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Lateral bracing of beams provided by standing seam roof system: concepts and case study

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Abstract
The standing seam roof (SSR) system is the most commonly used roof system for metal buildings due to its superior durability, water tightness, and energy efficiency. In this type of system, SSR panels attach to Z-shaped or C-shaped purlins with clips, and the purlins are in turn connected to rafters (i.e. roof beams). For the design of metal building rafters against lateral torsional buckling, bottom flange braces provide torsional bracing to the rafter and the SSR system provides some lateral bracing. However, the degree to which the SSR system can restrain the rafter against lateral movement has not previously been studied. To quantify the in-plane strength and stiffness of the SSR system and identify how it can be used to provide lateral bracing to the rafter, an experimental testing program has been conducted on standing seam roof assemblies. In this paper, a method for using the experimental results in the calculations of required bracing for metal building rafters is described. A case study is also provided which demonstrates that the SSR roof can contribute to the bracing of rafters and may reduce spacing or size of discrete torsional braces.

1. Introduction and Motivation

Metal building systems are popular for low-rise buildings because of their fast construction and cost efficiency. One of the main components of a metal building is the roof system, a common type of which is the standing seam roof (SSR) system. An SSR system consists of purlins, clip fasteners, SSR panels, and optional blanket insulation and thermal blocks, as is shown in Fig. 1. Z-shaped or C-shaped purlins provide support for the roof and are attached to the steel rafters of the building frame. The SSR panels are light-gauge corrugated metal sheets which span between the purlins and connect to each other through the standing seam created by roll-forming the two panel edges together. Clip fasteners are installed on the purlins and extend up into the standing seam, which after the seam is crimped provides a connection between the roof panels and purlins. Depending on the need for thermal insulation, blanket insulation and thermal blocks can also be installed underneath the roof panels.

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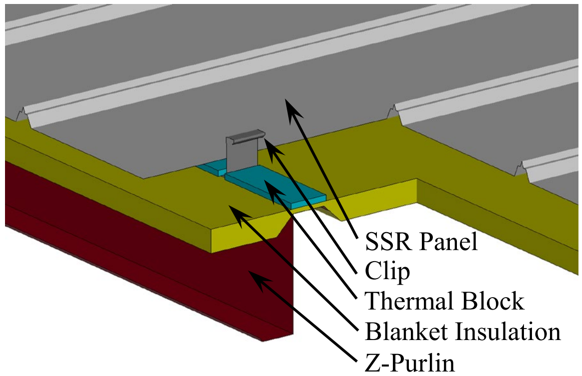

Figure 1: Schematic view of a standing seam roof (SSR) system

In a typical metal building system, there are different types of bracing at the roof level that restrain lateral movement of the entire building and individual members. The in-plane bracing in the roof plane of a metal building is provided by tension rod or cable bracing with X braces attached to the web of the rafter near the top flange. Another type of bracing involves top and bottom flange bracing of the rafter to prevent lateral torsional buckling of the rafter. This type of bracing is typically provided by the purlins at the rafter top flange and diagonal flange braces that extend from the purlin to the rafter bottom flange.

The flange brace and purlin create frame action that acts as torsional bracing for the rafter. Additionally, the SSR system provides some restraint against rafter lateral motion because it resists relative longitudinal motion of purlins. This concept is demonstrated in Fig. 2 as the lateral force associated with rafter lateral torsional buckling is applied to the purlins. A simplified free-body diagram of the SSR system with lateral bracing load is shown in Fig. 3. It is noted that this loading configuration is highly idealized as a single bracing load and simple supports.

Figure 2: Lateral bracing and load transfer of main frame

In the context of AISC 360-16 (AISC 2016), the locations where the roof X braces connect to the rafter may be considered point bracing (sometimes referred to as nodal bracing) for global stability of the rafter. A testing program on SSR assemblies (Wei et al. 2020) showed that the SSR panels remain relatively rigid compared to the clip deformations during early loading in a configuration like Fig. 3. Therefore, the interior purlins also act as point bracing for the rafter because the movement is controlled relative to the support, not the adjacent interior purlins. It is noted that bracing loads could be imposed at more than one interior purlin, and these loads may not be in the same direction.

