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RESEARCH ARTICLE

End Restraints in Steel Angles in Lattice Towers

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Abstract:

Introduction:

Test data on single angle compression members with various end connection arrangements is used to develop adjustment factors for effective buckling lengths. A connection length parameter is proposed and evaluated based on test data. Results from a total of 31 equal leg test angles with single-, double- bolts and fixed ends are used.

Methods:

Slenderness ratios considered ranged from 150 to 312. Angle sizes ranged from 38 x 38 x 3.2 (mm) to 89 x 89 x 6.4 (mm). Estimated connection lengths were about 12.5% of the member length for single-bolt joints; 24.7% for double-bolt joints and 45.6% for fixed joints. Computed effective length factors ranged from 0.544 to 0.875.

Results:

Results seem to indicate that it is possible to define and calculate connection length of a lattice tower angle member. Suggestions for incorporating connection length issues in routine designs are made.

Keywords: Bolted connections, Buckling capacity, Effective length, Slenderness ratio, Steel angles, Towers.

1. INTRODUCTION

Structural steel angle members are the basic load-carrying elements in electrical transmission towers. These members are usually connected by gusset plates or directly bolted to other members through one leg. Tower joints involve single, double, triple or multiple bolted angles. The buckling or compressive strength of these angles is a function of several parameters: Bi-axial eccentricity of the loads see (Fig. **1**), magnitude of restraint provided at the ends, slenderness ratios and pattern of failure either through flexural buckling or combined torsional-flexural buckling [1].

An angle strut is theoretically a restrained, eccentrically-loaded, bi-axially bent, thin-walled beam-column whose buckling load capacity is governed by end joint stiffness, and thereby, effective member length for buckling. However, the exact nature of end restraint effects in angle columns is too complex to assess [2]. Previous studies on bolted angles indicate that end connection effects are noticeable even for a single-bolted joint and that end restraints play an important role for members with slenderness ratios over 120 [3]. It was also shown that for slender 2- and 3- bolted angles, test buckling loads are consistently above theoretical values [4].

The current design procedure for tower angles is given in the ASCE Standard 10-15 [5]. The procedure defines effective slenderness in two categories: Short columns ($L/r \leq 120$), controlled by eccentricity of loads; and long columns ($120 \leq L/r \leq 250$), controlled by end restraint. (See Notation for definition of parameters). Various limits on width-to-thickness ratios of angles are defined which in turn control the design compressive stress of the angle column.

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(See Appendix **A** for applicable equations).

