CLOSURE

Investigation on the Performance of a Mathematical Model to Analyze Concentrically Braced Frame Beams with V-Type Bracing Configurations

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ABSTRACT

The discussion-paper published by Roeder et al. (2021), hereafter referred to as the responders for clarity, disputes the results published by Hadad and Fortney (2020) and the chevron effect (CE) analysis method published by Fortney and Thornton (2015, 2017), based on the responders' earlier research results and their understanding of the behavior of chevron beams. This paper provides the reply to the disputed topics.

WEAK BEAM VERSUS STRONG BEAM MECHANISMS

According to the literature, there are two failure mechanisms in chevron-braced bays: (1) a weak beam mechanism in which the buckling of the compression brace causes an unbalanced force to be applied on the beam and subsequently the formation of plastic hinges in the beam and where weak beams lead to considerable plastification in columns, beams, and braces, irrespective of brace slenderness, and (2) a strong beam mechanism where buckling of the compression brace is followed by yielding of the tension brace, the beam being sufficiently strong to remain elastic despite the vertical unbalanced force applied to it by the braces at mid-span. Chevron-braced frames (CBFs) with strong beams and weak braces exhibit a more uniform distribution of yielding with height than frames with weak beams and strong braces.

The intention behind explaining the mentioned mechanisms in the paper was to show the importance of chevron beams in determining the behavior of V-bracing and X-bracing CBF. The paper does not consider any mechanism superior to the other one. Below is the exact statement from the paper:

"It is not evident from the data in the literature which collapse mechanism is preferable." (Hadad and Fortney, 2020; emphasis added)

Although the responders consider the weak beam mechanism superior to the other failure mechanism based on their earlier research (Sen et al., 2016), they can review the other literature (Shen et al., 2015) to see how the weak beam mechanism is challenged. D'Aniello et al. (2015) showed the importance of chevron beam strength and stiffness in determining the behavior of concentrically braced frames. Thus, it is necessary to understand the actual demand on chevron beams and design them accordingly before taking a side on the controversial discussion about the desirable behavior of chevron beams. Thus, the authors investigated the performance of the CE method in the paper.

THE CHEVRON EFFECT ANALYSIS METHOD

The chevron effect (CE) method provides simple, closed-form solutions for normal and shear forces in the beam at the gusset to beam interface. There was no available information on these forces on the beam section until the CE analysis method (Fortney and Thornton, 2015, 2017) was published. Designers require a method to design these connections for buildings in a reasonable time frame. The responders criticize the authors' approach but provide no alternate method. Figure 3 in the responders' paper (Roeder et al., 2021) showed a broken line in the chevron region, which is exactly that part of the beam where the CE method shows the actual shear force and bending moment distributions. What do the responders propose for this region? The responders should have calculated the beam shear force demand for the connections in the analyzed frame using the CE method. The question of whether a beam that is inadequate per the CE method nevertheless performs adequately

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seems obvious but is not addressed by the responders' analyses. If the beams, selected using other criteria, have sufficient strength per the CE method, their adequate performance can be interpreted as supporting the CE method.

The finite element studies of Hadad and Fortney (2020) were intended to verify the reasonable accuracy of the simple closed-form solutions of the original two papers. That goal was achieved. The results of the paper showed the chevron effect can be reasonably analyzed with simple closed-form equations without the use of finite element analysis. With the addition of AISC *Seismic Provisions* Section F2.6c.4 (AISC, 2016), even a seismic special concentrically braced frame (SCBF) design will likely be adequate.

It is worth noting that in buildings with composite floor systems, very little axial force will be carried to the beam-to-column connections. That is the reason Fortney and Thornton (2015, 2017) focused on estimating the shear force and bending moment distribution in chevron beams. The responders' considered the results of a bare 2D frame model to show the importance of axial load in chevron beams. The responders' test model is probably not representative of actual design conditions.

Figure 3 in the responders' paper showed a beam with axial forces. These can be handled by the CE method because it looks at the whole beam, including the chevron zone. The design shears and moments in the chevron region may be bigger than the design values shown in Figure 3.

