Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

THE RESPONSE OF THE COLUMNS OF SPECIAL MOMENT FRAMES UNDER AXIAL AND LATERAL LOADING CYCLES

MOJTABA FARAHI and SAEED ERFANI

Civil Engineering Dept, Amirkabir University of Technology, Tehran, Iran

In order to assess the boundaries of the simultaneous demands on the column members of Special Moment Frames (SMFs), a thorough investigation in the following research were performed on several different archetype frames. Beside the boundaries of the simultaneous seismic demands, the fluctuation of these demands was also analyzed after numerous non-linear dynamic analyses on sample SMFs. These analyses paved the way to establish a representative framework for loading the column members in order to represent the seismic demands expected to be developed on these members. The maximum story drift among all analyses did not exceed 0.06, while a peak axial force more than 30% of their nominal axial yield strength was not captured among all the columns of the sample frames. Chosen archetype columns were loaded under introduced loading framework, and their response compared with the responses of the same columns when the lateral loading is implemented in conjunction with a constant level of axial loading.

Keywords: Column Members, Dual Loading Protocol, Seismic Demands, Bending and Axial Loading Interaction.

1 INTRODUCTION

There is no doubt that column members are prone to resist large story drifts and consequently bending moments while they also tolerate an axial force during a seismic event. Although these members have been subject of some studies and experiments until now; most of the previous research programs focused on the response of the column members under lateral drift histories while the axial force level in these members was assumed to be constant. Almost all of the experiments conducted on these members were under the same loading regime with a constant axial load in conjunction with lateral drift cycles (Kurata *et al.* 2005, Nakashima and Liu 2005, Xiao *et al.* 2009). There were differences between these experimental studies in terms of loading protocols and the maximum demands imposed on the samples. However, the effect of simultaneous change of the axial force demand on columns along with the change of plastic rotation in these members was neglected in all of them. On the other hand, the utilized loading frameworks in different research studies were introduced quite arbitrarily and with no root in the real seismic demands of these structural members. Hence, it was tried to develop a representative loading framework with robust reference to the realistic seismic demands on the columns of Special Moment Frames (SMFs). Simplified rain flow procedure was used by other researchers to establish loading protocols for different structural members (Krawinkler *et al.* 2000, Richards and Uang 2006, Newell and Uang 2008). This procedure was utilized again here to develop a representative dual loading protocol for the columns of SMFs during the evaluation of the seismic response of these members. Investigating the response of some column archetypes under the introduced dual loading protocol was the last part of this research.

2 SEISMIC DEMANDS ON THE COLUMNS OF SMFs

Three, six and ten-stories buildings with SMF lateral load resisting systems and with different plans were designed according to AISC 360-10 (2010). The seismic provisions of AISC 341-10 (2010) were also used to control the design of special moment frames of the archetype buildings. Maximum boundaries for seismic response spectral accelerations defined in FEMA P695 methodology (2009) were utilized to define the elastic equivalent earthquake load in order to evade a locally bias design. Totally, eight archetype buildings were designed under two levels of spectral accelerations represent the Maximum Credible Earthquake (MCE) and the Design Earthquake (DE).

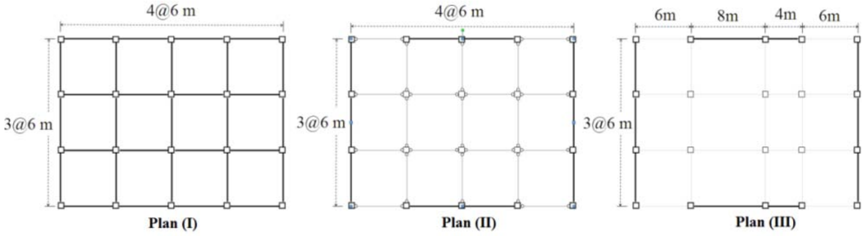

Figure 1. Plan view of the archetype buildings.

Nonlinear dynamic analyses were then performed on the sample moment frames of the designed archetype buildings. The nonlinear numerical models of these sample SMFs were developed with the aid of OpenSees software. Both geometric and material nonlinearities were taken into account. Far-field earthquake record set proposed by FEMA P696 was utilized in this study to conduct the required time history analyses. This set includes 44 individual seismic records with different magnitudes and other specifications. Each sample SMF was excited by each of the individual records with two different intensity levels referring to DE and MCE respectively.

The axial force and story drift ratio time histories for each column in each sample SMF were then extracted from the results of the dynamic analyses. Next, these time histories were converted to the series of symmetric cycles using the rain flow cycle counting method (Krawinkler *et al.* 2000), which made it simpler to interpret the results and to perform some statistical analyses on them to develop the intended dual loading protocol. In order to assess the seismic demands on the column members, numbers of demand indexes then calculated based on the response of these members. The number of damaging cycles and the sum of damaging cycle ranges can be referred as the cumulative demand indexes. On the other hand, the maximum peak and range in each series of cycles are the extreme demand indexes. The calculated cumulative and extreme demand indexes on the first story side column of the 2-bay frame of the 6-story archetype building with plan (III) have been summarized in Table 1. These demand indexes represent the results of the analyses under only the first ten records of the record set scaled to the MCE seismic intensity level. It was proved in previous experiments on column members that the yielding is initiated in these members when the story drift ratio reaches to the values around 0.02 (Newell and Uang 2008). So, the drift ratio cycles with the peaks greater than one-half of this ratio (ranges greater than 0.02) were considered damaging ones, while the drift ratio cycles with the ranges smaller than 0.002 are omitted from the response cycles. Besides, cycles with the range less than 0.01 were discarded from the series of axial force ratio response cycles.

