will present a message about the auto-promotion. Modeling of concentrated load items such as marker balls is covered in Appendix N.8 of the PLS-CADD manual. Marker balls or bird flight diverters may need to be installed at a specified interval along the span. The concentrated load automatic placement tool makes quick work of this task, and is demonstrated in our [concentrated load automatic placement YouTube video].

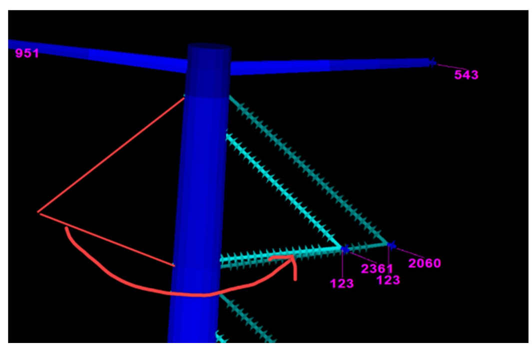
Another type of span loading is partial span icing. This function adds a uniform weight and wind area over a specified portion of the span. The most common use of this feature is to replicate an event where ice accretion may not be constant along the span requiring more complex sag-tension and load modeling. The only way to analyze this complex scenario is the use of FE sag-tension..

Chained Insulators

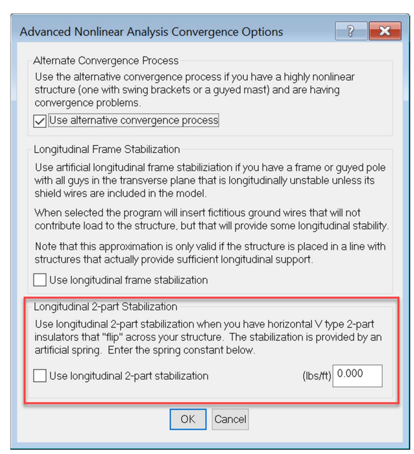
Certain scenarios may require that an insulator be attached to the end of another insulator instead of the supporting structure. This insulator chaining technique can be performed for some insulator combinations. A strain insulator, for example, can be chained onto a suspension insulator to replicate a floating dead-end. In reality, both the insulator attached to the wire, and the supporting insulator will move with wind and tension differences. In L4 both of these insulators will be allowed to move, because of the use of structural properties in this level of analysis. L2 and L3 results in only the insulator attached to the wire (the last insulator in the chain) being allowed to move or deflect. By checking the chained insulator option in the **Criteria/SAPS Finite Element Sag-Tension** dialog the software will allow all insulators in a chained set of insulators to move with changes in loading without requiring L4.



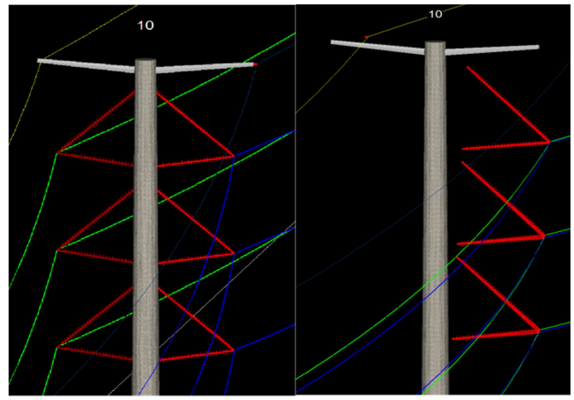
Insulator Flipping



One typically unclear concept in structure analysis is how a weather case or load case affects insulator swing for horizontal 2-part insulators. Horizontal 2-part insulators are notoriously unstable and have the potential to flip to the opposite side of the structure when a structure analysis is performed. This occurrence will most typically result in a warning about excessive joint rotations, and analysis non-convergence. Horizontal 2-part insulators are commonly used to model scenarios where the base of the insulators is allowed to pivot. Using a braced post connection may not be as accurate as braced post insulators do not allow for rotation at the insulator base. Because 2-part insulators are allowed to pivot, transverse loading on a wire may result in the insulator flipping to the opposite side of the structure as shown in the figure to the right.



