1) Additional calculations are needed to check torsional buckling, flexural buckling, and torsional-flexural buckling.
2) Different width/thickness ratio limits are used, which dictate the equation for design allowable stress.
3) Reduced area effects for shapes containing non-compact elements decrease allowable capacities.

Override Comp. Capacity (kips)	Override Comp. Capacity Unsup. (kips)	Override Comp. Control Criterion	Override Tension Capacity (kips)	Override Tension Control Criterion	Override Face Member ship
0	0		0		Automatic
0	0		0		Automatic
703.14	NA	L/r	600.2	Rupture	Automatic
703.14	NA	L/r	600.2	Rupture	Automatic
703.14	NA	L/r	600.2	Rupture	Automatic
703.14	NA	L/r	600.2	Rupture	Automatic
679.36	NA	L/r	530.1	Rupture	Automatic
679.36	NA	L/r	530.1	Rupture	Automatic
679.36	NA	L/r	530.1	Rupture	Automatic
679.36	NA	L/r	530.1	Rupture	Automatic
594.44	NA	L/r	0		Automatic
594.44	NA	L/r	0		Automatic
594.44	NA	L/r	0		Automatic
594.44	NA	L/r	0		Automatic
638.4	NA	L/r	581.6	Rupture	Automatic
638.4	NA	L/r	581.6	Rupture	Automatic
638.4	NA	L/r	581.6	Rupture	Automatic
638.4	NA	L/r	581.6	Rupture	Automatic
0	NA		0		Automatic

Figure 4 – Members Capacities and Overrides Table from PLS-TOWER™ (Version 15.00)

Fortunately, ASCE 10 provides the user direction on how to address these issues, so it is straight-forward to calculate a given member's capacity. These calculations can be accomplished by hand, or can be set-up with an automated method using Excel®, MathCad©, or any other software capable of performing repetitive calculations.

Because of the large number of members in most lattice structures, it is the authors' experience that using a spreadsheet format for calculating member capacities is an efficient means of evaluating multiple members. Figure 3 below displays an excerpt from one such spreadsheet. Note that for ease of viewing, the spreadsheet has been separated into multiple rows.

In addition to performing the repetitive calculations, using a spreadsheet format also allows the engineer to take advantage of the many exportable tables within PLS-TOWER™. This format allows much of the data necessary to calculate member capacities to be populated automatically, limiting data entry time and minimizing potential data entry errors.

By the same token, once capacities are determined based on the appropriate ASCE 10 requirements, PLS-TOWER™ includes an option of inputting a member's compression capacity as an override of the software generated value. This override is accomplished in the "Members Capacities and Overrides" table within the program. Again, this data is in table form and can be pasted directly from a spreadsheet, limiting data entry time. Figure 4 below contains a screenshot of the "Members Capacities and Overrides" table.

Figure 5 – Aluminum Lattice Tower Photo Courtesy of Exelon

Figure 6 – Wood Lattice Structure Photo Courtesy of Ameren Illinois

The table illustrated in Figure 4 allows the user to input an alternate tension or compression capacity into the model for each member. PLS-TOWER™ will then use this capacity limit when comparing to the force within each member and determining percent usages.

GROUP LABEL	MEMBER PROPERTIES		
	ANGLE TYPE	ANGLE SIZE	MEMBER LENGTH, L (ft)
A302.1	SAE	L6X6X0.4375	11.722
A302.2	SAE	L6X6X0.4375	14.267
A329	SAU	L3.5X3X0.25	20.36

GROUP LABEL	CONNECTION PROPERTIES									K			L
	BOLT DIA, D (in)	BOLT QTY	BOLT HOLE QTY	# OF SHEAR PLANES	CONNECT LEG	SHORT EDGE DIST (in)	LONG EDGE DIST (in)	END DIST, e (in)	BOLT SPACING, s (in)	x	y	z	(in)
A302.1	5/8	10	4	1	Both	1 11/16	3 7/16	1 1/2	3	0.5	0.5	0.5	140.66
A302.2	5/8	0	4	1	Both	1 1/4	3	1 1/2	3	0.5	0.5	0.5	171.2
A329	5/8	1	2	1	Short only	1 1/2	0	1 1/4	0	1	1	1	244.32

