Highrise Building Response Comparison—Use of Time Domain Scaling vs. Spectral Matching Input Ground Motion

Mohammad T. Bhuiyan
West Virginia State University
towhid@wvstateu.edu

Abstract

While performing non-linear response history analyses of highrise buildings, designers and researchers discover crucial modeling questions, including use of appropriately selected and scaled ground motion. Once appropriate ground motions are selected, the question becomes how these ground motion time histories can be modified to be compatible with the design target acceleration response spectrum. Modification can be performed in two ways: (a) direct time domain scaling of the acceleration time-histories of the ground motions, and (b) transforming the time-acceleration data into the frequency domain, making adjustments to be compatible with the target spectrum, and transforming back into the time domain. Both the methods are mentioned in *Guidelines for Performance-based Seismic Design of Tall Buildings* (PEER 2010/05) and FEMA P-1050-1, 2105 edition. ASCE 7-10 mentions the direct scaling approach but does not explicitly mention the other method. The objective of this paper is to determine the extent of differences in response of highrise buildings using both time domain scaled and frequency domain adjusted ground motions. For this purpose, several example structures were selected to be analyzed: (a) 42-story concrete dual core wall-frame structure, (b) 40-story steel space frame structure, and (c) 40-story buckling-restraint-braced frame structure. Detailed non-linear models of these structures were developed in PERFORM-3D, and seven sets of appropriate ground motions were selected for the non-linear time history analyses. Results from analyses show differences in the response of these buildings using time domain scaled and spectral matching input ground motions.

1. Introduction

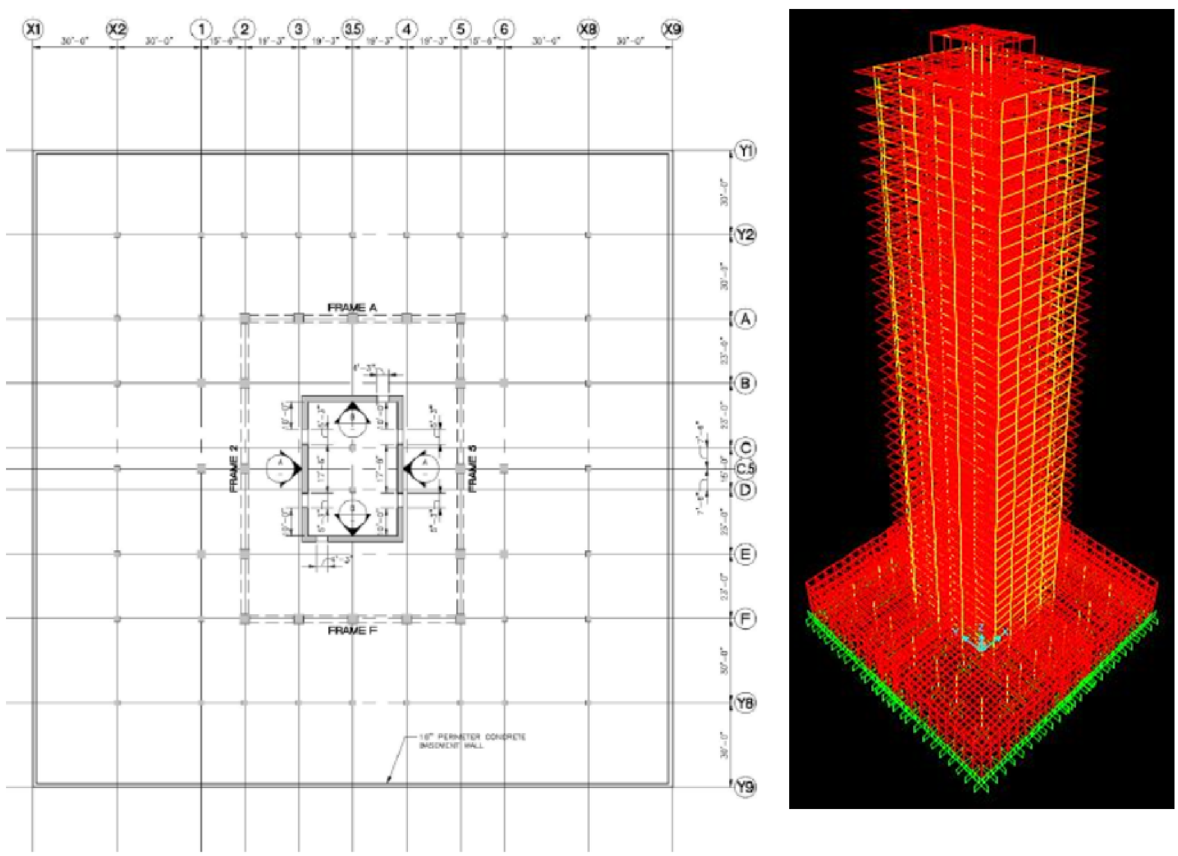
Recent decades have seen a surge in highrise building construction around the world in high seismic areas. While designing those buildings, it is of paramount importance to the designer to select appropriate ground motions and scale those motions for the numerical analysis and evaluation of the design. How to scale appropriately selected ground motion to be compatible with a target spectrum is an important decision for the designer. Two ways to do that are direct time domain scaling of ground motions and transforming the time-acceleration data into the frequency domain, making adjustments (to be compatible with the target spectrum), and transforming back into the time domain. Both methods are mentioned in building guidelines and codes. The objective of this paper is to determine the extent of differences in response of highrise buildings using both time domain scaled and frequency domain adjusted ground motions.

2. Case Study Buildings

Three structures were selected for this study: (a) 42-story concrete dual core wall-frame structure, (b) 40-story buckling-restraint-braced frame structure, and (c) 40-story steel space frame structure. The first two structures were used by Pacific Earthquake Engineering Research Center (PEER) “Tall Buildings Initiative” in their case studies (Moehle et al., 2011). The third structure was used by Hutt (2013) for his case study. Descriptions of those buildings are provided below.

2.1 42-Story Core Wall-Special Moment Frame

The buildings have 42 stories above ground, 4 stories below ground, and a penthouse as shown in Figure 1b. The dual systems have a core wall and four-bay special moment resisting frames at the perimeter of the building as shown in Figure 1a and b. A detailed non-linear model was developed in PERFORM-3D (2011) and a 3D rendering of the structure is shown in Figure 1b.



(a) (b)

Figure 1. (a) Typical plan view at ground floor and below (Moehle et al., 2011); (b) Three dimensional rendering of structure from PERFORM-3D model. Reprinted with permission.

2.2 40-Story Buckling-Restraint-Braced (BRB) Frame Structure

The footprint of the above ground structure is 170 ft by 107 ft as shown in Figure 2. It also shows the location of buckling-restrained chevron braces. The building consists of four basement levels as shown in Figure 3a. The footprint of the basement level is 227 ft by 220 ft. Lateral forces were entirely resisted by buckling-restraint braces. PERFORM 3D was used to develop a detailed non-linear model for the numerical analyses in this study.

