The Effect Of Panel Zone On The Column-To-Beam Strength Ratio Required To Prevent The Soft Story Of Steel Moment Frames

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LISBOA 2012

SUMMARY: THE EFFECT OF PANEL ZONE ON THE COLUMN-TO-BEAM STRENGTH RATIO
The strong column-weak beam condition has widely used to ensure the ductile capacity of steel moment frames. Many researches showed that soft story could be developed despite satisfying this condition. A lot of researches on the minimum column-to-beam strength ratio required to prevent the soft story were performed. Most of them used the analytic modeling methods without the panel zone. The purpose of this study is to evaluate the effect of panel zone on the minimum column-to-beam strength ratio required to prevent the soft story of steel moment frames. To identify the effect of panel zone, three analytic modeling methods (nonlinear centerline model without rigid end offsets, nonlinear centerline model with rigid end offsets, nonlinear model with panel zones) were used. NSGA-II was used to find the minimum column-to-beam strength ratio required to prevent the soft story. These ratios were compared and assessed through applying this method to 3-story example.

Keywords: column-to-beam strength ratio, panel zone

1. INTRODUCTION

ANSI/AISC 341-05 and ACI 318-05 use the strong column-weak beam concept to prevent early flexural failure, and to induce beam-hinge collapse mechanism. As shown in Eqns. 1.1 and 1.2, the sum of the upper and lower column bending strength ($\sum M_{pc}$) have to be greater than the sum of left and right column bending strength ($\sum M_{pb}$) on the column-to-beam joint to induce the occurrence of plastic hinge on beam in prior to the column. But since this is based on double curvature bending moment distribution, even if this condition is satisfied, plastic hinge could occur in column which creating a soft story. On actual structure, inflection point which was presumed to place in the center of the beam can move to end of the column or bending moment distribution of the column can realize the single curvature due to higher order mode and change of motion after the yield. (Park and Paulay, 1975).

ANSI/AISC 341-05 $$\frac{\sum M_{pc}}{\sum M_{pb}} > 1.0 \quad (1.1)$$

ACI 318-05 $$\frac{\sum M_{pc}}{\sum M_{pb}} \geq 1.2 \quad (1.2)$$

There have been studies about column-to-beam strength ratio which is required to prevent a soft story in moment framework. (Lee, 1996; Nakashima and Sawaizumi, 2000; Dooley and Bracci, 2001; Kuntz and Brouning, 2003; Medina and Krawinkler, 2005). But, existing studies were conducted using examples designed by engineers' experiences. They all used nonlinear centerline model, and no influence assessment according to analytical model was made.

Thus in this study, influence of analytical model on minimum bending strength ratio required to lead beam-hinge collapse mode of steel moment frame was analyzed. For an objective and rational assessment, optimal design method was used to obtain the design model which has beam-hinge collapse mode. This optimal design method uses the objective functions which minimize the structural weight and column-to-beam strength ratio, the constraints such as the inter-story drift constraint, plastic hinge formation constraint on column in joint of column-to-beam, and constraint upon the cross section ratio of vertically continuing columns. Panel zone is only considered as an influence factor in analytical model regarding the minimum bending strength ratio and 3 analytical models (nonlinear centerline model without rigid end offsets, nonlinear centerline model with rigid end offsets, nonlinear centerline model with panel zone) are used. Influence of analytical model was investigated by comparing the structural weight and minimum bending strength ratio of optimal designs while using the same optimal design method but differentiating the analytical model. This study employed 3 story steel moment frame example.

2. ANALYTIC MODELING

As showed in Fig. 1, the panel zone signifies cross-domain of column and beam at the joint. A shear deformation of panel zone has a significant effect on strength, stiffness and distribution of inelastic deformation of moment frame which receive earthquake load (Krawinkler and Mohasseb, 1987). Yet, existing studies on bending strength ratio (Lee, 1996; Nakashima and Sawaizumi, 2000; Dooley and Bracci, 2001; Kuntz and Brouning, 2003; Medina and Krawinkler, 2005) did not consider this fact. Therefore, this study compared to influence of panel zone of minimum bending strength ratio required to induce beam-hinge collapse mode of moment frame while considering nonlinear centerline model without rigid end offsets (Model M1), which was mostly used in existing study, nonlinear centerline with rigid end offsets (Model M2), and also nonlinear centerline model with panel zone (Model M3).

