Evaluation of Steel Panel Zone Stiffness Using Equivalent End Zone (EEZ) Model

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Abstract

The contribution of panel zone deformation to the story drift of steel moment frames is usually significant and should be taken into consideration using appropriate mechanical models. Two mathematical modeling procedures have largely been used to incorporate the effect of panel zone shear deformation directly in the analytical model, namely the Scissors and Krawinkler models. In both models, the strength and stiffness properties of the panel zone can explicitly be modeled by a rotational spring located at the beam-to-column intersection. Some engineering analysis software programs allow for the modeling of panel zone shear deformation explicitly, but most of them have implemented an end zone offset factor which adjusts the length of beams and columns in the panel zone region in a way that accounts for the contribution of panel zone implicitly.

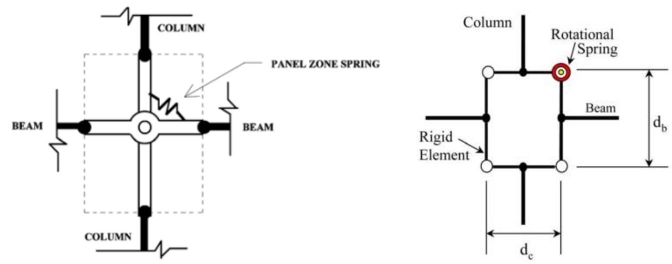
In this paper, an equivalent end zone model has been proposed where the adjusting end zone factor can be calculated explicitly for the different beam-to-column combinations in steel moment frames. An extensive numerical study has also been conducted to study the variation of the adjusting factor depending on the beam-to-column configurations and the number of moment frame bays. One important outcome of this study shows that the well-known centerline procedure often leads to unconservative estimation of the story drifts in steel moment frames. This is in contradiction with the existing belief that the use of centerline procedure is generally a conservative method for calculating the panel zone deformation implicitly. As a result, two compensating methods have been proposed to adjust the results obtained when using a centerline procedure. One method is to reinforce the panel zone by adding doubler plates accordingly and another method is to increase the calculated drift by an amplification factor (Z_{CL}). Required formulas are given and appropriate charts and graphs have been generated. Also, a centerline index (I_{CL}) has been introduced which provides the ability to predict when the use of a centerline procedure will produce unconservative results.

Introduction

Moment frame is a structural system that is widely used in steel building construction to resist gravity and lateral loads. Story drifts in such systems are largely caused by flexural and shear deformations of the beams and the columns, and by shear deformations in the beam-to-column joint panel zones. Panel zone is defined by “the column web area delineated by the extension of beam and column flanges through the connection, transmitting moment through a shear panel (Brandonisio, 2012; ANSI/AISC 360–10; Krawinkler et al., 1971). The contributions to the drift vary with each configuration, but in general beam bending is the largest contributor while column bending is the smallest. The contribution of panel zone deformation to the story drifts of steel moment frames is usually significant and should be taken into consideration using appropriate mechanical models.

When a steel beam-to-column joint is subjected to an unbalanced bending moment, a complex stress state develops in the panel zone region. This consists of normal stresses, mainly originating from the column, and shear stresses resulting from the moment transmitted from the beams. Experimental studies have shown that the panel zone behavior in the elastic range is mainly governed by shear deformations (Castro, 2005).

One desirable option is to incorporate the effect of panel zone shear deformations directly in the analytical model of moment resisting frames. Two mathematical modeling procedures have widely been used to incorporate the effect of panel zone shear deformation directly in the analytical model, namely the Scissors and Krawinkler models. In both models, the strength and stiffness properties of the panel zone can explicitly be modeled by a rotational spring located at the beam-to-column intersection. In a frame analysis program that consists only of line elements, panel zone behavior can be modeled in an approximate manner by means of the Scissors model (Figure 1a) or more accurately by creating a panel zone with rigid elements linked by hinges at three corners and a rotational spring in the fourth corner, as illustrated in Figure 1b (Krawinkler model). In the Scissors model, a rotational spring is introduced at the beam-to-column intersection partially constraining the relative rotation between the two elements. Links in the vicinity of the joint are often employed in order to model the rigid extension of the beam and column. In this model the sum of moments can be related to the joint shear force, and the spring rotation is equal to the panel zone shear distortion angle. The second approach, termed as the Krawinkler model, consists of a more realistic representation of the panel zone where the actual dimensions are considered by adding eight rigid elements per panel zone as shown in Figure 1b. The strength and stiffness properties of the panel zone can be modeled by a rotational spring located at one of the four panel zone corners. The right angles between the panel zone boundaries and the adjacent beams and columns are maintained in the Krawinkler model whereas they are not in the Scissors model. More details can be found in (FEMA-335C; Charney and Downs, 2004; Krawinkler, 1978).