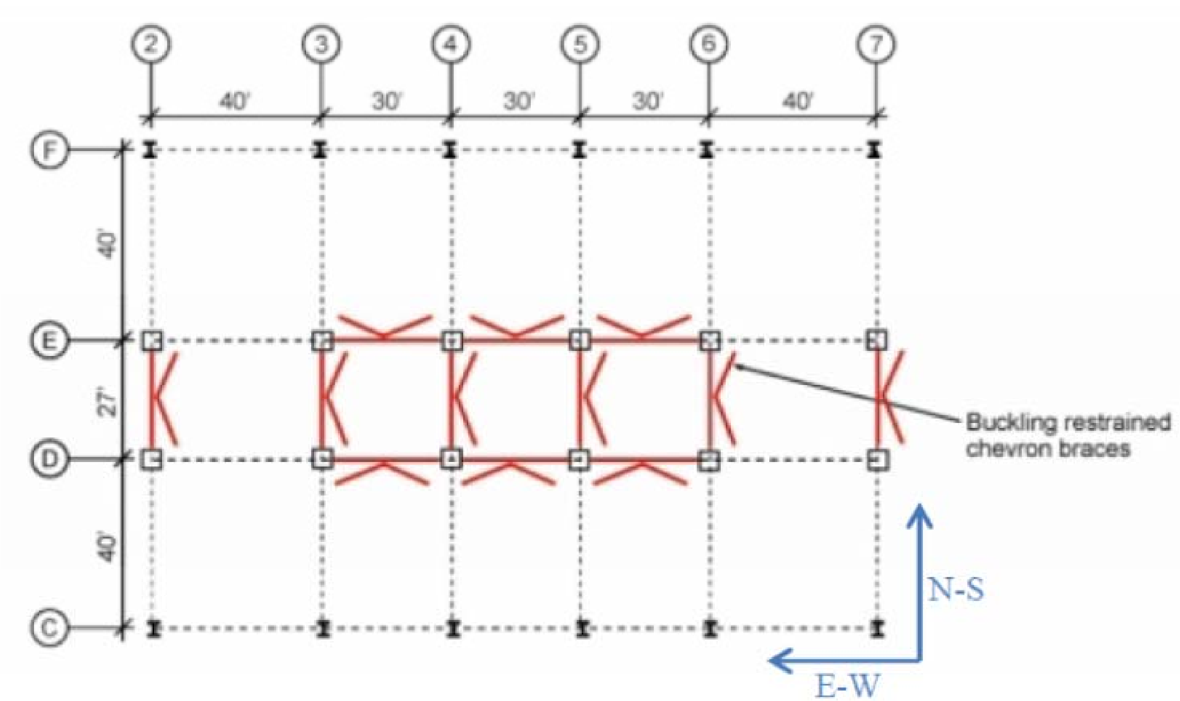
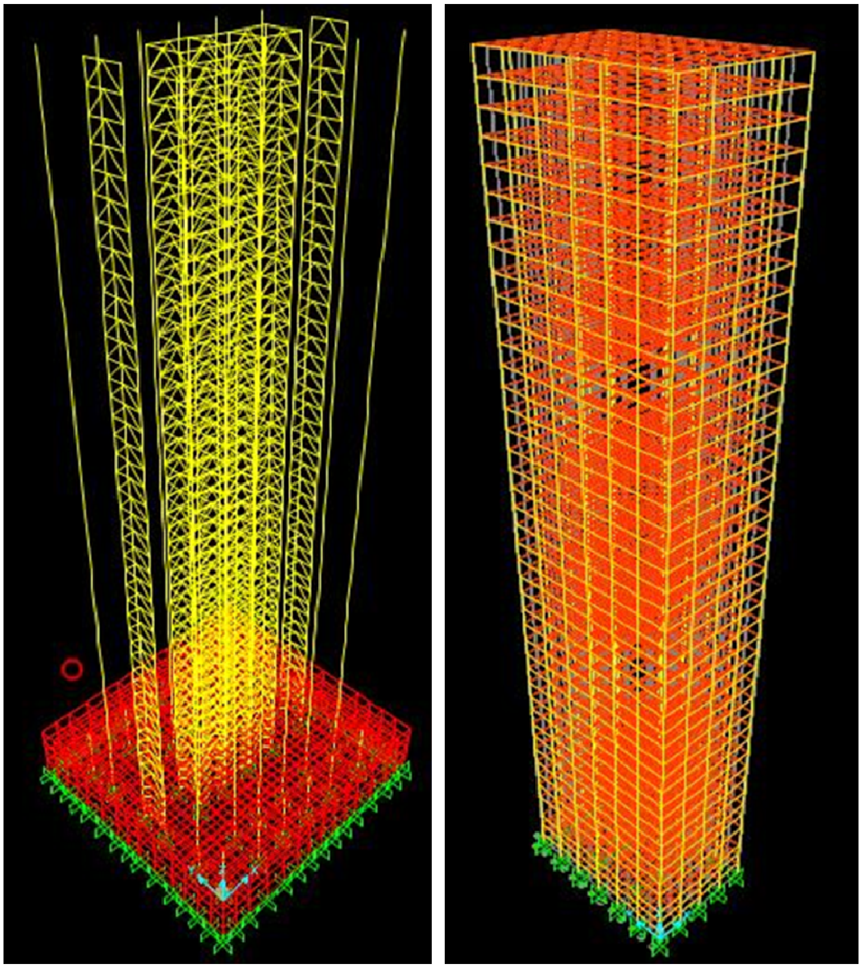


Figure 2. Typical plan view of the BRB building, above ground (Moehle et al., 2011). Reprinted with permission.

2.3 40-Story Steel Space Frame Structure

The steel space frame structure consists of special moment-resisting frames in both directions. This particular structure has three basement levels and a 120 ft by 80 ft footprint as shown in Figure 3b. Like the other two structures, detailed non-linear model was developed in PERFORM 3D (Figure 3b) for further study.



(a) (b)

Figure 3. (a) Three dimensional rendering of the BRB structure from PERFORM-3D model; (b) three-dimensional rendering of the space frame structure from PERFORM-3D model

3. Ground Motions Used in This Study

3.1 Spectral Matching Ground Motions

All the case study buildings are located in Log Angeles. Site-specific response spectra and a set of seven pairs of response spectrum compatible ground motions were provided by a research team from the PEER Center at University of California, Berkeley (Mahin, Yang, & Bozorgnia, 2008). The same spectra and spectrum compatible ground motions have been used by the PEER tall building initiative for analyzing tall concrete buildings. The actual recorded earthquake time histories listed in Table 1 were used and modified in frequency domain to match the target spectrum as shown in Figure 4. These seven pairs of ground motions will be called "frequency modified" motions in this paper.

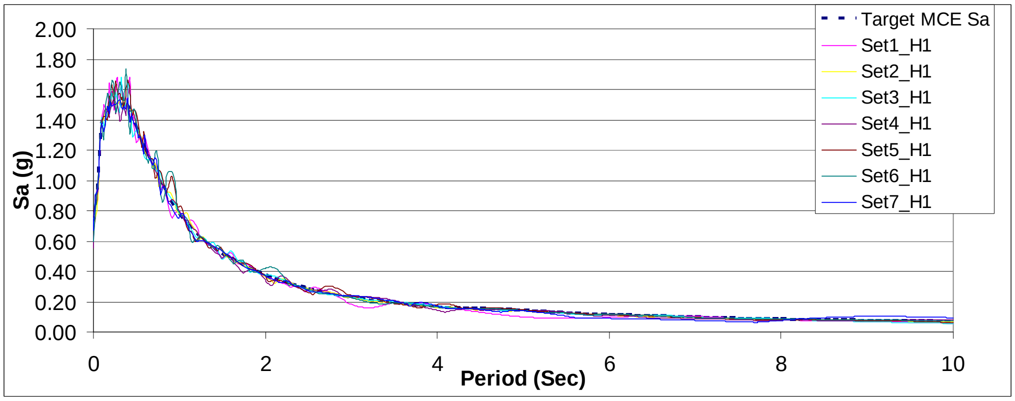


Figure 4. Site-specific response spectrum and seven pairs of spectrum compatible ground motions.

