Effective Length Factors of Gin Poles

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ABSTRACT

An iterative numerical method is used to find the first elastic buckling mode and critical buckling load of gin poles. The buckling loads are used to determine dimensionless, effective length factors, K_L, referenced to the total gin pole length. A dimensionless, relative stiffness ratio of the supporting structure to the gin pole is defined and incorporated into a parametric study of the effective length factors versus the "overhang" distance above the top lateral support. Other parameters include variations in rigging of load lines and two or three lateral supports. Results are presented in graphical format.

Keywords: gin pole, critical buckling, effective length factor, relative stiffness

INTRODUCTION

This study was a direct result of discussions at a committee that was meeting to draft the design portion of a structural standard for gin poles. The overall stability of gin poles required an effective length factor for elastic buckling of the entire gin pole. Effective length factors of 2 applied to the cantilevered length of the gin pole and of 1 applied to the overall length of the pole between top and bottom lateral supports were both suggested. Further discussion suggested that neither value was directly related to the overall stability of the gin pole, which acted as a structural system, and that neither value was conservative. It was recognized that the correct value ultimately depended on the stiffness of the structure that supported the gin pole, which varied widely in communication structure use. The object of this study was to determine the effective length factors of gin poles and to provide an insight to the overall stability of gin poles.

Gin poles have numerous applications in the construction industry. Gin poles are typically used by the communications industry as lifting devices that usually extend above the highest fixed point of a tower or other structure. They are used to raise, or lower, successive sections of structural steel, antennas or other equipment. Gin poles are masts typically fastened in a vertical position to a structure with a support at its base (basket support) and at least one support at its center or higher (bridle support). The top of the gin pole has a sheave assembly, called a rooster head, that is capable of rotating 360°. A load line from the ground hoist, *LLh*, passes up through the gin pole, over the rooster head sheave, and down to the lifted load. The loading of a vertical gin pole is comprised of an axial load from the top-mounted rooster head and a bending load due to load line eccentricity and horizontal tag forces on the lifted load. Structurally, the gin pole is a "beam-column" with vertical and horizontal supports at its base and a horizontal support at a bridle attachment location. A typical gin pole that is mounted on a guyed tower is shown in Figure 1.

The National Association of Tower Erectors (NATE), working with the Occupational Safety and Health Administration (OSHA), recognized the need for gin poles to have meaningful operational load charts for gin pole construction lifts. With NATE's support and under the direction of the Telecommunications Industry Association (TIA), Subcommittee TR14.7 developed—and, in 2004, released—ANSI/TIA-1019, *Structural Standards for Steel Gin Poles Used for Installation of Antenna Towers and Antenna Supporting Structures* (TIA, 2004). Its purpose is for gin pole use and for the development of gin pole load charts. This standard has been recently updated for the purpose of providing construction guidelines for the telecommunications and broadcast communication industries as ANSI/TIA-1019-A, *Standard for Installation, Alteration, and Maintenance of Antenna Supporting Structures and Antennas* (TIA, 2011).

While developing criteria for safe lift capacities for gin pole load charts, the communications industry recognized that the supporting structures for gin poles vary in stiffness. Support stiffness provided to a gin pole will vary with tower face dimension, vertical leg size, and basket and bridle locations relative to supporting guys. This concern lead to a study of elastic buckling capacities for gin poles related to such variations of support stiffness. This study was completed at the Electronics Research Inc. (ERI) facility in Chandler, Indiana, prior to completion of ANSI/TIA-1019 (TIA, 2004). Computer models, small-scale testing, and full-scale testing were conducted to help determine buckling

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loads. A relative stiffness ratio, *RSR*, equal to (stiffness of the supporting structure) ÷ (stiffness of the gin pole) was defined. The computer modeling suggested that an *RSR* value of 50 provided a reasonable lower boundary for elastic buckling, and an *RSR* value of 800 provided a reasonable upper boundary. A review of typical communication tower stiffnesses suggested that a practical range for the *RSR* was 100 (soft supports) to 800 (stiff supports). Standard gin pole load charts need to be conservative for a range of typical support conditions, and an *RSR* of 100 was selected to account for the softer support conditions. However, the user has the option to increase gin pole lift capacities using *RSR* values up to 800 if the actual support conditions for a particular lift are verified. These conditions need verification because any flexibility of the supporting structure allows sidesway between the basket and bridle. This is covered in the Special Engineered Lift provisions of ANSI/TIA-1019-A (TIA, 2011).

An overall effective length factor, *K*, was developed for gin poles with various support conditions. This *K* value is dependent on the *RSR*, on the use of only a bridle and basket support or the addition of a third support at the midway between the bridle and basket, and on restraint of the load line as it passes down through the basket. The effectiveness of the load line restraint varies with the tension in the load line, which varies with the number of parts used to support the load. Idealized load line configurations at the rooster head are shown in Figure 2 for one, two, and three parts of the load line. The lifted load, *P*, is offset a distance, *Roff*, from the pole centerline, while the load line down to the hoist, *LLh*, usually acts along the centerline. In Figures 2a, 2b, and 2c, the load line is laterally restrained at the pole base, and *LLh* equals *L*. In Figure 2d, the load line is not restrained above the hoist, and *LLh* is large relative to *L*.

The load line tension is equal to the lifted load divided by the number of parts, *N*, for frictionless sheaves. The total axial compressive force applied to the pole is 2*P* for one part and is reduced to 1.5*P* for two parts and to 1.33*P* for three parts.

Details concerning the selection of the appropriate *RSR* values are contained in Annex B, "Guide for Engineering Design," of ANSI/TIA-1019-A, which covers overall

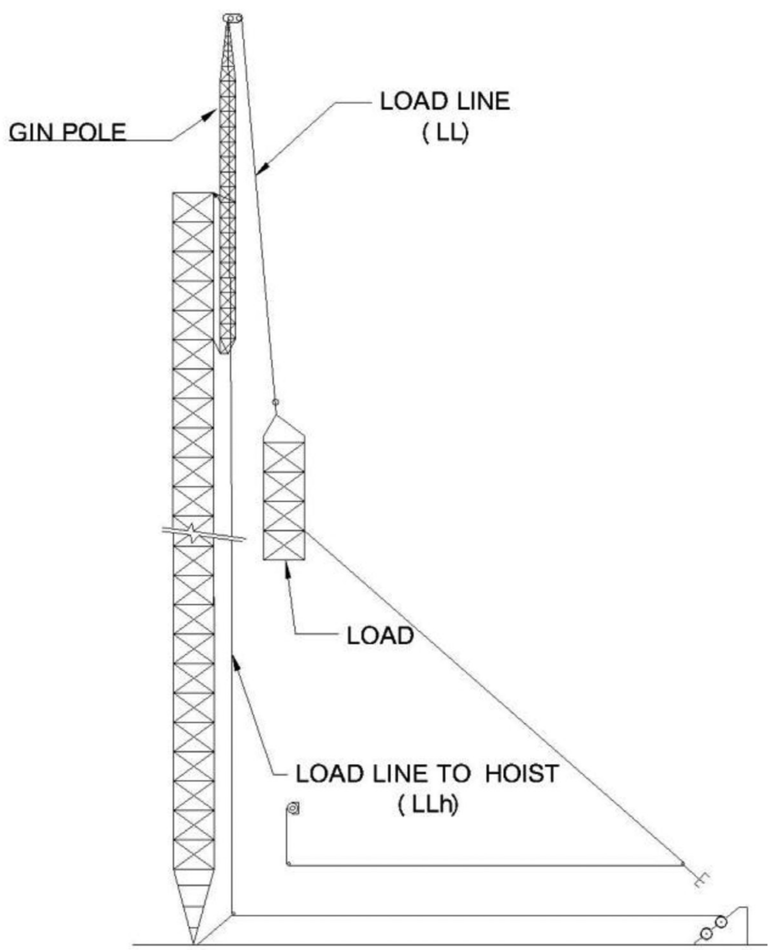


Fig. 1. Typical gin pole mounted on a guyed tower.

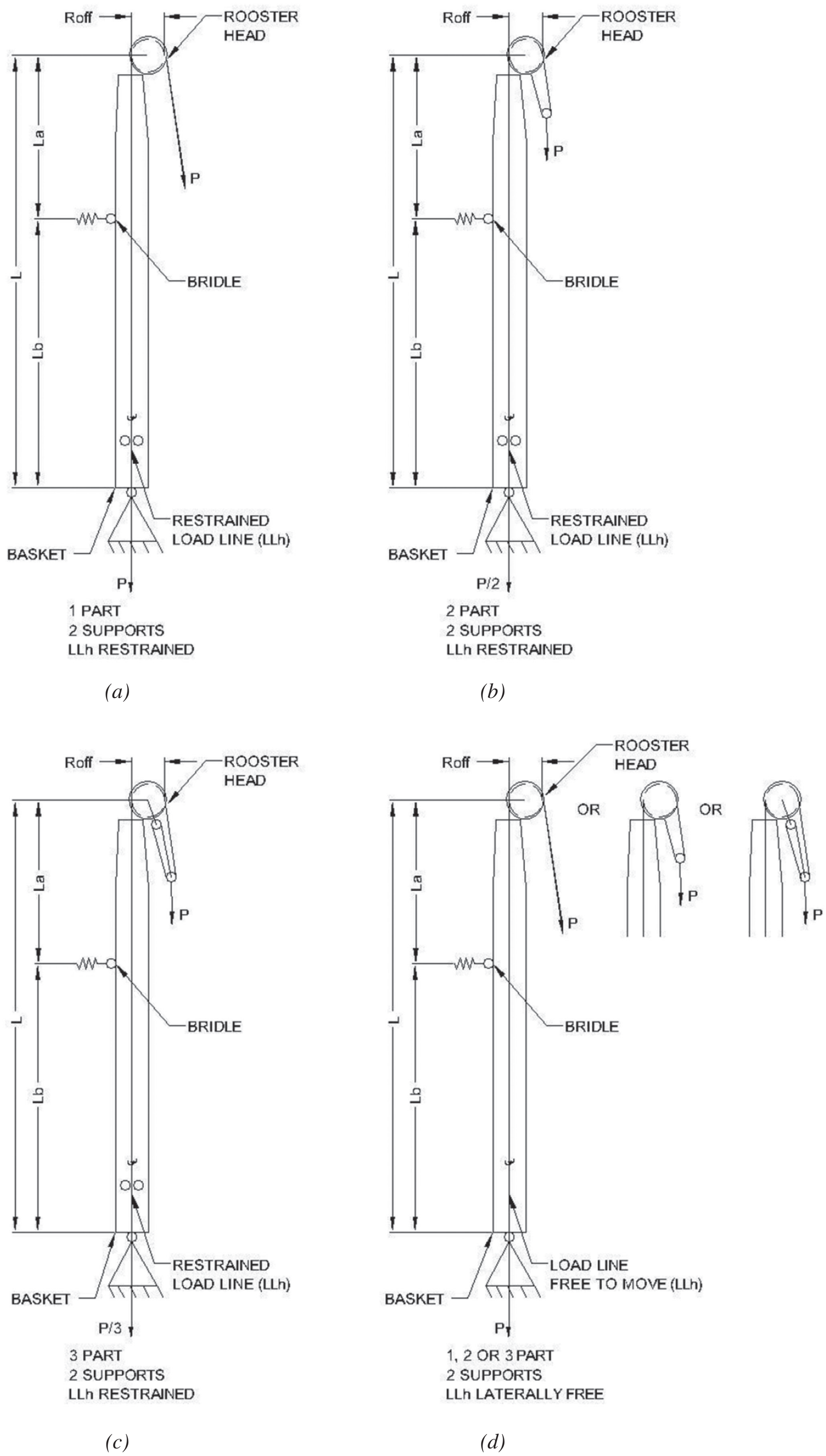


Fig. 2. Load line configurations.

stability criteria for a gin pole arrangement and provides alternate criteria for special engineered lifts. Chart B-1 in Annex B has acceptable variations in the overall effective length factor *K* based on the *RSR*, number of supports, number of load line parts, and load line restraint. It should be noted that the *RSR* is based on the total gin pole length and *K* is based on the cantilevered overhang length ("Section a," as noted in Figure 3), in ANSI/TIA-1019 and ANSI/TIA-1019-A.