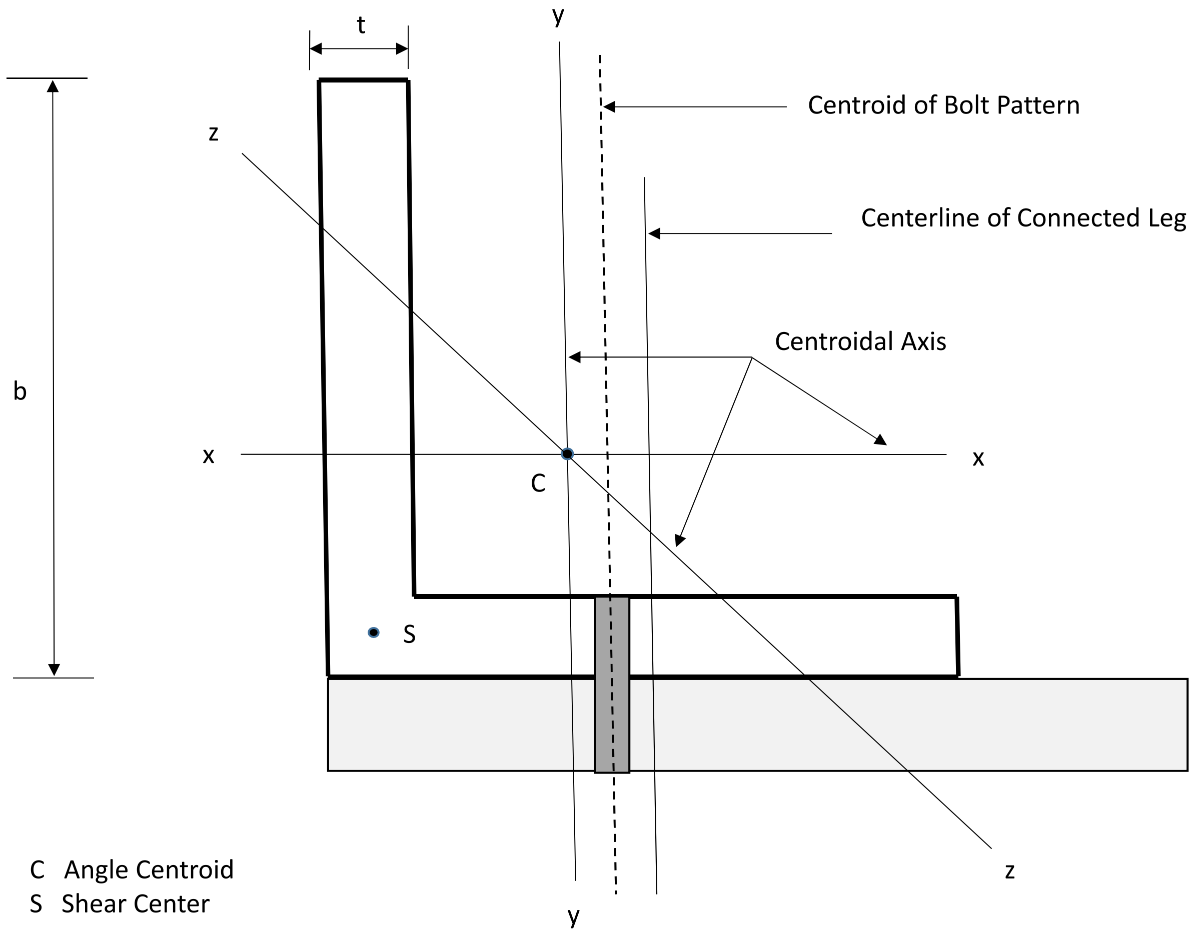

Fig. (1). Angle Cross Section Parameters.

Laboratory testing of angles is generally aimed towards determining the failure or buckling load; little effort is directed towards assessing the actual connection length parameter. Part of the difficulty is related to defining what exactly constitutes the connection or how far the clamping effect of bolting extends from the bolt(s). One relatively recent study [6] proposed the concept of 'equivalent reference length' or 'characteristic length' of a connection that allows a comparison of the connection with the connected member. Such a knowledge of connection length can help form the basis for quantifying its translational and rotational stiffness and eventually develop the stiffness matrix of the connection element for inclusion into finite element programs. This paper attempts to address that issue.

The objective of this paper is to:

1. Propose a definition for an angle column connection length including clamping effect of bolts
2. Utilize test data on single, double and fixed-end angles to derive effective length factors
3. Relate the effective length factors to connection lengths
4. Propose a simple adjustment to ASCE equations for slenderness to give more accurate buckling capacities.

Only elastic buckling of equal-leg single angles with identical end connections is considered in this paper. Residual stresses and initial imperfections, although often important from buckling perspectives, are not considered here.

2. CONNECTION LENGTH

The **clamping effect** of the bolts in a connection is known to extend over a finite distance from the member end. Fig. (**2**) shows the idealization of connection and its length L_C as proposed in this study and the assumed extent of the clamping zone. Each strut of length L is taken to consist of identical end connections, L_C. It is obvious that connection length and the clamping effect increases with number of bolts, thus decreasing the effective member buckling length. The effective beam-column length L_E is taken as center-to-center of connections. From Fig. (**2**):