3.2 Time Domain Scaled Ground Motions

Time domain scaling requirements for 3D dynamic analysis are provided in Section 16.1.3.2 of ASCE 7-10:

> For each pair of horizontal ground motion components a square root of the sum of the squares (SRSS) spectrum shall be constructed by taking the SRSS of the 5-percent damped response spectra for the scaled components (where an identical scale factor is applied to both components of a pair). Each pair of motions shall be scaled such that for each period in the range from 0.2T to 1.5T, the average of the SRSS spectra from all horizontal component pairs does not fall below the corresponding ordinate of the design response spectrum, determined in accordance with Section 11.4.5 or 11.4.7. (ASCE, 2011)

The problem with these requirements is that no guidance is provided on how to deal with different fundamental periods in the two orthogonal directions. Because an infinite number of sets of scale factors will satisfy the criteria, different engineers are likely to obtain different sets of scale factors for the same ground motions (Soules, 2013).

This study uses the two-step scaling method followed in FEMA P-751 (National Institute of Building Sciences, 2012):

i) Scale each SRSS'd pair to the average period (T_{avg}) as shown in Figure 5. This factor will be different for each of SRSS spectra. This scale factor is denoted by S_1 in Table 1. Here T_{avg} is the average of the fundamental periods in each principal direction.

ii) As shown in Figure 6, the average of the scaled spectra will match the target spectrum at T_{avg}. Now a second factor (S_2 in Table 1) is applied equally to each motion (already scaled once) such that the scaled average spectrum lies above the target spectrum from $0.2T_{avg}$ to $1.5T_{avg}$.

The final scale factor for each motion is the product of the two-scale factors. Detailed calculation steps are provided in Table 1 for the 40-story buckling restraint braced frame structure. Figure 7 provides a comparison of target spectrum and the average SRSS spectrum of 7-pairs of motions after the scaling factor in Table 1 applied to the motions. These seven pairs of ground motions will be called “amplitude scaling” motions in this paper.

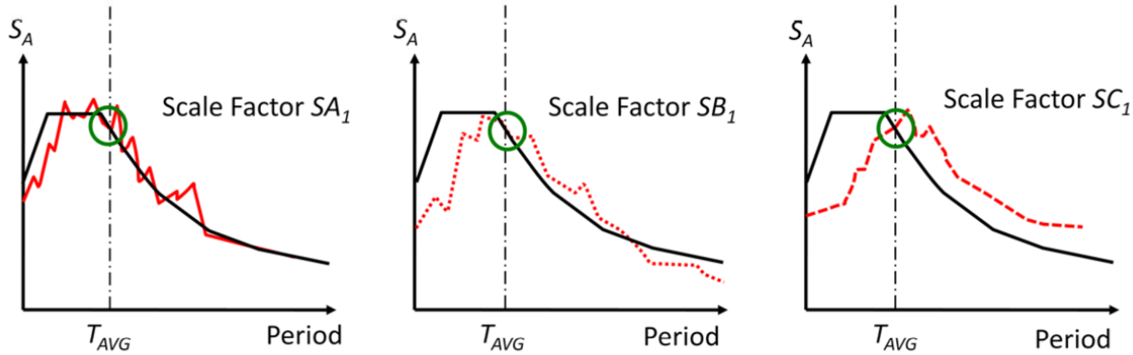


Figure 5. Step-1 of time-domain scaling (Soules, 2013).

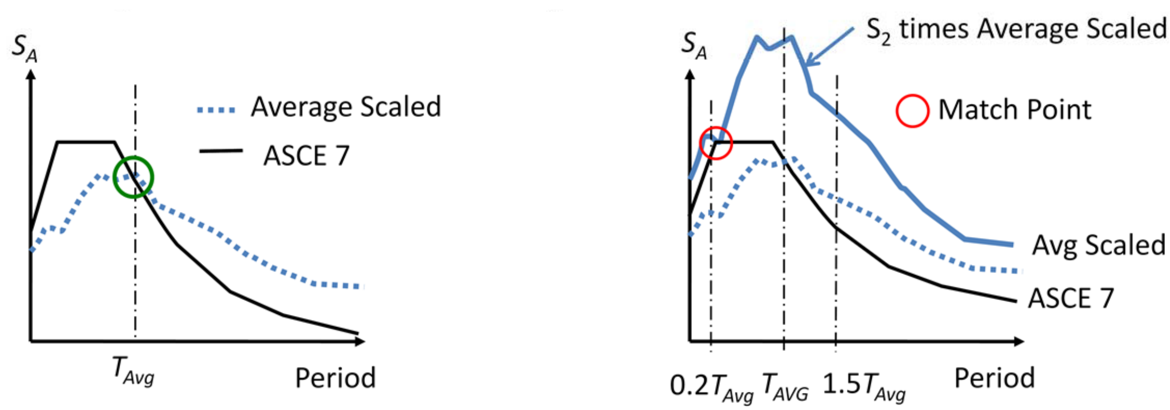


Figure 6. Step-2 of time-domain scaling (Soules, 2013).

Table 1. 40-story BRB scaling factor.

Record number	Earthquake Name	SRSS Ordinate at T=Tavg (g)	Target Ordinate at T=Tavg (g)	S_1	S_2	SS = S1*S2
Set 1	Superstition Hills-02	0.159	0.143	0.90	1.3	1.166
Set 2	Denali, Alaska	0.063	0.143	2.26	1.3	2.942
Set 3	Northridge-01 (Converter Sta)	0.155	0.143	0.92	1.3	1.193
Set 4	Loma Prieta	0.099	0.143	1.44	1.3	1.877
Set 5	Northridge-01 (Olive View Med FF)	0.102	0.143	1.39	1.3	1.812
Set 6	Landers	0.116	0.143	1.23	1.3	1.598
Set 7	Kocaeli, Turkey	0.078	0.143	1.81	1.3	2.357

ISBN 978-1-60643-379-9

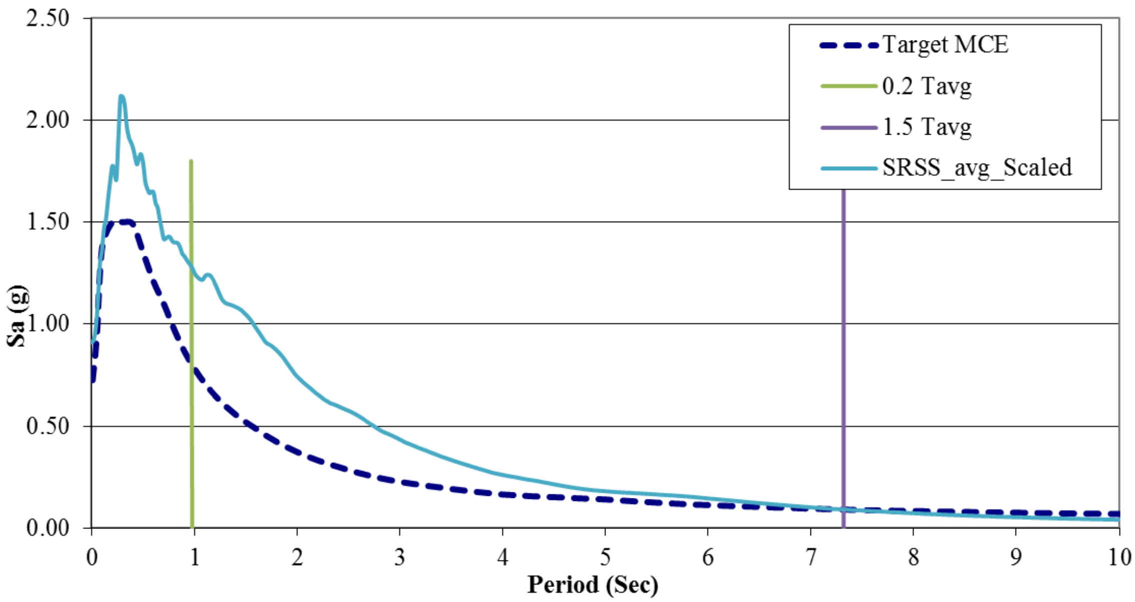


Figure 7. Average of SRSS spectrum after the application of scale factors listed in Table 1 for the buckling restraint braced frame structure.

