Effect of Column Flexural Stiffness and Strength on Story Drift Concentration for Two Story Braced Frames

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Abstract: Columns in concentrically braced steel frames are generally designed for axial force and column moment demands do not affect the member sizes. In the case that no column flexural stiffness is provided, a soft-story mechanism may occur in a braced frame as soon as the braces in one level reach their strength. Real frames often possess sufficient column flexural stiffness and strength that large concentrations of damage do not generally occur.

In a previous paper, the effect of the column flexural stiffness on 2 story braced frames with pinned column bases was quantified using direct mathematical formulation, frame push-over analysis and dynamic analysis. It was shown that increased column stiffness and strength tend to reduce the story drift concentration. This paper evaluates the effect of column base fixity, as well as column stiffness and strength, on drift concentration in two story braced frames.

1. INTRODUCTION

Methods to evaluate the effect of column strength and stiffness on the story drift concentration of yielding braced frame structures have been evaluated by MacRae, Kimura and Roeder (2004) when the columns have pinned connections to their foundation. It was shown that increased column flexural stiffness tends to decrease the story drift concentration.

In real frames, columns are not pinned at the foundation and do carry moment. Also, other types of system in which a shear-type frame (such as a moment frame or braced frame) is placed in parallel with a cantilever column (such as a slender structural wall) exist. In both of these cases, estimation of the drift demand of the system can be modeled as the combination of a shear-frame with that of a cantilever column. While the base condition of any column in a frame is probably not fully fixed, the assumption of the fixed base, together with the pinned base assumption, provide bounds on the base fixity for the evaluation of story drift concentration.

This paper investigates the behavior of systems consisting of both braced frames and continuous flexural columns. It quantifies the effect of column flexural stiffness and strength on the drift concentration using a direct mathematical formulation, frame push-over analysis and dynamic analysis. The base of the column is assumed to be fully fixed to the foundation. Minimum values of column stiffness and strength to limit the story drift concentration to specific values are proposed.

2. PUSHOVER BEHAVIOR OF FRAME WITH FIXED BASE COLUMN

2.1 Comparison between Braced Frame with Pinned and Fixed Base Column

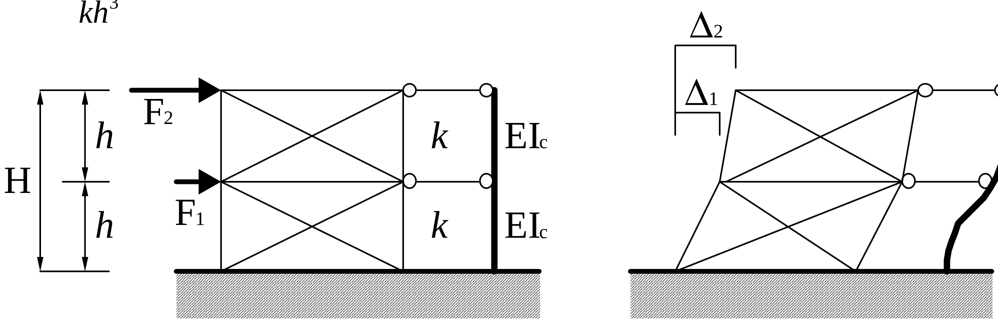
Fig. 1(a) shows the two story frame with same stiffness and strength at each level. There is one "continuous column", representing the flexural stiffness of all gravity seismic columns in the building. It is assumed that the connections of the left braced frame are totally pinned and the continuous column is fixed at the base. Only the column resists the concentration of deformation in one story. Drift concentration describes the ratio of the maximum story drift, Δ_1/h to maximum roof drift, Δ_2/H, in Fig. 1(b). In the real structures, the boundary conditions of the columns at the base are never pinned or fixed, and their rotational stiffnesses are almost during pin and fix. But if the drift concentrations for both extreme boundary conditions are clarified, that for the conditions during pin and fix can be approximately calculated.