As shown in Fig. 2, Model M1 expresses column and beam using lines without considering panel zone. Two lines symbolizing column and beam are placed at the center of each column and beam, and they meet in the center of the panel zone. Element of the column and beam creates plastic behavior to occur on the both ends.

As shown in Fig. 3, Model M2 is modeling panel zone by utilizing rigid end offsets. The node located in the center of panel zone is connected to nodes located in spot in distance of half of width of the beam by using rigid link for panel zone to make a rigid body motion then the line symbolizing the column and beam is connected to the already connected node. Element of column and beam is for plastic behavior to occur only at both ends.

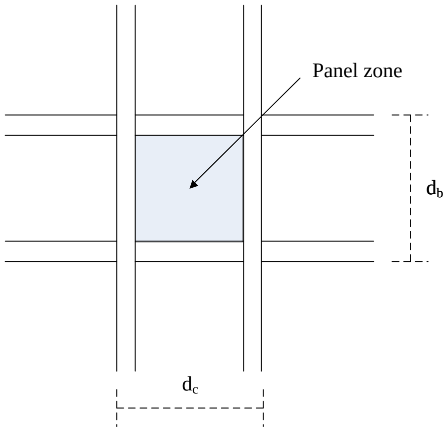

Figure 1. Definition of panel zone

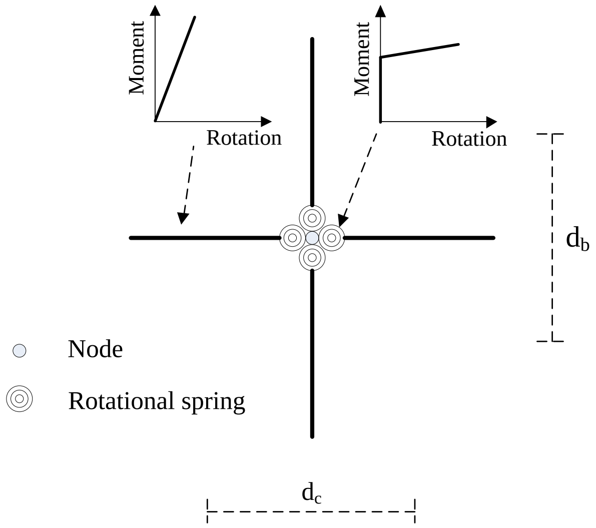

Figure 2. Nonlinear centerline model without rigid end offsets (Model M1)

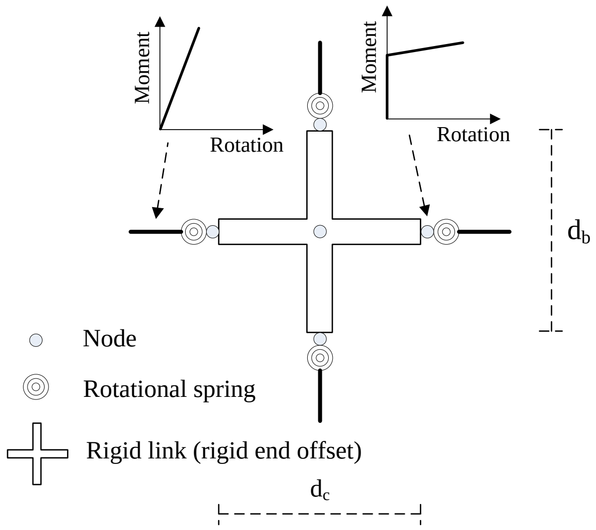

Figure 3. Nonlinear centerline model with rigid end offsets (Model M2)