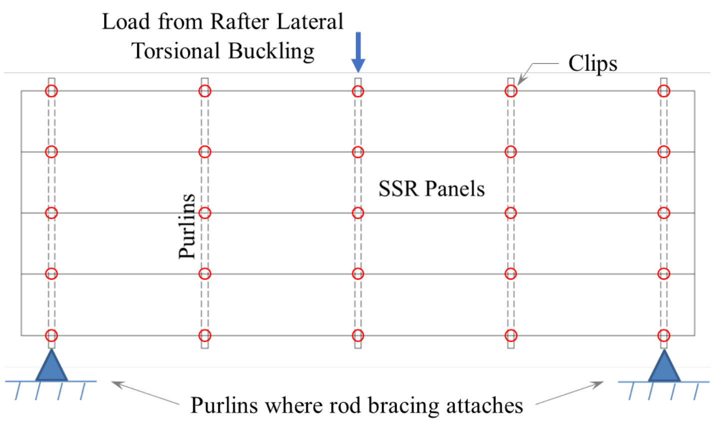

Figure 3: Lateral load from rafter lateral torsional buckling acting on purlins and SSR panels

AISC 360-16 (AISC 2016) Appendix 6 provides equations for calculating the required stiffness and strength for beam point bracing. However, the in-plane resistance of the SSR panels and their ability to brace the rafter have not been previously studied. To fill this gap, an experimental testing program was conducted to investigate the in-plane stiffness and strength of SSR assemblies. Detailed information of the testing program and test results is available in Wei et al (2020).

2. Proposed Method for Evaluating Rafter Bracing Provided by SSR System

For metal buildings, tension rod braces (X braces) are typically used to transfer lateral loads to the vertical lateral force resisting system. The rod bracing coupled with the in-plane stiffness of the SSR system can also provide lateral bracing to the rafters. Fig. 4 shows the assumed lateral displacements of a rafter as it undergoes lateral torsional buckling, wherein the rafter is constrained against translation at the intersections of rod bracing with the purlin line. Fig. 5 shows a section view of two adjacent rafters undergoing lateral torsional buckling in the same direction. It is assumed that the SSR system provides lateral bracing for rafters between these tension rod bracing points, while the rafter flange braces restrain the twist of rafter and thus provide torsional bracing.

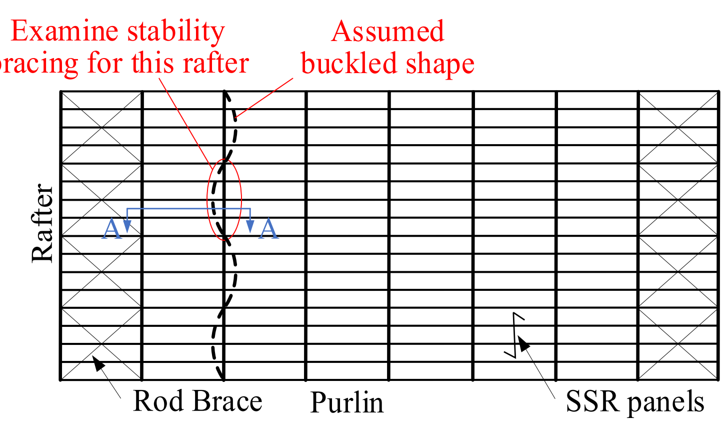

Figure 4: Plan view of typical metal building roof framing with assumed buckled shape of rafter

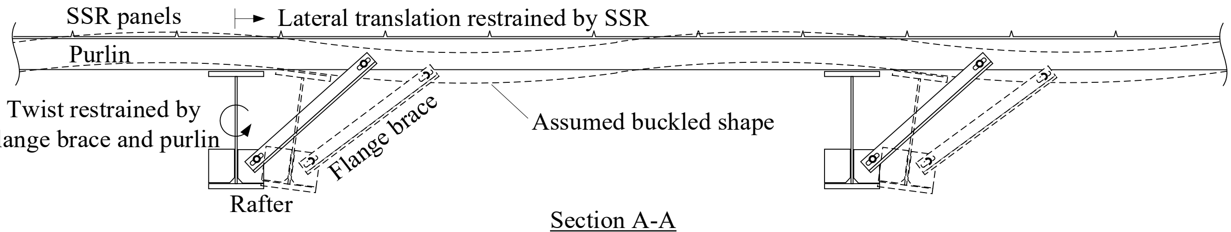

Figure 5: Section view of adjacent rafters braced by SSR and flange braces with assumed buckled shape