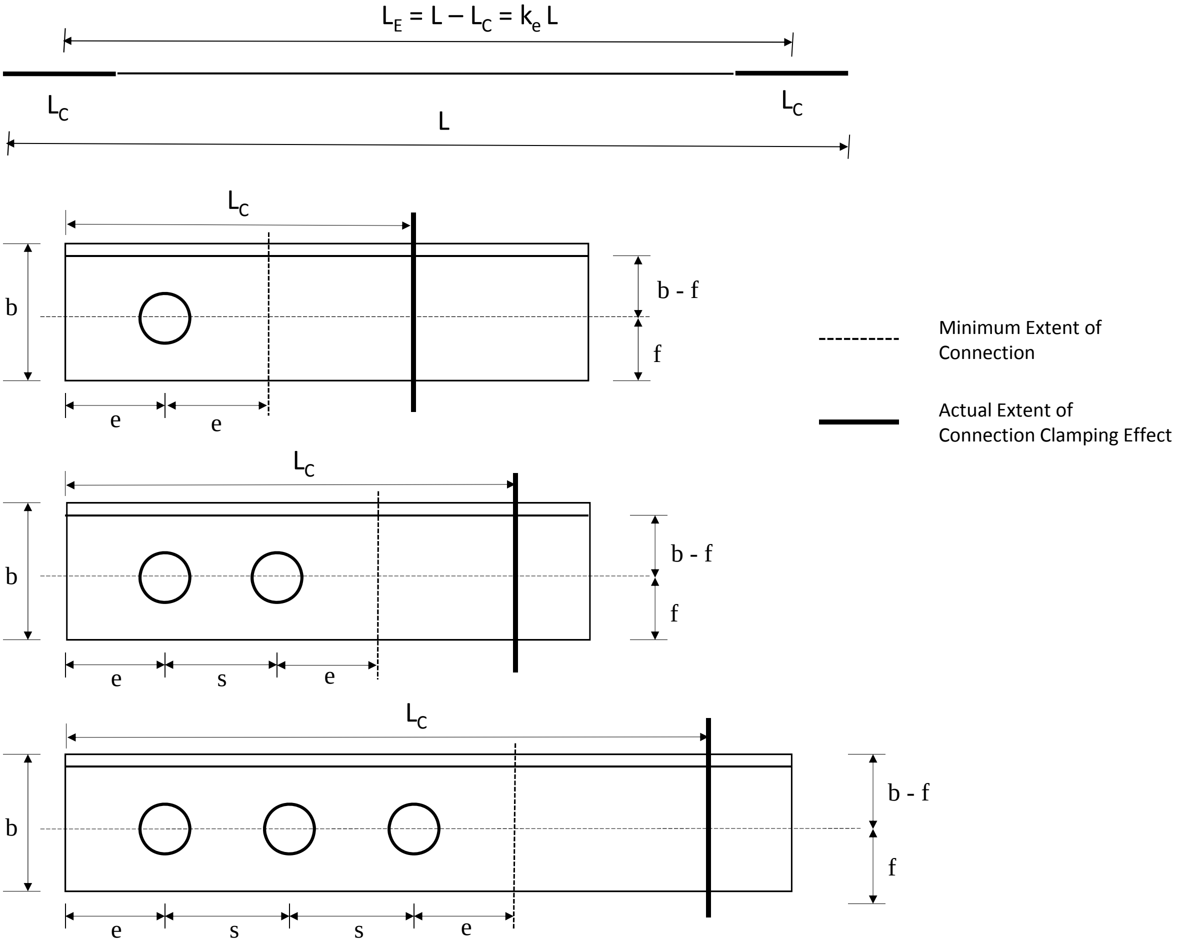

Fig. (2). Proposed Definition of Connection Length Parameter.

$$L = L_E + 2\,(L_C/2) \;= k_e L + 2\,(L_C/2) \tag{1a}$$

$$L_E = k_e L \tag{1b}$$

$$L_C = L - k_e L = L(1 - k_e] \tag{1c}$$

The parameter k_e is an *effective* slenderness coefficient which quantifies the influence of connection length L_C and the clamping effect.

A minimum connection length L_{CM} can be also defined just in terms of the end distance ‘e’ and bolt spacing ‘s’.

$$\text{1-bolt joint} \qquad L_{CM} = 2e \tag{2a}$$

$$\text{2-bolt joint} \qquad L_{CM} = s + 2e \tag{2b}$$

$$\text{3-bolt joint} \qquad L_{CM} = 2s + 2e \tag{2c}$$

3. EFFECTIVE LENGTHS

ASCE 10-15 [5] gives the following equations for effective lengths of lattice tower angles where restraint is the controlling factor for buckling strength rather than eccentricity.