The engineer is required to make an overall stability check of the gin pole lifting system with the selection of a proper effective length factor, *K*, to be used in an interaction equation based on axial and moment forces at the gin pole bridle.

Tagging of the load line and eccentricities at the rooster head and basket introduce bending moments into the pole. An idealized free-body diagram of a gin pole is shown in Figure 3a. The horizontal reaction at the basket is often above the bottom of the gin pole because of the rise of the inclined wire rope slings used for vertical support. L_a is the length from bridle to rooster head (known as the cantilever), and L_b is the length between basket and bridle. The total length of the gin pole, L, is greater than the length between the basket and the rooster head, $L_a + L_b$. It is conservative to assume that the height of the slings is zero and that L_b then equals $L - L_a$ as shown in Figure 3b. The typical gin pole is assumed to be prismatic, and any taper at the ends is neglected.

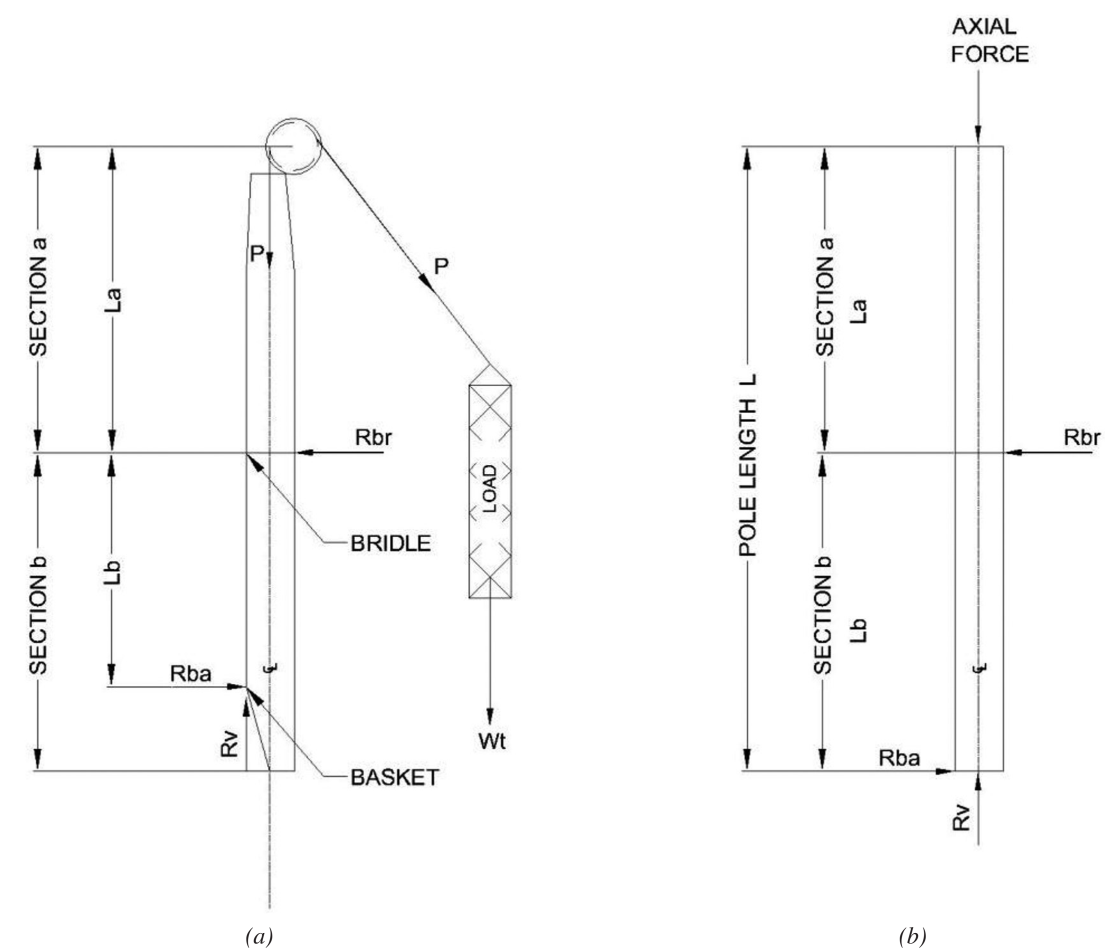
The overall stability of a structural system of columns, such as a gin pole, is usually checked separately for each column using an interaction equation similar to Equation H2-1 of the AISC *Specification for Structural Steel Buildings* (AISC, 2010). A simplified, conceptual format for allowable stress design (ASD) interaction of Equation H2-1 is shown as Equation 1:

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \le 1.0 \tag{1}$$

where

F_a = available axial stress, ksi

F_b = available bending stress, ksi



(a) *(b)*

Fig. 3. Free-body diagram of a gin pole.

f_a = required axial stress, ksi
f_b = required bending stress, ksi

The required axial stress for a gin pole is the axial load applied at the rooster head divided by the cross-sectional area of the prismatic pole. This required axial stress is constant over the entire length of the gin pole. The AISC *Specification* defines the available axial stress for an individual column member in Equation E3-2 for inelastic buckling and in Equation E3-3 for elastic buckling as functions of the elastic critical buckling stress, F_e, which is given in AISC *Specification* Equation E3-4 and shown here as Equation 2:

$$F_e = \frac{\pi^2 E}{(KL/r)^2} \tag{2}$$

where
E = modulus of elasticity, ksi
K = effective length factor
L = column length, in.
r = radius of gyration of column section, in.

The elastic critical buckling stress, F_e, of a column is used to determine if a cross-sectional area is elastic or inelastic at the onset of buckling. F_e is a function of the radius of gyration and is dependent on the elastic critical buckling load, P_{cr}. Many references such as Timoshenko and Gere (1961) give the equation for the elastic critical buckling load of a single column member as

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \tag{3}$$

The product $(K)(L)$ is a function of the boundary conditions at the column ends and has often been determined using the differential equations of the deflection curve of the column.

The elastic critical buckling load of a gin pole and other structural systems is more difficult to find using differential equations, and a numerical solution is an attractive alternative. Godden (1965) provides a numerical solution for P_{cr} for a prismatic beam with two supports and a cantilevered free end. This solution is similar to a gin pole with basket and bridle connected to a rigid supporting structure. There are numerous references to numerical solutions for elastic buckling, including Newmark (1943), Timoshenko and Gere (1961), Godden (1965) and Wang (1973).

When P_{cr} for a prismatic gin pole has been determined numerically, Equation 3 may be used to find the effective length of the gin pole, which is the product of a factor, K, and a referenced length. The effective length may be expressed in terms of any one of three possible reference lengths L, L_a or L_b. However, each of the three effective length factors K_L, K_{La} and K_{Lb} will usually have different values for any given value of P_{cr}. For a typical gin pole arrangement, the variations in each of these three effective length factors as the bridle attachment to a rigid supporting structure is moved from the basket to the rooster head is shown in Figure 4. Figure 4a extends over the entire length of the gin pole, while Figure 4b only extends over the range of the ratio L_a/L from 0.20 to 0.50.

The value of K_L increases from one at $L_a/L = 0.01$ to two at $L_a/L = 1.00$. K_{La} decreases from a very large value at $L_a/L = 0.01$ toward two as L_a/L approaches 1.00. K_{Lb} is one at $L_a/L = 0.01$ and approaches infinity as L_a/L approaches 1.00. It has been common practice to use K_{La} as the effective length factor for vertical gin poles and to use C for inclined or tilted poles. The use of the gin pole length, L, which is independent of bridle location, as the referenced length has the advantage that the effective length of a gin pole, $(K_L)(L)$, is proportional to K_L. The use of L_a or L_b as the referenced length has the disadvantage of the reference lengths varying with bridle location, which affects the resulting effective length $(K_{La})(La)$ or $(K_{Lb})(L - L_a)$.

Through the rest of this paper, L will be used as the referenced length; the effective length factor will be K_L; and the cantilever, L_a, will be expressed as the ratio L_a/L. If the alternate effective length factor K_{La} is required for any reason, K_{La} is given in Equation 4 as

$$K_{La} = \frac{K_L}{L_a/L} \tag{4}$$

For example, $K_{La} = 2K_L$ when $L_a/L = 0.50$, K_{La} is infinite when $L_a/L = 0$, and $K_{La} = K_L$ when $L_a/L = 1.00$. This is being pointed out because the K_{La} version of the effective length factors has been incorporated into the stability check of ANSI/TIA-1019 and ANSI/TIA-1019-A.

SCOPE

The scope of this study is to use a numerical analysis to determine the effective length factors, K_L, for prismatic gin poles in combination with the following design parameters:

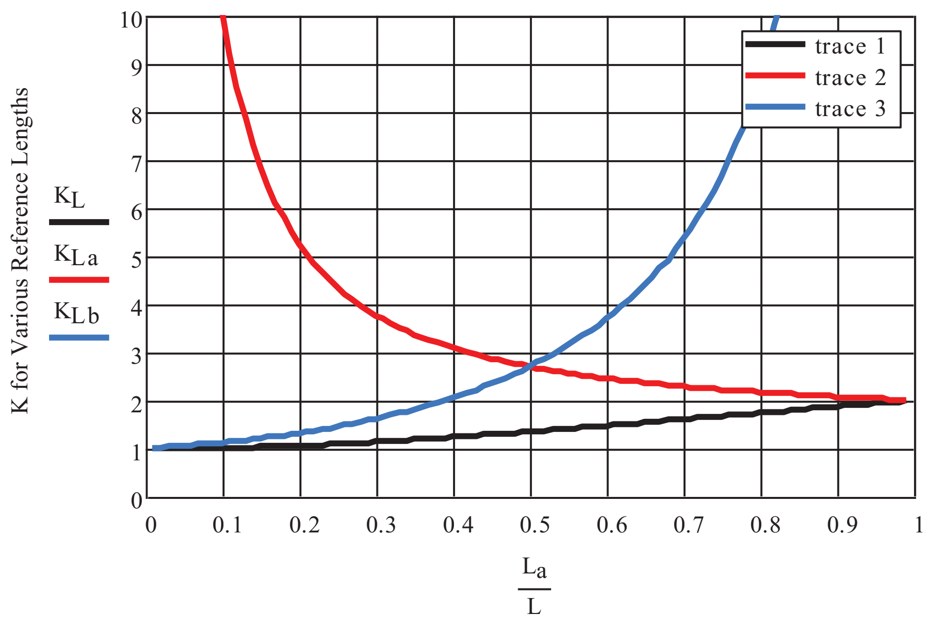
1. Location of the upper bridle along the pole.
2. Number of lateral supports, which is either two or three. If a third support is present, it is assumed to be located at the mid-point of L_b.
3. The relative stiffness of the supporting structure, which is defined as the ratio of the stiffness of the supporting structure between the basket and the upper bridle support to the flexural stiffness of the gin pole.
4. The load line down to the hoist, LLh, is either restrained through a point on the centerline of the pole at the basket or unrestrained (free case) with LLh remaining vertical.
5. One, two, or three parts of the load line supporting the lifted load. This is considered only if the load LLh is

restrained, allowing an additional, small lateral force to act against displacement at the top of the gin pole.

