8CUEE CONFERENCE PROCEEDINGS
8th International Conference on Urban Earthquake Engineering
March 7-8, 2011, Tokyo Institute of Technology, Tokyo, Japan

SEISMIC DAMAGE MECHANISM CONTROL OF RC DUCTILE FRAMES FROM A STIFFNESS POINT OF VIEW

Zhe Qu[1], Lieping Ye[2], Akira Wada[3]

1) Postdoctoral research fellow, Center for Urban Earthquake Engineering, Tokyo Institute of Technology, Japan
2) Professor, Department of Civil Engineering, Tsinghua University, China
3) Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Japan
m.quzhe@gmail.com, ylp@tsinghua.edu.cn, wada@serc.titech.ac.jp

Abstract: Devastating earthquakes have shown the difficulty in preventing weak story failure in ductile moment resisting frames. Rather than relying on the strength hierarchy between columns and beams, it is attempted to handle this problem by providing additional continuous stiffness to the frame. The effect of continuous stiffness on the story drift concentration of frame structures is evaluated through nonlinear dynamic analysis. Preliminary equation of estimating the continuous stiffness demand is obtained. A rocking wall-frame system to implement continuous stiffness in concrete structures is then introduced. The effectiveness of rocking walls to control the deformation pattern of reinforced concrete frames is demonstrated through numerical simulations of an example rocking wall-frame structure.

1. INTRODUCTION

The difficulty in suppressing the unintended weak story failure in frame structures is evident from building damages in devastating earthquakes (Villeverda 1991; AIJ, 1991; Ye, 2009). As a well-known effort to control the failure mechanism of concrete structures, the capacity design methodology developed by Paulay and Priestley (1980, 1992) has lead to a widely accepted concept of strong column-weak beam for seismic design of ductile moment-resisting frames. Some amplification factor is applied to the flexural strength demands for columns as stipulated in major seismic codes in the world for decades in the hope of better ensuring the global failure mechanism (SNZ, 2004; ACI, 2005; GB50011, 2001). Such kind of design measures have, however, been frequently questioned by the professions in view of the many unintended weak story failures that actually happened in strong earthquakes (Bondy, 1996; Villaverde, 1997; Ye, 2009).

Strong column-weak beam type global failure mechanism should not be the ultimate goal of seismic design. Rather, it's only one of the ideas to control the deformation pattern in ductile frames and to prevent weak story failure. Rather than the strength hierarchy between beams and columns, MacRae *et al* (2004) revealed that continuous columns (e.g. gravity columns) in concentrically braced frames can reduce the story drift concentration. This effect was also examined by Ji *et al* (2010) in a more analytical manner. Tagawa (2005) extends this effort to moment-resisting steel frames. The appreciation of the global effect of continuous stiffness over the height of the structure may lead to another and more promising solution for the prevention of weak-story mechanism. In what follows, the relationship between continuous stiffness and inter-story drift concentration is examined. Rocking wall-frame system for multi-story reinforced concrete structure is introduced and its efficiency is demonstrated through numerical analysis.

2. EFFECT OF CONTINUOUS STIFFNESS

2.1 Numerical model

Lumped-mass shear model with continuous column is adopted herein to evaluate the effect of continuous stiffness on the story drift concentration, where the shear model represents the ductile moment-resisting frame. The continuous column is connected to the lumped mass by ideal horizontal links. The shear springs have peak-oriented hysteresis and continuous column is assumed linearly elastic and pinned at the bottom. Each lumped mass has only 1 DOF in the horizontal direction. The effect of vertical loads is not considered.

9, 6 and 3-story models are considered. It is assumed for all the models that the story stiffness and mass is identical for every story in the moment frame and the fundamental period of the frame is tuned to be $0.1N$, where N is the number of story. The shear strengths of each story are proportioned in accordance with the Chinese seismic code (GB50011, 2001).