For members unrestrained against rotation at both ends:

$$kL/r = L/r \qquad 120 \leq L/r \leq 200 \tag{3a}$$

For members partially restrained against rotation at both ends:

$$kL/r = 46.2 + 0.615\, L/r \qquad 120 \leq L/r \leq 250 \tag{3b}$$

4. BUCKLING CAPACITY

The buckling capacity of an ideal, elastic column is given by the well-known Euler formula:

$$P_E = \pi^2 EI / (kL)^2 \tag{4}$$

For a pin-ended column, Equation (4) refers to an effective buckling length of $kL = L$, $k = 1$.

Defining *Test* capacity P_T in terms of an *effective* slenderness coefficient k_e:

$$P_T = \pi^2 EI / (k_e L)^2 = \pi^2 EA / (k_e L/r)^2 \tag{5}$$

where $I = Ar^2$

Solving Equation (5) for k_e, we have:

$$k_e = [\pi\, r/L]\, [(EA/P_T)^{1/2}] = [\alpha]\, [\beta] \tag{6}$$

Also, from Equations (4), (5) and (6):

$$P_E / P_T = k_e^2 = \eta \tag{7}$$

$$k_e = \sqrt{\eta} \tag{8}$$

Equation (1c) can be used now to determine L_C.

Equations (6) to (8) facilitate a semi-empirical determination of connection length from test data.

4.1. Columns with Full End Restraint

The other extreme for a pin-ended column is a fixed-end column where both ends are fully restrained against translation and rotation. For this condition, the theoretical Euler Capacity is:

$$P_E = 4\, \pi^2 EI / L^2 \tag{9a}$$

Also:

$$P_E / P_T = \eta = 4\, k_e^2 \tag{9b}$$

$$k_e = (\eta /4)^{1/2} = {\textstyle\frac{1}{2}} \sqrt{\eta} \tag{9c}$$

Some previous studies [2] indicate that member behavior approaches that of a fixed-ended column as the number of bolts in the end connections are increased.

4.2. Columns with Intermediate-level Restraint

Traditionally, angles with a single bolt are not considered to provide any rotational restraint [5] and are treated as pin-ended columns. Members with more than one bolt in the end connections can be considered as those with intermediate level restraint. The *effective* slenderness coefficient k_e in this case falls in-between those of the pin-ended case and fixed case (*i.e.*) between Equation (8) and (9c). Since there are no guidelines to use for 2- and 3- bolt situations and beyond, the associated coefficient should be determined empirically from test data.

5. TEST DATA

Test data on thirty one (31) single, equal-leg angles is selected from published literature [7]. The test angles chosen for this study ranged from 38 mm x 38 mm x 3.2 mm to 89 mm x 89 mm x 6.4 mm (1½ in. x 1½ in. x ⅛ in. to 3½ in. x 3½ in. x ¼ in.). Slenderness ratios ranged from 150 to 312 (elastic buckling). Yield strength of steel varied from 249 MPa (36 ksi) to 322 MPa (46.7 ksi). Bolts used were 15.9 mm (⅝ in.) is diameter with all bolt holes 17.5 mm (11/16 in.) in size. All angles were tested in a manner that simulates the actual joint situation in a lattice tower (*i.e.*) unrestrained rotation in space. The testing setup also ensured that load is applied at an eccentricity as in a real tower. For details of the testing machine, instrumentation, loading process etc the reader is referred to the paper cited under Reference [5]. Limited test data is available for 3-bolt connections and above; some from recent research [3] exhibited bolt slip during testing and are therefore omitted.

Tables **1**, **2** and **3**. show the results of calculations for effective slenderness coefficient k_e and connection length L_C for one-bolt, two-bolt and fixed-end angles, respectively.

The minimum connection length L_{CM} is also calculated in terms of the end distance ‘e’ and bolt spacing ‘s’ of the test specimens. These values are also shown in Tables **1** and **2**.

Fig. (**3**) shows the variation of k_e with the number of bolts in the end connection. Fig. (**4**) shows the variation of LC with the number of bolts in the end connection. For fixed end joints, in the absence of other guidelines, it is assumed that a 5-bolt connection simulates a state of fixity.