AISC 360-16 (AISC 2016a) Appendix 6 specifies the required strength and stiffness for lateral and torsional bracing of beams. The lateral bracing provided by the SSR system is categorized as point bracing at the purlin locations. The required lateral bracing strength, P_{Lbro}, and the required lateral bracing stiffness, β_{Lbro}, are given as follows for the condition without torsional bracing:

$$P_{Lbro} = 0.02\left(\frac{M_r C_d}{h_o}\right) \tag{1}$$

$$\beta_{Lbro} = \frac{1}{\phi}\left(\frac{10 M_r C_d}{L_{br} h_o}\right) \tag{2}$$

where

M_r = required flexural strength of the rafter within the panel under consideration, using LRFD or ASD load combinations

C_d = 1.0, except in the following case:
= 2.0 for the brace closest to inflection point in a beam subject to double curvature bending

h_o = distance between rafter flange centroids

ϕ = resistance factor

L_{br} = unbraced length adjacent to the point brace

Torsional bracing of the rafter, provided by the flange braces and purlins, is considered as point bracing. The required torsional bracing strength, M_{Tbro}, and the required torsional bracing stiffness, β_{Tbro}, for the case without lateral bracing are given as follows:

$$M_{Tbro} = 0.02 M_r \tag{3}$$

$$\beta_{Tbro} = \frac{\beta_T}{\left(1 - \frac{\beta_T}{\beta_{sec}}\right)} \tag{4}$$

where

$$\beta_T = \frac{1}{\phi}\frac{2.4L}{nEI_{yeff}}\left(\frac{M_r}{C_b}\right)^2 \tag{5}$$

$\beta_{sec} =$ infinity for a cross-frame like the flange brace-purlin assembly

E = modulus of elasticity of steel = 29,000 ksi

I_{yeff} = effective out-of-plane moment of inertia = $I_{yc} + (t/c)I_{yt}$

I_{yc} = moment of inertia of the compression flange about the y-axis
I_{yt} = moment of inertia of the tension flange about the y-axis
L = length of span
C_b = lateral-torsional buckling modification factor
c = distance from the neutral axis to the extreme compressive fibers
n = number of braced points within the span
t = distance from the neutral axis to the extreme tensile fibers
β_T = overall brace system required stiffness
β_{sec} = web distortional stiffness, including the effect of web transverse stiffeners, if any

AISC 360-16 states that lateral bracing, torsional bracing, or a combination of the two shall be provided to prevent the relative displacement of the top and bottom flanges (i.e., to prevent twist). Lateral bracing should be attached at or near the beam compression flange to restrain its lateral movement when buckled, meaning that the lateral bracing provided by the SSR can be considered as lateral bracing for positive bending moment (top flange in compression). Since lateral bracing and torsional bracing are provided by the SSR system and flange brace separately, AISC allows combined lateral bracing and torsional bracing using the following interaction equation given in AISC 360-16, Section 6.3 Commentary:

$$\frac{\beta_{Tbr}}{\beta_{Tbro}} + \frac{\beta_{Lbr}}{\beta_{Lbro}} \geq 1.0 \tag{6}$$

where β_{Tbr} and β_{Lbr} are the provided torsional and lateral bracing stiffness, respectively.

For negative bending moment (bottom flange in compression), lateral force from the bottom flange of the buckled rafter is transferred through the flange brace to the purlin. In this case, the flange brace plays two roles: a load path to transfer lateral load from the bottom flange to the SSR for lateral bracing, and a component of a triangular assembly that supplies torsional bracing to the rafter. AISC 360-16, Section 6.3 Commentary states that when point torsional bracing is combined with lateral bracing at the tension flange, Eq. (6) applies and, in addition, the torsional brace stiffness should satisfy the following:

$$\beta_{Tbr} \geq min\left(\beta_{Lbro} h_o^2, \beta_{Tbro}\right) \tag{7}$$

To examine the requirement for rafter bracing, it is necessary to obtain the bracing strength and stiffness provided by the purlins, SSR panels, and rafter flange braces. It was observed from the recent testing program (Wei et al. 2020) that for the specimens tested the initial stiffness of the SSR system was dominated by clip bending deformations and that the strength of the SSR system was governed by clip failure or pullout from the seam. Therefore, it is expected that the strength and stiffness of the SSR system for lateral bracing will scale proportionally with the number of clips on the purlin. The lateral bracing strength, P_{Lbr}, and the stiffness, β_{Lbr}, provided by the SSR can be obtained as follows:

$$P_{Lbr} = n_c f_c \tag{8}$$

$$\beta_{Lbr} = n_c k_c \tag{9}$$

where n_c is the number of SSR clips on one purlin over a length that is half the distance from the braced rafter to adjacent rafters on both sides (which is assumed to be the tributary width of SSR system used to brace the rafter), f_c and k_c are the strength and stiffness per clip, respectively, obtained from the test results of the specimen whose configuration (i.e. SSR panel profile and panel width, clip type and clip standoff, and use of thermal blocks and blanket insulation, etc.) is the closest match to the building's SSR configuration. See Wei et al (2020) for values of strength and stiffness per clip for eleven specific SSR configurations.

To obtain the torsional bracing strength and stiffness, the assembly of the purlin, rafter and flange brace can be analyzed using a truss analogy as shown in Fig. 6. The inflection points in the purlin are assumed to be located at midspan and the rafter is assumed to be axially rigid. For an applied moment at the top of the rafter, M, the moment and axial force diagram of the structure is shown in Fig. 7. It is noted that this model assumes a flange brace on one side, but a similar approach could be followed to determine bracing stiffness for flange braces on both sides of the rafter.

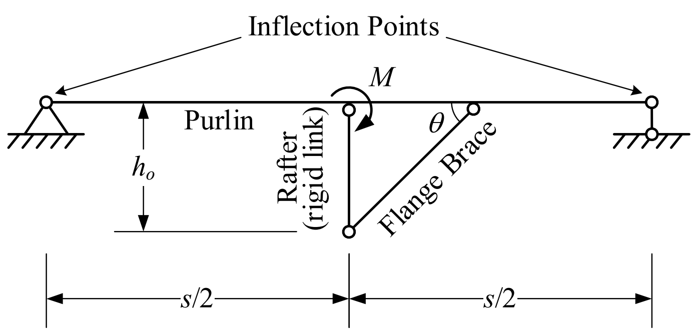

Figure 6: Assembly for analyzing torsional bracing strength and stiffness of rafter provided by flange brace and purlin

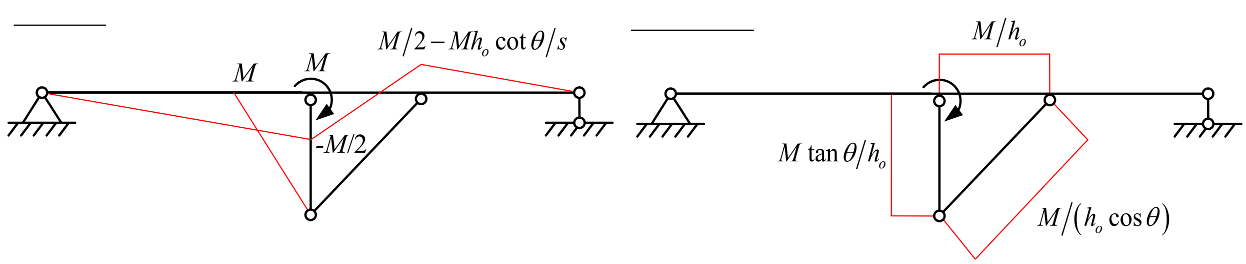

Figure 7: Moment and axial force diagram of the assembly subjected to concentrated moment at the top of rafter