a) Scissors model b) Krawinkler model

Figure 1: Panel Zone Mechanical Models

Alternatively, elastic panel zone deformation contributions to story drifts can be accounted for by adjusting the lengths of the beams and the columns in a manner that accounts implicitly for the contributions of the panel zone deformations to drift. Some engineering analysis software programs allow for the modeling of panel zone shear deformation explicitly, but most of them have implemented an end zone offset factor that adjusts the length of the beams and the columns in the panel zone region in a way that accounts for the contribution of the panel zone deformation implicitly. NEHRP Seismic Design Technical Brief No. 2 - NIST GCR 09-917-3 (Hamburger et al., 2009) suggested that the use of rigid offsets is not recommended unless the dimensions of the offsets are obtained by rational analysis. In the absence of such analyses, it suggested the use of centerline dimensions for beams and columns as a practical way of accounting implicitly for the contribution of panel zone deformations to story drifts. Using the centerline approach, the contributions of beam and column flexural deformations to story drifts are overestimated, while the contributions of panel zone shear deformations are ignored. It is largely believed by the engineering community that the resulting story drifts obtained from the centerline method are larger than those obtained from incorporating elastic panel zone shear deformations explicitly. This paper has challenged this belief by proposing a new model and conducting extensive parametric studies.

In this paper, an equivalent end zone model (EEZ model) has been proposed where the dimensions of the offsets are calculated explicitly by applying an adjusting end zone offset factor, α, for different beam-to-column combinations in steel moment frames. An extensive numerical study has also been conducted to study the variation of α depending on the beam-to-column configurations and the number of bays. One important conclusion of this study is that the well-known centerline procedure often leads to an unconservative estimation of the story drifts in steel moment frames. As a result, two compensating methods have been proposed to adjust the results obtained when centerline procedure is utilized, as it often underestimates the story drifts. Method 1 is to reinforce the panel zone by adding doubler plates accordingly and Method 2 is to increase the calculated drift by an amplification factor (Z_{CL}). Required formulas are given and appropriate charts and graphs have been generated. Also, a centerline index (I_{CL}) has been introduced which provides the ability to predict if using the centerline procedure is unconservative.

The method is based on the portal method assumption, which implies that a frame can be resolved into simple beam-column assemblies with points of inflections at mid-spans of beams and mid-heights of columns. In this study, a typical story of a moment resisting frame comprising of several external and internal connections (segments) is considered as shown in Figure 2. To study the performance of a typical story it would be sufficient to study the behavior of an external and an internal connection.

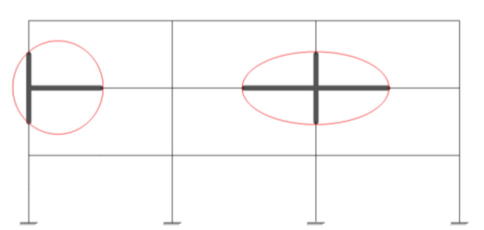
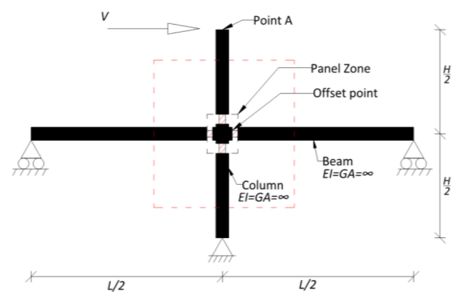


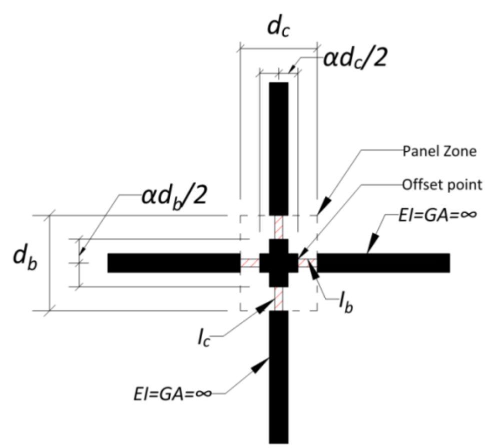
Figure 2: Moment Frame Comprised of External and Internal Connections

Proposed Model

The proposed model will incorporate the effect of panel zone shear deformation directly in the analytical model by calculating the dimensions of the offsets in the panel zone region depending on the beam-to-column combination in steel moment frames. As shown in Figure 3a, a typical internal beam-to-column subassembly subjected to a lateral force, V, is considered. The moments at the mid-span of the beams and mid-height of the columns are zero. It is assumed that the properties and span of the beams on both sides of the column are the same, and that a single column section is used over the full height of the subassembly. It is also assumed that the beams and columns are fully rigid ($EI = GA = \infty$) beyond the panel zone region and also between the center of the panel zone and offset points as shown in Figure 3b (thick bold lines).