Engineering judgement would tell you that the wire system provides some level of restraint against the insulator rotating around the pole. Running an analysis, however, provides the structural loads only to PLS-POLE or TOWER, and does not include the restraint from the wire. To prevent insulators from flipping in PLS-POLE, a stiffness value must be entered into the Conv. Options dialog found in **General/ General Data**. This can also be set in TOWER through the **F1/ Stabilize 2-part insulators** command. There is no defined way on what to set this value to, but if an exceptionally high value is needed to prevent flipping further research in PLS-CADD may be needed.



Wires clipped in L2 Wires clipped in L4

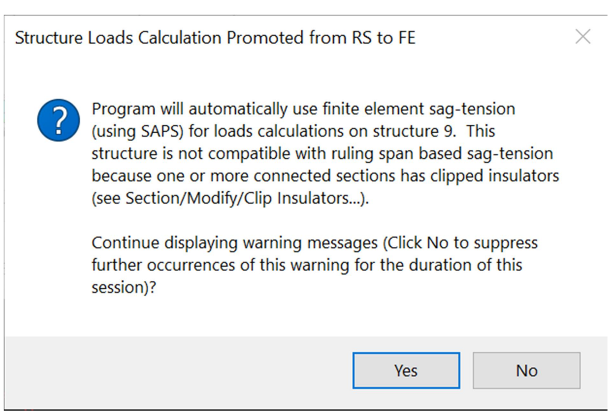
Given that the PLS-POLE or TOWER programs do not take wire/insulator interaction into account as they are not present in the structure models, a flipping insulator may require investigation in PLS-CADD. The first step is to clip wires in or display wires in an FE condition as this will promote the section to finite element analysis. The second step is to change the SAPS FE analysis level in **Criteria/SAPS Finite Element Sag-Tension** to L4. In L4, structure deflection will be shown, and if the load on the wires causes the insulator to flip the insulator geometry will represent this. You can see in the figure on the right that clipping the wires in and changing from L2 to L4 caused the structure to move and the insulators to flip.

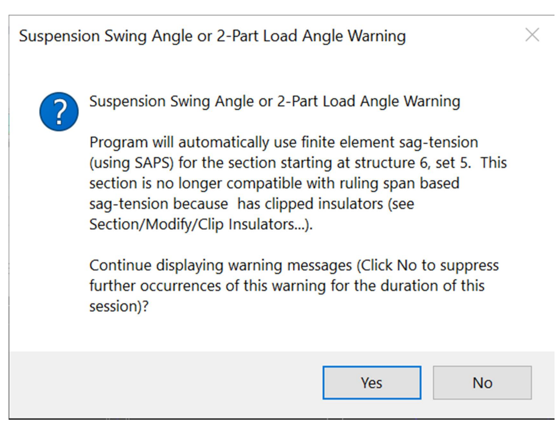
Engineering judgement will be required to find a fix for flipping insulators. Some measures can be taken during design to prevent insulator flipping. For example, using a short arm to attach the suspension string will change the axis of rotation to be inclined instead of vertical. This inclined axis of rotation will cause the weight of the wire to counteract flipping as the insulator would need to rotate upward to flip. Adjusting wind and weight spans or adding counter weights to these structures may also be valid solutions.

Common FE Questions

FE Auto-Promotion

When running reports in PLS-CADD you may have received the warning about promotion from RS to FE, and wondered why. While it may not make sense at first glance, reading the dialog further reveals that this warning is just informing the user that at least one part of the analysis required to be performed in FE, but the criteria settings were configured for RS. When running a structure check PLS-CADD will look at both the structure loading criteria and the insulator swing angle criteria. Both of these have the option to select RS or FE for the cable condition, and will provide a specific warning for each.

