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Permanent Stability Bracing of CFS Trusses

Sowri Rajan, P.E. [1] and William L. Babich, P.E[2]

Abstract

Permanent stability bracing of Cold-Formed Steel (CFS) roof/floor trusses is needed for the three major planes in a truss: Top chord, Bottom Chord and Web. Primary function of bracing is to prevent lateral instability of members as well as stiffen the overall roof/floor system. Brace force is dependent on the magnitude of applied loads and the level of out-of-planeness permitted. Traditionally, 2% of the axial compression force in a member is used as the brace (restraint) force, which is based on an out-of-plane deflection of L/200 where L is the member length. Continuous Lateral Restraint (CLR) forces are accumulated from similar members in several adjacent trusses and then transferred through Diagonal Braces (DB) to the bearings or other shear resisting elements (for example, metal decking). For chord and web members, a method to determine the forces in CLR and DB is presented using a statics based approach with varying number of braces and mode shapes for a maximum permitted out-of-planeness of L/200. For the chord members with more than two CLR's, a method for designing a Brace Collector Frame (BCF) based on the Net Lateral Restraining Force (NLRF) is presented.

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Introduction

As CFS trusses become more common in the construction of commercial, institutional, and industrial buildings, tools for designing the bracing for those trusses are being developed and improved. The importance of proper design and installation of bracing cannot be overstated for, in some systems, the bracing design can be as complex as the design of the trusses. Bracing must be designed to accept, resist, and transfer loads applied to the roof system and loads within the roof system. Primary function of bracing is to prevent lateral instability of members as well as stiffen the overall roof/floor system.

Primary intent of this paper is to address the “Stability Bracing” to prevent buckling of truss compression members from loads applied in the plane of the truss. Bracing required to resist the forces imposed on the truss system from lateral loads (wind or seismic) applied out of the plane of the truss are beyond the scope of this paper. While trusses are the focus of this paper, the design methods presented could be considered for other CFS frame designs also.

Background

Typically, vertical downward loads on a simply supported truss induce compression forces on the top chord and some webs, and vertical upward forces induce such forces on the bottom chord and some webs. Truss design drawing shows the compression members needing permanent stability bracing. Such bracing is typically provided in the planes of those members.

Force in the brace or “restraint” member is dependent on the magnitude of applied loads and the level of out-of-planeness permitted. The amount of out-of-planeness permitted for CFS trusses is governed by the tolerance limits on the (a) installed truss per AISI S214-07/S2-08[1] Truss Design Standard, and the (b) manufacturing of individual members (chords and webs) per AISI S201-07[2] North American Standard for Cold-Formed Steel Framing - Product Data.

Section F1.1 of AISI S214-07/S2-08 states that the maximum bow (out-of-planeness) in any chord member or panel shall be the lesser of L/200 or 2 inches (50.8 mm), where L is the length of the truss, chord member or panel in inches.

Section C7 of AISI S201-07 states that the manufacturing tolerances for structural members (chords and webs in trusses) shall comply with those listed in ASTM C955-06[3]. Table C7-1 in the Commentary on AISI S201-07, which is taken from ASTM C955-06, states that the maximum bow (out-of-planeness) for structural stud or track members shall be the lesser of 1/32 inch (0.8 mm) per feet length of the member or 0.5 inch (12.7 mm). For a typical 20 feet (6096 mm) long stud or track member, maximum bow is 20 * 1/32 = 5/8 inch (15.9 mm), but is limited by the 0.5 inch (12.7 mm) maximum limit. This equates to a maximum out-of-planeness of L/720 [(20*12)/0.5 = 720], which is more restrictive on the out-of-planeness than the L/200 permitted by AISI S214-07/S2-08. The higher out-of-planeness of L/200 requires more restraint force than the lower L/720 limit.