a) Internal Connection



b) Internal Connection Detail

Figure 3 : Panel Zone EEZ Model

Therefore, the total deformation of the frame subassembly at point A is purely caused by the flexural and shear deformations of four links between the offset points and the faces of the columns and beams (shown hatched in Figure 3b). Using structural analysis principles, the panel zone shear deformation, hence the total drift can be calculated. The proposed EEZ model and the Scissors model must have the same panel zone deformation contribution at Point A. Equating the EEZ and Scissors models will lead to the calculation of the dimensions of the offsets in the panel zone region, hence the end zone factor, α, analytically. This enables engineers to obtain the end zone factor (dimensions of the offsets) by a rational analysis as suggested by NEHRP Seismic Design Technical Brief No. 2 - NIST GCR 09-917-3 (Hamburger et al., 2009).

Theory

a. EEZ model

For an internal connection as shown in Figure 3a, the deflection at the top of the column (Point A), $\Delta_{EEZ}^{int.}$, can be obtained using structural analysis principles as follows:

$$\Delta_{EEZ}^{int.} = \Delta_{column}^{int.} + \Delta_{beam}^{int.} \qquad \text{Eq. 1}$$

Where

$$\Delta_{column}^{Int.} = \frac{V}{EI_c}(1-\alpha)d_b\left(\frac{(H-d_b)(L-\alpha d_b)}{4} + \frac{H^2}{\lambda_c}\right) \qquad \text{Eq. 2}$$

$$\Delta_{beam}^{int.} = \frac{V}{EI_b}(1-\alpha)d_c\left(\frac{(L-d_c)(L-\alpha d_c)}{4} + \frac{L^2}{\lambda_b}\right)\left(\frac{H}{L}\right)^2 \qquad \text{Eq. 3}$$

$$\lambda_c = \frac{GA_{sc}H^2}{EI_c} \qquad \text{Eq. 4}$$

and

$$\lambda_b = \frac{GA_{sb}L^2}{EI_b} \qquad \text{Eq. 5}$$

with

α: Rigid end zone offset factor
E: Modulus of elasticity
G: Elastic shear modulus
I_c: Second moment of area of the column
I_b: Second moment of area of the beam
d_c: Column depth
d_b: Beam depth
H: Typical story height (center to center of beams)
L: Beam span (center to center of columns)
A_{sc}: Effective shear area of the column
A_{sb}: Effective shear area of the beam

For an external connection shown in Figure 4, the analogous equations can be obtained as follows:

$$\Delta_{EEZ}^{ext.} = \Delta_{column}^{ext.} + \Delta_{beam}^{ext.} \qquad \text{Eq. 6}$$

Where

$$\Delta_{column}^{ext.} = \frac{V}{EI_c}(1-\alpha)d_b\left(\frac{(H-d_b)(L-\alpha d_b)}{4} + \frac{H^2}{\lambda_c}\right) \qquad \text{Eq. 7}$$

$$\Delta_{beam}^{ext.} = \frac{2V}{EI_b}(1-\alpha)d_c\left(\frac{(L-d_c)(L-\alpha d_c)}{4} + \frac{L^2}{\lambda_b}\right)\left(\frac{H}{L}\right)^2 \qquad \text{Eq. 8}$$

Eqs. 1-3 and Eqs. 6-8 show that the contribution of the columns on the total deformation of the external and internal connections are identical, whereas the beam contribution is doubled for an external connection. It will be shown that the behavior of a typical story of a moment frame is greatly influenced by the number of internal and external connections (number of bays).

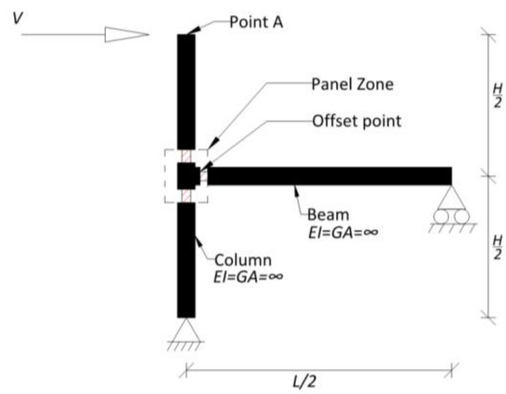


Figure 4: Panel Zone EEZ Model (External Connection)

b. Scissors Model

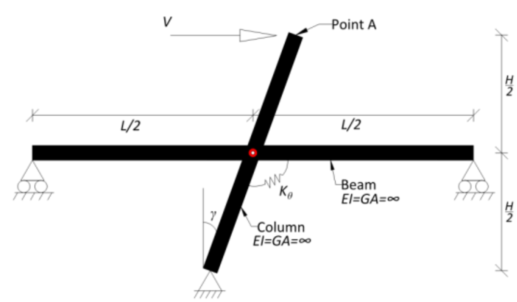


Figure 5: Panel Zone Scissors Model

Figure 5 shows an internal connection with rigid beams and columns where the stiffness of the panel zone is represented by a rotational spring located at the beam-to-column intersection. This is termed the Scissors model.