4. Results

As mentioned in Section 2, detailed, three-dimensional, non-linear models for all three case study buildings were developed in PERFORM-3D software. Each building was subjected to 14 pairs of ground motions, seven from amplitude scaling and seven from frequency modification. All of the figures in this section follow the same style: solid lines represent amplitude scaling individual earthquake motion response, dotted lines represent “frequency modification” motion response, and bold lines represent the average of the motions. For the most part, comparison between amplitude scaling vs. frequency modification will be done by comparing the average response lines.

4.1 42-Story Core Wall-Special Moment Frame

Figures 8 to 13 summarize the analyses results and comparison between amplitude scaling and frequency modification for the 42-story core wall-special moment frame building.

Figures 8 and 9 compare the results of story shear and story moment for moment frame and core wall, respectively. Higher demands were exhibited by frequency modification motion for story shear and story moment compared to amplitude scaling, seen in Figure 9. Significantly higher levels of responses were observed for inter-story drift and floor acceleration for frequency modification motion, as can be seen in Figures 10 and 11. So, if acceleration-sensitive equipment were placed in the building, it will be wiser to use amplitude scaling motion to evaluate the building performance.

Figures 12 and 13 show the results of axial strain in core wall and coupling beam rotation, respectively. As can be seen, differences were not significant; at some story levels, frequency modification showed higher responses, and at other story levels, amplitude scaling showed higher responses.

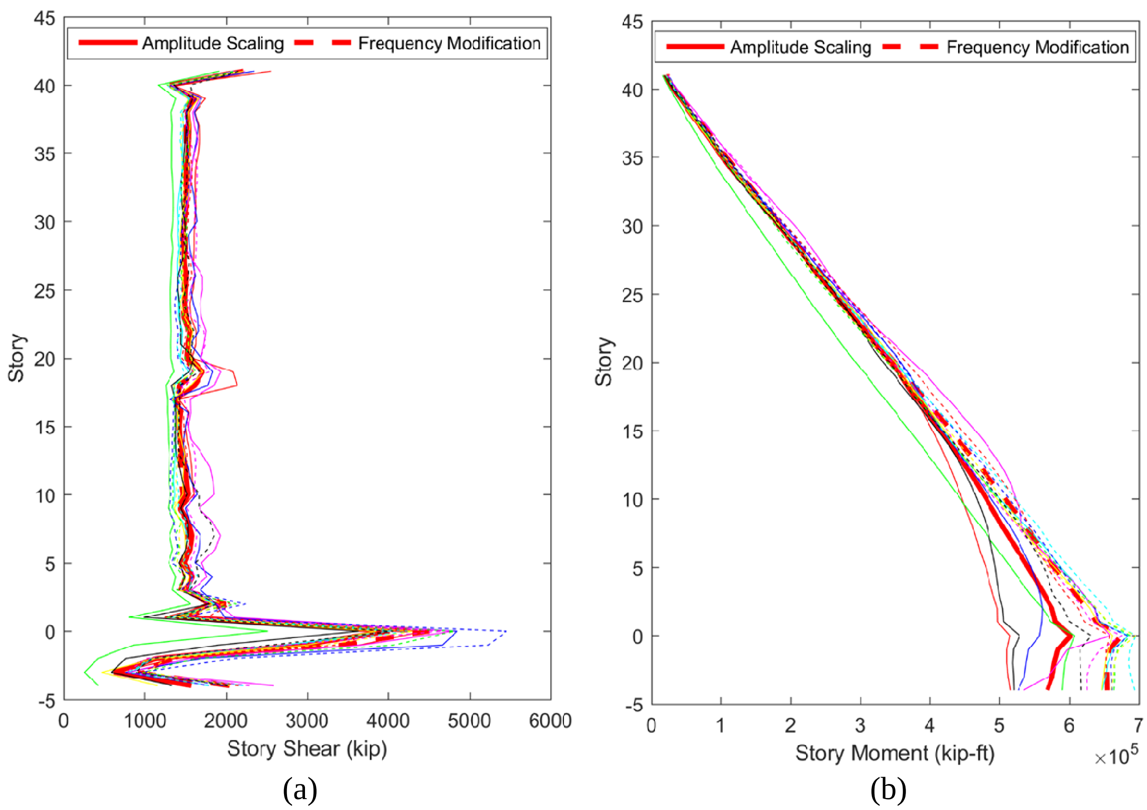
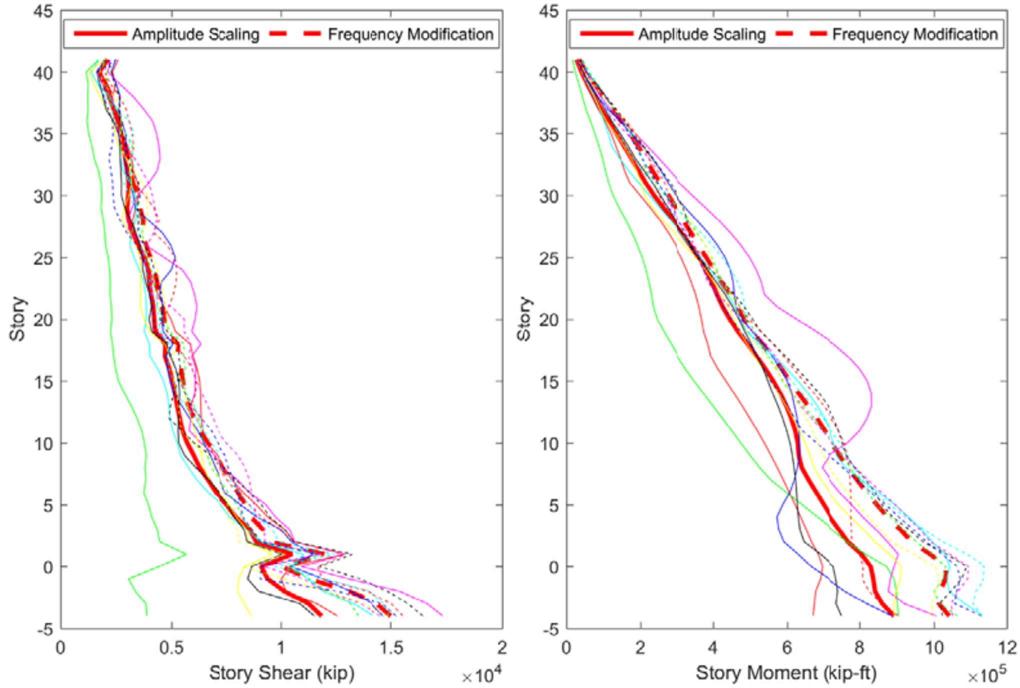
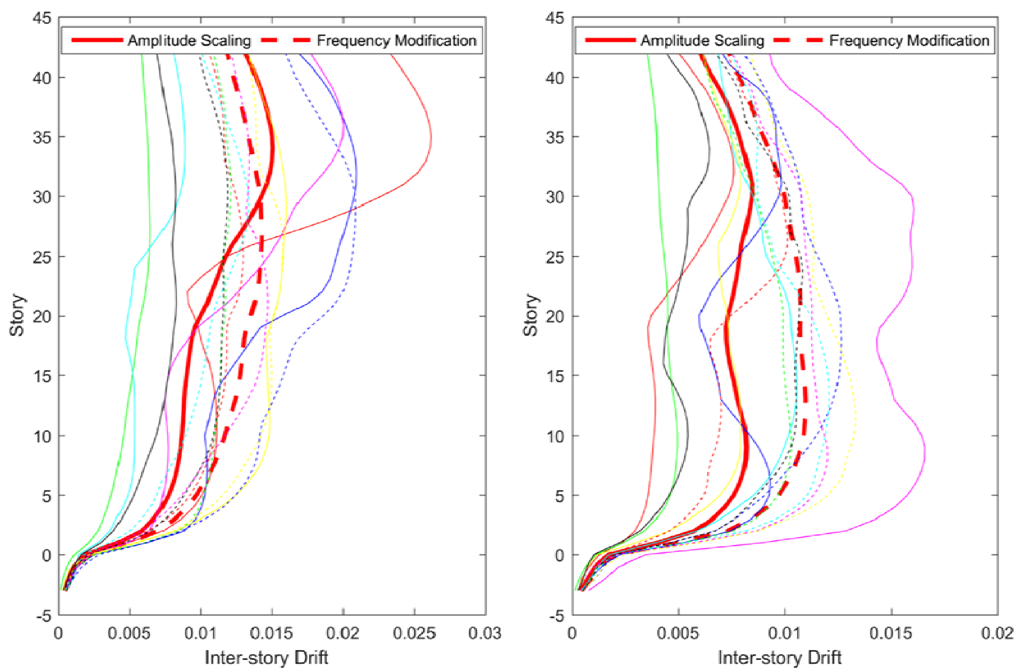