Traditionally, 2% of the axial compression force in a member is used as the restraint force, which is based on a maximum permitted out-of-planeness of L/200 and this also matches the limit per AISI S214-07/S2-08. Continuous Lateral Restraint (CLR) forces are accumulated from similar members in several adjacent trusses and then transferred through Diagonal Braces (DB) to the bearings or other shear resisting elements (for example, metal decking). Statics based calculations presented in this paper presume infinite stiffness for the CLR, DB and CLR / DB-to-member connections.

Force in CLR

The purpose of adding a CLR is to hold the compression member at the installed location and not allow it to buckle. If the member is straight, there's no force in the CLR. For a compression member with a maximum displacement at the middle of its unbraced length equal to the L/200 out-of-planeness permitted by AISI S214-07/S2-08, force in the CLR is based on the presumed deflected shape of the member. Unbraced length of a member is the length between locations of zero out-of-planeness. CLR force calculations for members with selected number of braces for few mode shapes are presented below.

For a compression member with one CLR at mid-length (Figure 1) subject to an axial compression load of "P", the CLR force is determined as follows:

Presuming a half sine wave deflected shape for the first mode,

R + R = B, where "B" is the CLR force and "R" is the Reaction at member ends

At mid-length location A, $\sum M_A = 0 \Rightarrow P*\Delta_A - R*L/2 = 0$, where $\Delta_A = L/200$

$P*(L/200) - R*L/2 = 0 \Rightarrow R = 0.01P$ and $B = 0.02P$ or 2% of P

For the second mode, by inspection, CLR force B = 0

For the third mode, the CLR force is determined as follows:

$\Delta = 0$ at $x = 0$, L/3, 2L/3 and L; $\Delta = L/600$ at $x = L/6$, L/2 and 5L/6

$\Delta = (L/600)*\text{Sin}\,(3\pi x/L)$; $\Delta_{L/2} = (L/600)*\text{Sin}\,(3\pi/2) = 0.00167L$

$\sum F_X = 0 \Rightarrow 2R - B = 0 \Rightarrow R = B/2$

At mid-length location A, $\sum M_A = 0 \Rightarrow P*\Delta_{L/2} - R*L/2 = 0$

$\Rightarrow P*(0.00167L) - (B/2)*(L/2) = 0 \Rightarrow B = 0.0067P$ or 0.67% of P

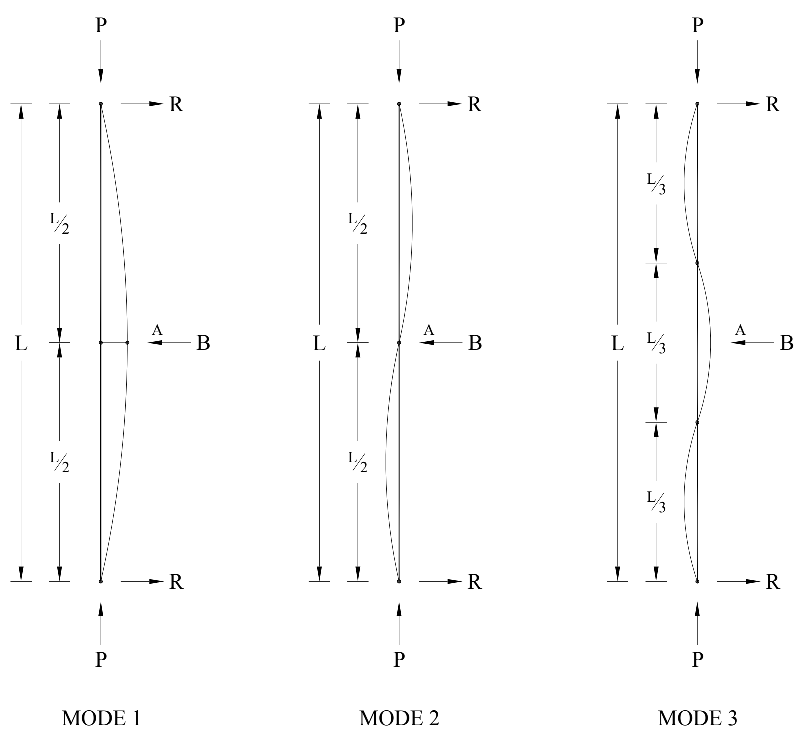

Figure 1 Compression Member with One CLR

For a compression member with two CLR's, one each at one-third its length (Figure 2), and presuming a half sine wave deflected shape for the first mode, the CLR force is determined as follows:

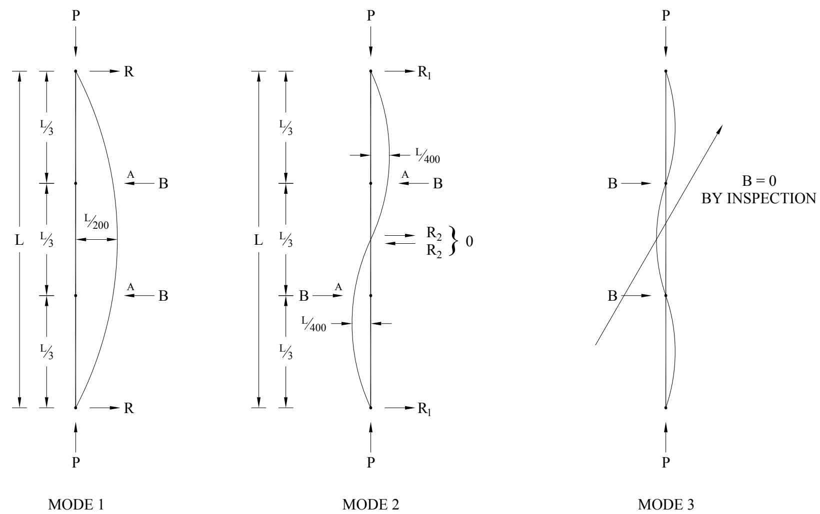

Figure 2 Compression Member with Two CLR's

Deflection at mid-length = L/200 => By inspection, B = R

$\Delta = 0$ at $x = 0$ and L; $\Delta = L/200$ at $x = L/2$

$\Delta_X = (L/200)*\text{Sin}(\pi X/L)$; $\Delta_{L/3} = (L/200)*\text{Sin}(\pi/3) = 0.00433L$

At one-third length location A, $\sum M_A = 0 \Rightarrow P*\Delta_{L/3} - R*L/3 = 0$

$\Rightarrow P*(0.00433L) - R*L/3 = 0 \Rightarrow R = B = 0.013P$ or 1.3% of P

For the second mode, the CLR force is determined as follows:

$\Delta = 0$ at $x = 0$, L/2 and L; $\Delta = L/400$ at $x = L/4$ and 3L/4

$\Delta_X = (L/400)*\text{Sin}(2\pi X/L)$; $\Delta_{L/3} = (L/400)*\text{Sin}(2\pi/3) = 0.00217L$

At one-third length location A, $\sum M_A = 0 \Rightarrow P*\Delta_{L/3} - R_1*L/3 + R_2*L/6 = 0$

$\Rightarrow P*(0.00217L) - R_1*L/3 + 0 = 0 \Rightarrow R_1 = 0.0065P$

At mid-length location, $\sum M = 0 \Rightarrow R_1*L/2 - B*L/6 = 0$

=> $3*R_1 = B$ => $B = 0.0195P$ or 1.95% of P

For the third mode, by inspection, CLR force B = 0

For a compression member with five evenly spaced CLR's (Figure 3), and presuming a half sine wave deflected shape for the first mode, the CLR force is determined as follows:

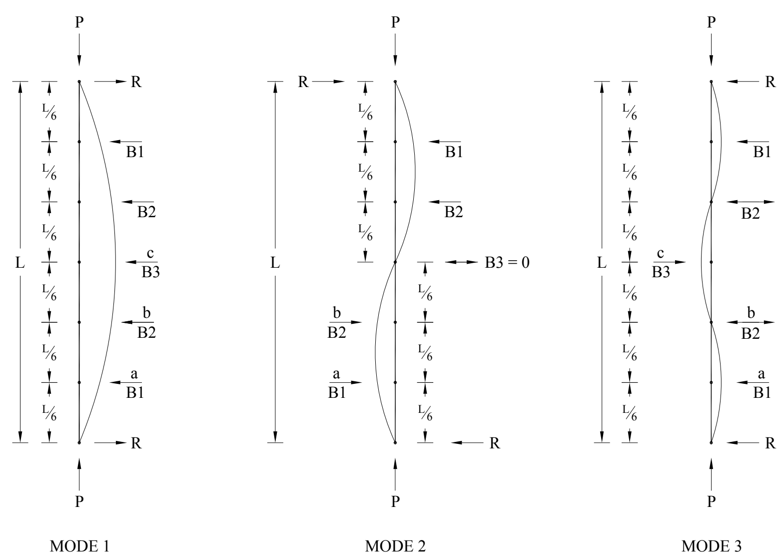

Figure 3 Compression Member with Five Braces

$\Delta = 0$ at $x = 0$ and L; $\Delta = L/200$ at $x = L/2$

$\Delta_X = (L/200)*\text{Sin}(\pi X/L)$; $\Delta_{L/6} = (L/200)*\text{Sin}(\pi/6) = 0.0025L$

$\Delta_{L/3} = (L/200)*\text{Sin}(\pi/3) = 0.00433L$; $\Delta_{L/2} = (L/200)*\text{Sin}(\pi/2) = 0.005L$

At one-sixth length location a, $\sum M_a = 0$ => $P*\Delta_{L/6} - R*L/6 = 0$

=> $P*(0.0025L) - R*L/6 = 0$ => $R = 0.015P$

At one-third length location b, $\sum M_b = 0$ => $P*\Delta_{L/3} + B_1*L/6 - R*L/3 = 0$

$\Rightarrow P*(0.00433L) + B_1*L/6 – (0.015P)*L/3 = 0 \Rightarrow B_1 = 0.004P$ or 0.4% of P

At mid-length location c, $\sum M_c = 0 \Rightarrow P*\Delta_{L/2} + B_1*L/3 + B_2*L/6 – R*L/2 = 0$

$\Rightarrow P*(0.005L) + (0.004P)*L/3 + B_2*L/6 – (0.015P)*L/2 = 0$

$\Rightarrow B_2 = 0.007P$ or 0.7% of P

$R = B_1 + B_2 + B_3/2 \Rightarrow 0.015P = 0.004P + 0.007P + B_3/2$

$\Rightarrow B_3 = 0.008P$ or 0.8% of P

For the second mode, the CLR force is determined as follows:

$\Delta = 0$ at x = 0, L/2 and L; $\Delta = L/400$ at x = L/4 and 3L/4

$\Delta_X = (L/400)*\text{Sin}(2\pi X/L)$; $\Delta_{L/6} = (L/400)*\text{Sin}(\pi/3) = 0.00217L$

$\Delta_{L/3} = (L/400)*\text{Sin}(2\pi/3) = 0.00217L$

Since deflection at L/6 and L/3 are the same, $B_1 = B_2$

At mid-length, $\Delta_{L/2} = 0 \Rightarrow B_3 = 0$

At one-sixth length location a, $\sum M_a = 0 \Rightarrow P*\Delta_{L/6} – R*L/6 = 0$

$\Rightarrow P*(0.00217L) – R*L/6 = 0 \Rightarrow R = 0.01299P$

At one-third length location b, $\sum M_b = 0 \Rightarrow P*\Delta_{L/3} + B_1*L/6 – R*L/3 = 0$

$\Rightarrow P*(0.00217L) + B_1*L/6 – (0.01299P)*L/6 = 0$

$\Rightarrow B_1 = B_2 = 0.01296P$ or 1.3% of P

For the third mode, the CLR force is determined as follows:

$\Delta = 0$ at x = 0, L/3, 2L/3 and L; $\Delta = L/600$ at x = L/6, L/2 and 5L/6

$\sum F_X = 0 \Rightarrow 2R + 2B_1 – B_3 = 0 \Rightarrow B_3 = 2(B_1 – R)$

At one-sixth length location a, $\sum M_a = 0 \Rightarrow P*\Delta_{L/6} – R*L/6 = 0$

$\Rightarrow P*L/600 – R*L/6 = 0 \Rightarrow R = 0.01P$

At one-third length location b, $\sum M_b = 0 \Rightarrow B_1*L/6 – R*L/3 = 0$

$\Rightarrow B_1 * L/6 - (0.01P) * L/3 = 0 \Rightarrow B_1 = 0.02P$ or 2% of P

$B_3 = 2(B_1 - R) = 2(0.02P - 0.01P) = 0.02P$ or 2% of P

Table 1 presents the percent force in the CLR (expressed as a percent of the axial compression force 'P') for various numbers of CLR's and mode shapes. CLR forces are in the same direction for the first mode. In other modes, the CLR forces act in opposite directions.

Table 1 Percent force in CLR for various modes

Mode #	Percent Force in CLR (% of P)								
	1 CLR	2 CLR's	3 CLR's		4 CLR's		5 CLR's		
	B1	B1	B1	B2	B1	B2	B1	B2	B3
1	2.00	1.30	0.83	1.17	0.56	0.91	0.40	0.70	0.81
2	0.00	1.95	2.00	0.00	1.64	1.02	1.30	1.30	0.00
3	0.67	0.00	1.61	2.28	2.08	1.28	2.00	0.00	2.00
4	0.00	0.97	0.00	0.00	1.33	2.15	1.95	1.95	0.00
5	0.40	0.26	0.97	1.37	0.00	0.00	1.12	1.94	2.24
6	0.00	0.00	0.67	0.00	0.89	1.43	0.00	0.00	0.00
7	0.29	0.19	0.12	0.17	0.89	0.55	0.80	1.39	1.60
8	0.00	0.16	0.00	0.00	0.41	0.25	0.97	0.97	0.00
9	0.22	0.00	0.09	0.13	0.06	0.10	0.67	0.00	0.67

The majority of the CLR forces in Table 1 are less than the traditional 2% of P. While designing an individual CLR to resist 2% of P is appropriate, it is conservative to design every CLR to resist the same percent force in a member with multiple CLR's, since all the CLR's will not be subject to the same force at the same time.

As an example, for the first mode of a member with 5 CLR's, the percent CLR forces are 0.4, 0.7, 0.8, 0.7, and 0.4 in each CLR, respectively (see Figure 3 and Table 1). The Net Lateral Restraining Force (NLRF) is the sum of all the percent forces since they all act in the same direction for the first mode. Thus, the NLRF is equal to 0.4+0.7+0.8+0.7+0.4=3, which is 3%. If the traditional 2% for every CLR is used for this condition, the resulting NLRF of 10% for the 5 CLR's is quite conservative when compared with the 3%. For other mode shapes wherein the CLR forces are in opposite directions, the NLRF could even be less than 3%. Table 2 and Figure 4 present the NLRF for various numbers of CLR's and mode shapes.

Table 2 Percent Net Lateral Restraint Force (NLRF)

# of CLR's	Percent Net Lateral Restraint Force (NLRF) for Mode #								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	2.00	0.00	0.67	0.00	0.40	0.00	0.29	0.00	0.22
2	2.60	0.00	0.00	0.00	0.52	0.00	0.38	0.00	0.00
3	2.83	0.00	0.94	0.00	0.56	0.00	0.41	0.00	0.31
4	2.94	0.00	1.58	0.00	0.00	0.00	0.68	0.00	0.33
5	3.00	0.00	2.00	0.00	0.60	0.00	0.44	0.00	0.67
6	3.04	0.00	2.28	0.00	1.10	0.00	0.00	0.00	0.61
7	3.07	0.00	2.47	0.00	1.49	0.00	0.44	0.00	0.34
8	3.08	0.00	2.60	0.00	1.78	0.00	0.82	0.00	0.00
9	3.09	0.00	2.69	0.00	2.00	0.00	1.15	0.00	0.34
10	3.10	0.00	2.78	0.00	2.18	0.00	1.42	0.00	0.66