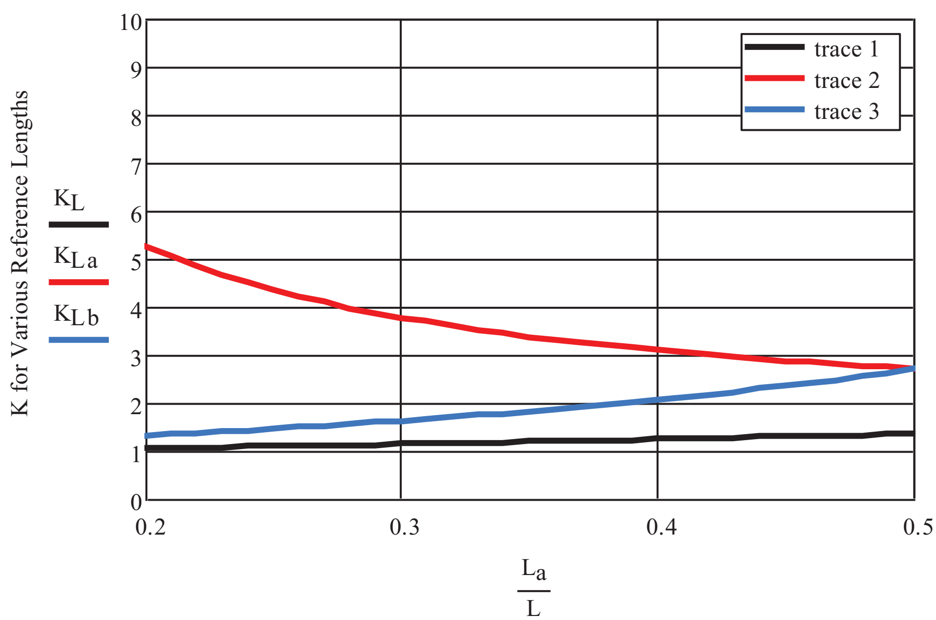
Results are presented in convenient graphical format.

METHOD OF ANALYSIS

A MathCAD program has been developed to determine the effective length factors for elastic buckling of gin poles. The calculated critical force, P_{cr}, values of the gin pole with units of force are calculated for given combinations of the gin pole values of E, I and L; the number and location of lateral supports; the stiffness of supporting structure relative to the gin pole stiffness; the restrained condition of *LLh*; and the number of line parts, if applicable. P_{cr} is then converted to equivalent effective length factor, K_L, which is independent of E, I and L.



(a)



(b)

Fig. 4. Effective length factor vs. bridle location: (a) entire length; (b) L_a/L from 0.20 to 0.50.

The MathCAD program is based on the method for the stability of rigid frames with nonuniform members as presented by Wang (1973). An iterative technique is used to determine the critical shape of the buckled structure, which is defined as the buckling mode and then P_{cr}. The pole is subdivided into a sufficient number of equal-length elements to minimize the effect of axial force on the stiffness of the individual elements. The direct stiffness method is used to assign element stiffness coefficients to the global stiffness matrix. A MathCAD built-in routine is then used to invert the stiffness matrix. Elastic springs are added at the support locations, and the lateral component of the tension in a restrained *LLh* is applied at the top of the gin pole as the pole deflects.

This modified program has been verified using published P_{cr} values for columns with hinged ends, with the fixed base and free top, with the fixed base and free top when the load is applied at the top while acting through the base, and for a strut with hinged ends and an elastic support at the midpoint from Timoshenko and Gere (1961). The program has also been verified using a gin pole example from Godden (1965).

GIN POLE MODEL

The gin pole is modeled as a vertical, prismatic column subdivided into 100 beam elements of equal length. The basket at the base is hinged to a rigid support. There is also an elastic, rotational spring attached to the rigid support. It is only used for verification of fixed-base conditions. The bridle is located at the top of any one of the 100 beam elements and is connected to a rigid support by an elastic spring. An additional elastic spring is added at the top of a beam element at or just below the mid-point between basket and bridle to model a third support. This gin pole model is shown in Figure 5a for two supports and in Figure 5b for three supports.

An axial force is applied downward at the top of the pole. This force represents the weight being lifted plus the tension in *LLh*. The *LLh* remains vertical if the line is unrestrained, and *LLh* becomes inclined as the top deflects laterally if *LLh* is restrained laterally at the basket. This effect of a restrained load line *LLh* is incorporated into the model by the application at the top of the pole of the horizontal component of the *LLh* tension. The application of these loads is shown on deflected pole configurations in Figure 6a for the unrestrained *LLh* and in Figure 6b for the restrained *LLh*.

The sheave at the top of the gin pole is assumed to be frictionless, and line tension is the same in all parts. The sheave is also assumed to have a zero diameter, with all line tensions acting at the centroid of the top section of the pole.

PARAMETERS

A typical gin pole is modeled as a prismatic beam with E = 29,000 ksi, I = 1,336 in.^{4} and L = 140 ft. In several cases, four combinations of I and L are considered. These combinations are I and L, $2I$ and L, I and $2L$, and $2I$ and $2L$. These four I and L combinations produce four different P_{cr} values for any given bridle location but only a single value of the effective length factor. This confirms that the effective length factor is independent of the values of I and L.

Variations of the boundary conditions are as follows:

1 Location of the upper bridle, which is expressed as the percentage of the pole cantilevered beyond the bridle, $100(L_a/L)\%$. The bridle location ranges from 1 to 100%. In some cases, an extra or third lateral support is located at the midpoint between basket and bridle.

2. The dimensionless relative stiffness ratio, *RSR*, of the supporting structure at the upper bridle relative to the pole stiffness is defined as

$$RSR = k_{ss}\,\frac{L^3}{EI} \tag{5}$$

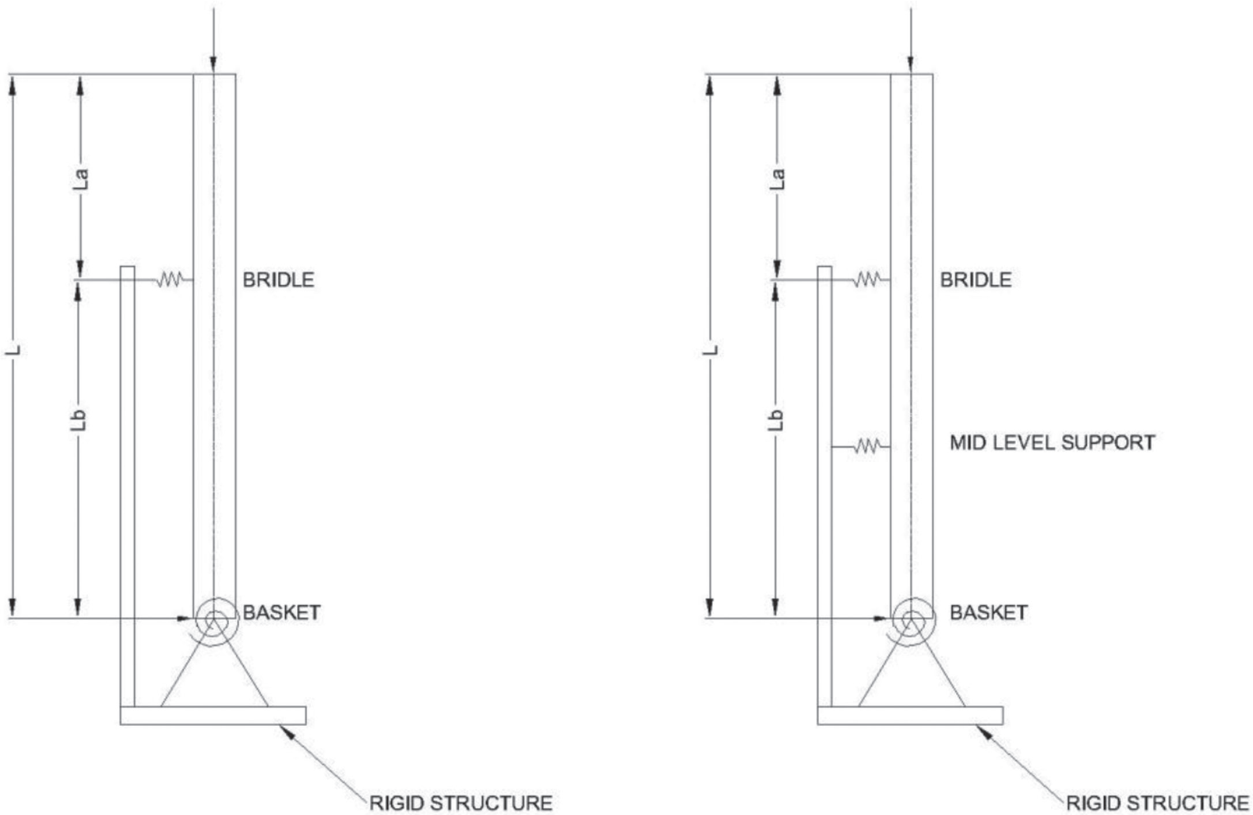
The spring stiffness of the supporting structure, k_{ss}, is the magnitude of each of a pair of lateral forces applied to the supporting structure at the basket and bridle locations that produces a unit lateral displacement between the basket and bridle, and is expressed in units of kips/in. Values of the *RSR* range from 0 to 10^{12}. The value $RSR = 10^{12}$ is the computer model's approximation of an infinite *RSR* and is used for a rigid supporting structure. The *RSR* values of 100, 200, 400 and 800 have been incorporated into ANSI/TIA-1019 and ANSI/TIA-1019-A. The *RSR* at the third lateral support is conservatively assumed to equal the *RSR* as defined in Equation 5 for stiffness at the bridle. The gin pole becomes statically indeterminate with the addition of the third lateral support, and the supporting structure is now subjected to three lateral forces rather than the couple associated with two lateral supports. The application of the *RSR* of Equation 5 to the case of three lateral supports is conservative.

Loads applied at the top correspond to *LLh* rigged for one, two or three parts and to an unrestrained *LLh*.