The Scissors model derived its name from the fact that the model acts similar to a pair of scissors, with a hinge at the center. The story drift of an internal connection for the Scissors model can be obtained as follows:

$$\Delta_{pz} = \frac{VH^2(1-\xi_x-\xi_y)}{0.95G\Pi_{PZ}} \qquad \text{Eq. 9}$$

$$K_\theta = \frac{0.95G\Pi_{PZ}}{1-\xi_x-\xi_y} \qquad \text{Eq. 10}$$

Where Π_{PZ} represents the volume of the panel zone region, i.e.

$$\Pi_{pz} = d_c d_b t_{PZ} \qquad \text{Eq. 11}$$

In which, t_{pz}, denotes the thickness of the panel zone. When there is no doubler plate, the thickness of the panel zone is the same as the thickness of the column web, t_{cw}.

The terms ξ_x and ξ_y represent the ratios of the column depth to the span length, and the beam depth to the column height respectively, i.e.

$$\xi_x = \frac{d_c}{L} \qquad \text{Eq. 12}$$

and

$$\xi_y = \frac{d_b}{H} \qquad \text{Eq. 13}$$

For a given connection, the end zone offset factor, α, can analytically be calculated by equating Eq. 9 with either Eq. 1 or Eq. 6, i.e.

$$\Delta_{EEZ} = \Delta_{pz} \qquad \text{Eq. 14}$$

Proposed Model Verification

The purpose of this section is to confirm that the EEZ model is an accurate method for taking into consideration frame deformations caused by panel zone shear deformation. Also, the associated derived equations for the EEZ model in the theory section above will be checked and verified in this section. After which, the EEZ model can be confidently utilized in structural analysis software packages.

The Panel zone effect is a very complex component of structural systems, and using finite element analysis (FEA) software programs such as LS-Dyna (LSTC) is the best way for studying its behavior. A four story moment frame and an internal connection, as shown in Figure 6 and Figure 7, are modeled using this highly sophisticated full nonlinear finite element analysis software to study the true behavior of the panel zone.

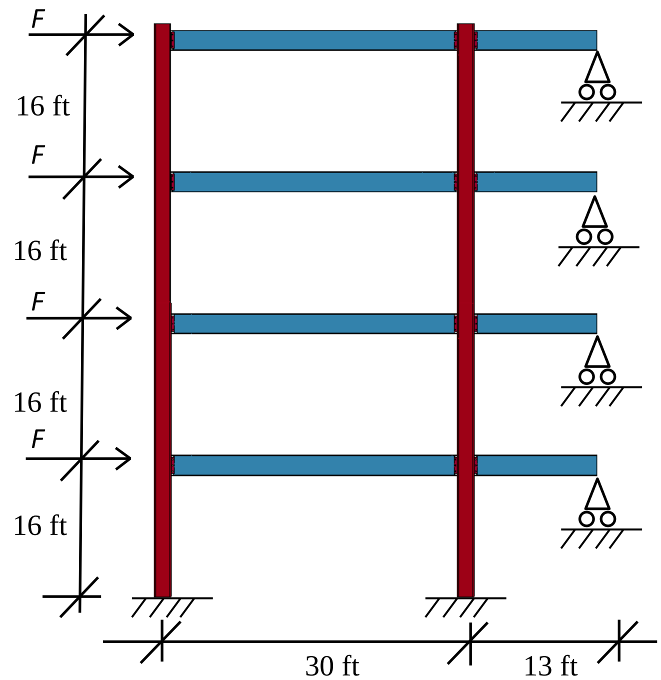


Figure 6: Four Story Frame Modeled in LS-Dyna

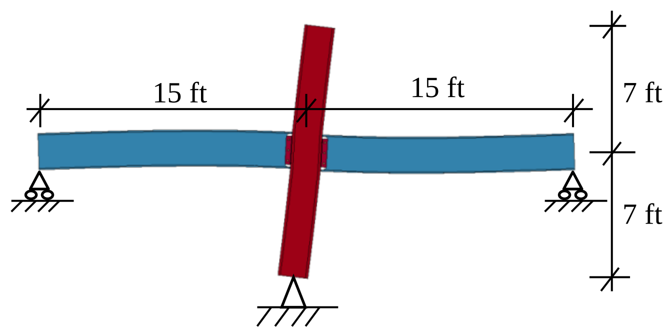


Figure 7: Internal Connection with W18X175 Column and W24X94 Beam Modeled in LS-Dyna