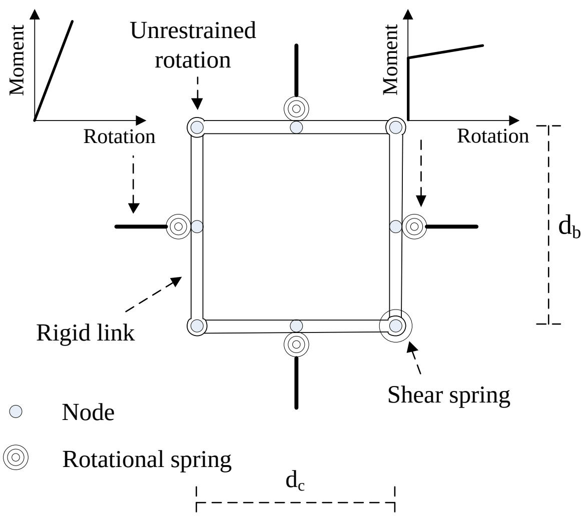

Figure 4. Nonlinear centerline model with panel zone (Model M3)

To consider the shear stiffness and strength of the panel zone, as shown in Fig.4, Model M3 used suggested model in FEMA 355c. A shear behavior of panel zone is expressed with shear spring which motion like shown in Fig. 5, this is decided by yielding point (γ_y, V_y) and plastic point (γ_p, V_p). Values of yield point and plastic point can be calculated by using Eqns. (2.1)-(2.4).

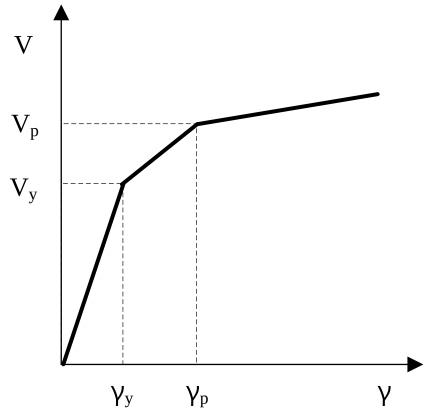

Figure 5. Trilinear shear force – shear distortion relationship of panel zone

$$V_y = 0.55 F_y d_c t_p \tag{2.1}$$

$$\gamma_y = \frac{F_y}{\sqrt{3}G} \tag{2.2}$$

$$V_p = 0.55 F_y d_c t_p (1 + \frac{3 b_c t_{cf}^2}{d_b d_c t_p}) \tag{2.3}$$

$$\gamma_p = 4\gamma_y \tag{2.4}$$

where V_y is the panel zone shear yield strength, F_y is the yield strength of the material, d_c is the depth of the column, t_p is the thickness of the web including any doubler plates, γ_y is the panel zone shear yield distortion, G is the shear modulus of the column material, V_p is the panel zone shear plastic strength, b_c is the width of the column flange, t_{cf} is the thickness of the column flange, d_b is the depth of the beam, γ_p is the panel zone shear plastic distortion.

3. THE OPTIMAL DESIGN METHOD FOR INDUCING BEAM-HINGE COLLAPSE OF STEEL MOMENT FRAMES

In this study, the optimal design method is employed to get steel moment frame design model which has beam-hinge collapse mode. This uses two objective functions. The purpose of this study is to evaluate minimum column-to-beam bending strength ratio required while inducing beam-hinge collapse mode according to the joint. Thus, the first objective function is set to minimize the structural weight of structure as shown in Eqn. (3.1). The second objective function is set to minimize the largest bending strength ratio at column-to-beam strength ratio of design model, as displayed in Eqn. (3.2). This is to analyze with practical design model in order to evaluate rationally minimum bending strength ratio.

$$\text{Minimize} \quad \sum_{i=1}^{m} \rho_i A_i l_i \tag{3.1}$$

$$\text{Minimize} \quad \alpha_{\max} \tag{3.2}$$

where ρ_i is the density of the ith element, A_i is the cross-sectional area of the ith element, l_i is the length of the ith element, m is the number of elements consisting of the structure, $\alpha_{\max}$ is the maximum plastic moment strength ratio among joints of the structure.