RESULTS

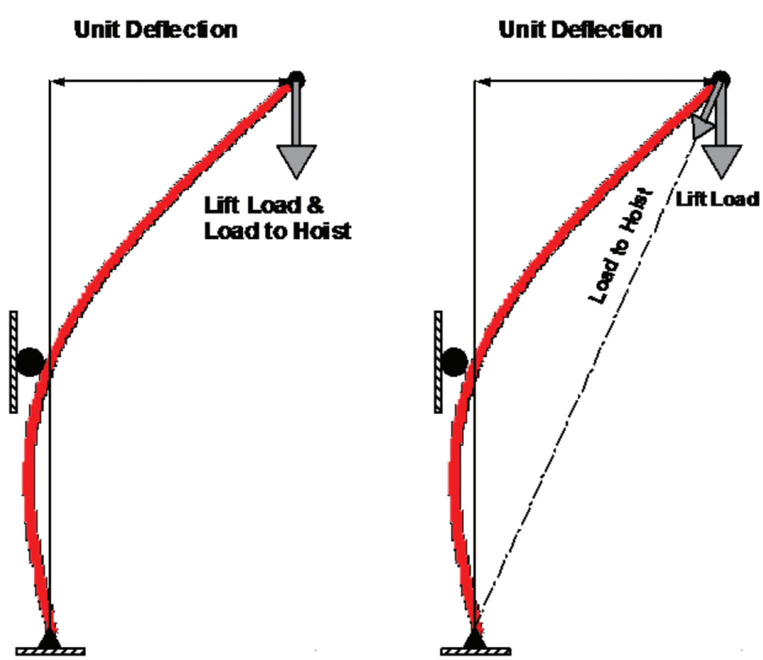
Buckling Mode or Shape

In the numerical analysis, the buckling mode is found by an iterative method for each combination of the gin pole parameters as an initial step in the determination of P_{cr}. While the buckling mode, or deflected shape, gives an insight to general behavior, the computer program only saved values of P_{cr} and K_L during the parametric study. Typical buckling modes for a pole with the *RSR* values of 0, 50, 100, 800 and 10^{12} (infinite ratio) were found in a separate study and are shown in Figure 7 for a bridle located at $L_a/L = 0.50$. The maximum



(a) *(b)*

Fig. 5. Gin pole model.



(a) *(b)*

Fig. 6. Loads applied at top of gin pole.

deflection for each of the *RSR* values, which occurs at the top for each mode, has been set as a unit deflection = 1.0. Actual deflections have not been determined, and comparison of the magnitude of deflections among the various modes is not possible. The mode or deflected shape for trace 1 is for a supporting tower with zero stiffness, and trace 5 is for a rigid supporting tower.

The sidesway or lateral defection at the bridle location is zero only for RSR = 10^{12} (infinite ratio). The lateral deflection at the bridle for $RSR = 800$ is approximately 0.01 of the unit deflection. The lateral deflection increases as the RSR decreases and is on the order of 0.20 of the unit deflection for $RSR = 50$. The mode shape for $RSR = 0$ is the straight line of a rigid-body rotation, and all flexing occurs in the supporting structure. When $RSR = 0$, the gin pole is an unstable, unbraced cantilever column that is pinned at the base.

Parametric Study

Results from the parametric study of the effective length factor K_L are shown as K_L in Figures 8 through 11 for gin poles with two lateral supports (one located at the basket and one at the bridle as shown in Figure 5). The ratio L_a/L values range from 0.20 to 0.50. The curves correspond to the *RSR* values of 100, 200, 400 and 800. These curves correspond to values in Table 5.1a and Table B-1 of ANSI/TIA-1019-A.

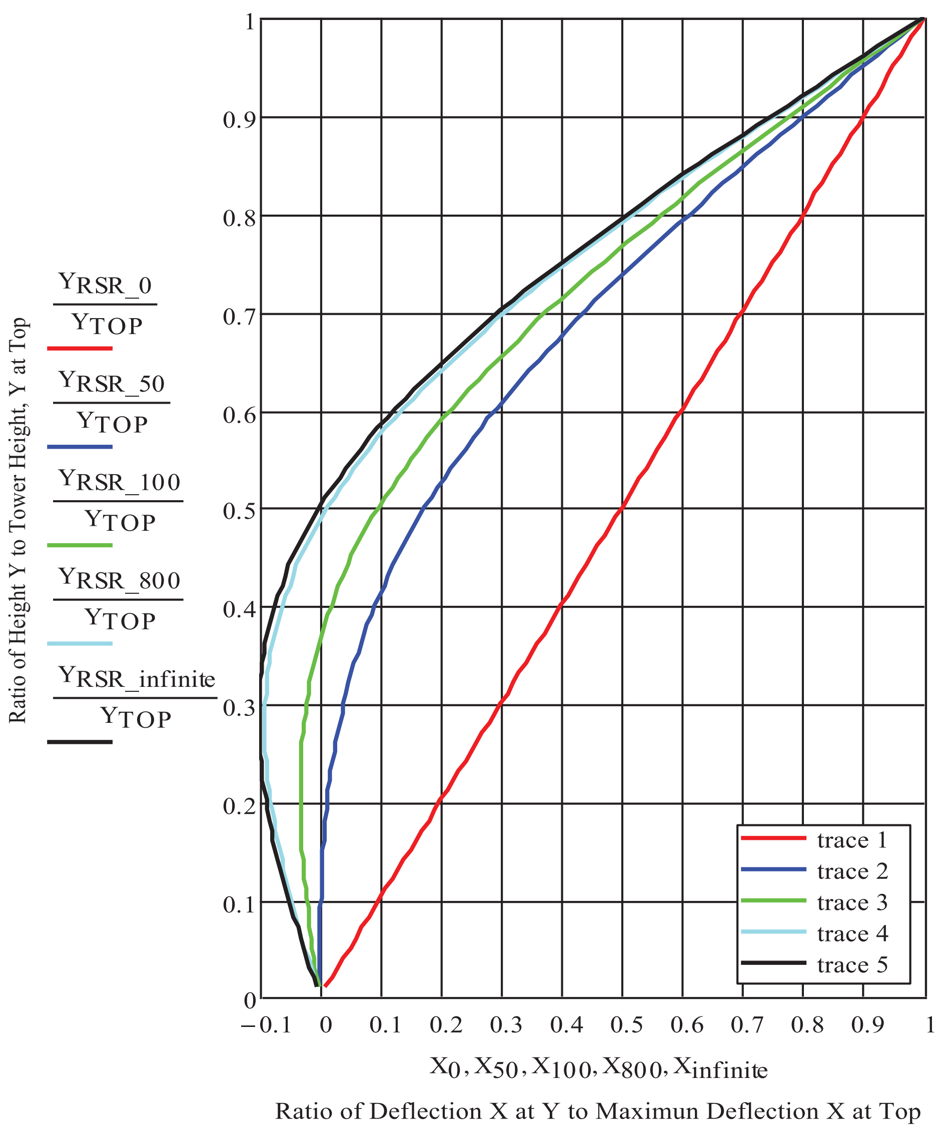


Fig. 7. Modes for five tower stiffness values, RSR; L_a/L= 0.5; parts = free; supports = 2.

Limiting *RSR* values of 50 (very soft) and 10^{12} (infinite ratio) are also shown as open symbols. Figure 12 is a second plot of Figure 11 with the range of the ratio L_a/L expanded to extend from 0.00 to 1.00. K_L results are presented in Figures 13 through 16 for gin poles with a third lateral support added at a height of $L_b/2$. Figures 8 and 13 are for a load line (*LLh*) that is restrained with parts = 1; Figures 9 and 14 are for an *LLh* that is restrained with parts = 2; Figures 10 and 15 are for an *LLh* that is restrained with parts = 3; and Figures 11, 12 and 16 are for either an unrestrained *LLh* or a restrained *LLh* with parts > 3.

The K_L values for Figures 8 through 16 are for vertical poles. Each figure corresponds to one combination of number of supports and rigging conditions. Figures 8 through 11 also apply to an inclined pole that is loaded only along its longitudinal axis.

All individual K_L curves increase with an increase of the ratio L_a/L. K_L values are smaller for poles with three supports than for corresponding poles with two supports. K_L values increase with the number of parts when *LLh* is restrained and are largest for the unrestrained *LLh*. In any of Figures 8 through 16, the values of K_L at any given L_a/L ratio vary inversely with the *RSR*.

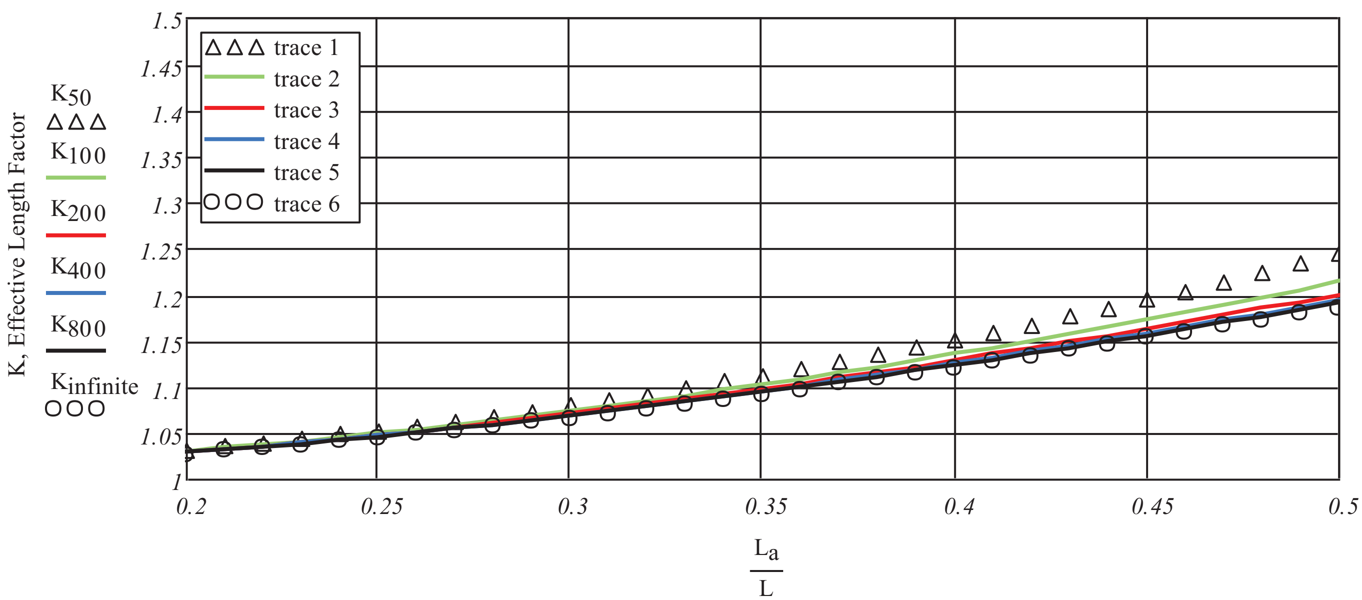


Fig. 8. K_L vs. L_a/L for six RSR values; parts = 1; supports = 2.