The maximum NLRF is 3.1%, i.e., the maximum total restraining force needed for stabilizing a member with multiple CLR's is 3.1% of the axial compression applied to that member. The 3.1% value is also corroborated by Catherine Underwood's research work at Virginia Tech[4]. For truss members with multiple CLR's, it is recommended to design the individual CLR's for 2% of the axial compression and the stabilizing DB members based on the 3.1% NLRF. To ensure a maximum NLRF of 3.1%, the force in CLR could be presumed as equal to 3.1% of the maximum axial compression force divided by the total number of braces. The accumulated CLR force from multiple trusses could then be transferred to the truss bearings through a frame in the plane of the member, wherein DB's are added between two or three trusses, and in between the CLR's. This frame is herein termed as Brace Collector Frame (BCF).

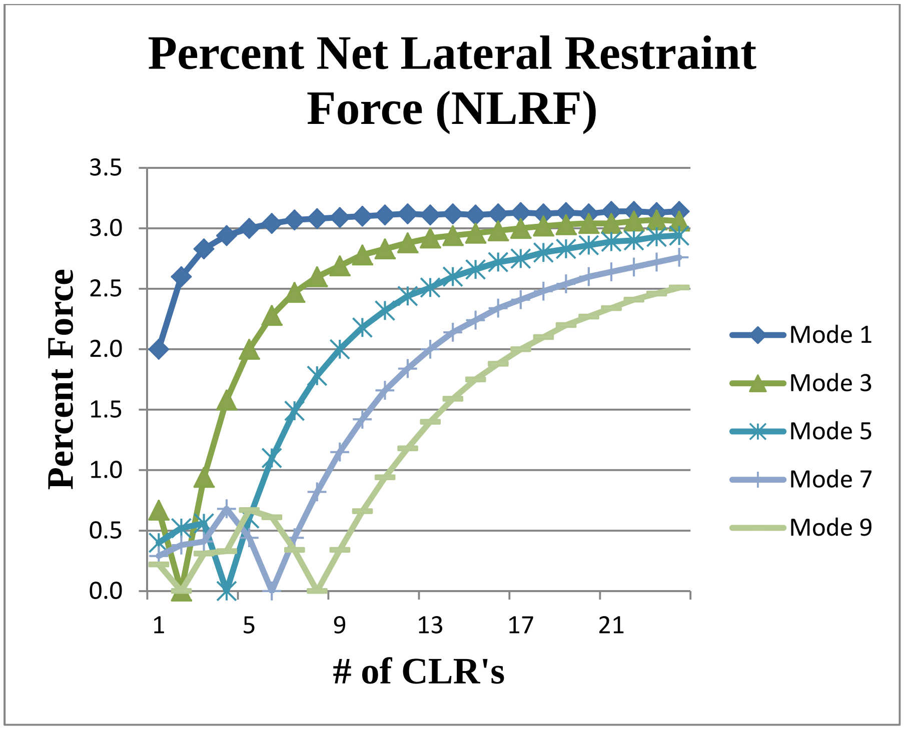

Figure 4 Percent Net Lateral Restraint Force (NLRF)

Stability Bracing Design Method

Based on the calculation of CLR force and the NLRF, a separate method of design is recommended for the two cases, viz., (a) compression members with not more than two CLR's and (b) compression members with more than two CLR's. Typical truss designs have webs with not more than two CLR's and chords have more than two CLR's.

(a) Compression members with not more than two CLR's

1) Design the CLR and CLR-to-member connections to resist 2% of the maximum axial compression force in the member accumulated over several trusses until the location of the DB or another resisting member. CLR's are typically located perpendicular to the length of the member, either at the middle or one-third the member length.