GROUP LABEL	SECTION PROPERTIES														
	LONG LEG WIDTH, w1 (in)	SHORT LEG WIDTH, w2 (in)	LEG THICK, t (in)	SECTION WEIGHT (lb/ft)	TOTAL AREA (in^2)	w/t	Centroid Y (in)	Centroid X (in)	Centroid Xo (in)	Radius of Gyration Rx (in)	Radius of Gyration Ry (in)	Radius of Gyration Rz (in)	Radius of Gyration Ro (in)	J (in^4)	Cw (in^6)
A302.1	6	6	7/16	5.94	5.05	11.57	1.630	1.630	1.996	1.870	1.870	1.190	3.313	0.323	0.899
A302.2	6	6	7/16	5.94	5.05	11.57	1.630	1.630	1.996	1.870	1.870	1.190	3.313	0.323	0.899
A329	3 1/2	3	1/4	1.84	1.57	11.25	1.010	0.760	1.089	1.110	0.914	0.631	1.804	0.033	0.027

GROUP LABEL	ADDITIONAL CONN. PROPERTIES				NET AREA, A_n (in^2)	λ				
	BOLT HOLE DIA, H (in)	BOLT GAGE, g (in)	# OF BOLT ROWS, n (in)	# OF BOLT LINES, m (in)		X	Y	Z	SINGLE LEG CONN.*	EQUIVALENT FOR TORSIONAL BUCKLING
A302.1	11/16	1 3/4	3	4	3.85	37.61	37.61	59.10	N/A	1.25
A302.2	11/16	1 3/4	0	0	3.85	45.78	45.78	71.93	N/A	1.25
A329	11/16	0	1	1	1.23	220.11	267.31	387.19	7.33	1.20

GROUP LABEL	Compression Resistance Factor, Φcc	FACTORED TENSION CAPACITY CHECKS					TENSION CAPACITY (kips)	CONTROLLING TENSION CHECK
		GROSS SECTION (kips)	NET SECTION (kips)	CONNECTION SHEAR (kips)	CONNECTION BEARING (kips)	BLOCK SHEAR (kips)		
A302.1	1.00	176.75	146.18	73.63	144.92	N/A	73.63	Shear
A302.2	1.00	176.75	146.18	N/A	N/A	N/A	146.18	Net Sect
A329	1.00	54.95	46.60	7.36	8.28	N/A	7.36	Shear

GROUP LABEL	FACTORED COMPRESSION CAPACITY CHECKS					COMPRESSION CAPACITY (kips)	CONTROLLING COMPRESSION CHECK
	MEMBER SLENDERNESS (kips)	LOCAL BUCKLING (kips)	TORSIONAL BUCKLING (kips)	CONNECTION SHEAR (kips)	CONNECTION BEARING (kips)		
A302.1	133.12	133.23	1,000.00	73.63	144.92	73.63	Shear
A302.2	99.54	133.23	1,000.00	N/A	N/A	99.54	L/r
A329	1.07	41.94	1,000.00	7.36	8.28	1.07	L/r

Figure 7 – Excerpt from Non-Standard Material Capacity Calculations Spreadsheet

Note that the capacity limit should only be overridden if it is the controlling limit state. PLS-TOWER™ no longer compares the capacity values from each limit state (L/*r*, shear, bearing, etc.) once an override value is input. Rather, only the override value will be applied.

Figure 8: Aerial Photo of the Lattice Tower, Photo Courtesy of Ameren Missouri

NON-STANDARD MATERIAL

Another area engineers need to be mindful of is the use of non-standard materials within lattice structures. “Non-standard material” includes any material that is not steel. The most common non-standard materials encountered are aluminum and wood. Figures 5 and 6 below show two examples.

Design Guide Selection

For these scenarios, the engineer needs to consider that ASCE 10 is applicable to steel structures only. Therefore, one of the first steps the engineer will need to complete is selecting an appropriate guide or standard to use for calculating the member capacities. While this selection sounds like a simple task, consideration needs to be given to the goals of the structural analysis. Current standards or guides should be applied for designing or analyzing a new structure. However, when analyzing an existing structure, either current guides or guides that were used in the original design can be employed. Owner input should be considered when deciding which guides should be applied.

There are multiple guides available to choose from, and many times it is not known what guide or standard was used in the original design. Some common references for aluminum design in relation to lattice structures are listed below:

1) Aluminum Design Manual (2015 Edition, The Aluminum Association)
2) Guide for the Design of Aluminum Transmission Towers (1972 Journal of the Structural Division, ASCE)

3) Task Group Report on Aluminum Latticed Structure Design (1975 IEEE Transactions on Power Apparatus and Systems)
4) Multiple client and manufacturer guidelines and standards

For wood, historical design documentation relating to lattice structure design is often difficult to locate. However, one good current resource is the National Design Specification for Wood Construction. The pre-cursor to this specification was first published in 1944, and was titled the National Design Specification for Stress-Grade Lumber and Its Fastenings. Additionally, the *ASCE Task Committee on Recommended Practice for the Design and Use of Wood Pole Structures for Electrical Transmission Lines* is currently under development and scheduled to be published in 2018.