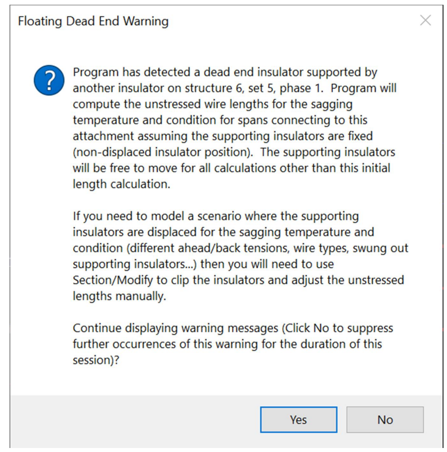




Two options exist for removing auto-promotion warnings. The first is to change the cable condition in the structure loads criteria (**Criteria /Structure Loads (methods 3,4)**) and the insulator swing criteria (**Criteria /Insulator Swing Uplift**) to FE. The second option is to remove the finite element feature that is causing the analysis to be promoted. Often this is because the wires are clipped in, but it is also possible that jumpers are used, or that concentrated loads are present in a section attached to the structure. It may be that just a single section is clipped in or that marker balls are on a single shield wire. In all cases, if one section requires that FE analysis be used for the wire system, all sections attached to the structure will use FE. Loads cannot be generated in RS for some wires on a structure, but not others. Typically users will change the load cases to FE, or ignore the notification. Clicking “No” will suppress the warning for the rest of the session.

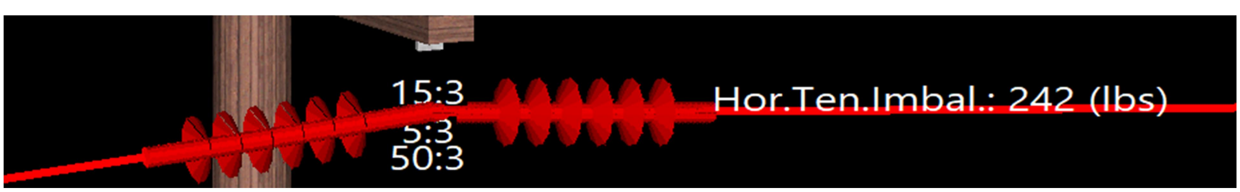
Chained Insulators

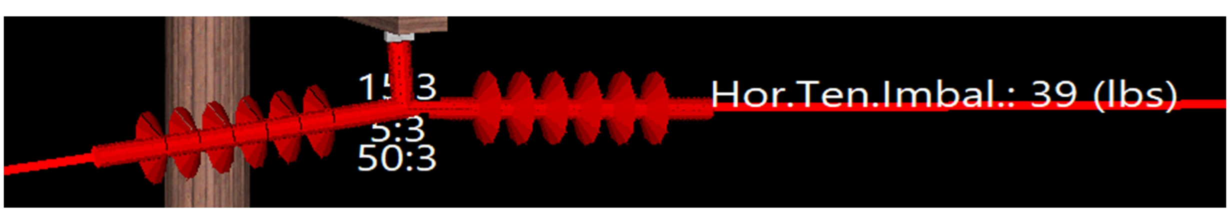
As mentioned earlier in this document unless L4 analysis is selected, or the checkbox to account for chained insulators, only the insulator that is attached to a wire will have the ability to move. When running a structure usage report or a clearance report where wind displaces wires and insulators the extra length from the swinging of the supporting suspension insulator can be a determining factor.



A common inquiry that stems from chained insulators is the warning on the right that will appear after modifying a section attached to a chained insulator. While this warning does specify the most common use of chained insulators (Floating Dead End) it applies to all situations where insulators may be chained such as a bifurcated dead end. This warning lets the user know that the unstressed length of the spans attached to the strain insulators will be calculated with the suspension insulator in the undeformed, straight down position. Once the wires are clipped in the suspension insulator will be allowed to swing toward the side with a higher tension. This becomes more noticeable when there is a large imbalance on either side of a floating dead end structure.

To get the full benefit of chained insulators users will want to have both the insulator chaining option selected in **Criteria /SAPS Finite Element Sag-Tension** and have the wires clipped in. The images below show the effect using the chained insulator option in L2 can have. The top image shows an imbalance of 242 lbs. This imbalance on each phase can result in excessive structure usage. This does not take the ability of the insulator to swing into account. Once the box for chained insulator analysis is checked the imbalance reduces down to just 39lbs per phase, and the suspension insulator is recognized as shown in the bottom image. This 6x reduction in imbalance can be the difference between a structure failing or passing due to more accurate loading.