The drift concentration factor, DCF is calculated from Eq. (1) and Eq. (2) (MacRae, Kimura and Roeder, 2004) in a braced frame with a pinned base column. Eq. (1) is valid when the bottom story yields and Eq. (2) is valid when both the top and bottom stories yield. Eq. (1) and Eq. (2) can respectively estimate the DCF for small and large column stiffness ratios, α. Here, μ_t is total roof ductility when the brace at first story yields, k is the frame shear stiffness, and EI/h^3 is the column flexural stiffness.

$$DCF = \frac{10\mu_t + 55\alpha\mu_t - 4 - 10\alpha + 75\alpha^2\mu_t}{5\mu_t(1+5\alpha)(1+3\alpha)} \quad (1)$$

$$DCF = 1 + \frac{1}{15\alpha\mu_t} \quad (2)$$

$$\text{where} \quad \alpha = \frac{EI_c}{kh^3} \quad (3)$$



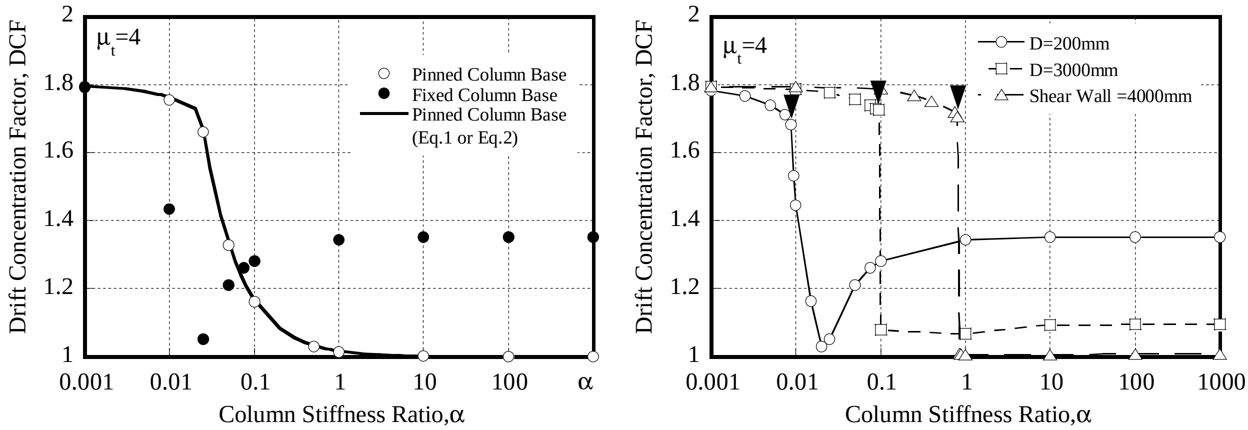
(a) System with Gravity Column (b) Deformed Shape

Figure 1 Idealization of Two Story Frame with Continuous Column Deformation and Forces

Fig. 2(a) compares the behavior of a DCF for the braced frame with pinned or fixed base columns. The lines are drawn by Eq. (1) or Eq. (2) for pinned column base at μ_t=4, and plots are the pushover analysis results. The columns are assumed to keep elastic to compare only the difference of boundary condition. μ_t is the total roof ductility when any brace yields in the frame.

Pushover analysis was carried out using the computer program DRAIN-2DX (Prakash, Powell and Campbell, 1993). When α is very low, DCFs for pinned and fixed base columns are almost same. As α increases, DCF for fixed base column suddenly decreases and converges about 1.4, even though DCF for pinned base column decreases and converges to 1.0. The difference of boundary conditions of the columns is influenced with DCFs especially for very high α, because the column at pinned base moves linearly, and that at fixed base is like a cantilever for very high α.

Fig. 2(b) shows compares the yield moment strength of steel column for DCF. The moment strength, M_c is calculated the following.