2) Design the DB and DB-to-member connections to resist the vector value of the accumulated force from CLR's. For truss webs, DB's are typically located in its plane between two or three trusses to transfer the force from the DB to the roof and/or ceiling diaphragm. Diaphragm could be structural sheathing or gypsum boards. It is typical to locate the DB's within 3 inches (76.2 mm) from the CLR and terminate its other end within 3 inches (76.2 mm) from the ends of lined-up web in the adjacent second or third truss. Based on typical diaphragm-to-truss attachment with two #10 screws, it is recommended to limit the maximum accumulated force from CLR's to 400 lb. (1.8 KN) for transfer thru the DB. For truss chords, DB's are typically located in its plane between two or three trusses to transfer the force from the DB to the truss bearings. The same 400 lb. (1.8 KN) limit of accumulated force for transfer thru the DB is recommended based on typical chord-to-bearing clip connections with four #10 screws.

b) Compression members with more than two CLR's

1) Design the CLR and CLR-to-member connections to resist 2% of the maximum axial compression force in the member accumulated over several trusses until the location of the DB or another resisting member. CLR's are typically located perpendicular to the length of the member, at the specified spacing in the truss design drawings.
2) For the design of BCF, apply an axial load to each CLR equal to 3.1% of the maximum axial compression force in the member divided by the number of CLR's. Accumulate this force over several trusses until the location of BCF, wherein DB's are typically added between two or three trusses, and in between the CLR's.
3) Design the DB and DB-to-member connections to resist the vector value of the accumulated force from CLR's. For truss chords, DB's are typically located in its plane between two or three trusses to transfer the force from the DB to the truss bearings. It is typical to locate the DB's within 3 inches (76.2 mm) from the CLR's and between adjacent two or three trusses. The end DB in the BCF is subject to maximum axial compression and typically it governs the location of BCF in a multiple truss layout. Based on typical chord-to-bearing clip connections with four #10 screws, it is recommended to limit the maximum accumulated force from CLR's to 400 lb. (1.8 KN) for transfer thru the end DB.

The methods given above are to assist the practicing design professional in providing an appropriate layout of stability bracing for CFS trusses. While the design of the CLR, DB and location of BCF could be determined from the methods given above, care should be exercised when deciding the element to which the DB's force is terminated. For truss webs, DB's should be terminated as close to the top and/or bottom ends of the trusses as possible (within 3 inches or 76.2 mm is recommended) such that the horizontal component of the force in DB could be transferred to the roof and/or ceiling diaphragm. DB could even be terminated at a blocking member added between the truss chords to avoid lateral bending of truss webs.

For truss top chords without a diaphragm, i.e., with purlins and standing seam or a similar roof deck, the purlin should be designed as a beam-column since it's subject to both vertical loads (gravity, live, snow and wind) and lateral loads from being a stability brace for the chord. For truss top chords with raised heels, i.e., truss height at bearing above 6 inches (152.4 mm), it is recommended to design a vertical DB (also called as Blocking) between trusses over the bearing to transfer the DB force from top chord down to the bearing. For sloping top or bottom chords of trusses, it is recommended to use the span of the sloping member as the span of BCF and design a vertical DB between trusses at slope-change locations.

CLR Stiffness

Statics based approach in this paper presumes the CLR and DB to be infinitely stiff. The use of installation tolerance (L/200) instead of the manufacturing tolerance (L/720) on out-of-planeness permits higher deflection and in turn results in higher force in the CLR and in turn, the DB. This use of higher force could be a justification to ignore checking the CLR and DB stiffness, but further study on it is needed. CLR or DB-to-compression member connection stiffness also needs to be included in the study.

A sample calculation of CLR strength and stiffness per Section D3.3 of AISI S100-2007[5] Specification is given below. Typical CFS trusses spaced at 4 feet (1219.2 mm) on centers imply the length of CLR is 4 feet (1219.2 mm). Typical CLR members used in the CFS truss industry are 150F125-33 structural hat channel and 362S162-33 C-stud.