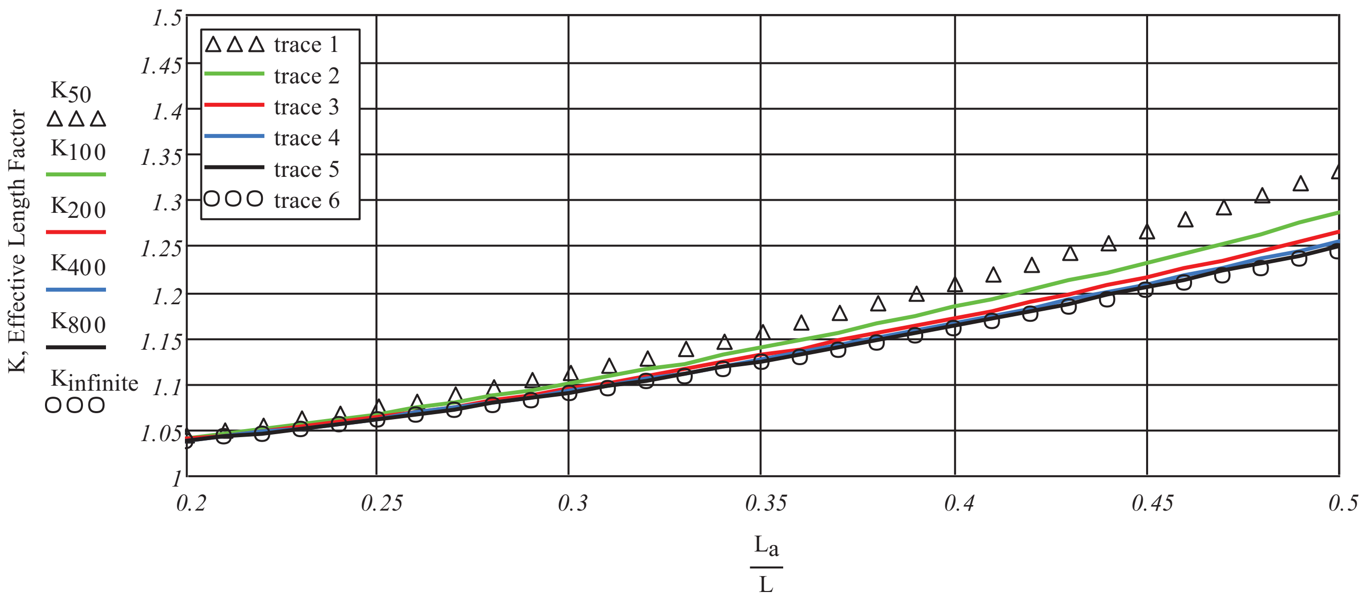


Fig. 9. K_L vs. L_a/L for six RSR values; parts = 2; supports = 2.

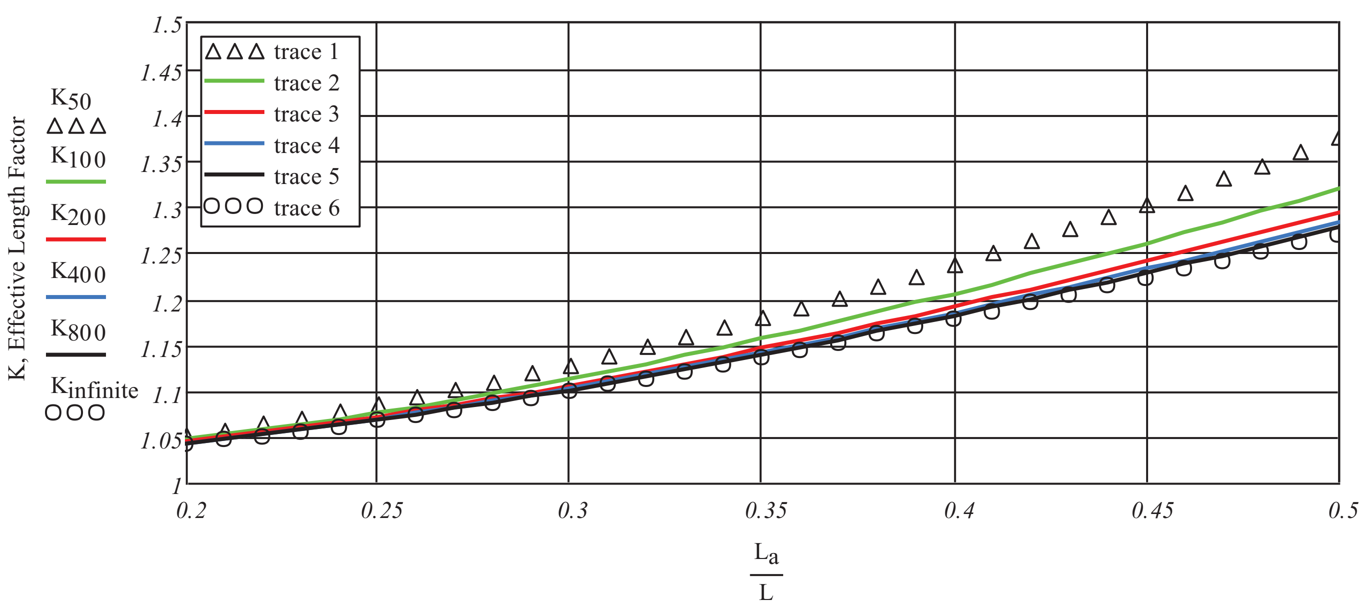


Fig. 10. K_L vs. L_a/L for six RSR values; parts = 3; supports = 2.

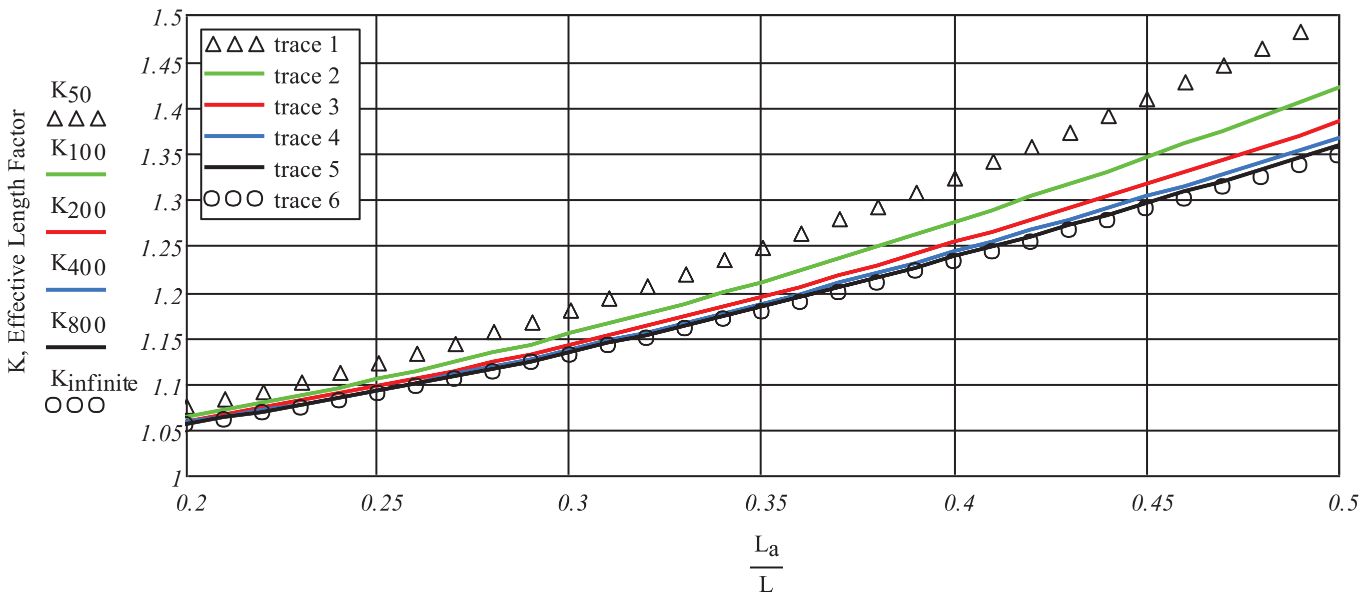


Fig. 11. K_L *vs.* L_a/L *for six RSR values; parts = free; supports = 2.*

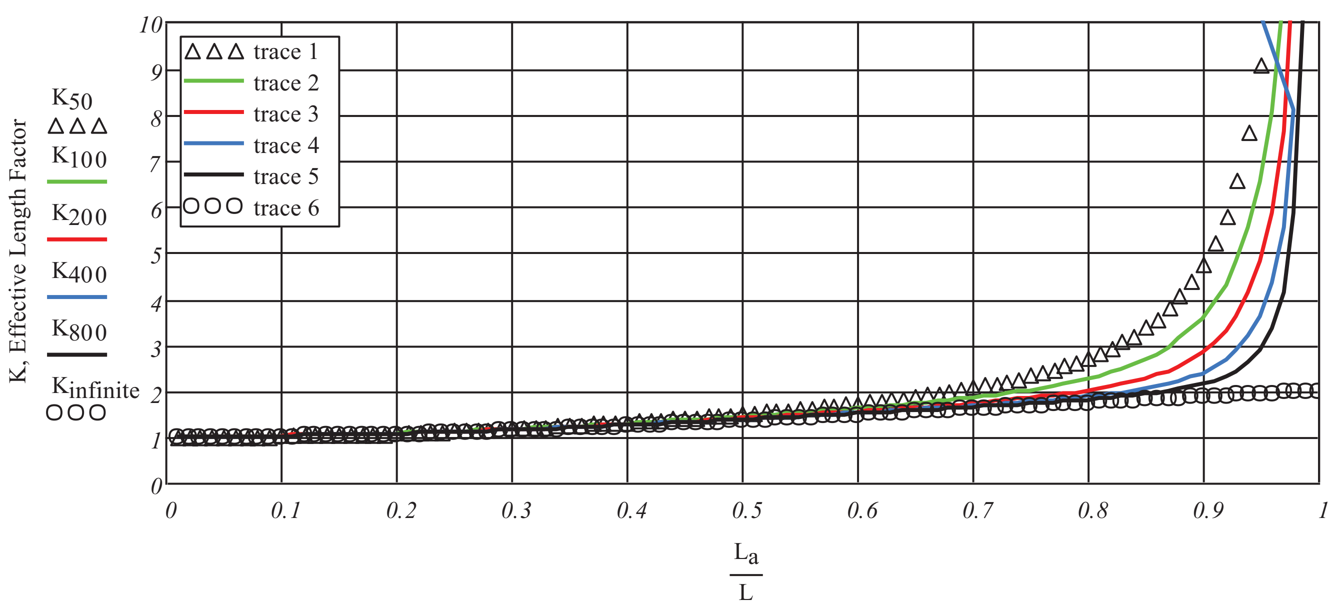


Fig. 12. K_L *vs.* L_a/L *for six RSR values; parts = free; supports = 2.*

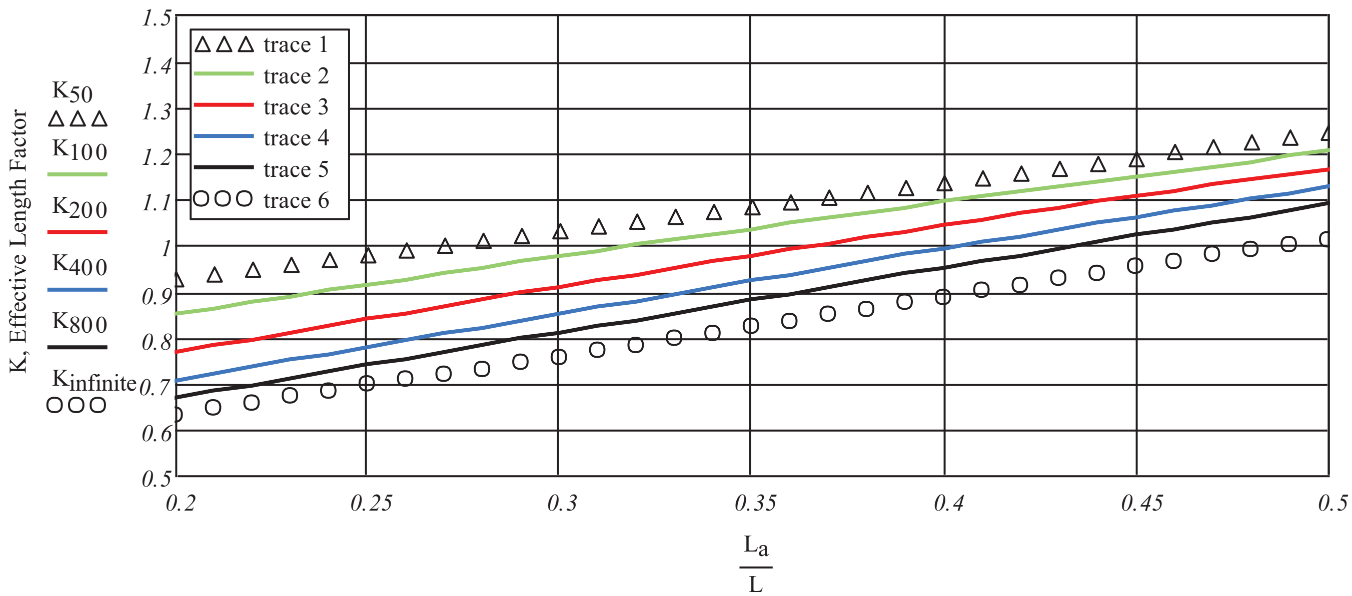


Fig. 13. K_L vs. L_a/L for six RSR values; parts = 1; supports = 3.