(a) Comparison of column boundary conditions

(b) Comparison of column yield strength for fixed base

Figure 2 DCF of Two Story Shear Structure with Various Column Flexural Stiffness, α, and Roof Ductility, μ_t, using Static Pushover Analysis

$$M_c = \varepsilon_y EI_c/(D/2) \quad (4)$$

Here, *D* is column diameter, and ε_y is yield strain.

Three kinds of all column capacity in the frame were selected corresponding to steel column diameter 1) 200mm, 2) 3000mm and 3)RC shear wall with depth 4000mm. The column for case 1) almost keeps elastic, and that for case 3) becomes yield as soon as α increases. The column strength is influenced with DCF. Making the closed form solution for DCF of the braced frames with fixed column base, it may be shown using the non-dimensional new parameter for column moment strength ratio, χ_c.

$$\chi_c = \frac{M_c h}{EI_c} \quad (5)$$

In Fig.2 (b), the kink, the black triangle point, in the curve shows where column behavior changes from first story only to both stories yields. Its value is different among 3 kinds of lines.

Fig.3 shows the relationship between α_c and χ_c. The plots are the analytical results, and the line is approximated by the analytical results. α_c is α when the kink occurs, as α increases. The approximate equation for α_c and χ_c is defined as the following.

$$\alpha_c = \frac{4.0 * 10^{-4}}{\chi_c} \quad (6)$$

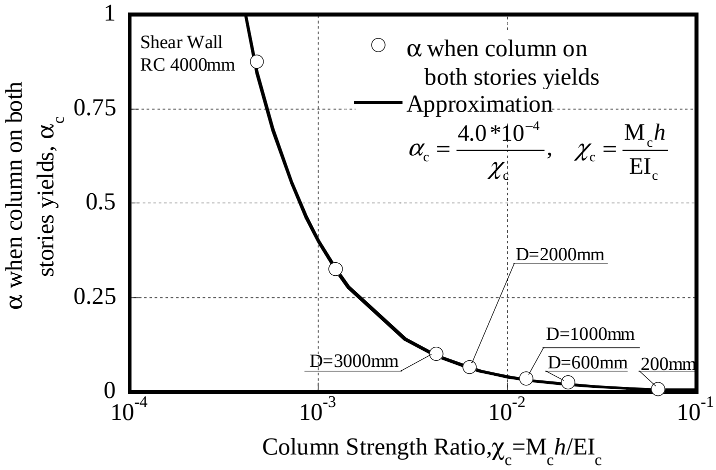


Figure 3 Relationship between α_0 and χ_c

The line is very fitting to the plots, so Eq. (6) is available to find their relationship.

2.2 Estimation for Drift Concentration Factor for Fixed Base Column in range of lare α

The value of DCF for the braced frame with fixed base column also consists of 2 kinds of closed form solution. When α is larger than α_c, it is shown that DCF is almost same as shown Fig. 2(b). Eq. (7) is the approximation of DCF when α is larger than α_c. Eq. (7) is consists of 3 equations with the value of χ_c. First equation of Eq. (7) is for the case of small column strength (low α), and Third equation is for the case of large column strength (high α). χ_{c1} and χ_{c2} are the range for changing the tendency of DCF. χ_{c1} is constant, and χ_{c2} is the value calculated from Fig.4.

$$DCF = \begin{cases} 1 & \chi_c < \chi_{c1} \\ 1 + 0.35\dfrac{\chi_c - \chi_{c1}}{\chi_{c2} - \chi_{c1}} & \chi_{c1} < \chi_c < \chi_{c2} \\ 1.35 & \chi_{c2} < \chi_c \end{cases} \tag{7}$$