Figure 8. Moment frame; comparison of (a) Story shear; (b) Story moment. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



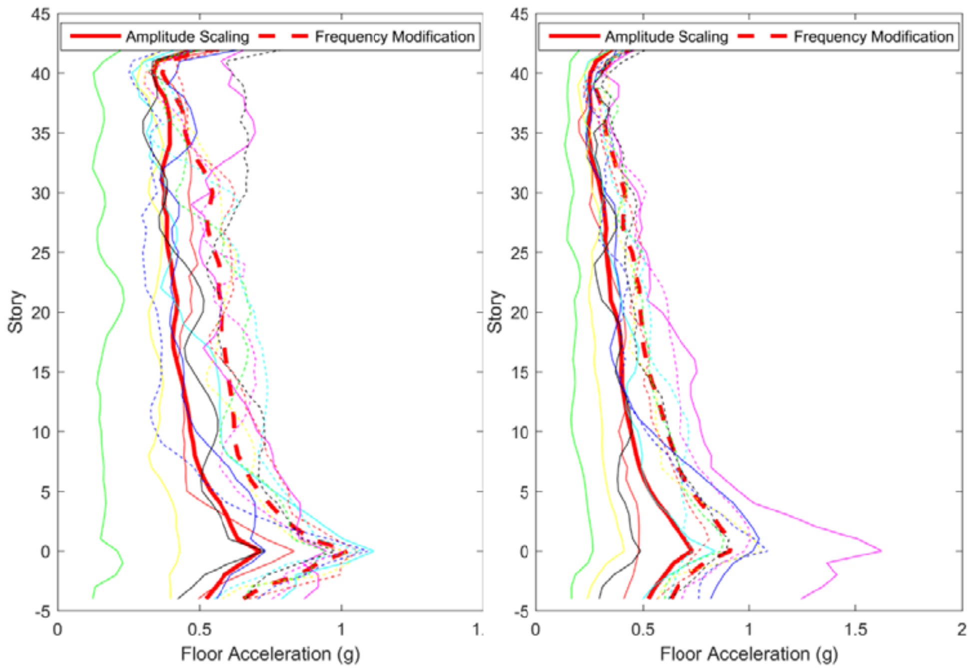
(a) (b)

Figure 9. Core wall; comparison of (a) Story shear; (b) Story moment. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



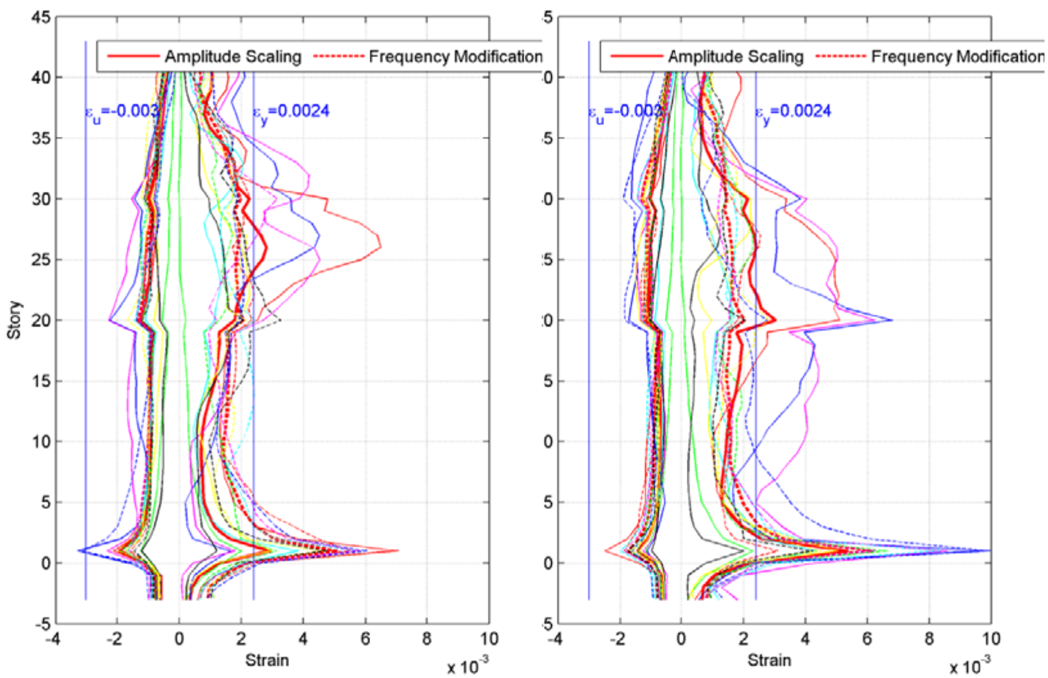
(a) (b)

Figure 10. Comparison of inter-story drift: (a) EW drift; (b) NS drift. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