The engineer should carefully consider which guide or standard is selected, and also consult with the tower owner to investigate the possibility that an internal guide or standard was used in the original structure development.

Finally, the engineer should remember to update the material properties within PLS-TOWER™. This update is especially critical for the Modulus of Elasticity value, as changes to this property will impact member deflections, which will modify the stiffness matrix and ultimately the force distribution in the individual members.

Analysis

Once a guide is selected, the process for analyzing the non-standard material in the lattice structure is relatively similar to the process for evaluating non-standard shapes. The engineer will use the chosen guide to calculate the appropriate capacities of each member, and once again PLS-TOWER™'s "Member's Capacities and Overrides" table will be used to input the updated capacities.

Similar to the process for the non-standard shapes, the authors' experience is that using a spreadsheet format is one of the most efficient ways for calculating the capacities of the numerous members within the structure. Figure 7 below displays an excerpt from one such spreadsheet for an aluminum lattice tower.

BENDING EFFECTS

A final topic considered is the concept of bending effects within a member. In some cases, towers requiring analysis may contain non-standard bracing schemes or loading conditions that induce moments within members. PLS-TOWER™ does not calculate or analyze stresses because of moments, since the program assumes that the tower is properly triangulated. As a result, the equations within the program are specified to check capacities related to axial loading only. Given this consideration, the engineer must verify the structural capacity of members in bending through tools outside of PLS-TOWER™. The purpose of this section is to provide guidance on how to approach analysis involving non-axial loading.

As discussed above, PLS-TOWER™ considers only axial forces within members. The software checks the axial forces per the requirements outlined in Chapter 3 of the ASCE 10-15 standard. For members experiencing bending in addition to axial loading, the engineer should reference the equations outlined in Sections 3.12 (Axial Compression and Bending) and 3.13 (Axial Tension and Bending) of the ASCE 10 standard (2015). The equations within this section are set-up to check a given member's utilization ratios. As a result, the axial utilization of a member influences the remaining capacity to resist flexure, and vice-versa. In other words, if a given member experiences a small axial load relative to its axial capacity, the member will be able to handle a significant flexural load. However, if the same member is loaded axially near its axial capacity limit, it will only be able to accommodate a very small flexural load before becoming over-utilized.

While this method of checking combined loading is not unusual, it does present a challenge to the engineer tasked with checking multiple load cases. Essentially, each member's utilization ratios must be checked for the forces from each load case separately, to ensure that the member is not overstressed. This process is more cumbersome when compared to the typical axial checks, in which a member's axial capacity does not change depending on the magnitude of axial force present in the member.

As a result of needing to carry-out repetitive calculations, the use of a spreadsheet is highly recommended to help streamline the effort. Again, taking advantage of PLS-TOWER™'s ability to import and export data can help speed up the process.

In addition to the effort necessary to calculate member utilization ratios, the engineer must also employ an alternative method to determine the forces and moments present within members subject to combined loads. This alternative method is necessary since PLS-TOWER™ does not require enough information from the user to complete analysis on members subject to non-axial loading. Specifically, the "TOWER – Version 14.0" manual states the following:

> "Beam elements in TOWER are not intended to give moments which can be used for the calculation of accurate bending stresses in the angles, as the program does not have the ability to model the correct eccentricities of each connection and to provide the actual orientation of the member around its longitudinal axis in space." (Power Line Systems 2015).

As a result, it becomes necessary to use a software package that has the ability to accurately account for bending when distributing loads within members. In some cases, the engineer may also complete hand calculations to determine the maximum forces within a member. However, because of the number of members present in most lattice structures, hand calculations can quickly become cumbersome. Therefore, alternative software aids are recommended. Engineers should have a thorough understanding of these software aids, to ensure the assumptions in the software are appropriate and reasonably accurate given the analysis undertaken.

The end goal of either hand calculations or utilization of a separate software package is to determine the combined loading profiles (axial, shear, moment, etc.) of the structure members. After the member loadings have been determined, the values can be placed into a separate computational spreadsheet to evaluate the combined stresses and determine whether the utilization equations from ASCE 10 are satisfied.

Analysis

To illustrate this process in more detail, the following example involving a cross-arm loaded in bending will be discussed. Though the example below covers a single scenario, the same approach is applicable to a variety of situations that involve members experiencing combined stresses. The basic steps are to develop accurate load distribution and check the member forces against the appropriate standards.