The same structures were modeled in the structural analysis software ETABS (CSI) where the shear rigidity of the panel zone was implemented by a rotational spring at the beam-to-column joint using the ETABS panel zone feature. The stiffness of the rotational spring in the panel zone feature was calculated manually using Eq. 10. In the next phase, the end zone factor was calculated utilizing the EEZ model and applied to the ETABS model using the rigid end zone offset feature. Results from all three analyses showed very good agreement with each other meaning that the EEZ model can confidently be used to quantify the end zone factor, α.

Centerline Method Indices

Results from an extensive parametric study showed that the centerline procedure does not necessarily lead to conservative results when calculating story drifts. Based on the analyses of more than 1,000 beam-to-column combinations it was concluded that the centerline procedure leads to unconservative results in 80% of the cases in 3-bay frames and 90% of the cases in 5-bay frames. Based on the EEZ model, a new centerline index, I_{CL}, for internal and external beam-to-column combinations were developed as follows:

$$I_{CL}^{int.} = \frac{\Pi_{\text{pz}}}{10}\left(\frac{d_b}{I_c} + \frac{d_c}{I_b}\right) \quad \text{Eq. 15}$$

$$I_{CL}^{ext.} = \frac{\Pi_{\text{pz}}}{10}\left(\frac{d_b}{I_c} + 2\frac{d_c}{I_b}\right) \quad \text{Eq. 16}$$

A centerline index of less than 1.0 indicates that the centerline procedure underestimates the story drifts and can lead to unconservative results. To compensate for the difference, an amplification factor, Z_{CL}, was derived for any internal and external beam-to-column combination as follows:

$$Z_{CL}^{int.} = 1 + 3\left(\frac{\frac{10}{\Pi_{\text{pz}}} - \frac{d_b}{I_c} - \frac{d_c}{I_b}}{\frac{H}{I_c} + \frac{L}{I_b}}\right) \quad \text{Eq. 17}$$

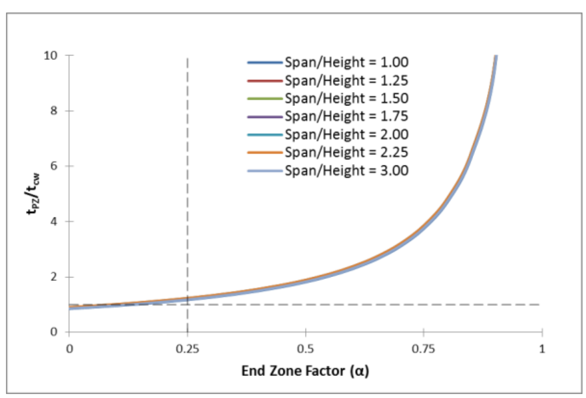
$$Z_{CL}^{ext.} = 1 + 3\left(\frac{\frac{10}{\Pi_{\text{pz}}} - \frac{d_b}{I_c} - 2\frac{d_c}{I_b}}{\frac{H}{I_c} + 2\frac{L}{I_b}}\right) \quad \text{Eq. 18}$$

These factors can be employed to amplify the story drifts calculated from centerline analyses where necessary.

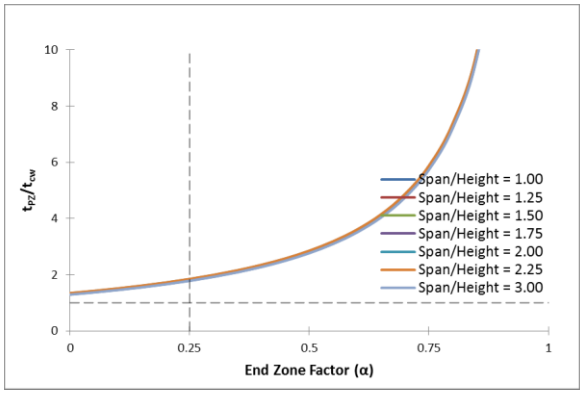
Parametric Study

Consider an external and an internal beam-to-column connection with W36x150 beams and W27x258 columns with the story height of 16 ft and beam span of 30 ft. The associated end zone factor, α, was calculated as $\alpha = 0.12$ for the external connection and no real α ($0 \leq \alpha \leq 1$) could be calculated for the internal connection using Eq. 19. This means that the associated rigidity of the EEZ model with $\alpha = 0$ (centerline method) is stiffer than the shear rigidity of the panel zone. This indicates that the centerline method underestimates the story drift for this connection and leads to an unconservative design. This important finding prompted the authors of this paper to conduct more investigation on the comparative stiffness of the centerline method to the more accurate modeling procedure using panel zone methods. Further investigations showed that the centerline procedure often leads to unconservative estimations of the story drifts in steel moment frames.