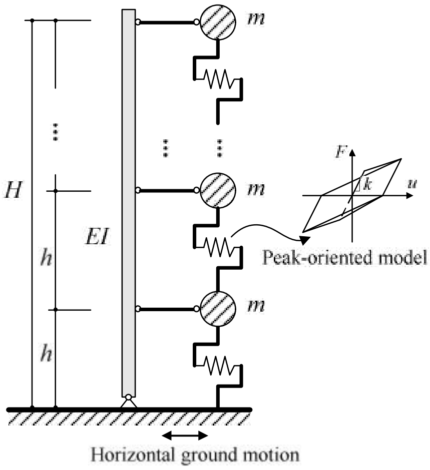


Figure 1 Lumped mass model with continuous column

As suggested by MacRae *et al* (2004), stiffness ratio α as defined in Equation 1 is used herein as a dimensionless measure of the continuous stiffness.

$$\alpha = \frac{EI}{kh^3} \tag{1}$$

where EI is the sectional bending stiffness of the continuous column, h is story height and k is story stiffness of the frame.

In the following discussion, α varies in the range of 0.001 to 10 by proportioning the cross section of the continuous column.

The models are subjected to a suite of 22 ground motion records selected from the PEER/NGA strong motion database as well as the China Strong Motion Network Center (CSMNC) database of the 2008 Wenchuan earthquake. All the ground motions are scaled so that the spectral acceleration at the structure's fundamental period $S_a(T_1)$ equals $\alpha_1 g$, where α_1 is the base shear coefficient in the seismic code and g is the acceleration of gravity.

2.2 Relationship of drift concentration-stiffness ratio

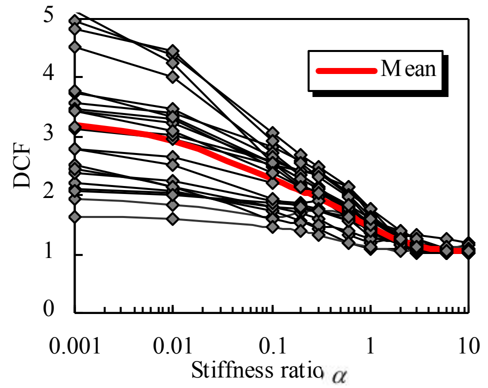
Nonlinear dynamic analysis is carried out and the drift concentration factor (DCF) results are shown in Figure 2. DCF is defined in Equation 2.

$$\mathrm{DCF} = \frac{\mathrm{IDR}_{\max}}{u_r/H} \tag{2}$$

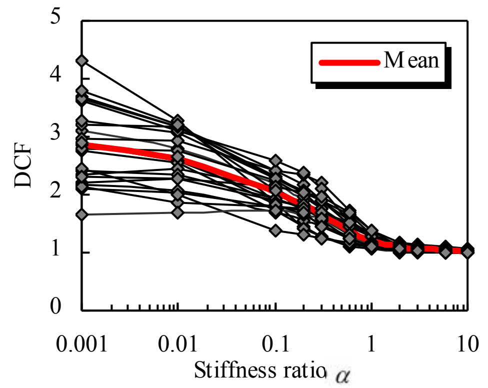
where $\mathrm{IDR}_{\max}$ is the maximum inter-story drift ratio among stories. u_r is the roof displacement and H is the total height of the structure.

DCF is considered as a measure of uniformity of the deformation pattern over the height of the structure. It is observed that DCF decreases rapidly with the increase of stiffness ratio α, suggesting that the continuous stiffness is very effective in reducing the inter-story drift concentration.

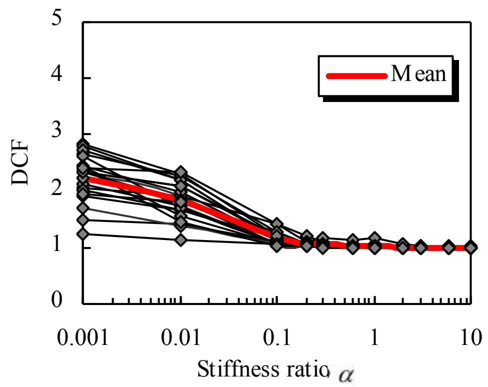
Besides, DCFs in higher structures are larger until α is large enough to produce a unity DCF, in which cases the continuous columns behaves almost like a rigid body rotating around the base pin.