$$\chi_{c1} = 4.75 * 10^{-4}, \quad \chi_{c2} = 4.0 * 10^{-3} \mu_t \tag{8}$$

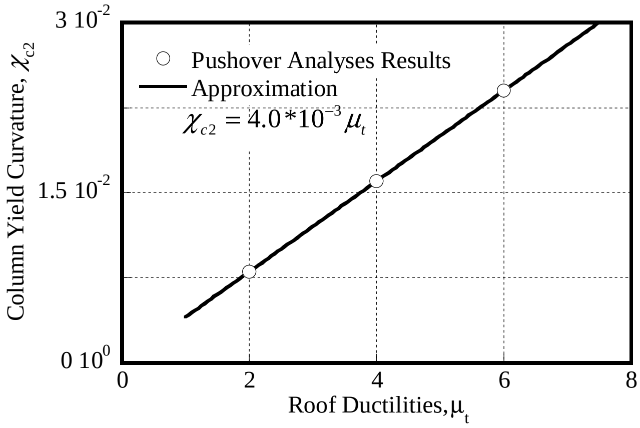
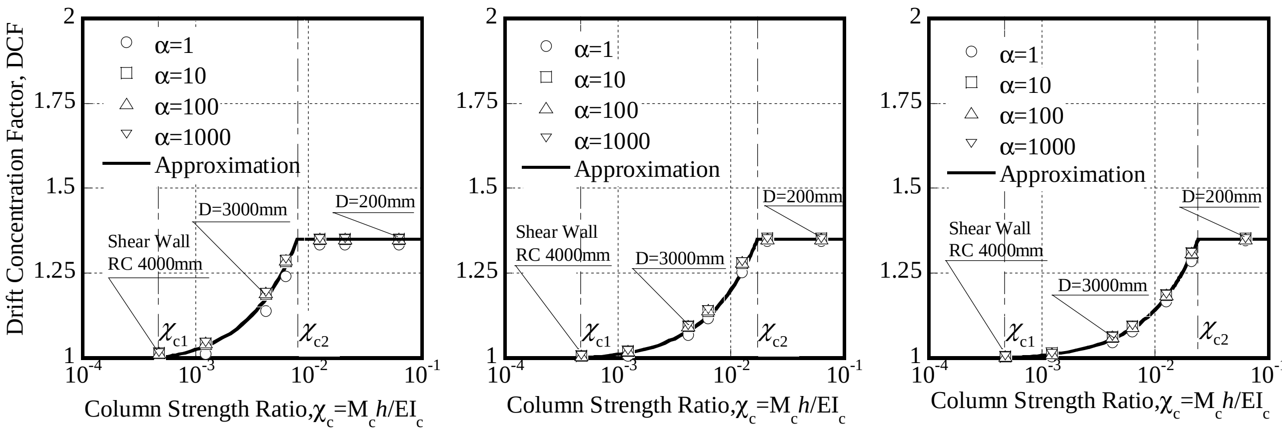


Figure 4 Relationship between χ_{c2} and μ_t

χ_{c2} depends on the roof ductility, μ_t, and is linearly related to μ_t. Plots are pushover analysis results, and the line is approximated from them.



(a) μ_t=2 (b) μ_t=4 (c) μ_t=6

Figure 5 Relationship between DCF and χ_c

Equations derived above for DCF are given in Fig.5 (a)~(c) respectively for ductilities of 2, 4 and 6. The derived equations are referred to as pushover analyses results. Results of approximation and pushover analyses are almost same as would be expected.