Figure 8a shows the variation of the panel zone thickness amplification factor, $\frac{t_{pz}}{t_{cw}}$, for an external connection in terms of end the zone factor, α, by solving for $\Delta_{EEZ} = \Delta_{pz}$. The term, t_{cw}, denotes the thickness of the web of the column and, t_{pz}, denotes the thickness of the panel zone. Figure 8b provides the same information for an internal connection. In all connections the story height has the constant value of 16 ft where Span/Height ratio is varying from 1.00 to 3.00 to show the effect of Span/Height ratio on the results. The results indicate that the chance of being unconservative is larger for an internal connection regardless to the Span/Height ratio.



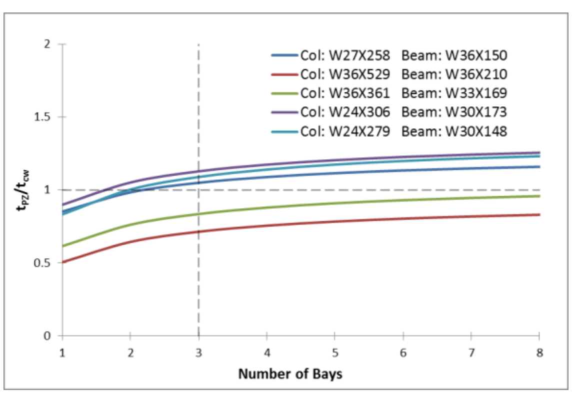
a) External Connection



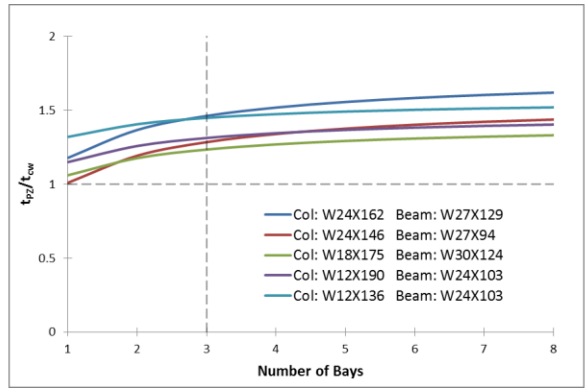
b) Internal Connection

Figure 8: Panel Zone Thickness Amplification Factor for an External and an Internal Moment Connection Based on the End Zone Factor, α. Column: W27x258 Beam: W36x150

More beam-to-column combinations were considered to further demonstrate and consolidate the fact that the centerline procedure is not a conservative way of modeling the panel zone. Figure 9a shows the panel zone thickness amplification factor, $\frac{t_{pz}}{t_{cw}}$, for different beam-to-column combinations in multi-bay moment resisting frames in seismic-governed regions where strong column-weak beam condition is required to be satisfied. Figure 9b provides similar information for wind-governed regions where strong column-weak beam does not have to be met. The graphs show that the panel zone thickness amplification factor varies greatly depending on the beam-to-column combination as well as number of bays.



a) Seismic Condition Governs

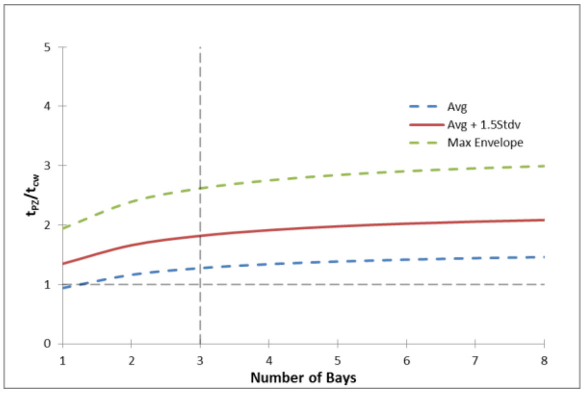


b) Wind Condition Governs

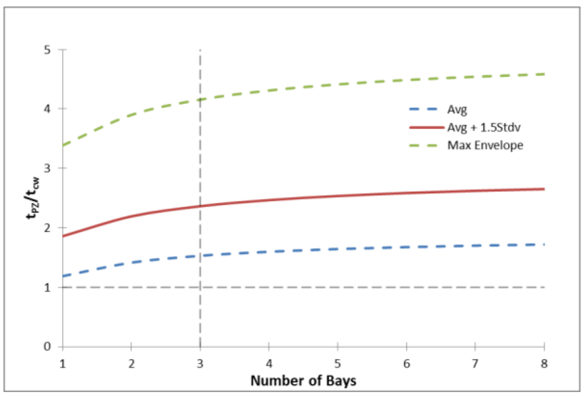
Figure 9: Centerline Panel Zone Thickness Amplification Factor for Moment Frames with Typical Beam-to-Column Combinations used in Practice