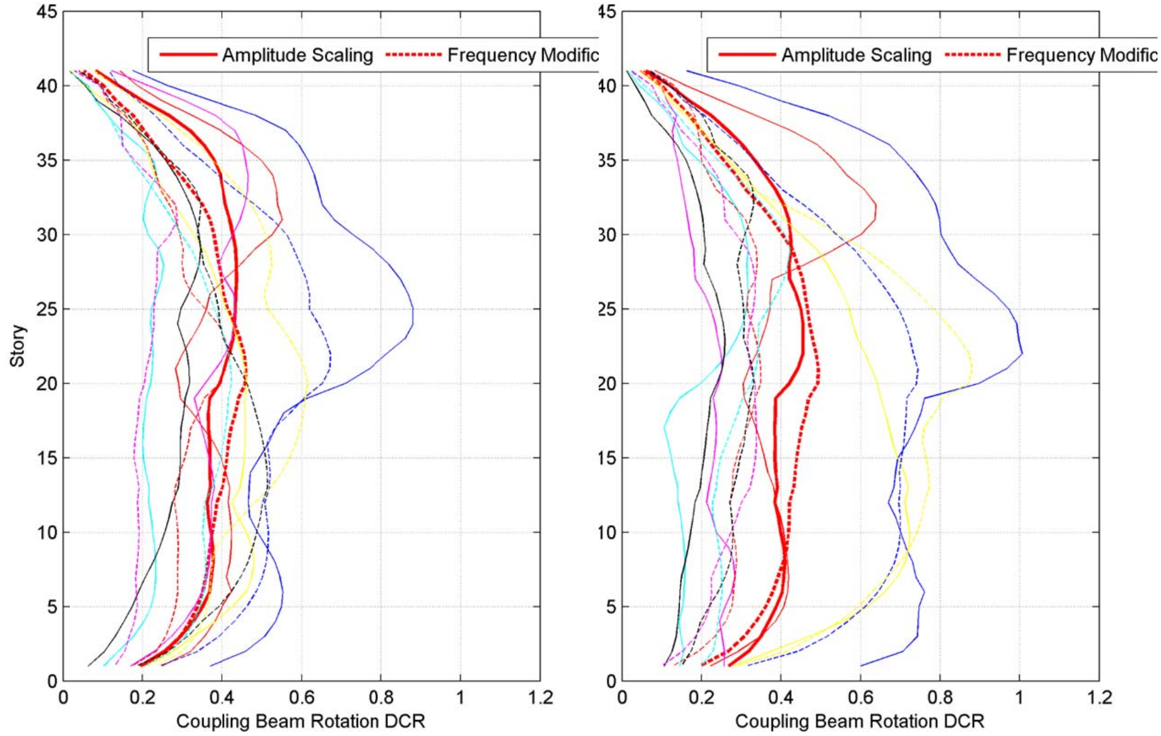
(a) (b)

Figure 11. Comparison of floor acceleration: (a) EW story acceleration; (b) NS story acceleration. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



(a) (b)

Figure 13. Comparison of axial strain in core wall: (a) at P2 location; (b) at P10 location. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



(a) (b)

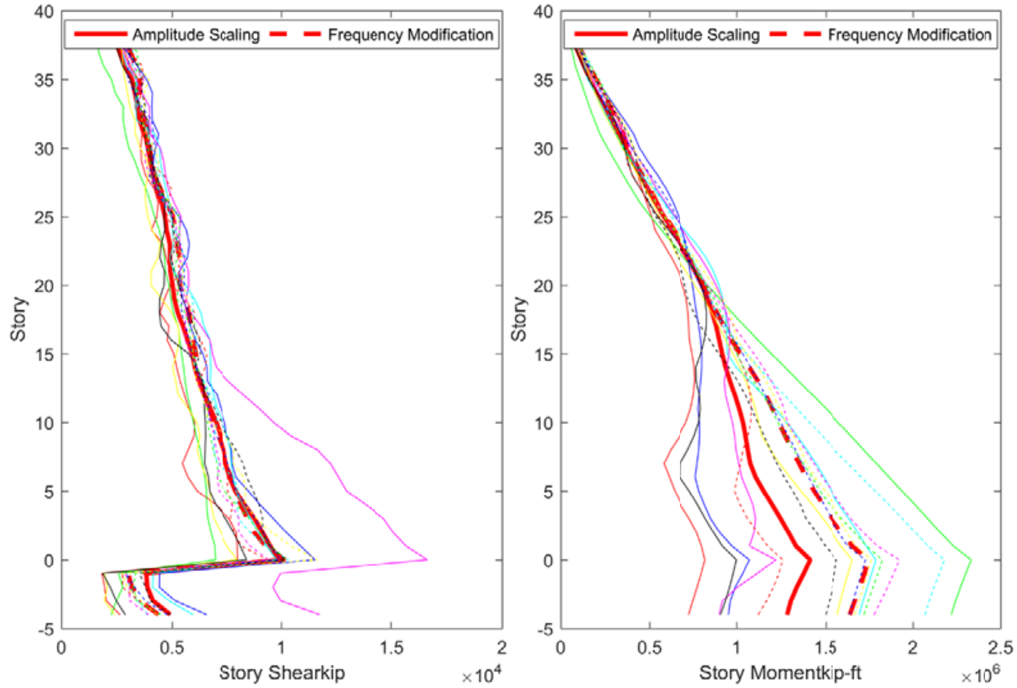
Figure 13. Comparison of coupling beam (CB) rotation: (a) CB between P3-P2; (b) CB between P11-P10. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.

4.2 40-Story Buckling-Restraint-Braced (BRB) Frame Structure

Figures 14 to 16 summarize the analysis results and comparisons between amplitude scaling vs. frequency modification for the 40-story (BRB) frame structure.

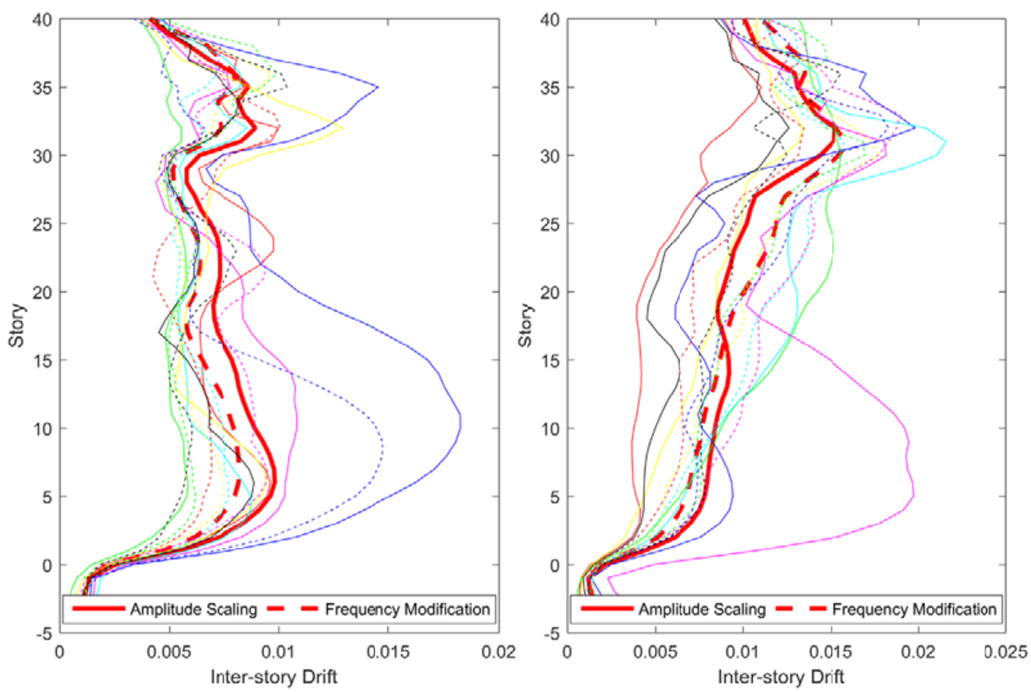
Figure 14 compares the results of story shear and story moment. Higher demands were exhibited by frequency modification motion for story moment, as can be seen in Figure 14b. Inter-story drift, in Figure 15, do not show a significant differences; at some story levels, frequency modification showed higher responses, and at other story, levels amplitude scaling showed higher responses.

