Closure:

Design for Local Member Shear at Brace and Diagonal-Member Connections: Full-Height and Chevron Gussets

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INTRODUCTION

The authors would like to thank Dr. Richards for the work he has performed and the light that work has shed on the behavior of these connections. Dr. Richards' analyses inform the understanding of the forces and displacements corresponding to the progression from elastic behavior, to the design limit state, and to the complete shear-yielding mechanism. Additionally, the analyses also explore the inelastic behavior of the beam after the web-yield mechanism is developed, shedding light on the possible behavior of conditions in which the local web shear was not considered in design.

Both the original paper (Sabelli and Saxey, 2021) and the closure (Richards, 2023) address the "concentrated stress method" (CSM) for design of chevron connections (center beam-brace connections in V-braced, inverted-V-braced, and two-story, X-braced frames). The CSM builds on the work of Fortney and Thornton (2015 and 2017) and Hadad and Fortney (2020). The CSM was developed specifically as an alternative to the "uniform stress method" (USM), the term Sabelli and Saxey apply to the Fortney-Thornton model for clarity. Both the USM and CSM are methods of determining local shear demand corresponding to the application of a moment at the member flange; this moment is the result of the brace forces and the eccentricity of the flange from the work point. Similar to panel-zone shear, the force couple delivering this moment creates a shear corresponding to the moment and the moment arm. The USM uses a set moment arm based on the gusset-plate plastic section modulus across a horizontal section at the beam flange, which results in the design strength being limited by the onset of beam shear yielding at the midpoint of the connection region. By contrast, the CSM allows the beam shear yielding to progress outward from the beam midpoint along the connection length such that the stresses at the gusset-flange interface corresponding to the moment are redistributed, concentrating at each end. In the CSM, the design strength is defined by a combination limit state: shear yielding of the beam over the majority of the connection length and inelastic action (gusset yielding, web local yielding, or web crippling) in the remaining regions at each end. The length of those end zones is the minimum required such that a force equal to the beam shear strength can be transferred without exceeding any of the three limit states (gusset yielding, web local yielding, or web crippling). By minimizing the length required to deliver the force couple, the moment arm is increased, and thus, the required shear strength of the beam is reduced for a given set of brace forces, permitting designers to reduce or eliminate the calculated need for web reinforcement.

In practice the CSM has been used to demonstrate that beams in typical V-braced or inverted-V-braced frames generally do not require reinforcement and that beams in two-story, X-braced frames may require modest adjustment to gusset length to avoid the calculated need for reinforcement. While chevron gussets are an important case for application of the method, the CSM is applicable to other cases in which a gusset or bracket is utilized to deliver a moment to the strong axis of a W-shape.

We are encouraged that Dr. Richards' work appears to confirm that the CSM is reliable for the chevron connections studied and that the CSM does not appear to be excessively conservative. As such, it can be considered as a piece with our work in the effort to provide economy as well as reliability for the design of these connections. Additionally, his work provides sufficient basis to refine the model of stress distribution at the gusset-flange interface in order to simplify some of the equations presented in our paper.

This closure explores the implications of adopting a stress distribution inferred from Dr. Richards' discussion

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and other implications of the work on design of these connections and discusses the implications of his findings for design of chevron connections.

RICHARDS' FINITE ELEMENT ANALYSIS EXAMINATION OF DESIGN EXAMPLE

Dr. Richards analyzed a finite element model (FEM) based on the design example from the original paper, comparing the horizontal force in the lower gusset used in the design example to the value at different stages of the FEM analysis. Direct comparison of analysis to design may be complicated by numerous factors, including the differences between design strength and expected strength. In this case, however, the FEM utilized the specified yield strength rather than expected yield strength and included only 1% strain hardening. The FEM was also configured such that the proportion of story shears (the sum of the horizontal components of the braces) between the levels above and below the chevron connection closely match those used in our design example. Additionally, in the case of the CSM, the behavior is defined by shear yielding of the beam, for which a resistance factor of 1.0 is used. Thus, the forces in the FEM analysis can be compared to those in the design example.

The FEM analysis shows that the CSM has a reasonable level of conservatism. Dr. Richards identifies the formation of the mechanism as corresponding to 815 kips of lateral force 4% over the corresponding value in the design example (782 kips).

Although not presented directly in our paper or noted in Richards' discussion, the lateral force corresponding to the USM indicating shear yield is 456 kips, 74% of the force at which the FEM shows von Mises stress exceeding 50 ksi in a localized region of the beam web (616 kips). This indicates that engineers wishing to avoid any yielding in the connection region under design loads may utilize the USM conservatively, with significant margin.