Table 1. The summary of story drift ratio demand indexes for a sample column.

Rec No.	**Total Cycles No. ***	**Damaging Cycles No.**	**Max Peaks**	**Max Range**	**Cumulative Damage**
1	107	40	0.011	0.017	0.205
2	98	48	0.010	0.017	0.306
3	101	51	0.044	0.041	0.444
4	98	36	0.012	0.015	0.217
5	120	47	0.019	0.026	0.344
6	85	31	0.008	0.012	0.200
7	86	37	0.008	0.014	0.205
8	93	36	0.015	0.022	0.291
9	204	89	0.012	0.016	0.502
10	202	64	0.018	0.029	0.444

* All Experienced Cycles (Cycles with range values smaller than 0.002 were not omitted)

The extreme and cumulative drift ratio demand indexes on the columns of the peripheral SMFs are exceeded those calculated for the columns of space SMFs at the both seismic motion intensities. Furthermore, greater maximum drift ratios and the relevant cumulative damage indexes were generally obtained for the columns of the 3-story frames in comparison with the other frames with different number of stories. As it was expected, maximum extreme demand indexes as well as the cumulative ones were captured in the columns of the first story of different SMFs where the axial gravity action is the maximum. These assessed indexes have also shown that the seismic response of the side columns in the SMFs with unequal spans is more critical than the response of the columns in the SMFs with equal spans. Although the story drift ratios increased considerably with the increment in the excitation intensity from DE to MCE, the increment in the axial force demand in the columns was negligible. The maximum story drift ratio captured for the columns of sample SMFs was about 0.06, and the peak axial force developed in one of the columns of the sample SMFs was close to 30% of its nominal axial capacity.

3 DEVELOPING DUAL LOADING PROTOCOL FOR THE COLUMNS OF SPECIAL MOMENT FRAMES

A representative loading framework was also designed for the loading of the column members of SMFs. As the main concept of developing such a loading framework, the proposed loading protocol should result in the same demand indexes as the indexes evaluated during the mentioned analyses (Krawinkler *et al.* 2000). This loading framework was developed based on the seismic response (the drift ratio and axial force ratio time histories) of the critical columns under the both levels of base excitations. The column with the maximum cumulative demand indexes for each of the both seismic demands of the interest was chosen as the critical column.

Table 2. Suggested lateral loading protocol (seismic Intensity level DE).

Load Step	Drift Ratio Range	No. of Cycles
1	0.002	12
2	0.006	12
3	0.01	12
4	0.015	10
5	0.025	6
6	0.04	4
7	0.06	3
8	0.08	1

Table 3. Suggested lateral loading protocol (seismic Intensity level MCE).

Load Step	Drift Ratio Range	No. of Cycles
1	0.004	12
2	0.006	12
3	0.012	10
4	0.015	10
5	0.025	6
6	0.04	6
7	0.06	2
8	0.08	1
9	0.12	1

Percentile values were calculated for the response cycles of the critical columns under the different seismic records and then lognormal distributions were fitted to these values. As the next step, the percentile values that represent reasonable target demand values for the intended dual loading protocol were extracted. As an instance, the average number of cycles captured in the response of the critical member under the seismic excitations was suggested as the total number of cycles in the representative loading protocol (Krawinkler *et al.* 2000). The cumulative cyclic ranges and the maximum cyclic range and peak that is caused by the suggested axial and lateral loading protocols should be also consistent with the 90% values obtained for the relevant response cycles of the critical columns. These percentile values determine some criteria for the intended loading protocols, while its whole framework can be finalized referring to the Cumulative Density Function (CDF) fitted to the response cycles of the critical columns. If the CDF for the cycles of each of the loading protocols is developed, it should be close to the CDF of response cycles of the relevant critical column. Based on the mentioned methodology, the drift ratio loading protocols introduced in Table 2 and Table 3 have been developed in order to represent the drift ratio cycles imposed to a column during seismic events with different DE and MCE intensity levels. Furthermore, a unique axial loading protocol was developed for the both seismic intensity levels DE and MCE since there was not a considerable difference between the axial force demands captured in the columns of the sample SMFs at these both seismic intensity levels. It was also assumed that the axial force cycles of the axial loading protocol would be applied in-phase with the story drift ratio cycles of the lateral loading protocol. Table 4 summarizes the axial loading protocol which was also offset in the purpose that the effect of initial gravity loading would be preserved.