Developing a computer program based on the EEZ model, together with modern computing power, led to the possibility of analyzing massive amounts of beam-to-column combinations in multi-bay frames. This led to the creation of the extended version of Figure 9 where the maximum envelope and mean panel zone thickness amplification factor $\left(\frac{t_{pz}}{t_{cw}}\right)$ curves were developed for more than 1,000 beam to column combinations. Also, a mean plus 1.5 times standard deviation curve was plotted in Figure 10 that shows very good agreement with the maximum envelope curve. This indicates that the mean plus 1.5 times standard deviation curve can be used in practice for the calculation of the panel zone thickness amplification factor, $\frac{t_{pz}}{t_{cw}}$, where the centerline procedure is utilized. It also indicates that the centerline procedure usually leads to unconservative result unless a doubler plate with an appropriate thickness is employed. This has been referred to as Method 1 in this paper.

Eq. 17 and Eq. 18 were also employed to conduct an extensive parametric study on different beam-to-column combinations where the drift amplification factor, Z_{CL}, was plotted against the number of bays. Story drift magnifying factors can be employed to amplify the story drifts calculated from centerline analyses where necessary.



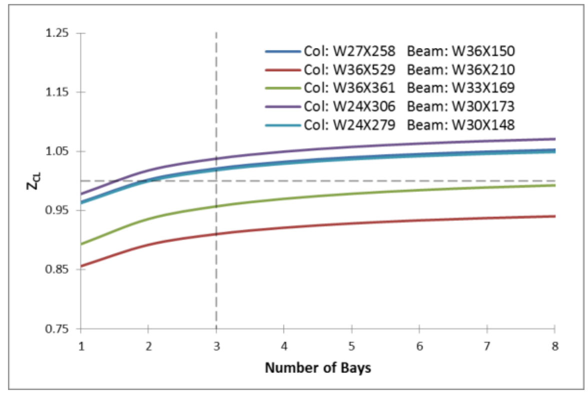
a) Seismic Condition Governs



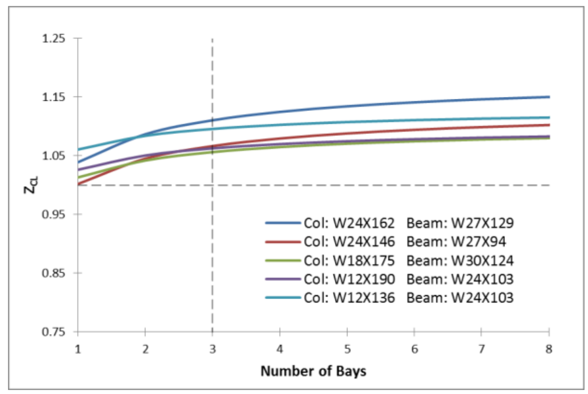
b) Wind Condition Governs

Figure 10: Maximum Envelope, Mean and Mean Plus 1.5 Times Standard Deviation Panel Zone Thickness Amplification Factor for Moment Frames with More Than 1000 Beam-to-Column Combinations

The results showed that the story drift amplification factor is largely dependent on the number of bays as well as beam-to-column configurations as shown in Figure 11. The same procedure was conducted for more than 1,000 beam-to-column combinations in seismic and wind-governed regions, and the maximum envelope, mean and mean plus 1.5 times standard deviation curves were generated as shown in Figure 12. The mean plus 1.5 times standard deviation may be used to compensate the underestimation of the story drift where the centerline procedure is used.

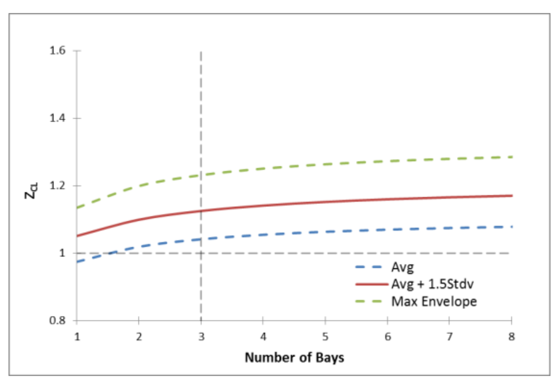


a) Seismic Condition Governs

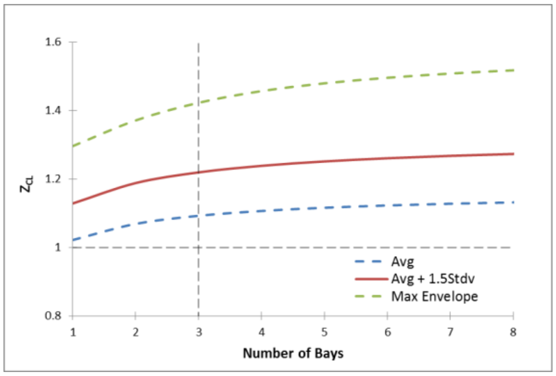


b) Wind Condition Governs

Figure 11: Centerline Drift Amplification Factor for Moment Frames with Typical Beam-to-Column Combinations Used in Practice