STRESS DISTRIBUTION INFERRED FROM FINITE ELEMENT ANALYSIS

While Dr. Richards' finite element analyses generally validate the CSM design method, the stress distributions apparent in his analyses differ slightly from that assumed in the original paper [Figure 15 in Sabelli and Saxey (2021)]. Dr. Richards observes that the shear between the gusset and the flange appears essentially to be confined to the center region of the gusset, shear stresses in the end regions being low and in the opposite direction (Figure 8 in the Richards discussion). That is, the shear appears to be transferred between the regions we identified as the "z" regions (the end regions of the gusset that transfer moment by means of a force couple), and it appears that the force transferred between the gusset and beam in the z regions essentially corresponds to normal stress. The CSM as presented in Sabelli and Saxey (2021), by contrast, assumes the shear is uniform along the entire gusset length. It is worth noting that the z regions posited in the CSM are evident in the Richards analyses (Figure 9 of the Richards discussion). While it is not possible to determine a precise length of these regions from the FEM analysis, the larger-than-design lateral forces resisted suggest that an effective moment arm larger than assumed in design, and thus that the stresses are more concentrated.

Based on these observations, the CSM stress distribution can be adjusted to simplify the design method. Figure 1 shows the stress distribution assumed in our paper (CSM1, adapted from Figure 15 in Sabelli and Saxey) alongside a modified stress distribution inferred from Figure 8 in the Richards discussion (CSM2). The subscript "1" indicates that the quantities are with respect to gusset 1, the lower gusset. (Sabelli and Saxey present a method of apportioning the available beam shear strength in two-story, X-braced frames such that each gusset can be designed independently.) The figure shows forces $F_{1,1}$ and $F_{1,2}$ acting on gusset 1; the gusset length (L_{g1}) and z region lengths (z_1) are also shown. The difference in the z region lengths between CSM1 and CSM2 is exaggerated for clarity.

The CSM2 stress distribution suggests refinement of certain aspects of the design method developed using the CSM1. Nevertheless, either stress distribution, CSM1 or CSM2, may be employed in the CSM method, with only modest differences in the calculated design strength.

Using the CSM2 model, the minimum length of the z region (based on the limit state of gusset yielding) is the length required to deliver a normal force equal to the effective beam shear strength:

$$z_1 \geq \frac{V_{ef1}}{\phi_t F_y t_{g1}} \tag{1}$$

where

F_y = specified minimum yield stress, ksi (MPa)

V_{ef1} = effective member shear strength, kips (N)

t_{g1} = gusset thickness, in. (mm)

z_1 = length of concentrated stress region at ends of gusset, in. (mm)

ϕ_t = resistance factor for tension (0.90)

The equations in Sabelli and Saxey (2021) that are different for CSM2 from the original equation using CSM1 are presented in an Appendix to this closure.

CSM2 STRESS DISTRIBUTION: EXAMINATION OF DESIGN EXAMPLE

To assess the implications of the refinements suggested by Dr. Richards' work, the modified equations in this discussion based on the CSM2 model are applied to the design example. [The reader is referred to the original paper (Sabelli and Saxey, 2021) for a complete description of the condition and for determination of values shown.] Values are compared to those in Sabelli and Saxey (2021), which were determined using the CSM1 model. Whereas the CSM in Sabelli and Saxey is presented as a design method that can be used to establish the required gusset length and thickness, in this closure, those quantities are given. For comparison to the FEM analysis, equations are developed to determine the lateral force that, given the gusset length and thickness present, results in shear yielding of the beam.

The minimum length of the z region is:

$$z_1 \geq \frac{V_{ef}}{\phi_t F_y t_g} \tag{1}$$

$$= \frac{196 \text{ kips}}{(0.90)(50 \text{ ksi})(0.75 \text{ in.})}$$

$$= 5.81 \text{ in.}$$

A value of 7.31 in. was calculated using the CSM1 model in Sabelli and Saxey. In both cases, this value governs over those corresponding to local web yielding (Equation 40 in Sabelli and Saxey) and local web crippling (Equation 42 in Sabelli and Saxey).

This length z_1 can be used to establish the moment arm for the flexural force couple, and thus the maximum moment that the gusset can deliver corresponding to gusset yielding in the z regions and beam shear yielding in the remainder of the connection length. Equation 26 in Sabelli and Saxey gives the required beam shear strength corresponding to a given moment at the gusset interface; here that equation is adapted to solve for the interface moment:

$$M_{f1} = V_{ef}\left(L_{g1} - z_1\right)$$

$$= (196 \text{ kips})\left[(56 \text{ in.}) - (5.81 \text{ in.})\right]$$

$$= 9{,}840 \text{ kip-in.}$$

where

L_{g1} = gusset length, in. (mm)

M_{f1} = moment at gusset-to-flange-interface due to brace forces, kip-in. (N-mm)