The study has basically considered three constraint conditions. The first condition is to constraint inter-story drift as shown in Eqn. (3.3). Generally, earthquake-resistant design of moment frame is determined by the inter-story drift condition of structure than strength condition of elements (Foutch and Yun, 2002). Therefore, this study has only considered inter-story drift condition while excluding strength condition. The second condition is to consider constraint condition where plastic hinge does not occur on end of column which forms the joint to induce the beam-hinge collapse mechanism as shown in Eqn. (3.4). The third condition is that cross-sectional area of lower column is bigger or equal to cross-sectional area of upper column in vertically continuing column to consider the constructability as shown in Eqn. (3.5). In case of optimizing design using the Model M3, Eqn. (3.6) is considered as an additional constraint condition. This means plastic deformation in panel zone is not permitted. This study has employed Non-dominated Sorting Genetic Algorithm II (NSGA-II) to solve the problem composed of objective function and constraint condition. (Deb et al., 2002).

$$\frac{\Delta}{\Delta_a} \le 1.0 \tag{3.3}$$

$$N_{pc} = 0 \tag{3.4}$$

$$\frac{A^c_{i+1,j}}{A^c_{i,j}} \le 1.0 \tag{3.5}$$

$$\frac{\gamma_{\max}}{\gamma_p} \le 1.0 \tag{3.6}$$

where Δ and Δ_a are the maximum and allowable inter-story drift ratio, respectively, N_{pc} is the number of plastic hinges formed at the column part consisting $A^c_{i,j}$ is the cross sectional area of the ith story and jth column, $\gamma_{\max}$ is the maximum shear distortion of panel zone obtained from the analysis result.

4. APPLICATION

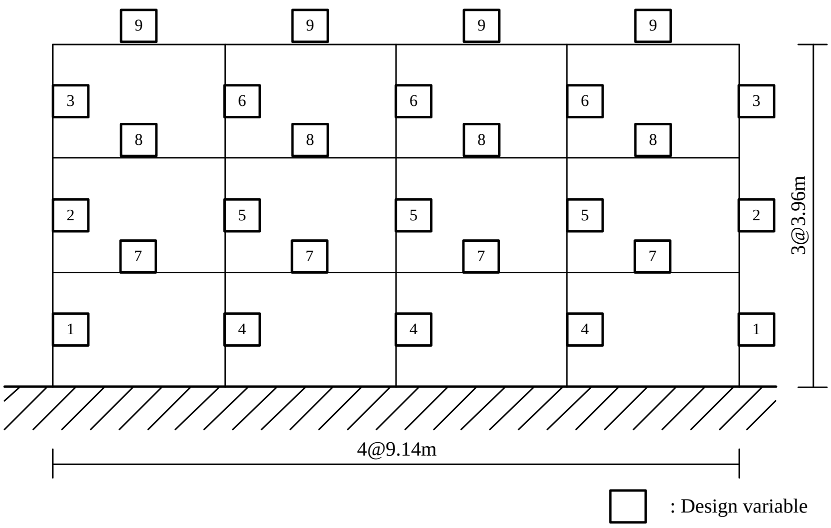

Figure 6. Example

This study used the 2D 3 story steel moment frame which Gupta and Krawinkler (1999) and Hasan et al. (2002) used like Fig. 6 to evaluate the minimum bending strength ratio required to prevent a soft story. Design variables for structural optimization were used 6 and 3 as the performance of cross section on column and beam, respectively. The list of cross section which design variable of column and beam can select arbitrarily were set as 16, respectively and the number of popsize used in NSGA-II is 20. The structure is placed is LA region of United States and ground level is D while the importance factor of structure is presumed to be 1.0. Structural steels used in beam and column are each A36, A572 Grade 50 steel. The calculation process of Equivalent lateral force as proposed in ASCE 7-05 as an earthquake load was used and structural analysis employed OpenSees. Linear analysis was conducted to evaluate the constraint condition of inter-story drift. In order to review the constraint condition for preventing occurrence of plastic hinge on column, pushover analysis was performed to figure out the collapse mechanism. Lateral load pattern employed in non-linear analysis used an inverted triangle pattern and target displacement used value fall under 5% of overall height of structure by referencing 5% of maximum inter-story drift ratio which is collapse prevention level (C.P.) presented in FEMA 356. In order to analyze the effect of panel zone on minimum bending strength ratio required to induce the beam-hinge collapse mechanism of example structure, structure was modeled by employing Model M1, Model M2, and Model M3 analytical model and optimal design method mentioned in 3rd chapter is applied to each model.