Examples

PLS-CADD Modeling Examples
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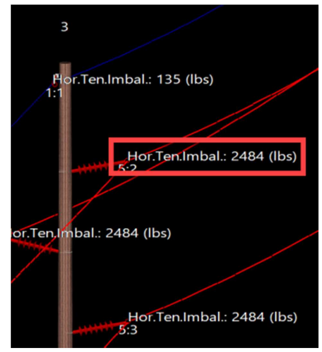
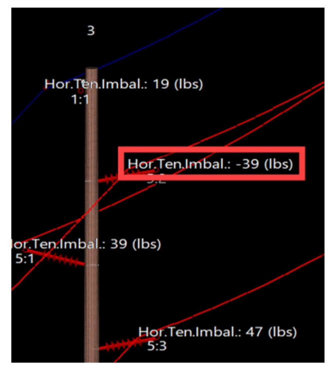
Structure Loading

1. Open FE_Varying_Spans Model.
2. Run structure check on structure 3. This is the RS usage. The pole model passes the check even though there are widely varying spans on either side of structure 3.
3. Go to **Sections /Table** and under "Command to Apply" select Clip for all sections.
4. Go to structure 3 in 3D view. Turn on tension imbalance in horizontal component of tension in the **Sections /SAPS Label Options** dialog.
5. Note the large imbalances in tension toward the long span for the displayed weather case.
6. Run another structure check. Now that these longitudinal imbalances are taken into account they cause the structure to fail the structure check.
7. Change model to L3 through **Criteria /SAPS Finite Element Sag-Tension**. Again view structure 3 in 3D view. Note how the imbalance is significantly less. This is due to structure flexibility evening out the imbalance and reducing the load.
8. Run another structure check and note that the usage has greatly decreased.
9. Change to L4. Run another structure test and you will notice the usage is approximately the same, or slightly less. Since this is a symmetrical model with simple loading the usages are very similar between L3 and L4 runs. On models with loading in different directions such as a tap structure or running angle the usages may have a greater difference, but will typically be similar.

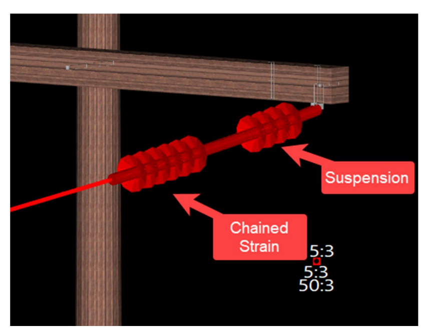




Chained Insulator

1. Open the FE_Chained_Insulators model.
2. Go to structure 6 in the 3D view.
3. Notice that the suspension insulator is drawn along with both strain insulators on either side.
4. Use the section delete function to delete the 69kV transmission conductor between sections 6 and 7.

5. Notice that the strain insulator and suspension insulator almost line up as the tension from the back span pulls the insulators in that direction. This is due to having the wires clipped in or displayed in FE, and including the option for chained insulators in L2.



6. Now go to **Criteria /SAPS Finite Element Sag-Tension** and uncheck the option to "Include chained insulators in L2 and L3 models". You can see at this point that the suspension insulator swings back to its undeformed position. Since the suspension insulators are not taken into consideration the strain insulators are held in their originally modeled positions.
7. Either use **Ctrl+Z** or **Edit /Undo** two times to take the model back to its original starting point. You could also close the model without saving, and re-open.

8. Repeat step 4 and delete the conductors between structures 6, and 7. At this point we are at the same position as we were in step 5, but will take a different route to show how the conductor display can affect chained insulator analysis.
9. Go to **Sections /Table** and select “Unclip” in the command to apply for all sections. Click the Apply button in the table to apply the changes and a warning will appear similar to the one shown in the Chained Insulaors section of this tech note telling the user that if the insulators supporting wires are displaced from their modeled position insulators need to be clipped. Click No to move past this warning, and click OK to exit the sections table.