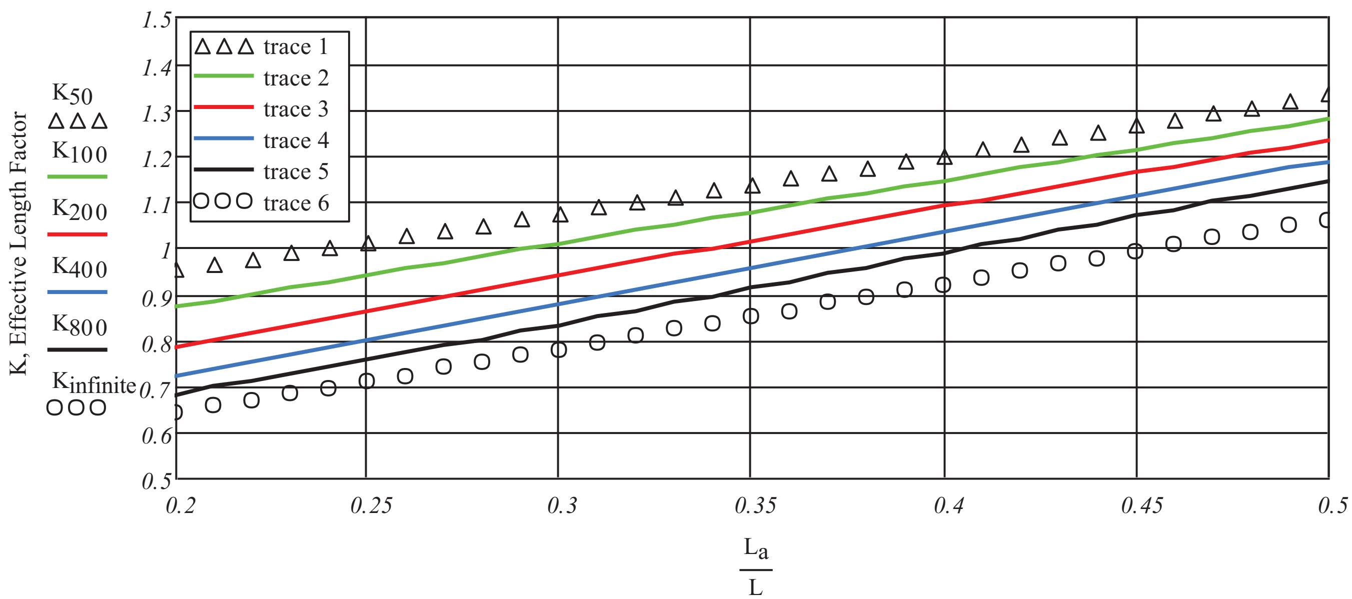


Fig. 14. K_L vs. L_a/L for six RSR values; parts = 2; supports = 3.

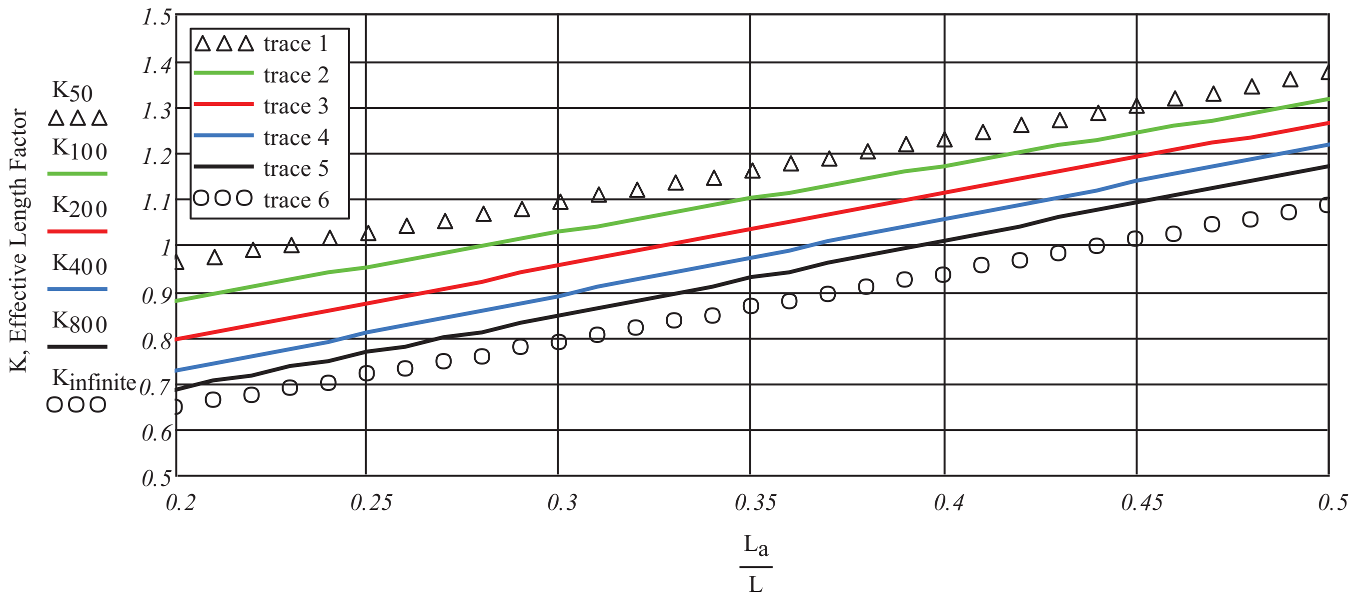


Fig. 15. K_L vs. L_a/L for six RSR values; parts = 3; supports = 3.

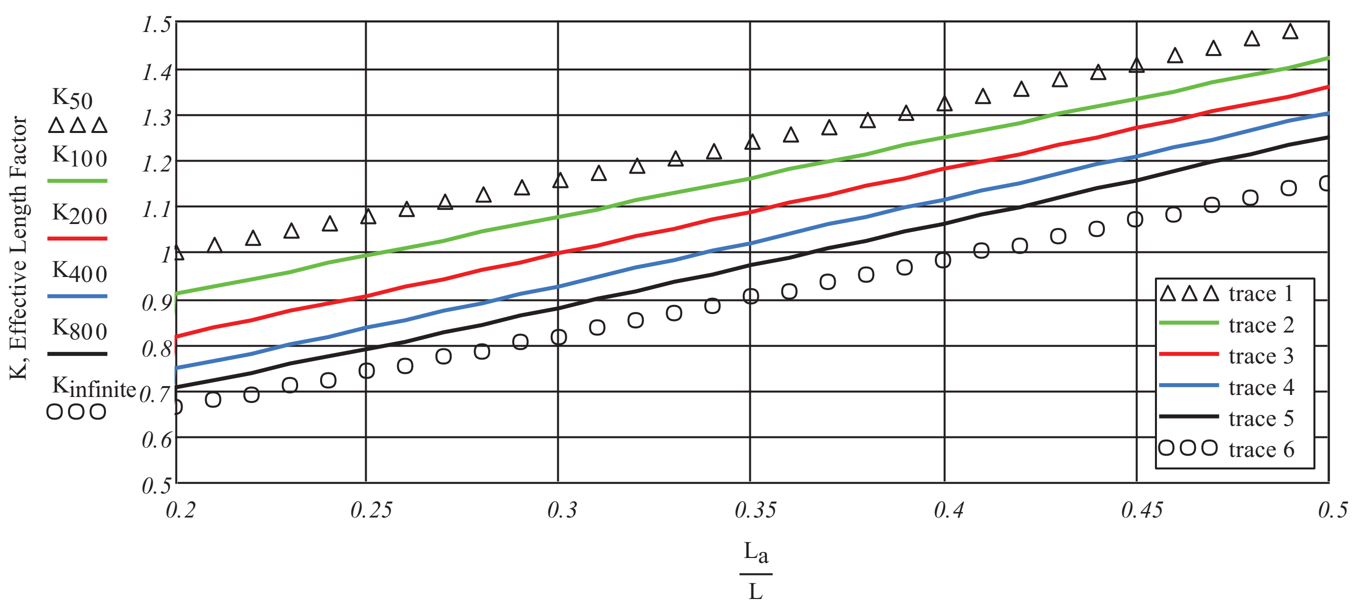


Fig. 16. K_L vs. L_a/L for six RSR values; parts = free; supports = 3.

DESIGN EXAMPLES

Example 1

Given:

Find K_L and F_e for the typical gin pole with E = 29,000 ksi, I = 1,336 in.^{4}, and L = 140 ft with supports = 2. Assume A = 11.62 in.^{2} and r = 10.71 in. to calculate P_{cr} from K_L values. Gin pole is mounted at top of a 300-ft cantilevered steel shaft with I = 250,000 in^4. First, determine k_{ss} and the *RSR* for L_a = 30 ft, 50 ft and 70 ft. Then, determine the effective length factor, K_L, the effective length $K_L(L)$, P_{cr} and F_e for riggings with an unrestrained *LLh* and with a restrained *LLh* and parts = 1.

Solution:

Consider a vertical, cantilevered steel member that is 300 ft long with I = 250,000 in.^{4}. Apply a 1-kip concentrated force normal to the member at the free end and a −1-kip concentrated force normal to the member in a distance $L - L_a$ or $140 - L_a$ below the free end as shown in Figure 17. Use a first-order, elastic analysis to find the difference, Δx, between the lateral displacements at the two load points. Either a matrix analysis or superposition of cases 21 and 22 of AISC *Steel Construction Manual* Table 3-23 (AISC, 2011) gives:

L_a = 30 ft, Δx = 0.654 in.
L_a = 50 ft, Δx = 0.463 in.
L_a = 70 ft, Δx = 0.296 in.