a) Seismic Condition Governs



b) Wind Condition Governs

Figure 12: Maximum Envelope, Mean and Mean Plus 1.5 Times Standard Deviation of the Drift Amplification Factor for Moment Frames with More Than 1,000 Beam-to-Column Combinations

First Story Effect

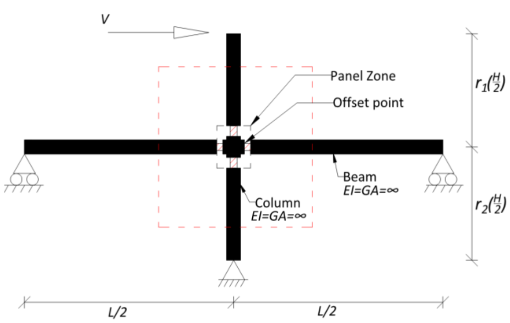


Figure 13: EEZ Model

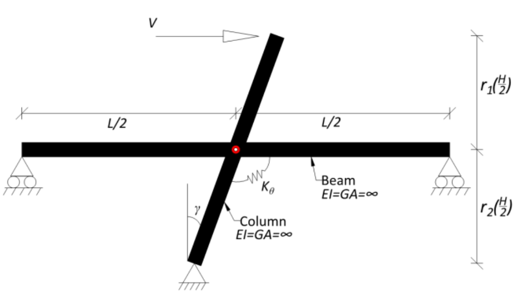


Figure 14: Scissors Model

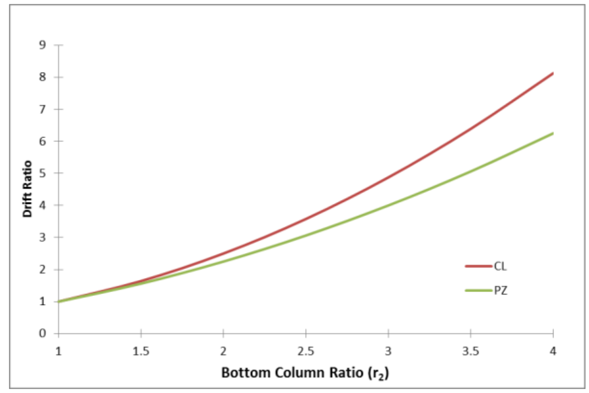


Figure 15: Rate of Drift Increase in the First Story

Results also show that as the span is increased, behavior in the panel zone is not affected (Figure 8). Using either the EEZ model offsets or panel zone method, the rate of increase does not change with changing span lengths. However, when the story height is increased, the rate of deformation increase for those two methods are different. Figure 13 and Figure 14 show the EEZ model and the Scissors model, respectively, given that the beam and the column contribution are the same. Assuming that$\xi_x = 0.1$ and $\xi_y = 0.2$, the plot shown in Figure 15 can be generated. That plot shows that as the story height is increased by a factor r_2, the end zone offset method will grow faster than the centerline method. For that reason, in some cases where the bottom story is high enough or the base is pinned, the bottom story drift is conservative using centerline dimensions.

Conclusions

In this paper, an equivalent end zone model (EEZ model) has been proposed where the dimensions of the end zone offsets are calculated explicitly with applying an adjusting end zone factor, α, for different beam-to-column combinations in steel moment frame systems. The proposed model has been checked and verified using the finite element analysis software, LS-Dyna. Development of a computer program based on the EEZ model together with modern computing power, led to the possibility of analyzing massive amounts of beam-to-column combinations in multi-bay frames. An extensive numerical study was also conducted to study the variation of the adjusting end zone factor, α, depending on the beam-to-column configurations and the number of bays. It has been shown that the centerline procedure often leads to an unconservative estimation of the story drifts in steel moment frames. This is in contradiction with the existing belief that the use of the centerline procedure is generally a conservative method for calculating the panel zone deformation implicitly. As a result, two compensating methods have been proposed herein to adjust the results obtained when using the centerline procedure. Required formulas are given and appropriate charts and graphs have been generated. Also, a centerline index (I_{CL}) is introduced which provides the ability to predict when using the centerline procedure will produce unconservative results.

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