Command To Apply
Unclip
Unclip
Unclip

10. In 3D view structure 6 now has the insulators in line. This goes against the warning that just appeared, but that is because of the wire display condition. As discussed earlier in this tech note, displaying wires in FE conditions can show the wire’s reaction to loading as if it were clipped in. Next we will change the wire display condition to show that even though the chained insulator option is checked in the SAPS criteria dialog, both FE and the chained insulators options need to be checked for this analysis to work.

Display Cond-ition
Initial RS
Initial RS
Initial RS

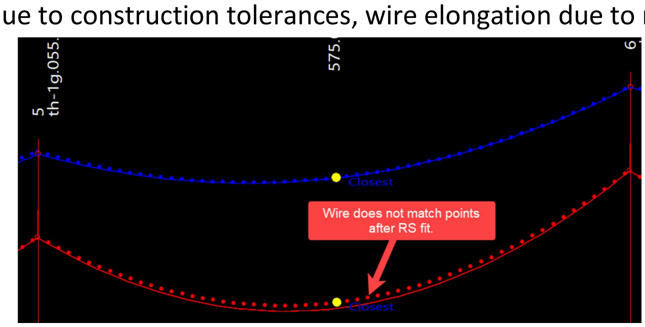
11. Go to **Sections /Table** again and change the Display Condition from Initial FE to Initial RS. Now when you click apply you will see that the chained insulators revert to their modeled location and the suspension insulators are removed.

Graphical Sagging

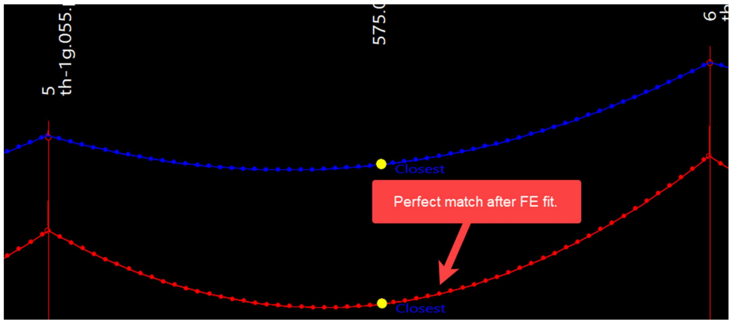
1. Open the FE_Graph_Sag model.
2. Navigate to **Sections /Table** and use the Command to Apply column to apply the “Find Graph Sag Fit Points Command” for the shield wires. Click “Apply” and a Fit point dialog will appear. Change the Feature code for wire fit to Feature Code 302, and leave all other settings as-is. In profile view you will see the fit points selected. You will also see that the fit points end up being approximately at mid span.

Command To Apply
Find Graph Sag Fit Points
Find Graph Sag Fit Points

3. Go to **Sections /Table** again and apply the command to Graph Sag Fit to Points. Choose mode A to sag wire under the ruling span assumption. This will sag the section so that at least one of the spans meets the fit point. Given that sagging was done in ruling span, all sections will have the same horizontal component of tension.
4. Follow the same process as steps 2 and 3, but for the red conductor wire, with one exception. Instead of using Feature Code 302, use 301 to find the sag point for the conductor. At this point both the shield wires and conductor should be sagged very closely to the red and blue points.
5. Inspect the line in profile view to see that span 1-2 for the conductor, and 5-6 for the shield wire matches the fit point perfectly while the other spans have some difference from the points throughout the span. This could be due to construction tolerances, wire elongation due to non-uniform load, etc.



6. To get the wires to fit more closely FE will need to be used to allow tension imbalances. Again go to sections/table to apply the command to graph sag fit to points. Choose Fit Mode B to fit using FE. This will adjust the wire lengths in each individual span to match the fit point. All spans should now have a vertical margin of 0.



7. Inspect along the line in profile view to verify.
8. Something to keep in mind is that this approach, while often very close, may have false solutions in very hilly terrain. The wire will pass through the fit point, but may be above or below all other points. When this occurs, further refinement through the Sections/Graphical Sag function will be needed.
9. It is also important to note that a ruling span fit, or manually adjusting the tension to get the wire near the points should be performed first. This reduces the amount of cable length adjustment needed, and gives more accurate results for creep/load conditions.