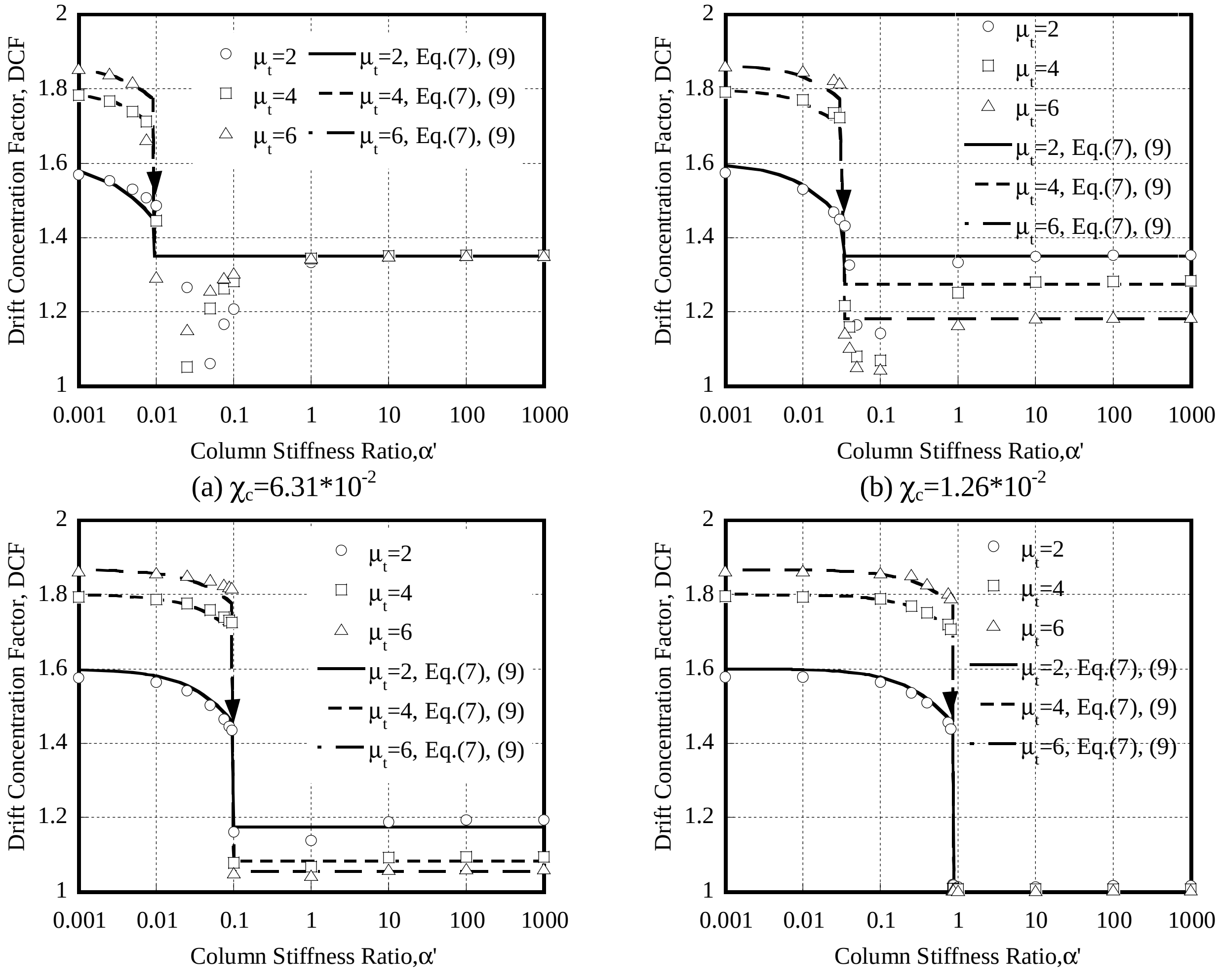
2.3 Estimation for Drift Concentration Factor for Fixed Base Column in range of small α

When α is smaller than α_c, DCF is calculated using Eq. (1) which is modified from α to α'. α' is the modified coefficient of α, as shown in Eq. (10).

$$DCF = \frac{10\mu_t + 55\alpha'\mu_t - 4 - 10\alpha' + 75\alpha'^2\mu_t}{5\mu_t(1+5\alpha')(1+3\alpha')} \quad (9)$$

where $\alpha' = \alpha\left(\frac{\alpha_0}{\alpha_c}\right)$ (10)

α_c is the value calculated from Eq. (6). α_0 is the kink in the curve for the frame with pinned column base in Fig.2 (a). And α_0 is calculated from the value of α when Eq. (1) and Eq. (2) are equal.