<u>150F125-33 hat channel as CLR:</u>

L = 48 in. (1219.2 mm); E = 29500 ksi (203,395 N/sq.mm)

Effective Area at yield, A = 0.179 sq.in. (115.5 sq.mm)

Axial stiffness = EA/L = 110 kips/in (19.3 KN/mm)

Per Section C4 of AISI S100-2007 Specification, Nominal axial compression strength for 48 in. (1219.2 mm) length, P_n = 0.43 kips (1.91 KN)

Per Section D3.3 of AISI S100-2007 Specification, and conservatively estimating the nominal compression strength of a member in a truss as 100 kips (444.8 KN, typical values the authors have seen from CFS truss designs are much lower), Required strength of CLR, $P_{br,1}$ = 0.01*100 = 1 kip (4.45 KN), which is more than the available nominal strength of 0.43 kips (1.91 KN) for 150F125-33. Reverse calculation shows that the 150F125-33 hat channel would work for truss members with a nominal compression strength of 0.43/0.01 = 43 kips (191 KN).

For a compression member with infinite number of CLR's, Required stiffness of CLR, $\beta_{br,1}$ = 8*100/48 = 16.7 kips/in (2.9 KN/mm) which is less than the available axial stiffness of 110 kips/in (19.3 KN/mm) for 150F125-33.

<u>362S162-33 C-stud as CLR:</u>

L = 48 in. (1219.2 mm); E = 29500 ksi (203,395 N/sq.mm)

Effective Area at yield, A = 0.262 sq.in. (169 sq.mm)

Axial stiffness = EA/L = 161 kips/in (28.2 KN/mm)

Per Section C4 of AISI S100-2007 Specification, Nominal axial compression strength for 48 in. (1219.2 mm) length, P_n = 2.26 kips (10.1 KN)

Per Section D3.3 of AISI S100-2007 Specification, and presuming a nominal compression strength of 100 kips (444.8 KN), Required strength of CLR, $P_{br,1}$ = 0.01*100 = 1 kip (4.45 KN), which is less than the available nominal strength of 2.26 kips (10.1 KN) for 362S162-33.

For a compression member with infinite number of CLR's, Required stiffness of CLR, $\beta_{br,1}$ = 8*100/48 = 16.7 kips/in (2.9 KN/mm) which is less than the available axial stiffness of 161 kips/in (28.2 KN/mm) for 362S162-33.

The above calculation justifies ignoring the check on CLR stiffness in the statics based design methods for CFS trusses when typical bracing members like 150F125-33 or 362S162-33 are used. However, further study on CLR or DB-to-compression member connection stiffness is needed.

Conclusions

For CFS truss members, a method to determine the forces in CLR was presented using a statics based approach with varying number of braces and mode shapes for a maximum permitted out-of-planeness of L/200. To assist the design professional, design methods for two cases were presented – compression members with not more than two CLR's and for those with more than two CLR's. For truss chord members with more than two CLR's, a method for designing a Brace Collector Frame (BCF) based on the Net Lateral Restraining Force (NLRF) was presented. Sample calculation of CLR stiffness with typical hat and C-stud members was presented.

Appendix – Abbreviations

BCF = Brace Collector Frame

CFS = Cold-Formed Steel

CLR = Continuous Lateral Restraint

DB = Diagonal Brace

NLRF = Net Lateral Restraint Force

Appendix – Notation

A = Effective area at yield strength

B = Force in CLR

E = Modulus of elasticity

L = Compression member length

M = Bending moment at a specific location

P = Applied axial compression load

P_n = Nominal axial compression strength

$P_{br,1}$ = Required strength of CLR

R = Reaction at ends or a specific location

x = Specific location along the length of a member

$\beta_{br,1}$ = Required stiffness of CLR

Δ = Deflection at a specific location

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Appendix - References

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