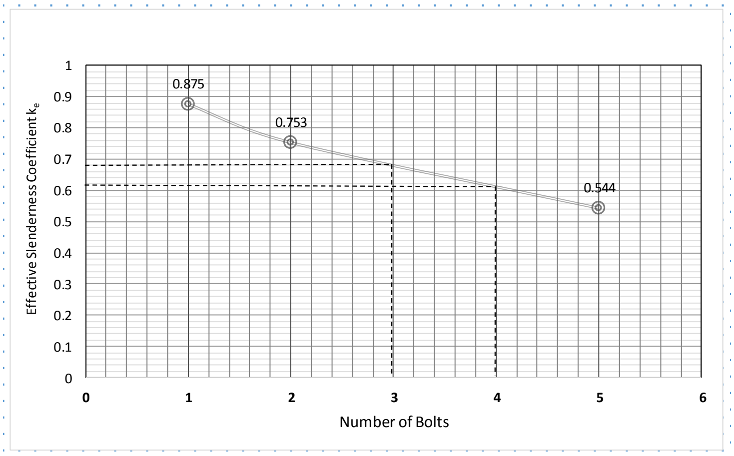

Fig. (3). Variations of K_e with number of bolts.

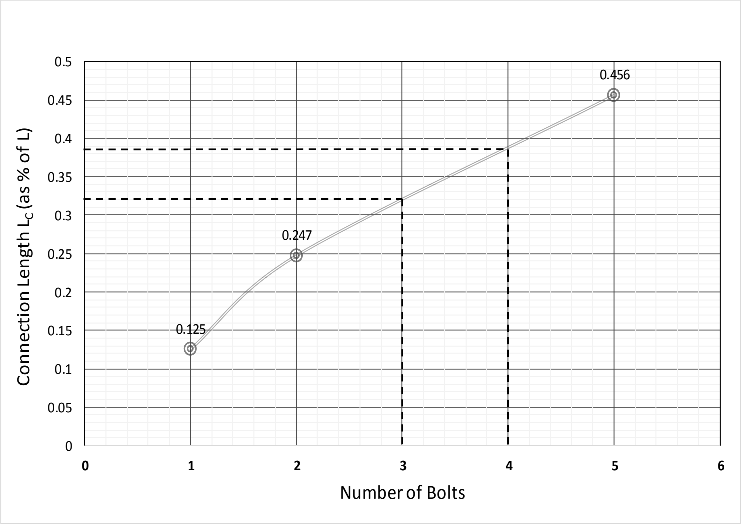

Fig. (4). Variations of conection length L_c with number of bolts.

Table 1. Calculations for Selected Test Angles with Single-Bolt End Connections.

No.	Angle Size (mm)	F_y (MPa)	Length L (mm)	Area A (mm^2)	r_z (mm)	L/r_z	F_a (MPa)	P_T (kN)	k_e	L_C*	L_{CM}*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	38 x 38 x 3.2	264	1588	232	7.52	211	58.6	13.6	0.869	0.066	0.040
2	38 x 38 x 3.2	264	1969	232	7.52	262	44.5	10.3	0.804	0.098	0.032
3	38 x 38 x 3.2	264	2350	232	7.52	312	32.1	13.6	0.792	0.104	0.027
4	51 x 51 x 3.2	264	2654	313	10.1	263	35.9	11.3	0.910	0.045	0.024
5	51 x 51 x 3.2	264	3112	313	10.1	308	27.6	8.6	0.869	0.065	0.020
6	64 x 64 x 6.4	263	3175	766	12.5	254	41.4	31.7	0.860	0.070	0.020
7	64 x 64 x 6.4	263	3797	766	12.5	304	32.8	25.1	0.807	0.096	0.017
8	76 x 76 x 4.8	322	3874	703	15.1	257	32.2	22.6	0.964	0.018	0.016
9	76 x 76 x 6.4	253	3810	927	15.0	254	37.9	35.1	0.897	0.051	0.017
10	76 x 76 x 6.4	253	4559	927	15.0	304	27.1	25.1	0.887	0.057	0.014
11	89 x 89 x 4.8	262	5321	824	17.7	301	27.6	30.1	0.891	0.055	0.0120
12	89 x 89 x 6.4	254	5321	1090	17.6	302	24.4	26.6	0.945	0.028	0.012
								Average	0.875	0.063	0.021

*As a fraction of total length L, at each end

End distance ‘e’ of all specimens = 31.8 mm (1¼ in.)