Significantly higher level of responses were observed for floor acceleration for frequency modification motion, as can be seen in Figure 16. Again, if acceleration-sensitive equipment were placed in the building, it will be wiser to use amplitude scaling motion to evaluate the building performance.



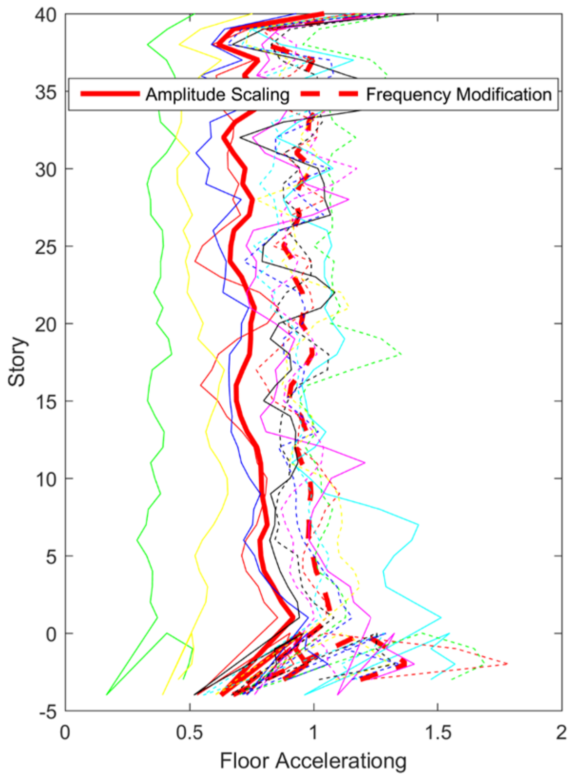
(a) (b)

Figure 14. Comparison of (a) Story shear; (b) Story moment. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.

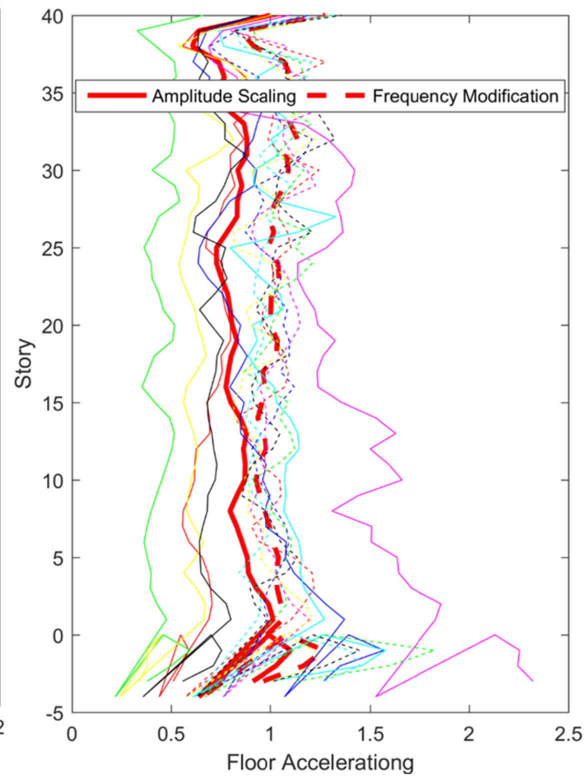


(a) (b)

Figure 15. Comparison of inter-story drift: (a) EW drift; (b) NS drift. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



(a)



(b)

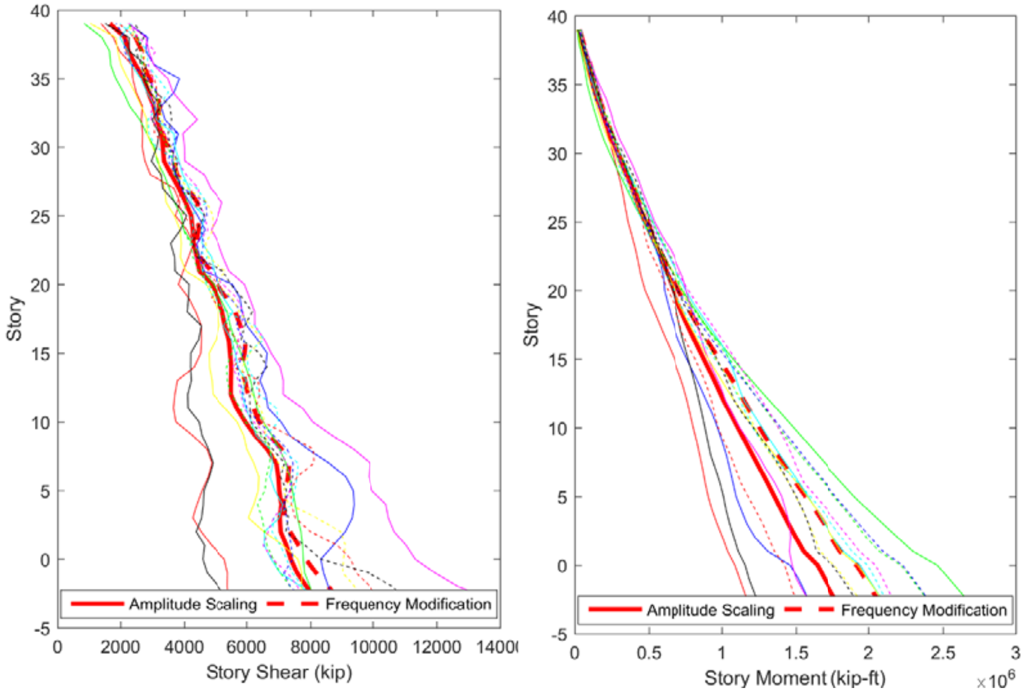
Figure 16. Comparison of floor acceleration: (a) EW story acceleration; (b) NS story acceleration. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.

4.3 40-Story Steel Space Frame Structure

Figures 17 and 18 compare the results of story shear, story moment, and inter-story drift. The figures do not show a significant difference.