The strength of the torsional bracing provided by the flange brace and the purlin, i.e., the maximum moment that can be applied, is reached when the limit state of any component occurs. The torsional bracing strength can therefore be obtained by setting the maximum moment acting on the purlin equal to its flexural strength and by setting the maximum axial force experienced by the purlin and flange brace equal to their compressive strength (note that the applied moment can be reversed, and that the compressive strength is typically smaller than the tensile strength), which is also limited by the connections of the flange brace to the rafter and purlin, and is given by:

$$M_{Tbr} = \min\left(2M_{a,p}, P_{n,p}h_o, P_{n,b}h_o\cos\theta, V_{n,bolt}h_o\cos\theta\right) \quad (10)$$

where $M_{a,p}$ is the available flexural strength of the purlin to resist rafter bracing loads (after consideration of gravity and wind loads), $P_{n,p}$ is the compressive strength of the purlin between the points of rafter and flange brace attachments, $P_{n,b}$ is the compressive strength of the flange brace, and $V_{n,bolt}$ is the nominal shear strength of the bolted connections (due to bolt shear, bearing, and tear-out) at the ends of flange brace. Dimension h_o and angle θ are shown in Fig. 6.

The torsional bracing stiffness is found for the configuration shown in Fig. 6 by determining the rafter twist, ϕ, associated with an arbitrary applied moment, M. Using the principle of virtual work, the rotation of the rafter section when subjected to an applied moment, M, is obtained as follows:

$$\phi = \frac{M}{EI_p}\left(\frac{s}{12} + \frac{h_o^2}{3s\tan^2\theta} - \frac{h_o}{6\tan\theta}\right) + \frac{M}{EA_p h_o \tan\theta} + \frac{M}{EA_b h_o \cos^2\theta \sin\theta} \qquad (11)$$

where I_p is the moment of inertia of the purlin, A_p is the cross-section are of the purlin, A_b is the cross-section area of the flange brace, s is shown in Fig. 6, and E is the modulus of elasticity.

Therefore, the torsional bracing stiffness provided by the flange brace and the purlin is given by:

$$\beta_{Tbr} = \frac{M}{\phi} = \frac{E}{\frac{1}{I_p}\left(\frac{s}{12} + \frac{h_o^2}{3s\tan^2\theta} - \frac{h_o}{6\tan\theta}\right) + \frac{1}{A_p h_o \tan\theta} + \frac{1}{A_b h_o \cos^2\theta \sin\theta}} \qquad (12)$$

Eq. (12) provides a theoretical estimate of the torsional bracing stiffness based on the flange brace configuration shown in Fig. 6. It is noted that this equation is based on an idealized configuration and does not consider double flange braces or some sources of flexibility (e.g. connection flexibility). However, a similar procedure could be followed to obtain the torsional bracing stiffness for two-sided flange bracing systems or systems with additional sources of flexibility.

To summarize, checking the adequacy of the rafter lateral bracing can be conducted in two steps as follows:

1. Check the lateral bracing initial stiffness. Calculate the required lateral bracing stiffness, β_{Lbro}, and required torsional bracing stiffnes, β_{Tbro}, using Eq. (2) and Eq. (4), respectively. Calculate the provided lateral bracing stiffness, β_{Lbr}, and provided torsional bracing stiffness, β_{Tbr}, using Eq. (9), and Eq. (12) (or equivalent approach), respectively. Substitute these four values into Eq. (6), and the resulting interaction inequality needs to be satisfied. For negative bending, Eq. (7) also needs to be satisfied.

2. Check the lateral bracing strength. Calculate the required lateral bracing strength, P_{Lbro}, and required torsional bracing strength, M_{Tbro}, using Eq. (1) and Eq. (3), respectively. Calculate the provided lateral bracing strength, P_{Lbr}, and provided torsional bracing strength, M_{Tbr}, using Eq. (8), and Eq. (10), respectively. One of the following two inequalities needs to be satisfied: $P_{Lbr} > P_{Lbro}$ or $M_{Tbr} > M_{Tbro}$.

3. Case Study

A prototype metal building designed by MBMA (NBM 2018) located in Orlando, Florida is selected to calculate typical values of required strength and stiffness for rafter bracing. Fig. 8 shows the roof framing details of the prototype metal building. Rafter dimensions are: flange width $b_f = 6$ in., thickness $t_f = 0.25$ in., web depth $h = 25$ in., and web thickness $t_w = 0.1345$ in. Rod brace spacing is 20 ft and purlin spacing is 5 ft. The SSR system has a configuration similar to a tested specimen in Wei et al. (2020) whose strength and stiffness per clip are given by $f_c = 0.792$ kip and $k_c = 0.152$ kip/in. The moment of inertia of the purlins $I_p = 10.15$ in.^{4}. Bracing requirements for the rafter segment between grid lines 2-3 and E-G is evaluated in this section. It should be noted that this example only provides the check for the particular rafter segment of interest and positive moment is assumed. In practice, it would be necessary to check each bracing span individually considering all the stability requirements. Also, this example uses LRFD, but a similar procedure could be used with ASD.