Edge distance ‘f’ of specimens = 20.6 mm to 38.1 mm (13/16 in. to 1½ in.)

Table 2. Calculations for Selected Test Angles with Double-Bolt End Connections.

No.	Angle Size (mm)	F_y (MPa)	Length L (mm)	Area A (mm^2)	r_z (mm)	L/r_z	F_a (MPa)	P_T (kN)	k_e	L_C*	L_{CM}*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	38 x 38 x 3.2	260	1264	232	7.52	168	134.2	31.1	0.721	0.139	0.096
2	38 x 38 x 4.8	260	1226	340	7.45	165	161.3	54.7	0.672	0.164	0.099
3	51 x 51 x 3.2	260	1645	313	10.1	163	105.8	33.4	0.836	0.082	0.073
4	51 x 51 x 3.2	260	2153	313	10.1	213	100.0	31.1	0.661	0.169	0.056
5	64 x 64 x 4.8	265	1988	582	12.6	158	118.9	69.4	0.815	0.092	0.061
6	64 x 64 x 4.8	265	2610	582	12.6	207	95.4	55.6	0.694	0.153	0.046
7	76 x 76 x 6.4	322	2379	927	15.0	158	113.1	105	0.835	0.082	0.0051
8	76 x 76 x 6.4	322	3169	927	15.0	211	80.7	74.7	0.752	0.124	0.038
9	76 x 76 x 7.9	249	3118	1150	15.0	208	81.4	93.4	0.749	0.125	0.039
10	76 x 76 x 7.9	249	3867	1150	15.0	258	69.0	79.2	0.656	0.172	0.031
11	89 x 89 x 6.4	260	3626	1090	17.6	206	71.7	78.3	0.808	0.096	0.033
12	89 x 89 x 6.4	260	4502	1090	17.6	256	43.4	47.6	0.835	0.083	0.027
								Average	0.753	0.123	0.054

* As a fraction of total length L, at each end

Bolt spacing ‘s’ = 57.2 mm (2¼ in.)

End distance ‘e’ of all specimens = 31.8 mm (1¼ in.)

Edge distance ‘f’ of specimens = 20.6 mm to 38.1 mm (13/16 in. to 1½ in.)

6. DISCUSSION

As seen in Tables **1** to **3**. and in Fig. (**3**), the effective slenderness coefficients derived from test results are consistently less than 1.00. As anticipated, the value of k_e decreased as the number of bolts increased. The value obtained for the single-bolt case is 0.875; which means, contrary to assumptions that such a joint does not provide any restraint, there is a certain clamping effect associated with the bolt. For the two-bolt case, the k_e value is 0.753 which indicates a larger restraint than a single-bolt. Interpolating, the following values for 3-bolt and 4-bolt cases were obtained:

3-bolt $k_e = 0.680$

4-bolt $k_e = 0.610$

Table 3. Calculations for Selected Test Angles with Fixed End Connections.

No.	Angle Size (mm)	F_y (MPa)	Length L (mm)	Area A (mm^2)	r_z (mm)	L/r_z	F_a (MPa)	P_T (kN)	k_e	L_C*	L_{CM}*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	76 x 76 x 4.8	257	3048	703	15.1	202	184.8	129.9	0.512	0.244	Not Applicable
2	76 x 76 x 6.4	253	2248	927	15.0	150	224.1	207.7	0.627	0.187	
3	76 x 76 x 6.4	253	2997	927	15.0	200	172.4	159.7	0.536	0.232	
4	76 x 76 x 6.4	253	3747	927	15.0	250	114.5	106.1	0.526	0.237	
5	76 x 76 x 6.4	253	4496	927	15.0	300	74.5	68.9	0.544	0.228	
6	89 x 89 x 6.4	260	3505	1090	17.6	199	155.1	169.0	0.567	0.217	
7	89 x 89 x 6.4	260	5258	1090	17.6	299	87.6	95.5	0.502	0.249	
								Average	0.544	0.228	