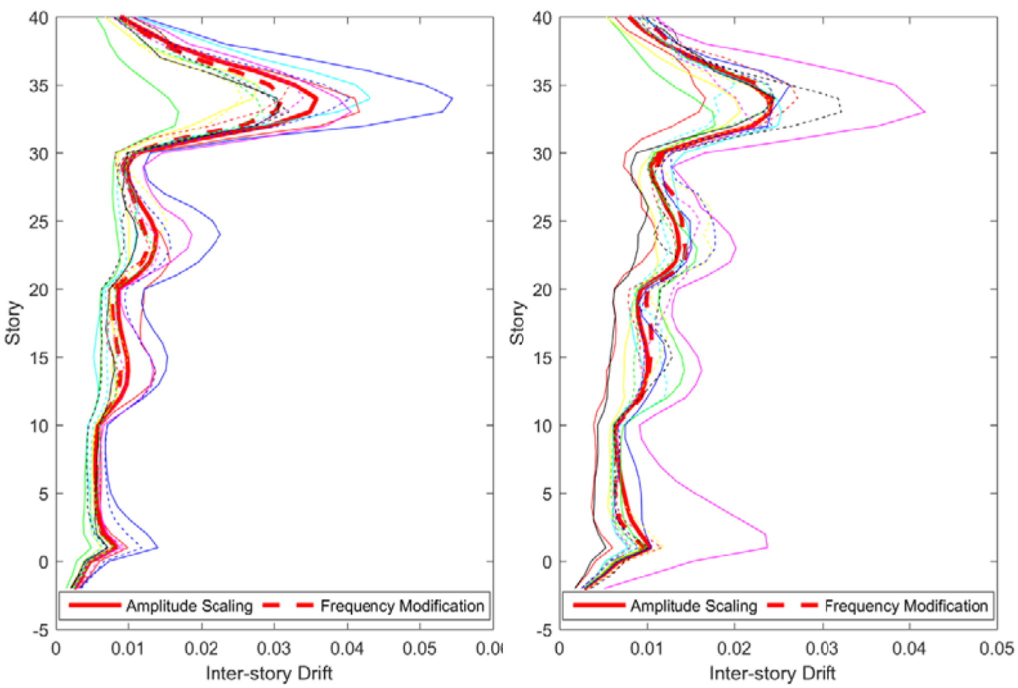
But much higher level of responses were observed for floor acceleration for frequency modification motion, as can be seen in Figure 19. Once again, if acceleration-sensitive equipment were to be placed in the building, it will be wiser to use amplitude scaling motion to evaluate the building performance.

ISBN 978-1-60643-379-9



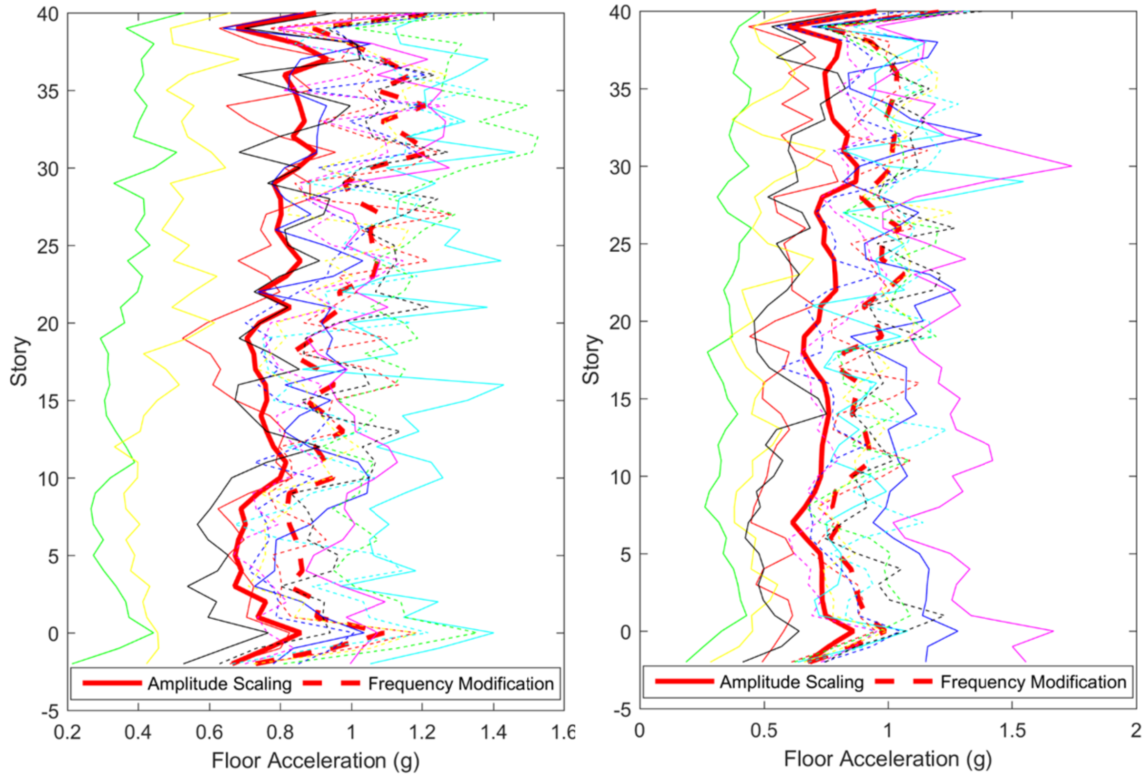
(a) (b)

Figure 17. Comparison of (a) story shear; (b) story moment. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



(a) (b)

Figure 18. Comparison of inter-story drift: (a) EW drift; (b) NS drift. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.



(a) (b)

Figure 19. Comparison of floor acceleration: (a) EW story acceleration; (b) NS story acceleration. *Solid lines for amplitude scaling; dotted lines for frequency modification and bold lines for average of response*.

5. Conclusion

Three selected buildings were analyzed with seven pairs of amplitude scaled and seven pairs of spectral matching ground motions. Comparison shows that, in general, use of spectral matching ground motions yields higher demand. But use of time domain scaled ground motions will provide comparable structural design of a high-rise building.

When spectral matching ground motions were used, significantly higher levels of floor acceleration were observed. Therefore, if acceleration sensitive equipment were to be placed in a high-rise building, it is advisable to use amplitude scaled ground motions to evaluate the building performance.

References

ASCE. (2011). *ASCE 7-10, Minimum design loads for buildings and other structures*. Reston, VA: American Society of Civil Engineers.

Hutt, C. M. (2013). Non-linear time history analysis of tall steel moment frame buildings in LS-DYNA. *Proceedings of the 9th European LS-DYNA Conference*. Salt Lake City, UT: ARUP.

Mahin, S., Yang, T., & Bozorgnia, Y. (2008). Personal communication.

Moehle, J., Bozorgnia, Y., Jayaram, N., Jones, P., Rahnama, M., Shome, N., Tuna, Z. …, & Zareian, F. (2011, July). *Case studies of the seismic performance of tall buildings designed by alternative means*. *Task 12: Report for the tall buildings initiative*. Berkeley, CA: Pacific Earthquake Engineering Research Center.

National Institute of Building Sciences. (2012, September). *2009 NEHRP recommended seismic provisions: Design examples*. Retrieved from https://www.fema.gov/media-library-data/1393877415270-d563663961c9f40e88ce3ad673377362/FEMA_P-751.pdf

PERFORM 3D. (2011). *Nonlinear analysis and performance assessment of 3D structures*. Walnut, CA: Computers and Structures, Inc.

Soules, J. G. (2013, June). *Instructional material complementing FEMA P-751, Design examples*. Retrieved from https://www.fema.gov/media-library-data/1393890432586-c071850c3050c34da135376baa478a1b/P-752_Unit13.pdf

Biography

MOHAMMAD T. BHUIYAN is currently an assistant professor of Civil Engineering at West Virginia State University. He earned his BSc in Civil Engineering from Bangladesh University of Engineering & Technology, Dhaka; an MSc in Earthquake Engineering jointly from Universite Joseph Fourier, France, and ROSE School, Italy; and a PhD in Earthquake Engineering from ROSE School with a joint program at Georgia Tech, Atlanta. His research interests include tall buildings, earthquake engineering, and soil-structure interaction. Dr. Bhuiyan may be reached at towhid@wvstateu.edu.