(a) 9 story



(b) 6 story



(c) 3 story

Figure 2 Relationship between drift concentration factor (DCF) and stiffness ratio α

2.3 Continuous stiffness demand

Controlling target of DCF needs to be carefully chosen so that it can ensure high probability that weak story failure mechanism can be suppressed. It's considered not practical and also not necessary to require the DCF to be unity since unreasonably large continuous stiffness would be required. Here the DCF of the 1st mode vibration of the structure is simply selected as the controlling target. The required α (denoted as α_{dem}) can be collected from the average curve of the above results for structures with different numbers of stories (Figure 3a). When plotted against the number of stories, α_{dem} shows an almost linear relationship with the number of storiy (Figure 3b).

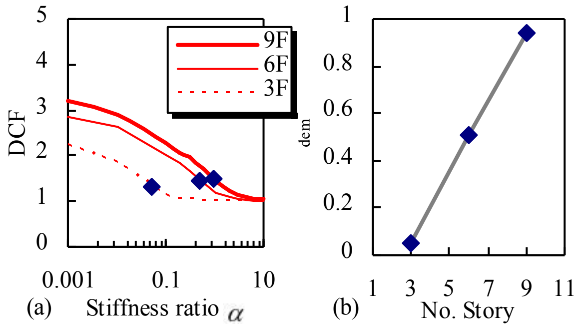


Figure 3 Relationship of number of story and demand stiffness ratio α_{dem}

Quantitative relation between α_{dem} and number of story N can then be found by linear regression as shown in Equation 3. With this equation, the required continuous stiffness can be readily estimated only from the number of story, based on which the cross sections of the continuous components can be checked and determined.

$$\alpha_{\text{dem}} = 0.148N - 0.368 \tag{3}$$

In what follows, this equation is used to estimate the required stiffness of rocking wall in order to prevent weak story failure in reinforced concrete moment frames.

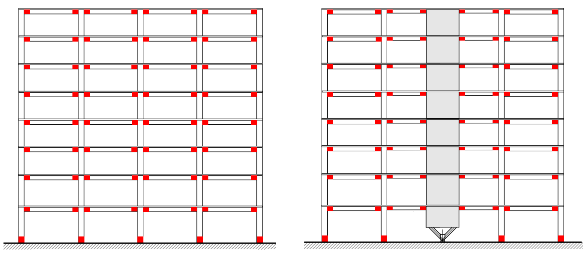
3. CONTINUOUS STIFFNESS IN RC FRAME

3.1 Introduction to rocking walls

In steel frames, gravity columns serve as the continuous components that provide continuous stiffness to mitigate the risk of weak story collapse. In reinforced concrete frames, however, it's not easy to construct such gravity columns. Instead, concrete walls often provide strong resistance to weak story failure if shear failure in the wall can be successfully prevented. An innovative solution is provided and demonstrated by the retrofit project of G3 Building on the Suzukakedai campus of Tokyo Tech, in which post-tensioned continuous concrete walls with pin bearing at the bottom (so-called "rocking walls") are attached to the existing steel reinforced concrete frame (Wada *et al*, 2009).

To verify the effectiveness of rocking walls in controlling the deformation pattern, reinforced concrete (RC) moment frame as shown in Figure 4a is enhanced by replacing the middle column with a piece of rocking wall (Figure 4b). Their responses to strong ground motions are evaluated through nonlinear dynamic analysis.

The original RC frame is 8-story high and is seismically designed in accordance with the Chinese seismic code (GB50011, 2001). In the lower 4 stories, column cross section is 600×800mm and beam cross section is 350×700mm. In the upper 4 stories, the cross sections are reduced to 600×600mm for columns and 300×700mm for beams.



(a) Pure frame (F) (b) Rocking wall-frame (RWF)

Figure 4 Pure frame and rocking wall-frame

In the rocking wall-frame structure (Figure 4b), the cross section dimensions of the rocking wall are determined based on the required continuous stiffness EI calculated from Equation 3. However, an amplification factor of 2.0 is imposed to consider the stiffness loss due to cracking of the rocking wall. The resulting cross section of the rocking wall is 3600×300mm. The reinforcement of the rocking wall is shown in Figure 5. The rocking wall is supported by steel pin-bearing at the bottom which can resist large shear force while providing little rotational constraint.