* As a fraction of total length L, at each end

6.1. Connection Lengths

Connection lengths L_C also proportionately increased as the number of bolts increased. From Tables **1** to **3** and in Fig. (**4**), the connection lengths derived from test results are consistently non-zero and clearly indicate a clamping effect. The value obtained for the single-bolt case is 0.125; which means, 12.5% of member length L and indicating a finite clamping effect associated with the bolt. For the two-bolt case, the L_C value is 0.247 or 24.7% of member length L, at each end. This indicates a larger clamping effect than a single-bolt. Interpolating, the following values for 3-bolt and 4-bolt cases were obtained:

3-bolt $L_C = 0.320$ (32% of member length L at each end)

4-bolt $L_C = 0.390$ (39% of member length L at each end)

In comparison with the minimum connection length L_{CM} defined in terms of end distance and bolt spacing, the actual connection lengths were between 4 to 6 times that of the value of L_{CM}.

7. CORRELATION WITH DESIGN

To verify if the computed effective slenderness coefficients k_e can be used to obtain more accurate design capacities, the parameter is applied to two test angles selected from the set used in this study. The capacity of the two angles (one single-bolted and one double-bolted) is computed using the ASCE 10-15 procedure and then adjusted using the effective slenderness parameter k_e. **Appendix B** shows the calculations. In both cases, the angles were first assumed as having no restraint at ends (Equation 3a) and then the slenderness is modified with k_e. Results show that the adjusted design capacities are very close to the test loads.

7.1. Intermediate-level Restraint

With the effective slenderness coefficient k_e obtained above for 3-bolt and 4-bolt cases, we can tentatively define the *adjusted* Euler capacity of struts with 3-bolt and 4-bolt connections approximately as follows:

$$P_E = \pi^2 EI / (k_e L)^2 = (1/k_e^2)\, \pi^2 EI / L^2 \tag{10}$$

$$\text{3-bolt} \quad P_E = (1/k_e^2)\, \pi^2 EI / L^2 = (1/0.680^2)\, \pi^2 EI / L^2 = 2.163\, \pi^2 EI / L^2 \tag{11a}$$

$$\text{4-bolt} \quad P_E = (1/k_e^2)\, \pi^2 EI / L^2 = (1/0.610^2)\, \pi^2 EI / L^2 = 2.687\, \pi^2 EI / L^2 \tag{11b}$$

CONCLUSION

In the preceding sections, a definition for the connection length of an angle beam-column in a lattice tower is proposed where the clamping effect of the bolts is quantified. Test data on single-bolt, double-bolt and fixed-end angles is utilized to develop simple expressions for effective length factors. Connection lengths were determined from the calculated effective slenderness coefficient. For 3-bolts and above, the associated slenderness coefficient is deduced from the graph showing its variation with end restraint. The validity of making a simple modification to ASCE design equations using k_e is examined.

Although modest, this study showed that it is possible to define and determine connection effects in angle columns in lattice transmission towers using carefully measured test data as a basis. Only a limited number of angle sections and slenderness ratios are studied in this paper. The results reported in this study are by no means exhaustive and further studies are warranted before the concepts discussed here can be generalized. Future investigations may include a larger database of test results, encompassing more angle sizes and slenderness levels, and effects of bolt size and connection geometries. An effort in any of those directions will be a worthwhile undertaking whose goal is to prescribe a more rational basis to the issue of quantifying end restraint effects in transmission towers and thereby more robust designs.

LIST OF NOTATIONS

$\mathbf{b}$ = Angle Leg Size
$\mathbf{d}$ = Bolt Diameter
$\mathbf{e}$ = End Distance
$\mathbf{f}$ = Edge Distance
$\mathbf{k}$ = Slenderness or Effective Length Coefficient
$\mathbf{k_e}$ = Effective Slenderness Coefficient including Connection Length and Clamping Effect
$\mathbf{r}$ = Radius of Gyration
$\mathbf{r_z}$ = Radius of Gyration about axis z-z
$\mathbf{s}$ = Bolt Spacing
$\mathbf{t}$ = Thickness of Angle Leg
$\mathbf{w}$ = Flat Width of Angle Leg including bend radius
$\mathbf{A}$ = Area of Cross Section
$\mathbf{C_c}$ = As defined
$\mathbf{E}$ = Modulus of Elasticity
$\mathbf{F_a}$ = Design Compressive Stress
$\mathbf{F_u}$ = Specified Tensile Strength of Member
$\mathbf{F_y}$ = Steel Yield Stress
$\mathbf{I}$ = Moment of Inertia = $A*r^2$
$\mathbf{L}$ = Length of the Member
$\mathbf{L_E}$ = Effective Length including Connection
$\mathbf{L_C}$ = Connection Length including Clamping Effect
$\mathbf{L_{CM}}$ = Minimum Connection Length
$\mathbf{L/r}$ = Slenderness Ratio
$\mathbf{P_D}$ = Design Compressive Strength
$\mathbf{P_E}$ = Euler Buckling Load
$\mathbf{P_T}$ = Test Compression Capacity
$\boldsymbol{\alpha}, \boldsymbol{\beta}$ = Derivation Parameters
$\boldsymbol{\eta}$ = P_E/P_T
$\boldsymbol{\lambda}$ = kL/r or k_eL/r
$\boldsymbol{\psi}$ = 2.62 for MPa units and 1.0 for ksi units