The scope for this example included replacing the existing wood cross-arm with a new steel member. As shown in Figures 8 and 9, the configuration of this tower included cantilevered ends of the cross-arm. In addition, no bracing is present at the center of the cross-arm where the middle insulator is located. Therefore, the reason this particular tower does not lend itself well to standard analysis in PLS-Tower™ is that the cross-arm is functioning as a continuous beam loaded primarily in bending.

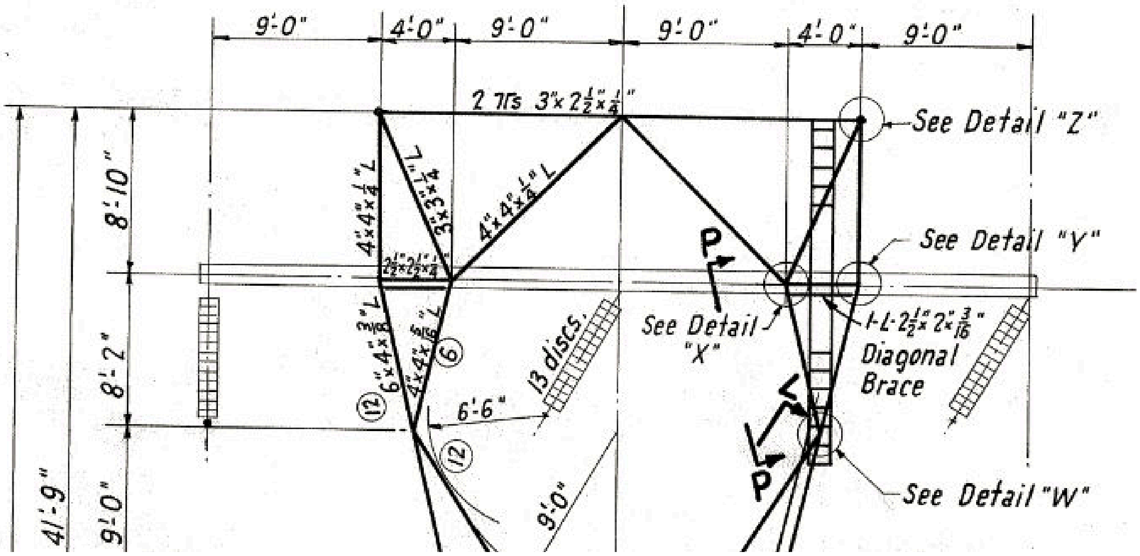

Figure 9: Lattice Tower Detail, Courtesy of Ameren Missouri

Though multiple load cases must typically be evaluated, the discussion in this example will focus on a single load case for the sake of simplicity. The load case evaluated was a “Heavy Ice” case, which considers no wind, one inch of ice, and a temperature of 0°F.

Similarly, while the entire lattice structure must be analyzed to ensure no overstresses exist, the portion of the analysis presented will focus on the cross-arm member, as it is the primary member experiencing non-axial loading.

In order to develop the member forces acting on the new steel cross-arm, RISA-3D™ was used as an alternative software aid. This program accounts for moment, shear, and torsional forces, in addition to axial forces. Figures 10 and 11 below display the model overviews from PLS-TOWER™ and RISA-3D™ respectively.