Here, k_{ss} is the force applied at the bridle and at the basket that causes a unit lateral displacement between the bridle and basket. This is equal to the unit load divided by Δx. For L_a = 30 ft, k_{ss} = 1.53 kips/in.; for L_a = 50 ft, k_{ss} = 2.16 kips/in.; and for L_a = 70 ft, k_{ss} = 3.38 kips/in. These values of k_{ss} are functions of the supporting structure and the basket and bridle locations. Equation 5 is used to find the dimensionless *RSR* values for the given gin pole:

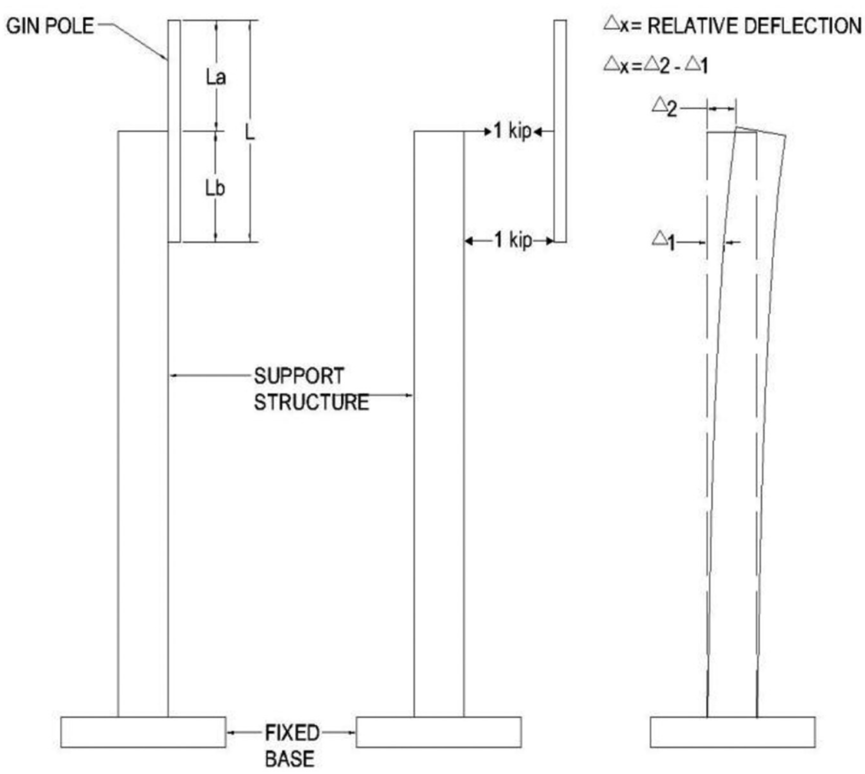


Fig. 17. Support structure loads for Example 1.

Table 1. Example 1 Calculation Summary									
Rigging	Figure	L_a (ft)	L_a/L (%)	RSR	K_L	$K_L(L)$ (in.)	P_{cr} (kips)	P_{cr}/A (ksi)	F_e – Eq. 2 (ksi)
Fixed/1 part	8	30	21.4	187	1.033	1735	127.0	10.93	10.91
Fixed/1 part	8	50	35.7	264	1.098	1845	112.3	9.67	9.64
Fixed/1 part	8	70	50.0	414	1.191	2000	95.6	8.32	8.21
Free	11	30	21.4	187	1.070	1798	118.3	10.18	10.16
Free	11	50	35.7	264	1.198	2013	94.4	8.12	8.10
Free	11	70	50.0	414	1.362	2288	73.0	6.29	6.27

Table 2. Example 2 Calculation Summary									
Rigging	Figure	L_a (ft)	L_a/L (%)	RSR	K_L	$K_L(L)$ (in.)	P_{cr} (kips)	P_{cr}/A (ksi)	F_e – Eq. 2 (ksi)
Fixed/1 part	13	30	21.4	187	0.82	1378	201.4	17.33	17.29
Fixed/1 part	13	50	35.7	264	0.97	1680	135.5	11.66	11.63
Fixed/1 part	13	70	50.0	414	1.12	1982	97.3	8.38	8.36
Free	16	30	21.4	187	0.86	1445	183.1	15.67	15.72
Free	16	50	35.7	264	1.08	1814	116.2	10.00	9.98
Free	16	70	50.0	414	1.29	2167	81.4	7.01	6.99

$$RSR = k_{ss}\frac{L^3}{EI} \tag{5}$$

For L_a = 30 ft, the RSR = 187; for L_a = 50 ft, the RSR = 264; and for L_a = 70 ft, the RSR = 414.

Figure 8 is then used to find the effective length factor K_L for the rigging with a restrained LLh and parts = 1, and Figure 11 is used to find K_L for the rigging with an unrestrained LLh. The effective length is then K_L times the entire pole length, L = 140 ft, or 1,680 in.

P_{cr} is then found using Equation 3, and the stress at elastic buckling, F_e, is then equal to P_{cr} divided by A. F_e may also be found directly using Equation 2. The calculation summary is shown in Table 1.

Example 2

Given:

Repeat Example 1 with a third support added midway between the basket and bridle.

Solution:

Values of Δx, L_a/L and the RSR for the three values of L_a remain the same as for Example 1. Figures 13 and 16 are used to find K_L values for three supports. New values of $K_L(L)$, P_{cr}, P_{cr}/A and F_e from Equation 2 are determined the same way as in Example 1.

The calculation summary is shown in Table 2.

DISCUSSION

A review of Figures 8 through 11 and Figures 13 through 16 suggests that in the range of the ratio L_a/L from 0.2 to 0.5, the ratio L_a/L has a greater impact on the effective length factor, K_L, and thus on the effective length, $K_L \times L$, than any other parameter of the study.

In each of the Figures 8 through 11, which are for two lateral supports and a particular rigging case, the K_L values over the range of the *RSR* values are closely spaced at $L_a/L = 0.2$ and start to diverge as L_a/L increases to 0.5. The K_L values vary inversely with *RSR*. The K_L values for all combinations of *RSR* and L_a increase with the rigging cases in the following order from the restrained case with parts = 1, to the restrained case with parts = 2, to the restrained case with parts = 3, and to the unrestrained case with any number of parts.

In each of the Figures 13 through 16 with three lateral supports and a particular rigging case, the K_L values over the range of *RSR* values have already diverged at $L_a/L = 0.2$ and converge slightly as L_a/L increases to 0.5. The K_L values again vary inversely with *RSR*. The K_L values for all combinations of the *RSR* and L_a again increase with the rigging cases in the same order as for two lateral supports.

Results of this parametric study are presented in terms of K_L, while K_{La} values are tabulated in ANSI/TIA-1019 and ANSI/TIA-1019-A. Because K_L values are easily converted to K_{La} values using Equation 4, ANSI/TIA-1019 and ANSI/TIA-1019-A K_{La} values are easy to verify. Future incorporation of Figures 8 through 11 and Figures 13 through 16 in the TIA *Standard* would eliminate the need for double interpolation.

The calculation of the elastic critical buckling load, P_{cr}, when K_L is known, is based on Equation 3, which may be rewritten as Equation 6:

$$P_{cr} = (1/K_L)^2\, \pi^2 (E)(I)/L^2 \tag{6}$$

Because the term $(E)(I)/L^2$ is a constant for any given gin pole, P_{cr} is directly proportional to the term $(1/K_L)^2$, which is defined here as the elastic buckling capacity factor, *EBC*. Figures 8 through 11 and Figures 13 through 16 may be may be revised into graphs of *EBC* versus the ratio L_a/L to directly show the relative effect of the parameters of this study on the elastic critical buckling load, P_{cr}. When P_{cr} has been found directly, the elastic critical buckling stress, F_e, of Equation 2 is simply

$$F_e = P_{cr}/A \tag{7}$$

where A = total area of gin pole legs, in.^{2}

As an example of this conversion to *EBC* for the gin poles with two supports, Figure 11, for K_L versus the ratio L_a/L for the unrestrained case with two supports, has been modified into Figure 18 for *EBC* versus the ratio L_a/L. In Figure 18, the values of EBC—and thus, the values of P_{cr}—decrease as L_a increases.

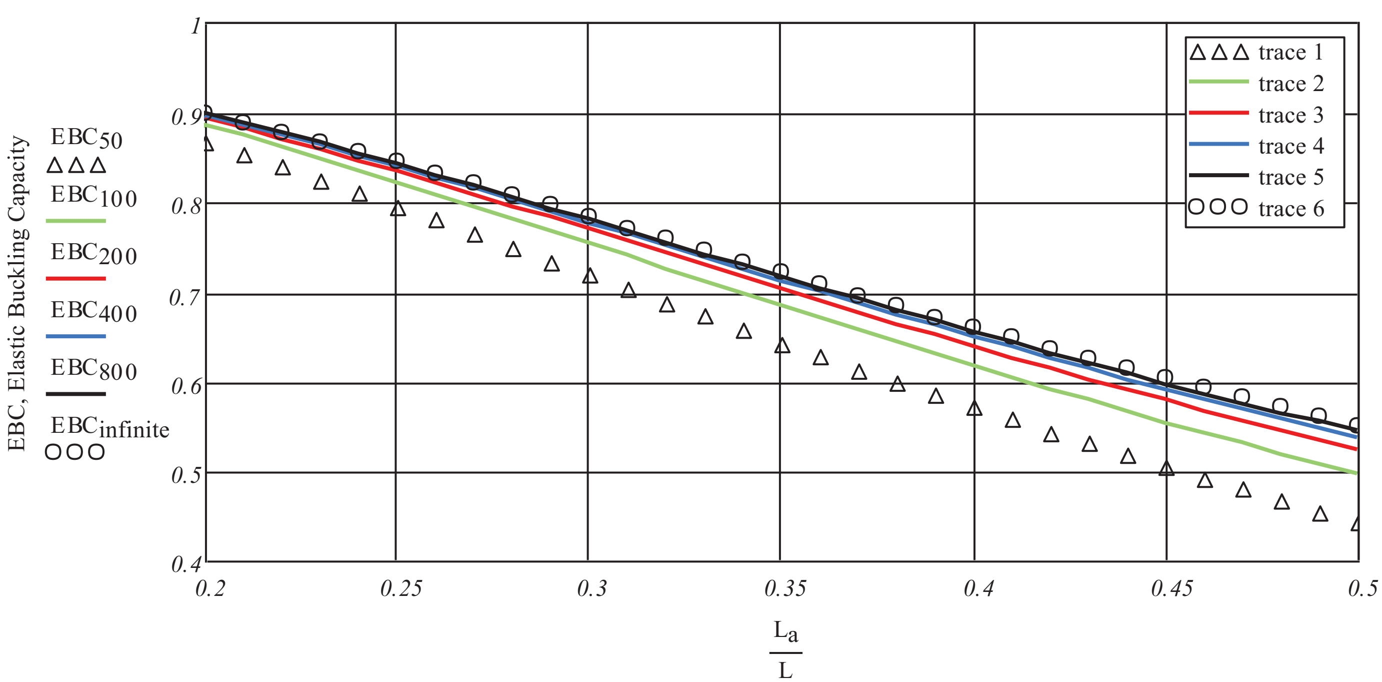


Fig. 18. EBC vs. L_a/L for six RSR values; parts = free; supports = 2.

The unrestrained rigging (free case) was selected for Figure 18 because it resulted in the largest K_L values of the study, which correspond to the smallest P_{cr} values. Figures 8 through 10 could also be converted, and such resulting figures for *EBC* could be used directly to determine P_{cr}.