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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APPENDIX A

Design Compressive Stress (Based on ASCE 10-15)

$C_c = \pi\ [2E/F_y]^{½}$ (A-1)

$F_a = [1 - ½\ \xi^2]\ F_y\ \xi = \lambda/C_c$ for $\lambda \leq C_c$ (A-3a)

$(w/t)_{max} = 25$

(w/t) lim1 = $80\ \psi\ /\ (F_y)^{½}$ = 13.0 for 262 MPa steel, 11.7 for 322 MPa steel (A-4a)

(w/t) lim2 = $144\ \psi\ /\ (F_y)^{½}$ = 23.4 for 262 MPa steel, 21.1 for 322 MPa steel (A-4b)

Design Compressive Strength = $P_D = A\ F_a$

APPENDIX B

Example Calculations (Based on ASCE 10-15) Using Effective Slenderness Coefficient k_e

Case 1 One-bolt Angle 64 x 64 x 6.4 (2” x 2” x ¼”)

Test # 6, Table (**1**)

F_y = 263 MPa (38.2 ksi). Assume E = 200 GPa (29,000 ksi)

A = 766 mm^2 (1.19 in^2)

Width to thickness ratio check: *w/t* = (64-2*6.4)/6.4 = 8 < $80\ /(F_y)^{1/2}$ = 12.94

$C_c = \pi\ [2E/F_y]^{½} = 122.7$

L/r = 254

λ= kL/r = L/r = 254 (no restraint at ends)

Apply Adjustment for λ With k_e Computed for Single-bolt Case.

$(k_e)(\lambda) = 0.875 * 254 = 222.25$

Therefore, kL/r > C_c

Revised $F_a = [\pi^2\ E]\ /(k_e\ \lambda)^2$ = 39.95 MPa (5.795 ksi)

Revised Design Compressive Strength = $P_D = A\ F_a$ = 30.61 kN (6.88 kips)

P_T = Test capacity = 31.6 kN (7.1 kips)

The revised P_D containing the effective length factor k_e is very close to the test load P_T.

Case 2 Two-bolt Angle 76 x 76 x 6.4 (3” x 3” x ¼”)

Test # 10, Table (**2**)

F_y = 322 MPa (46.7 ksi). Assume E = 200 GPa (29,000 ksi)

A = 927 mm^2 (1.44 in^2)

Width to thickness ratio check: *w/t* = (76-2*6.4)/6.4 = 9.88 < $80\ /(F_y)^{1/2}$ = 11.71

$C_c = \pi\ [2E/F_y]^{½} = 110.7$

L/r = 211

λ = kL/r = L/r = 211 (no restraint at ends)

Apply Adjustment for λ With k_e Computed for Double-bolt Case.

$(k_e)(\lambda) = 0.753 * 211 = 158.88$

Therefore, kL/r > C_c

Revised $F_a = [\pi^2\ E]\ /(k_e\ \lambda)^2$ = 78.18 MPa (11.34 ksi)

Revised Design Compressive Strength = $P_D = A\ F_a$ = 72.50 kN (16.29 kips)

P_T = Test capacity = 74.7 kN (16.8 kips)

The revised P_D containing the effective length factor k_e is very close to the test load P_T.

Note: The effective width of angle '*w*' used in the *w/t* check includes the fillet radius taken as 2 times *t*.

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