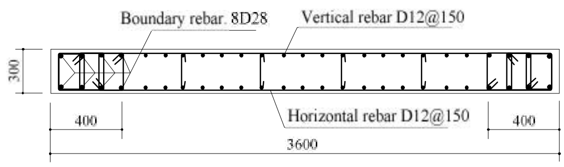


Figure 5 Reinforcement of rocking wall

3.2 Numerical assessment of damage mechanism

The above pure frame (F) and the rocking wall-frame (RWF) are modeled by fiber-based beam element in ABAQUS 6.8 with user-defined material models for concrete and steel fibers. Details of the user-defined material models can be found in Qu (2009). A set of 10 ground motion records are used as earthquake input, which is a subset of the above mentioned 22 ground motions used to evaluate the relationship between DCF and stiffness ratio α. In order to provide an identical earthquake scenario, the ground motions are scaled by non-structure-specific intensity measure PGV, rather than $S_a(T_1)$ as previously did. All the records are scaled to PGV=50cm/s.

3.3 Results and discussions

Inter-story drift ratio (IDR) responses of the rocking wall-frame (RWF) to the ground motion set are shown in Figure 6, where the mean and one deviation responses are compared with those of the pure frame (F). It is obvious that the maximum inter-story drift of the rocking wall-frame is much smaller than that of the pure frame. Most importantly, deformation in the rocking wall-frame is more uniformly distribution over the height of the structure compared to the pure frame. The drift concentration factors (DCF) of rocking wall-frame under various ground motions are much smaller than those of the pure frame (Figure 7).

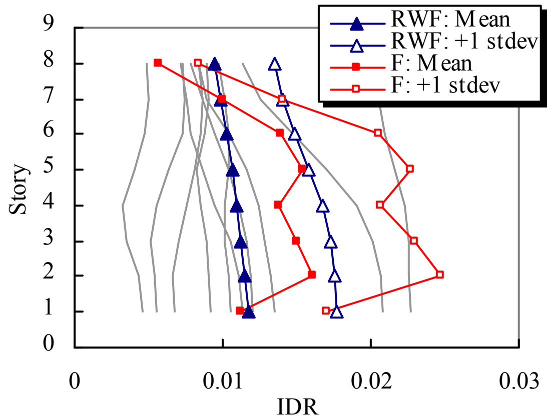


Figure 6 Inter-story drift ratios (IDR) of rocking wall-frame

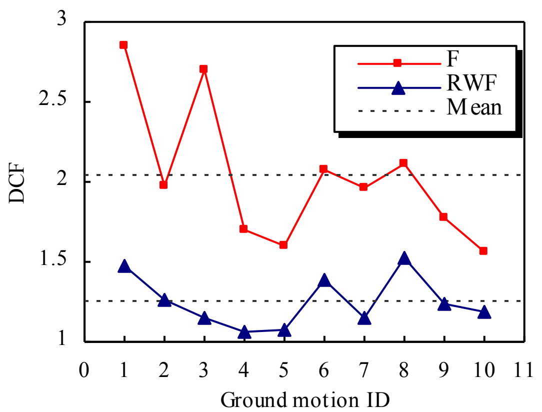
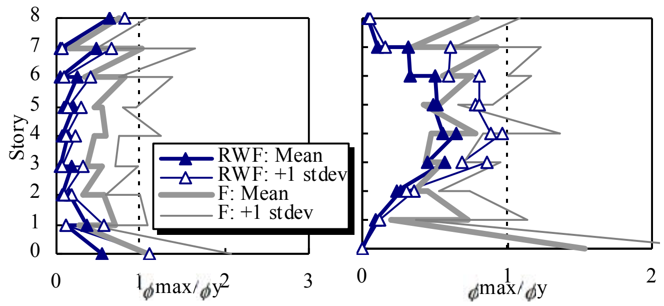


Figure 7 Drift concentration factors (DCF) of rocking wall-frame and pure frame

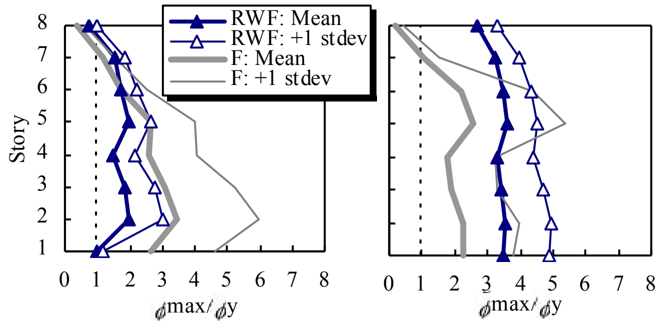
In terms of curvature ductility ϕ_{max}/ϕ_y, Figure 8 and 9 compare the damage mechanism of the rocking wall-frame and pure frame. There's only marginal damage in the rocking wall and columns in the rocking-wall frame structure as the mean and one deviation ductility are almost below 1.0 (Figure 8). On the other hand, damages to the beam ends in the middle span of the rocking wall-frame are increased and more uniformly distributed (Figure 9). They concentrate the energy dissipation of the whole structure.