The lateral force corresponding to this moment is determined using the eccentricity of the gusset-to-flange interface to the beam centerline, adapting Equation 7 in Sabelli and Saxey (with the total moment on the gusset interface in the case of chevron beams being M_{f1}):

$$M_{f1} = \frac{F_{V1} d_m}{2} \tag{2}$$

where

F_{V1} = gusset shear component parallel to member axis at interface with flange, kips (N)

d_m = member depth, in. (mm)

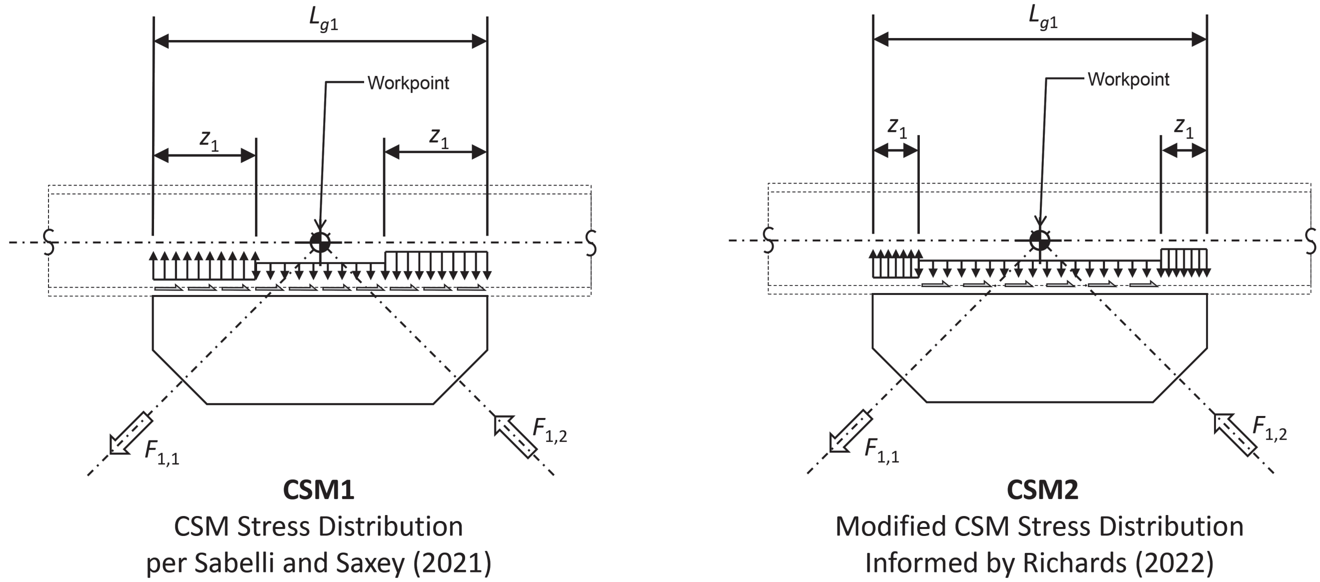

Fig. 1. CSM1 and CSM2 stress distributions.

Thus

$$
\begin{aligned}
F_{V1} &= \frac{2M_{f1}}{d_m} \\
&= \frac{2(9{,}840 \text{ kip-in.})}{24.3 \text{ in.}} \\
&= 810 \text{ kips}
\end{aligned}
$$

The corresponding value using CSM1 is 782 kips. The CSM2 value is closer to the mechanism-formation value identified by Dr. Richards, with only 1% conservatism rather than 4% using CSM1. Recognizing that the determination of the condition that represents the limit state is somewhat arbitrary, the CSM2 does not represent a significant increase in accuracy in the connection design strength. The modified equation for z-region length (Equation 1), however, is simpler than the original method and provides for a better understanding of the local behavior.

For completeness, the gusset should be checked for both the combined shear and normal forces in the center region between z regions, and for the combined normal, shear, and flexural forces on a critical section (Figure 19 in Sabelli and Saxey). For brevity, these calculations are not presented here. However, the authors note that, in both cases, the demand-to-capacity ratios calculated using CSM2 are slightly lower than those determined using CSM1.

APPLICATION

Dr. Richards' FEM analyses specifically address the behavior of chevron connections in which the local beam shear may exceed the beam shear capacity. Previous work suggests that, if the CSM is used, this condition is largely confined to beams in two-story, X-braced frames. Due to design for axial forces, beams in V-braced and inverted-V-braced frames with typical gusset lengths generally have sufficient shear capacity for shear demand calculated using the CSM. (If the USM is used, it is more likely that beams in such frames will be determined to have insufficient shear capacity.) The FEM analyses specifically examine the behavior of conditions limited by gusset yielding in the z regions. The behavior of conditions limited by web local yielding or web crippling may differ for beam deformations beyond those corresponding to CSM limit state.

Dr. Richards' findings, and the implications for refining the stress distribution model, appear to be applicable across the entire range of the CSM. That is, the authors believe the CSM2 model can be used to determine the design strength for other cases in which a gusset or bracket delivers a moment to the strong axis of a W-shape.