Table 4. Suggested Axial loading protocol.

Load Step	**Axial Force Ratio Peak**	**No. of Cycles**
1	**-12.15**	**12**
2	**-12.15**	**12**
3	**-12.15**	**12**
4	**-10.15**	**10**
5	**-6.15**	**6**
6	**-4.15**	**4**
7	**-4.15**	**4**

4 THE BEHAVIOUR OF ARCHETYPE COLUMNS UNDER THE PROPOSED CYCLIC LOADING FRAMEWORK

After the loading framework which can represent the realistic demands on column members during a seismic event has been developed, the behavior of some archetype columns can be deliberately investigated implementing the introduced loading protocols. Hence, the nonlinear micro finite element models were provided first for some Hollow Structural Sections (HSS) in ABAQUS software. The overall response of steel columns may be dominantly affected by the local effects like as local bucking at large deflections. Since micro finite element models are able to capture deliberately these kinds of local effects, this type of nonlinear modeling procedure was utilized in this part of the research. Square HSSs with different widths equal to 12,14,16,18 and 20 inches and with the same thickness of 5/8 inches were chosen as the archetype columns. All of these sections were assumed to be built up of ASTM A36 carbon steel material (2014) with the yield stress equal to 248 MPa (36 ksi). The loading protocols developed for MCE seismic intensity level was only implemented in this part to reach a better grasp of the highly non-linear response of the column archetypes.

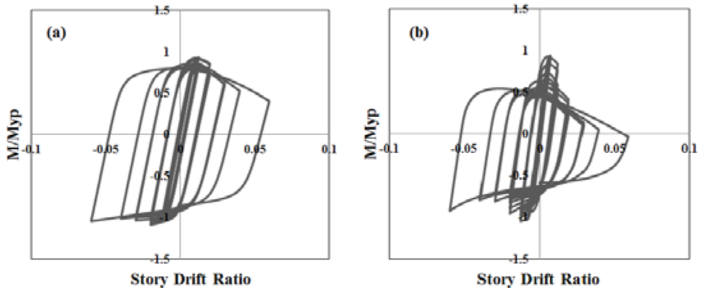

Figure 2. Moment-End rotation response of (a) HSS12×12×5/8, and (b) HSS 20×20×5/8 under the suggested loading framework.

The end moment- rotation responses of sections HSS12×12×5/8 as the most compact section and section HSS 20×20×5/8 as the most slender section have been depicted in Figure 2. As it is evident from these figures, the more slender a section is, the more deterioration could be expected in its strength during the loading. This fact could prove the dominant effect of the local buckling in the overall seismic response of a steel column. The negative post peak slope which captured in the hysteresis behavior of the columns also contradicts the accuracy of the convenient macro modeling procedures utilized to represent the behavior of these members with a simple linear or non-linear hardening.

5 SUMMARY

After performing numerous time history analyses, the boundaries and the characteristics of the axial force and the story drift ratio demands on columns were fairly established for the seismic events with MCE and DE intensity levels. It was proved that they might experience the axial force around 0.3 of their yielding capacity as well as the drift ratios up to 0.06. A representative loading framework which is based on the real seismic demands on column members was then developed for these members. Deliberate micro finite element modelling was also utilized to capture the detailed behavior of some archetype columns under the suggested loading protocol, and consequently the critical aspects of the seismic behavior of column members were highlighted.

References

AISC, Seismic provisions for structural steel buildings, ANSI/AISC 341-10, Chicago, 2010.

AISC, Specification for structural steel buildings, ANSI/AISC 360-10, Chicago, 2010.

ASTM A36/A36M-14, Standard Specification for Carbon Structural Steel, ASTM International, West Conshohocken, PA, 2014.

Federal Emergency Management Agency (FEMA), Quantification of building seismic performance factors, FEMA P695, Washington, DC, 2009.

Krawinkler, H., Gupta, A., Medina, R., and Luco, N., Loading histories for seismic performance testing of SMRF components and assemblies, Rep. SAC/BD-00/10, SAC Joint Venture, Sacramento, Calif, 2000.

Kurata, M., Nakashima, M., and Suita, K., Effect of Column Base Behavior on the Seismic Response of Steel Moment Frames, *Journal Of Earthquake Engineering*, 9(2), 415-438, 2005.

Nakashima, M., Liu, D., Instability and Complete Failure of Steel Columns Subjected to Cyclic Loading, *Journal of Engineering Mechanic*, 131, 559-567, 2005.

Newell, J., and Uang, C. M., Cyclic behavior of steel wide-flange columns subjected to large drift, *Journal of Structural Engineering*, 134(8), 1334-1342, 2008.

Richards, P., and Uang, C. M., Testing protocol for short links in eccentrically braced frames, *Journal of Structural Engineering*, 132(8), 1183–1191, 2006.

Xiao, Y., Li, H., and Zhou, T., Seismic behavior of wide-flange steel column with confined potential plastic hinge, *Journal of Constructional Steel Research*, 65, 808-817, 2009.