From these results, the effectiveness of the rocking wall to control the deformation patter and damage mechanism is demonstrated.



(a) Side column (b) Rocking wall

Figure 8 Curvature ductility (ϕ_{max}/ϕ_y) in columns and rocking wall



(a) Beam in the side span (b) Beam in the middle span

Figure 9 Curvature ductility (ϕ_{max}/ϕ_y) in beams

4. CONCLUSIONS

An attempt is made to control the seismic damage mechanism and to prevent weak-story failure in ductile moment frames by continuous stiffness. The effect of continuous stiffness on the drift concentration of frame structures are evaluated through simple numerical models and preliminary equation of estimating the required stiffness ratio α is obtained assuming the controlling target to be the DCF of the 1st mode vibration. Rocking wall-frame system is introduced as a manner to increase the continuous stiffness for reinforced concrete frame. A case study of an 8-story ductile RC frame is provided which demonstrated the effectiveness of the rocking wall to control the seismic damage mechanism.

Acknowledgements:

The authors acknowledge support from National Natural Science Foundation of China (Major program No. 90815025), Ph.D. Programs Foundation of Ministry of Education of China (No. 200800030001) and Special program fund of Ministry of Construction of China.

References:

ACI 318M-05 (2005), "Building code requirements for structural concrete and commentary". Farmington Hills, Michigan, US: American Concrete Institute.

AIJ (1997), "Report on the Hanshin-Awaji earthquake disaster-Building series volume 1: Structural damage to reinforced concrete building". AIJ. (in Japanese)

GB50011 (2001), “Code for seismic design of buildings”. Ministry of Construction of China, Beijing.
Ji, X.D., Kata, M., Wang, T. et al. (2009), “Effect of gravity columns on mitigation of drift concentration for braced frames”. *Journal of Constructional Steel Research*, **65**(12), 2148-2156.
MacRae, G.A., Kimura, Y., Roeder, C. (2004), “Effect of column stiffness on braced frame seismic behavior”. *Journal of Structural Engineering, ASCE*, 130(3), 381-391.
Paulay, T. (1983), “Deterministic design procedures for ductile frames in seismic areas”. *ACI publication*, **SP-63**, 357-381.
Paulay, T., Priestley, M.J.N. (1992), “Seismic design of reinforced concrete and masonry buildings.” New York: John Wiley & Sons, Inc.
Qu, Z. (2010), “Study on seismic damage mechanism control and design of rocking wall-frame structures.” Beijing: Doctor thesis, Tsinghua University. (in Chinese)
SNZ (2004), “Concrete structures standard (NZS 3101.1).” Standards New Zealand, Wellington, New Zealand.
Tagawa, H. (2005), “Towards an understanding of seismic response of 3D structures - stability & reliability”. Doctor Thesis, Washington: University of Washington.
Villaverde, R. (1991), “Explanation for the numerous upper floor collapses during the 1985 Mexico City earthquake.” *Earthquake Engineering & Structural Dynamics*, **20**(3), 223-241.
Villaverde, R. (1997), “Discussion of ‘A more rational approach to capacity design of seismic moment frame columns’ By K. Dirk Bondy.” *Earthquake Spectra*, **13**(2), 321-322.
Ye, L.P., Lu, X.Z., Zhao, S.C., et al. (2009), “Seismic collapse resistance of RC frame structures.” *Journal of Building Structures*, **30**(6), 67-76. (in Chinese)
Wada, A., Qu, Z., Ito, H., et al. (2009) “Seismic retrofit using rocking walls and steel dampers”. Proc. ATC/SEI Conference on Improving The Seismic Performance of Existing Buildings and Other Structures, San Francisco, CA, U.S., Dec. 2009