CONCLUSIONS

Dr. Richards' work appears to validate the use of the CSM for establishing the adequacy of chevron connections. Additionally, the analyses inform a refined stress-distribution model that can be used to simplify equations for the design of these connections.

APPENDIX: REVISED CSM DESIGN EQUATIONS BASED ON CSM2 STRESS DISTRIBUTION

To aid the designer employing the CSM, Table A.1 provides the CSM equations that can be modified based on the CSM2 stress distribution shown in Figure 1. Table A.1 shows the original equation (based on the CSM1 model), the revised equation (based on the CSM2 model), and the reference equation number from Sabelli and Saxey (2021). Refer to Sabelli and Saxey for the definition of symbols.

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Table A.1. Modified Equations Utilizing CSM2 Stress Distribution			
Quantity	**Equation Number**	**Original Equation (Based on the CSM1 Model)**	**Modified Equation (Based on the CSM2 Model)**
Minimum gusset thickness based on stress in *z* region	35	$t_{g1} \geq \sqrt{\left(\frac{F_{V1}}{\phi_v 0.6 F_y L_{g1}}\right)^2 + \left(\frac{R_{z1}}{\phi_t F_y (L_{g1} - e_{z1})}\right)^2}$	$t_{g1} \geq \frac{R_{z1}}{\phi_t F_y (L_{g1} - e_{z1})}$
	36	$t_{g1} \geq \sqrt{\left(\frac{F_{V1}}{\phi_v 0.6 F_y L_{g1}}\right)^2 + \left[\frac{R_{z1}}{\phi_t F_y \left(L_{g1} - \frac{M_{f1}}{R_{z1}}\right)}\right]^2}$	$t_{g1} \geq \frac{R_{z1}}{\phi_t F_y \left(L_{g1} - \frac{M_{f1}}{R_{z1}}\right)}$
Minimum gusset thickness based on stress in center region	37	$t_{g1} \geq \sqrt{\left(\frac{F_{V1}}{\phi_v 0.6 F_y L_{g1}}\right)^2 + \left(\frac{F_{N1}}{\phi_t F_y (L_{g1} - 2z_1)}\right)^2}$	$t_{g1} \geq \frac{\sqrt{\left(\frac{F_{V1}}{\phi_v 0.6}\right)^2 + \left(\frac{F_{N1}}{\phi_t}\right)^2}}{F_y (L_{g1} - 2z_1)}$
	38	$t_{g1} \geq \sqrt{\left(\frac{F_{V1}}{\phi_v 0.6 F_y L_{g1}}\right)^2 + \left[\frac{F_{N1}}{\phi_t F_y \left(\frac{2M_{f1}}{R_{z1}} - L_{g1}\right)}\right]^2}$	$t_{g1} \geq \frac{\sqrt{\left(\frac{F_{V1}}{\phi_v 0.6}\right)^2 + \left(\frac{F_{N1}}{\phi_t}\right)^2}}{F_y \left(\frac{2M_{f1}}{R_{z1}} - L_{g1}\right)}$
Minimum gusset length based on stress in *z* region	39	$L_{g1} > \frac{M_{f1}}{V_{ef1}} + \frac{V_{ef1}}{t_{g1} \phi_t F_y}$ (approximate)	$L_{g1} \geq \frac{M_{f1}}{V_{ef1}} + \frac{V_{ef1}}{t_{g1} \phi_t F_y}$ (exact)
Minimum *z* region length based on stress in *z* region	41	$z_1 \geq \frac{L_{g1}}{2} - \sqrt{\frac{L_{g1}^2}{4} - \frac{M_{f1}/\phi_t}{\sqrt{(F_y t_g)^2 - \left(\frac{F_{V1}}{\phi_v 0.6 L_{g1}}\right)^2}}}$	$z_1 \geq \frac{L_{g1}}{2} - \sqrt{\frac{L_{g1}^2}{4} - \frac{M_{f1}}{\phi_t F_y t_g}}$
Maximum *z* region length based on stress in center region	45	$z_1 \leq \frac{1}{2}\left[L_{g1} - \frac{F_{N1}/\phi_t F_y t_{g1}}{\sqrt{1 - \left(\frac{F_{V1}}{\phi_v 0.6 F_y t_{g1} L_{g1}}\right)^2}}\right]$	$z_1 \leq \frac{L_{g1}}{2} - \frac{\sqrt{\left(\frac{F_{V1}}{\phi_v 0.6}\right)^2 + \left(\frac{F_{N1}}{\phi_t}\right)^2}}{2 F_y t_{g1}}$
Horizontal force in critical region	77	$F_{X crit} = \frac{X_{crit}}{L_g} F_V$	$F_{X crit} = \frac{X_{crit} - z}{L_g - 2z} F_V$