Figure 19 is a plot of *EBC* values for the four different rigging cases and an *RSR* of 200. These *EBC* values are conversions from the red lines (trace 3) for K_{200} in Figures 8 through 11. The effect of the rigging cases of Figure 19 on *EBC*—and thus, on the elastic buckling capacity, P_{cr}—is greater than the effect of the relative tower stiffness, the *RSR*, of Figure 18.

As an example of this conversion to *EBC* for three supports, Figure 16, for K_L versus the ratio L_a/L for the unrestrained (free) case with any number of parts has been converted into Figure 20 for *EBC* versus the ratio L_a/L for the unrestrained (free) case with any number of parts and three supports. In Figure 20, the values of *EBC* again decrease as L_a increases. However, the relative tower stiffness, *RSR*, has a greater effect on *EBC* for gin poles having three supports than for gin poles having two supports.

Figure 21 is a plot of *EBC* values for the four different rigging cases for an *RSR* of 200. These *EBC* values are converted from the red lines (trace 3) for K_{200} in Figures 13 through 16.

The *EBC* values for gin poles with three supports are approximately twice the *EBC* values for gin poles with two supports for smaller values of the ratio L_a/L. As the ratio L_a/L approaches 0.5, the *EBC* values for three supports are only slightly higher than the *EBC* values for two supports.

The application of a couple acting at the bridle and baskets to determine the spring stiffness, k_{ss}, which is used in Equation 5, is only valid for a gin pole with two supports and an unrestrained load line to hoist, *LLh*. When *LLh* is restrained, the horizontal reaction at the bridle is reduced as the horizontal reaction at the basket is increased. Three statically indeterminate horizontal reactions replace a couple when a third support is added. In either of these two cases, the use of a couple underestimates the relative tower stiffness. The *EBC* values based on this determination of k_{ss} underestimate the elastic buckling capacity.

The relative stiffness ratio, *RSR*, is not a constant for any given supporting structure but varies with the location of bridle and of basket on the structure. This is demonstrated in the example problems. The location of bridle and basket relative to guy wires in guyed towers also affects the relative stiffness ratio. The value of k_{ss} for guyed towers is to be determined using a commercial computer program, such as TnxTower (Tower Numerics Inc., 2016), which incorporates cable elements.

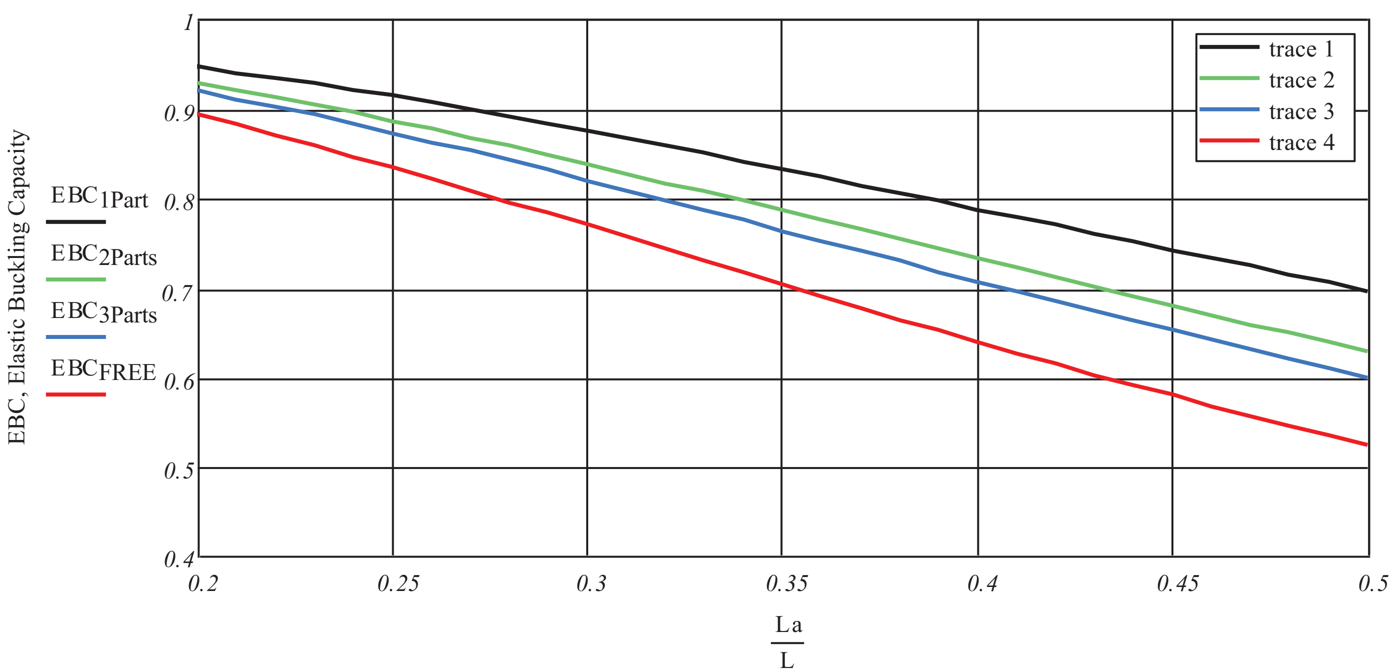


Fig. 19. EBC vs. L_a/L for four rigging cases; RSR = 200; supports = 2.

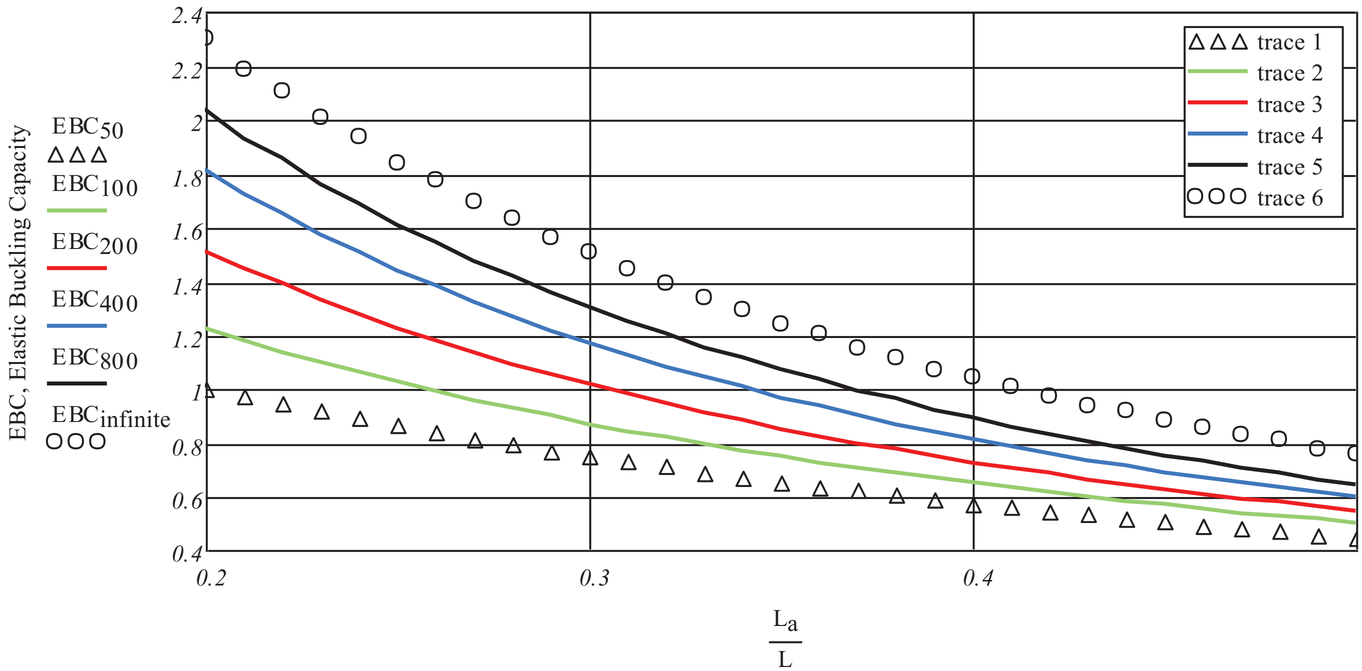


Fig. 20. EBC vs. La/L for six RSR values; parts = free; supports = 3.

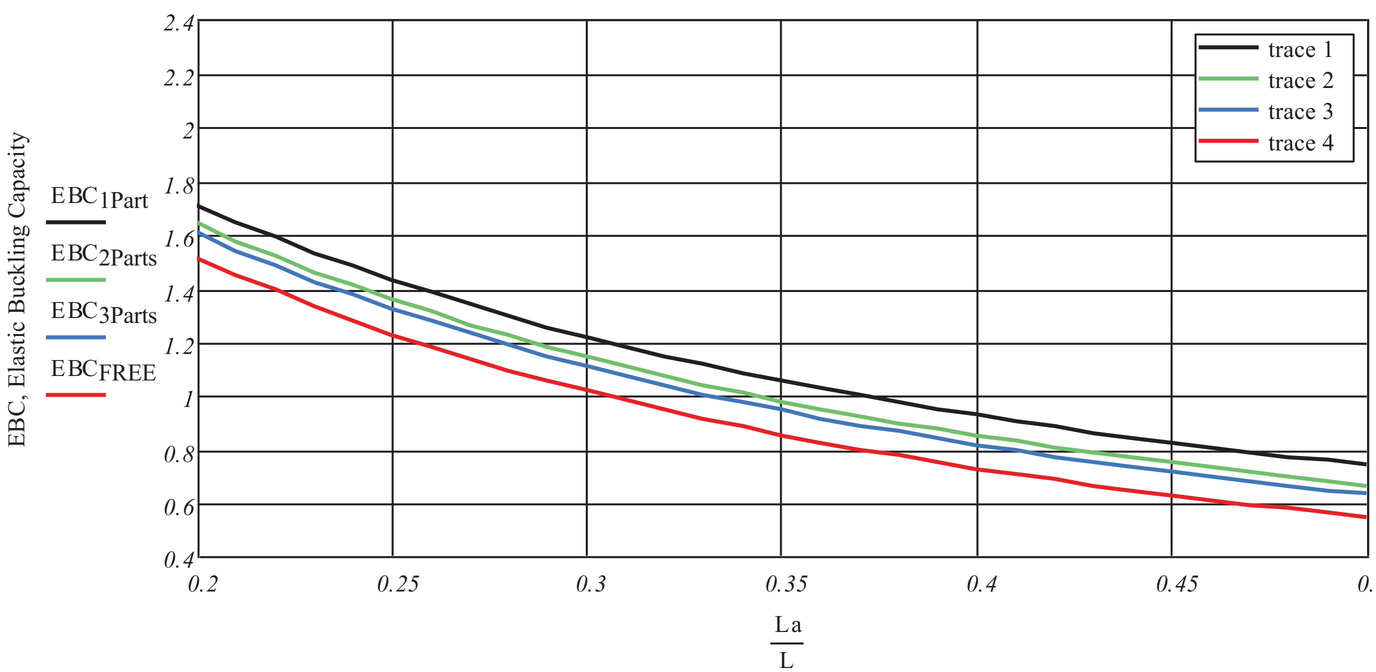


Fig. 21. EBC vs. La/L for four rigging cases; RSR = 200; supports = 3.

ACKNOWLEDGMENTS

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