Additionally, the responders' design relies on the fixity of the beam-to-column connection. This fixity induces shear in the beam that counteracts the chevron effect in the elastic range of drift. For elastic systems, the brace force direction (i.e., tension or compression) correlates with the drift direction such that both reverse in unison, and the offsetting of the beam-shear effects may be reliable. This correlation between brace force direction and drift direction likely holds for an SCBF. The large peak forces associated with the initial buckling strength of the brace in compression may occur only once, or once in each direction. For both of these peak-force conditions, the shear from the beam fixity reduces the chevron-effect shear force within the connection. However, for buckling-restrained braced frames, such correlation between drift direction and brace-force direction no longer holds after yielding of the braces. As such, the beam shear from the moment-frame behavior could be additive to the chevron shear. Recommendation to ignore the chevron effect generally and not limited to the specific configuration and system studied by the responders is irresponsible and could lead to unanticipated and potentially undesirable mechanisms in systems the responders have not considered or analyzed. The responders' failure to examine, or even consider, the statics of the connection results in their erroneous conclusion that the chevron does not exist because, in the case they studied, it is offset by another effect.

The authors do believe the CE method is not the ultimate method in the analysis of chevron configured brace frames, and thus, they appreciate and encourage the discussions on the CE analysis method and the efforts to further improve its accuracy. However, the inclusion of the chevron effect phenomenon, as confirmed by other researchers (Sabelli and Saxey, 2021), is a necessity to understand the shear force and bending moment demands on chevron beams. Until more accurate and convenient methods are available, the CE method is encouraged to be used in the analysis and design of new structures.

FINITE ELEMENT ANALYSES TO INVESTIGATE THE CHEVRON EFFECT METHOD

To evaluate the accuracy of the CE analysis method, the authors studied the shear force and bending moment distributions along the whole length of the beams in a group of beam-gusset assemblies through finite element analysis. The beam length in Figures 7 to 11 of the original paper is 300 in. as presented in Table 1 (Hadad and Fortney, 2020). The results published in the paper show:

- The existence of chevron effect and the success of the CE analysis method in identifying the phenomenon through its simple closed form solutions.
- The reasonable accuracy of the CE analysis method in estimating the beam shear force and bending moment in chevron beams, specifically in the beam-to-gusset plate connection region, while it requires no finite element analysis and a relatively small amount of time to be performed.

Because the paper investigated the performance of the CE analysis method that was introduced earlier (Fortney and Thornton, 2015, 2017), the same modeling approach was used in the finite element models (i.e., simply supported beams with gusset plate(s) in the middle carrying the brace loads).

The responders believe the chevron beams in braced frames should not be considered as simply supported beams due to the relative rigidity in the connection region. They also consider the gusset to be part of the beam increasing its strength. It could be helpful if the responders reported forces across section cuts at one or more chevron connections at the time of maximum shear force, such as shown in Figure 1. Such section cuts would reveal whether the shear force outside the connection region is offsetting the chevron shear, whether the moment on Section 1 is less than that determined based on brace axial forces (due to brace resisting moment), whether the gusset reinforces the web (as the proposed by the responders), or whether the distribution of shear force between the two is better described by the CE method.

Also, a reanalysis of the frame presented in the responders' paper without moment connections at the roof beam, perhaps with a beam that does not meet the required shear strength as determined using the CE method, could improve the discussion. The beam at the roof level in the responders' analyses appears to be a heavy beam with moment connections. Are such measures required in order for a design that does not consider the chevron effect to perform well?

Considering all the assumptions in the responders' analysis model, do the responders have a simple way of analyzing braced frames based on these considerations or have a complex finite element computer program is required? Until such time as a simple closed-form solution calculation method is available, the authors believe that the CE analysis method, as verified by the paper, is adequate to produce an acceptable design very quickly.

DUCTILITY FACTOR AND STRESS DISTRIBUTIONS IN THE BEAM-TO-GUSSET PLATE CONNECTION INTERFACE

The ductility factor is considered in the literature (Richard, 1986; Hewitt and Thornton, 2004) as one possible solution to accommodate the stress concentrations in the design of welds connecting gusset plates to beams. The authors decided to examine the value of this factor based on the results obtained from the chevron beam-gusset assemblies studied in the research (Hadad and Fortney, 2019, 2020). To do so, the authors compared the actual stress distribution at gusset-to-weld interface versus the average of the stress values. None of the stress values were calculated based on CE method. The results clearly showed the factor needs to be changed.