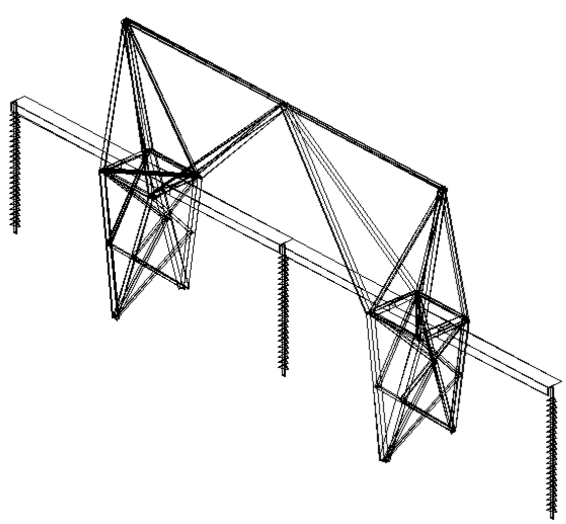

Figure 10: PLS-TOWER™ Model Overview

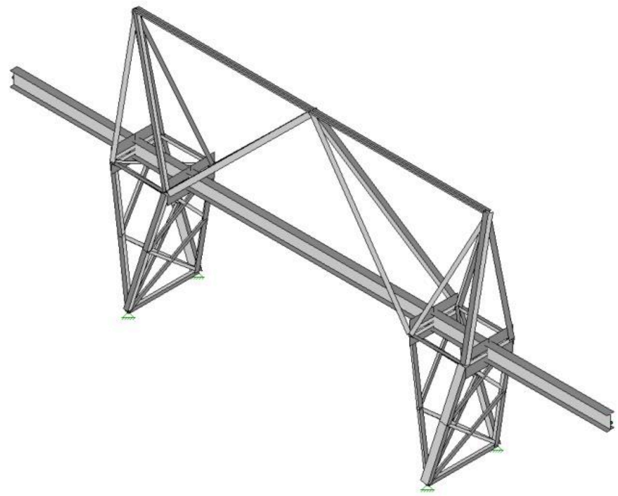

Figure 11: RISA-3D™ Model Overview

In order for RISA-3D™ to accurately check bending, the model requires additional information when compared to the PLS-TOWER™ model. This additional information includes specifying member orientation, unbraced lengths related to the member flanges, and detail of moment and torsional end releases. Note that the requirement of this additional information is not specific to RISA-3D™. Any software that analyzes bending will require similar inputs to develop accurate checks. As mentioned above, engineers need to understand the processes being used within any software package aid to verify the results produced are appropriate and reasonably accurate.

Although RISA-3D™ does serve as an excellent tool to analyze the bending effects, a shortcoming of the program is that ASCE 10 criteria are not included as an optional code check. Given this limitation, RISA-3D™ was used to generate the loads present in the cross-arm member, but the program could not be used for evaluation of the member capacities.

Results

Under the Heavy Ice case analyzed, the largest bending moment occurred near the cross-arm-cage interface, and was found to be approximately 41.4 kip-ft. In addition to the bending force, the maximum axial force was found to be approximately 0.85 kips in tension.

Having determined the maximum loadings the cross-arm needs to resist, the next step was to select a trial shape size and determine whether the cross-section contained enough capacity to satisfy the utilization equations from ASCE 10. A W10x22 was chosen to replace the existing wood cross-arm.

The first effort in evaluating the W10x22 focused on determining whether the cross-section contained any elements that may be susceptible to local buckling. Local buckling is checked based on the requirements contained in ASCE 10-15 Section 3.9, and must be carried out for elements supported on one longitudinal edge (flanges) as well as elements supported on both longitudinal edges (web) (2015).

After determining that local buckling was not a concern for this shape, a few other values needed to be calculated to check the combined utilization. The design axial tension value was calculated per Section 3.10, and the allowable moment capacities were calculated per Section 3.14. These values were then plugged into the axial tension and bending equation from Section

3.13 (ASCE 2015). The results of this effort showed that the proposed W10x22 cross-arm was approximately 89% utilized under the Heavy Ice case. It is interesting to note that for this cross-arm, nearly all of the utilization is attributed to the bending demands on the arm. The axial tensile force of 0.85 kips only contributes 0.3% to the utilization.

This utilization aligns well with the value obtained from the PLS-TOWER™ model, which specifies an axial usage of 0.31% for this same cross-arm. It is worth noting the PLS-TOWER™ model issues the following warning to alert the user of potential issues with the cross-arm member:

> "A potentially damaging moment exists in the following members (make sure your system is well triangulated to minimize moments):"(2017)

The dramatic difference between 89% and 0.3% percent usages for the same cross-arm under the same load case illustrates why it is critical to investigate non-axial forces for members experiencing combined loadings.

CONCLUSION

The analysis of lattice towers that require non-traditional modeling methods has become increasingly relevant in recent years. There are multiple factors driving this trend including the aging of the transmission infrastructure and the increased difficulties around the permitting process and obtaining right-of-way for new lines. These factors have resulted in transmission line owners placing increased emphasis on using existing lines to transmit additional power and new communications. This emphasis has led to a heightened demand to analyze existing lattice structures, many of which may pre-date ASCE 10 or the Manual of Practice No. 52. Engineers need to be competent in understanding what checks software programs are performing and especially aware of instances where software programs could be leaving analysis gaps. As illustrated in the example above, these analysis gaps can result in significant member over-stresses if not properly evaluated.

By using the direction provided in this paper, it is the authors' hope that engineers will be better prepared to recognize these analysis gaps and apply non-standard analysis methods as necessary to bridge the gaps and complete proper structural analyses.

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