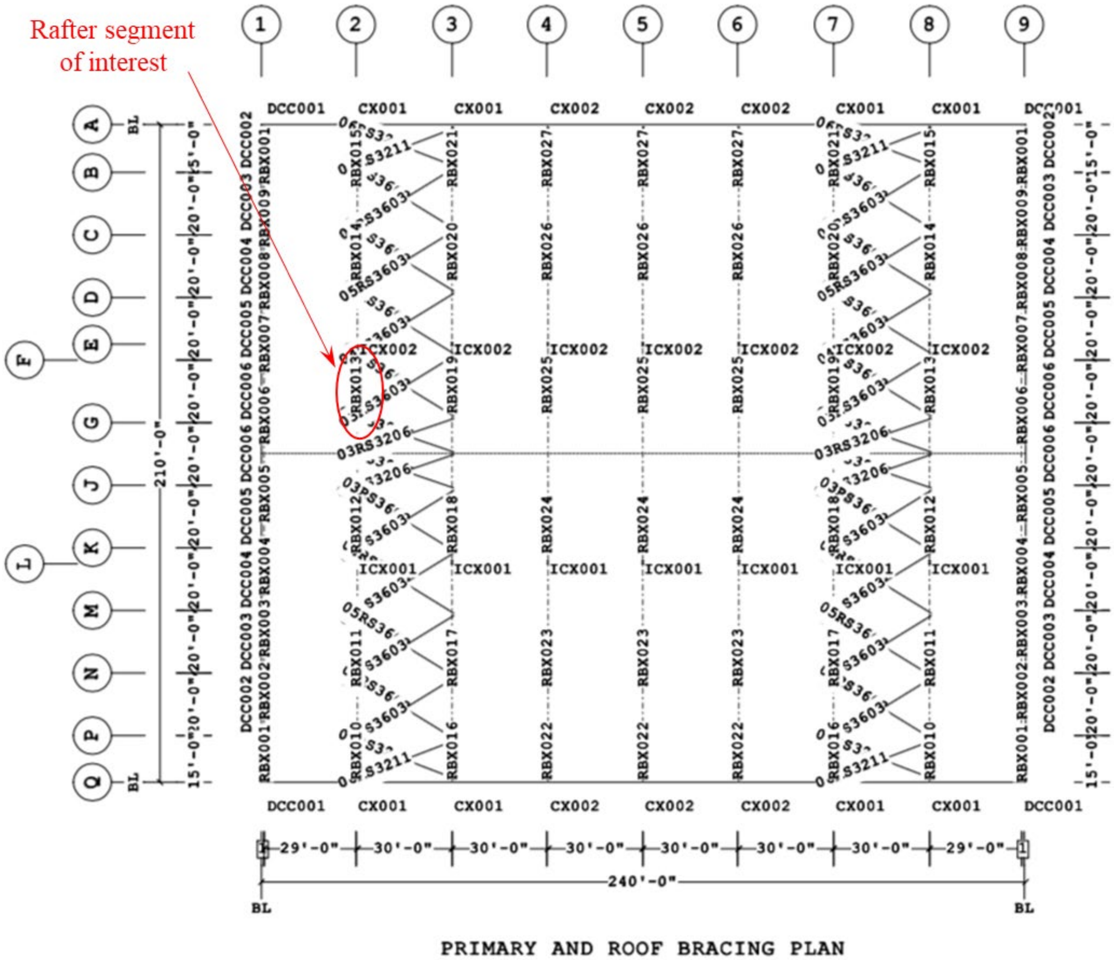

Figure 8: Plan view of roof framing detail of prototype metal building [from NBM (2018)]

Assuming that the middle portion of the rafter is buckling between the points where the diagonal rod bracing attach to the rafter (i.e. identified as "rafter segment of interest" in Fig. 8), the unbraced length for rafter lateral bracing is the spacing of purlins, $L_{br} = 5$ ft. This is consistent with the definition of L_{br} for point bracing in AISC 360-16 Section 6.1 commentary. It is noted that in the testing program the test setup used a span equal to 20 ft (corresponding to L_{br} = 10 ft), but because the initial stiffness of the specimens was dominated by clip deformation and not SSR panel deformations, the initial stiffness is expected to be similar if the span were half as long.