(a) χ_c=6.31*10^{-2} (b) χ_c=1.26*10^{-2}

(c) χ_c=4.20*10^{-3} (d) χ_c=4.73*10^{-4}

Figure 6 Relationship between DCF and modified α'

Fig.6 (a)~(d) show the relationship between DCF and modified α' respectively for χ_c=6.31*10^{-2}, 1.26*10^{-2}, 4.20*10^{-3} and 4.73*10^{-4}. The curves are the approximation for Eq. (7) and (9), and the plots are pushover analyses results respectively for μ_t=2, 4 and 6. In the diagrams, the black triangle is the boundary point between Eq. (7) and Eq. (9). Eq. (7) is used to calculate DCF at less than the point, and

Eq. (9) is at more than the point. They are similar and DCF can be estimated by these equations well. It is shown in Fig.6 (d) that when χ_c is low, DCF keeps high value by of α about 1. DCF suddenly decreases at the point, and it becomes unity. But it is shown in Fig.6 (a) that when χ_c is high, DCF suddenly decreases at α of about 0.01 and it converges about 1.4. χ_c and α are important to estimate DCF for the braced frame with fixed base columns.

2.4 Estimation for DCF with Strength Distribution of Braced Frame

In section 2.1~2.3, it is assumed that the strength distribution of braced frame is unity over height in order to lead the equation for DCF with column stiffness ratio α and column yield curvature ratio χ_c. But the frame shear demand and frame shear capacity are different and are independent of the α and χ_c. Their difference is represented by the parameter, β which is the ratio of second story strength to first story strength.

Fig.7 shows the relationship between α_c and χ_c respectively for β=3/4, 5/6, 11/12 and 1. The plots are the analytical results, and the lines are drawn by Eq. (11) which is closed form solution for α_c with χ_c and β as the following.

$$\alpha_c = \frac{4.0*10^{-4}*(3\beta-2)}{\chi_c} \qquad (\frac{2}{3} \le \beta \le 1) \tag{11}$$

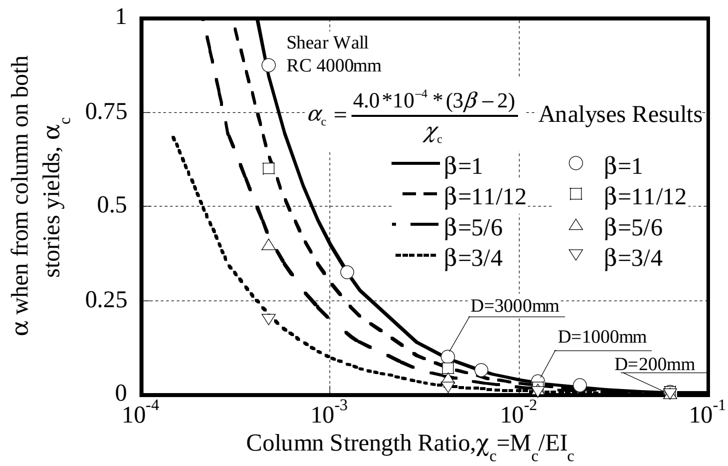


Figure 7 Relationship between α_0 and χ_c respectively for β=3/4, 5/6, 11/12 and 1

The equations for DCF of brace frame with pinned column base were developed for β and shown to fit the pushover analysis results (Kimura and MacRae, 2002). Using modified Eq. (9), the equation for DCF including β is shown as following.

$$DCF = \frac{4\beta(\mu_t-1)+10\alpha'(\mu_t-1)+6\beta^2\mu_t+45\alpha'\beta\mu_t+75\alpha'^2\mu_t}{\mu_t(2+3\beta+15\alpha')(\beta+5\alpha')} \tag{12}$$

Here, α' is calculated from Eq. (10) and Eq. (11). Eq. (7) can also be useful in the range of large α, changing β.