As the result of analysis, total of 19 designs (Model M1 : 6, Model M2 : 9, Model M3 : 4) are obtained as shown in Fig. 7. In all three cases, the minimum bending strength ratio required to induce the beam-hinge collapse of steel moment framework increased as the structural weights decreased. The result of Model M1 and Model M2 were confirmed to show a similar tendency however, in case of Model M3, which considered the shearing deformation of panel zone and limited its plastic deformation, had relatively bigger value when compared to Model M1 and M2. As shown in Table 4.1, even if beam-hinge collapse mechanism was induced through Eqn. (3.4), confirmation of constraint condition of inter-story drift like Eqn. (3.) applied as a dominant design element can be made.

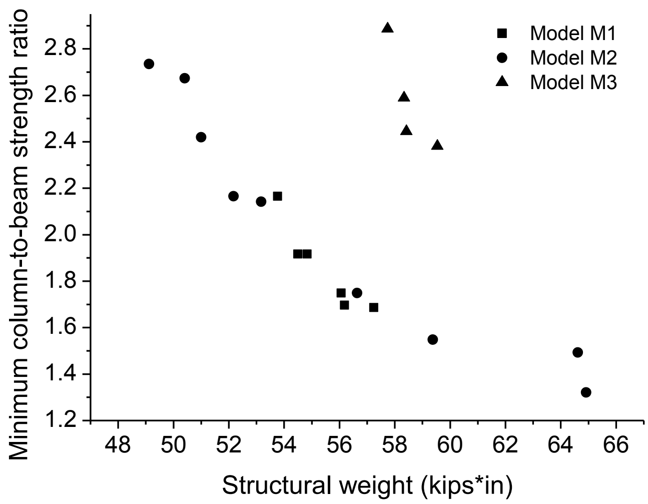

Figure 7. The solutions obtained from the optimal design algorithm

5. CONCLUSION

This study analyzed influence of analytical model regarding minimum bending strength ratio required to induce beam-hinge collapse mode of a steel moment frame. In order to obtain the design model adapting beam-hinge collapse mode, optimal design method using constraint condition where plastic hinge does not incur at end of column which composes the joint was employed. Three analytical models where panel zone was not considered (Model M1), shear strength of panel zone is considered as an infinite stiffness (Model M2), and shear stiffness of panel zone is considered while restricting its plastic behavior (Model M3) were employed to compare the influence of minimum bending strength ratio. The influence of analytical model was evaluated by comparing objective function and value of constraint condition in design model obtained from differencing the analytical model while applying identical optimal design method to example of three story steel moment framework.

As the result of analysis, all three cases had minimum bending strength ratio above 1.0 and minimum bending strength ratio required to induce the beam-hinge collapse of steel moment framework is inversely related with the structural weight. Distributions of Model M1 and M2 had a similar tendency however, in case of Model M3, which considered the shearing deformation while limiting plastic deformation has a relatively bigger value of bending strength ratio when compared to Model M1 and M2.

Table 4.1. The values of objectives functions and constraints of Model M1, M2 and M3

Model type	Objective functions		Constraints			
	Equation (3.1)	Equation (3.2)	Equation (3.3)	Equation (3.4)	Equation (3.5)	Equation (3.6)
Model M1	53.77	2.17	0.98	0.00	1.0	-
	54.50	1.92	0.98	0.00	1.0	-
	54.83	1.92	1.00	0.00	1.0	-
	56.06	1.75	0.96	0.00	1.0	-
	56.18	1.70	0.96	0.00	1.0	-
	57.25	1.69	0.93	0.00	1.0	-
Model M2	49.12	2.73	0.97	0.00	1.0	-
	50.41	2.67	0.92	0.00	1.0	-
	51.00	2.42	0.88	0.00	1.0	-
	52.17	2.17	0.85	0.00	1.0	-
	53.17	2.14	0.81	0.00	1.0	-
	56.63	1.75	0.72	0.00	1.0	-
	59.38	1.55	0.68	0.00	1.0	-
	64.62	1.49	0.62	0.00	1.0	-
	64.92	1.32	0.66	0.00	1.0	-
Model M3	57.74	2.89	1.00	0.00	0.83	0.57
	58.34	2.59	1.00	0.00	0.83	0.88
	58.42	2.45	1.00	0.00	0.83	0.88
	59.54	2.38	0.98	0.00	0.83	0.83

AKCNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2012-0001247).

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