It is assumed that the moment demand is $M_r = M_y = 2818$ kip-in for the rafter with compression at the top flange. With C_d = 1.0, and h_o = 25.25 in., the required strength of rafter lateral bracing is given by:

$$P_{Lbro} = 0.02\left(\frac{M_r C_d}{h_o}\right) = 0.02\left(\frac{(2818 \text{ kip-in.})(1.0)}{25.25 \text{ in.}}\right) = 2.2 \text{ kip} \tag{13}$$

The required stiffness of rafter lateral bracing is given by:

$$\beta_{Lbro} = \frac{1}{\phi}\left(\frac{10 M_r C_d}{L_{br} h_o}\right) = \frac{1}{0.75}\left(\frac{10(2818 \text{ kip-in.})(1.0)}{(5 \text{ ft})(12 \text{ in./ft})(25.25 \text{ in.})}\right) = 24.8 \text{ kip/in.} \tag{14}$$

The required flexural strength of rafter torsional bracing is given by:

$$M_{Tbro} = 0.02 M_r = 0.02(2818 \text{ kip-in.}) = 56.4 \text{ kip-in.} \tag{15}$$

For the selected rafter segment, values of the following quantities can be obtained: $I_{yeff} = I_y = 9$ in.^{4} for doubly symmetric section, L = 20 ft, n = 3. A uniform moment is assumed with C_b = 1.0 which leads to β_T = 7790 kip-in. The flange brace and purlin can be considered as a cross frame and therefore the stiffness of the rafter web does not reduce the torsional bracing stiffness, i.e. β_{sec} = infinity. Therefore,

$$\beta_{Tbro} = \beta_T = 7790 \text{ kip-in./rad} \tag{16}$$

As is shown in Fig. 8, the spacing of rafters is 30 ft. The spacing of the clips on the purlins is equal to the panel width (24 in.), and thus there are n_c = (30 ft)(12 ft/in.)/(24 in.) = 15 clips on each purlin within one rafter spacing. Using the values for f_c and k_c from the test results, the lateral bracing strength and stiffness provided by the SSR is given by:

$$P_{Lbr} = n_c f_c = (15)(0.792 \text{ kip}) = 11.9 \text{ kip} \tag{17}$$

$$\beta_{Lbr} = n_c k_c = (15)(0.152 \text{ kip/in.}) = 2.28 \text{ kip/in.} \tag{18}$$

Assume that the flange brace is at an angle of $\theta = 45°$ and the flange brace consists of an L2×2×1/8. From the AISC Steel Construction Manual (AISC 2016b) and the AISI Cold-Formed Steel Design Manual (AISI 2017) the following are obtained: $M_{n,p}$ = 124 kip-in., $P_{n,p}$ = 57.8 kip, $P_{n,b}$ = 10.7 kip, where $M_{n,p}$ is the nominal flexural strength of the purlin. For this example, the flexural strength of the purlin available to resist rafter bracing loads after consideration of gravity and wind loads is given as, $M_{a,p}$ = 37.2 kip-in (calculations not shown here). It is also assumed that limit states associated with the bolted connections on the two ends of flange brace do not control (which may not be typical). Therefore,

$$M_{Tbr} = \min\left(2M_{a,p}, P_{n,p}h_o, P_{n,b}h_o\cos\theta\right)$$
$$= \min\left[2\left(37.2\text{ kip-in.}\right),\left(57.8\text{ kip}\right)\left(25.25\text{ in.}\right),\left(10.7\text{ kip}\right)\left(25.25\text{ in.}\right)\left(\cos 45^\circ\right)\right] \quad (19)$$
$$= 74.4\text{ kip-in.}$$