3. DYNAMIC ANALYSIS BEHAVIOR OF FRAME WITH FIXED BASE COLUMN

It was shown that the static drift concentration of two story braced frame is lead with column flexural stiffness and strength. In the relationships above, lateral loading distribution was assumed to be inverse triangular. Since the inertial loads change with time during earthquake, DCF may be different than that by pushover analysis. The two story frames with fixed column base are analyzed, whose models are 3 types of frame with β=1, 5/6 and 2/3 same as the frames with pinned column base

(Kimura, MacRae and Roeder, 2002). Modeling was also carried out using the computer program DRAIN-2DX. The earthquake records used were El Centro NS, Hachinohe NS and Kobe NS whose acceleration was twice. Before the dynamic time history analysis, the modal analysis of the frames gives a fundamental period, *T*, as shown in Table 1. The period for the braced frame with pinned column base is almost same, even though α for the frame is different. But that with fixed column base is significantly different, because both the braced frame stiffness and the continuous column stiffness are added to the structure stiffness for the period. It is seen that the column stiffness ratio, α increases, the period decreased. In this paper, the reduction in the period of the structure due to increasing α, is not discussed, so the frames for α of less than 1 were carried out.

Table 1 Natural Period of the Braced Frames with Continuous Column

Frame Model	α	0.0	0.01	0.1	1	10	100
Case1 (β=1)	T	0.336	0.330	0.300	0.220	0.098	0.033
Case2 (β=5/6)		0.336	0.341	0.314	0.228	0.090	0.033
Case3 (β=2/3)		0.336	0.356	0.331	0.237	0.100	0.033

Fig.8 shows dynamic DCF_d plotted against static value, DCF. Circular, square and triangle respectively indicate the case of χ_c= 0.0631, 0.0126 and 0.0042. The dynamic drift concentration factor, DCF_d was computed from the peak story drift and the peak roof drift, even though these occurred different times. Dynamic DCF is compared to static DCF at same roof ductility, μ_t. It may be seen that DCF_d is almost similar to DCF.

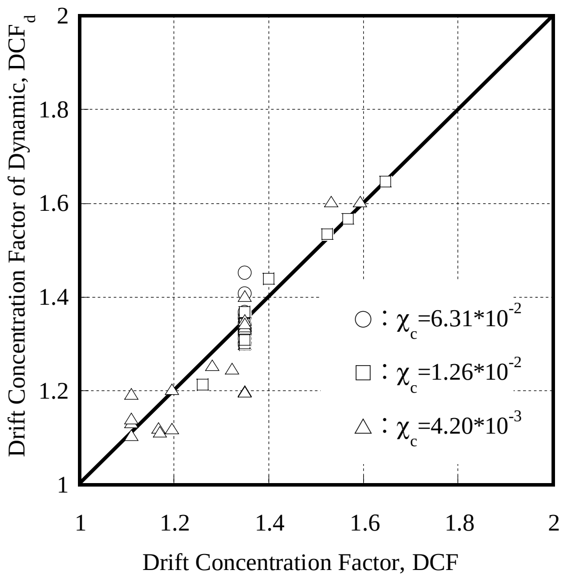


Figure 8 Comparison between dynamic DCF_d and static DCF

4. CONCLUSIONS

Pushover and dynamic inelastic time history analyses are performed on concentrically braced frames with continuous columns fixed at base to investigate the effect of column flexural stiffness and strength. It was shown that:

1) Continuous columns over the height of the structure may be seismic and gravity columns. These boundary conditions at the base, are influenced with the drift concentration of the structure. DCF for the braced frames with pinned column base, gradually decreases as column stiffness ratio, as α increases. But DCF for those with fixed column base, suddenly decreases and converges a value, as

column stiffness ratio, α, increases.

2) The drift concentration fixed at base is related to the strength of the continuous columns. DCF for low column strength ratio, χ_c, early becomes low, as α increases. And DCF for high χ_c, keeps high even though α increases.
3) Equations (7) and (9) approximately estimate static DCF for the brace frame with fixed column base.
4) Peak drift concentration is almost equal to the static demand for the same roof ductility. So Equation (7) and (9) is available to estimate the dynamic drift concentration for two story frames with fixed column base.

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