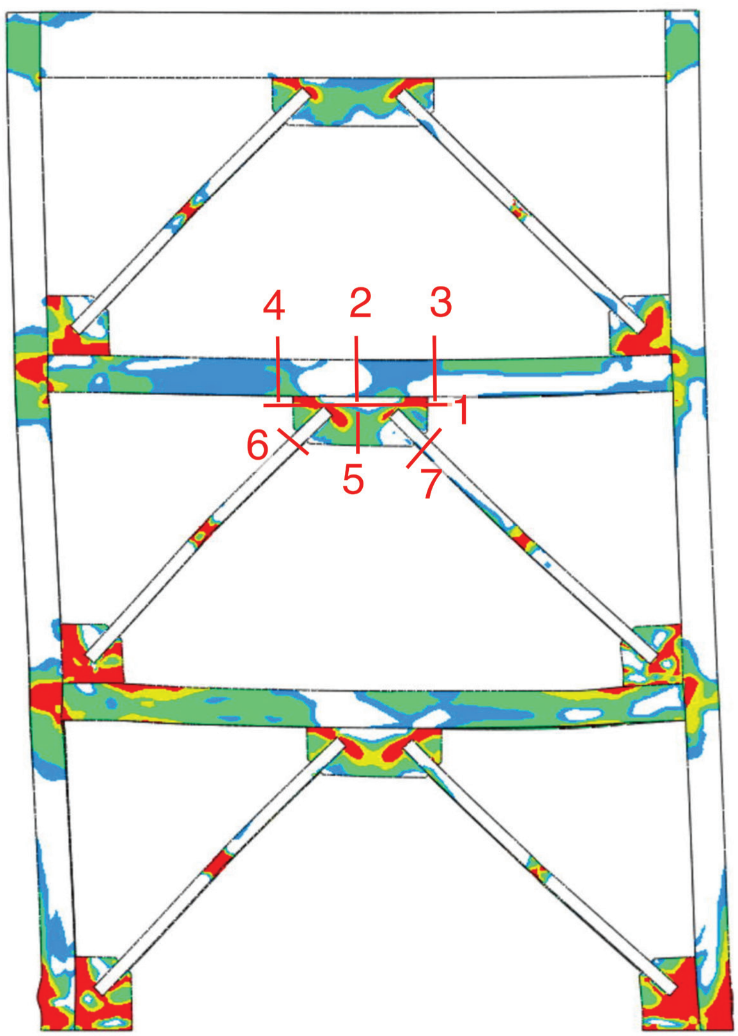

Fig. 1. Suggested sections that could be studied in the responders' model.

With respect to Figure 2 in the responders' discussion, it should be noted that this test was one of two tests that were identical except for the weld sizes. The weld sizes in the Figure 2 tests were sized for the gusset edge forces while the identical test had the weld increased by the AISC ductility factor of 1.25. In this second test the welds survived the fracture of the brace with no cracks. The requirement of AISC *Seismic Provisions* Section F2.6c.4 (AISC, 2016) is a direct result of the Figure 2 test, but did not explicitly involve a chevron gusset.

The solution suggested by the authors to use the gusset plate shear strength in designing the weld connecting the gusset plate to the chevron beam is obviously not the only possible solution. It is just a suggestion by the authors. Other researchers are highly encouraged to participate in this effort and suggest better solutions.

CONCLUSION

The chevron effect analysis method is the pioneering method in identifying the chevron effect in chevron configured concentrically braced frames. The method provides simple closed form solutions for structural designers to estimate the shear force and bending moment distributions along the chevron beam length without requiring them to run computationally expensive finite element analyses. The performed investigations showed the reasonable accuracy of the method.

The authors appreciate the attention of the responders, the reviewers' helpful comments, and other structural engineers and researchers for their feedbacks on the method since it has been published. Such comments help the authors in improving the chevron effect analysis method.

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