The torsional bracing stiffness provided by the flange brace and the purlin is given by:

$$\beta_{Tbr} = \frac{E}{\dfrac{1}{I_p}\left(\dfrac{s}{12}+\dfrac{h_o^2}{3s\tan^2\theta}-\dfrac{h_o}{6\tan\theta}\right)+\dfrac{1}{A_p h_o\tan\theta}+\dfrac{1}{A_b h_o\cos^2\theta\sin\theta}}$$

$$= 29000\text{ ksi}\Bigg/\left[\frac{1}{10.15\text{ in.}^4}\left(\frac{360\text{ in.}}{12}+\frac{\left(25.25\text{ in.}\right)^2}{3\left(360\text{ in.}\right)\left(\tan^2 45^\circ\right)}-\frac{25.25\text{ in.}}{6\left(\tan 45^\circ\right)}\right) + \frac{1}{\left(1.05\text{ in.}^2\right)\left(25.25\text{ in.}\right)\left(\tan 45^\circ\right)}+\frac{1}{\left(0.491\text{ in.}^2\right)\left(25.25\text{ in.}\right)\left(\cos^2 45^\circ\right)\left(\sin 45^\circ\right)}\right]$$

$$= 10122\text{ kip-in./rad}$$

(20)

Check the adequacy of the rafter bracing:

1. Check the rafter bracing stiffness. The requirement is given as follows:
   $$\frac{\beta_{Tbr}}{\beta_{Tbro}}+\frac{\beta_{Lbr}}{\beta_{Lbro}} > 1.0$$
   $$\frac{10122\text{ kip-in./rad}}{7790\text{ kip-in./rad}}+\frac{2.3\text{ kip/in.}}{24.8\text{ kip/in.}} = 1.39$$
   $1.39 > 1.0$ OK
   Since this portion of the rafter is subjected to positive bending, the additional check on torsional bracing stiffness associated with negative bending is not required.

2. Check the rafter bracing strength. The requirement is that one of the following two inequalities must be satisfied:
   $P_{Lbr} \geq P_{Lbro}$
   $11.9\text{ kip} \geq 2.2\text{ kip}$ OK
   $M_{Tbr} \geq M_{Tbro}$
   $74.4\text{ kip-in.} \geq 56.4\text{ kip-in.}$ OK

The provided rafter bracing is therefore adequate.

It should be noted that this example only provides the check of bracing requirements for the rafter segment of interest. In practice, it would be necessary to check each bracing span individually.

4. Conclusions

In this paper, an approach for evaluating lateral bracing requirements of a rafter considering both the flange braces and standing seam roof (SSR) lateral bracing was identified based on AISC 360-16. The requirement for rafter lateral bracing can be satisfied by a combination of torsional bracing provided by rafter flange bracing and lateral bracing from the SSR system. If SSR panels are present on the roof, which is typical in metal buildings, considering the SSR panels may allow the frequency or size of the flange braces to be reduced. In some cases, it may even be possible to eliminate flange braces in the positive moment regions of the rafter if the SSR roof provides enough lateral bracing stiffness and strength.

It is noted that the lateral bracing strength and stiffness provided by the SSR system is based on the results of the experimental testing program which did not include vertical loads associated with gravity loads or wind loads. However, gravity loads and wind loads may affect the lateral bracing stiffness and strength associated with each clip. The interaction between vertical loads and lateral bracing loads deserves further study.

It is recommended that more experimental tests be conducted to further characterize the effect of different parameters, such as panel type and clip configuration, on the in-plane strength and stiffness of SSR systems. The experimental program that has been conducted examined a limited number of specific SSR assemblies, but does not give sufficient information about the many SSR combinations that are possible. Further work is required to produce generalized tables of stiffness and strength that are applicable to a broad range of SSR assemblies. Since the in-plane stiffness of SSR systems has been shown in the current tests to be governed almost exclusively by clip deformations and the strength of the system is associated with clip failure or clip pull-out, it may be possible to conduct (or leverage existing data from) small-scale tests on individual clips to characterize system stiffness and strength. Furthermore, the effect of gravity and uplift loads on the ability of the clips to resist lateral bracing loads requires further investigation. Lastly, a study is warranted on the purlin and flange brace assembly to investigate the effects of far-side and near-side flange braces for rafters, the angle of the flange braces, lapped purlins over the rafter, and the effect of gravity/uplift loads on the overall strength and stiffness of the assembly.

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