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PHYSICALLY SIMPLIFIED MODEL OF MULTI-STORY BUILDINGS FOR THEIR QUICK DYNAMIC ANALYSIS

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Abstract. *To increase the tendency of practicing engineers, engaged in the seismic design and evaluation of structural systems, to performing dynamic or Time History Analyses (THA) one way is reducing the volume of data, engaged in THA, and therefore, the volume of dynamic calculations. This would increase the computational efficiency in seismic structural analyses. One way for reducing the volume of input data and the corresponding output and information is the physical simplification of Multi-Degree-Of-Freedom (MDOF) systems, so that instead of working with* $n\times n$ *matrices, resulted from the n-Degree-Of-Freedom system, the engineer works with* $n_r\times n_r$ *matrices* ($n_r<<n$)*, belonging to a physically simplified system which has* n_r *degrees of freedom. For multi-story shear beam type buildings finding the equivalent simplified system is not very difficult. In fact, it is possible to introduce for a multi-story building an equivalent building with the same overall height, but having fewer number of stories with the same story mass while the stories' heights are more so that their stiffness values are less and the proportion of stiffness and mass of the original building is kept in the simplified model. In this way the modal frequencies of the reduced model will be correspondingly equal to the first few modal frequencies of the original building. However, the amount of base shear force and base moment of the reduced model will be less than that of the original building, and will be related to them by some specific factors which are functions of the ratio of number of stories of the original building and the reduced model. Several examples of response time histories calculated for a series of multi-story buildings and their simplified reduced models, obtained by using the proposed method, show that by using the proposed simplification technique the volume of elaborations needed for THA of building systems are reduced drastically. The amount of reduction in the 'required calculation time', and also the achieved level of precision in response values both depend on the number of stories of the original building and the ratio of number of stories of the original building and the reduced model.*

1 INTRODUCTION

The tendency of practicing engineers, engaged in seismic design and evaluation of structural systems, to performing dynamic or Time History Analysis (THA) of structures is very little. The main reason behind this fact is the very large volume of elaborations and computational materials required in THA of structures. These include the several time steps in which the response values should be calculated on the one hand, which make the calculations very time consuming, and the input, and particularly output data required for evaluation, on the other hand, which requires a large storage volume in the computer for saving and handling the data. On this basis, if the volume of data, engaged in THA, is reduced by some way it would be very useful for increasing the computational efficiency in seismic structural analyses.

Since mid 80s some researchers have tried to present simple dynamic or pseudo-dynamic analysis methods for this purpose. Cruz and Chopra (1986) have presented some simplified procedures for earthquake analysis of buildings [1]. Lai and his colleagues (1992) have also proposed a simplified analysis method for evaluation of earthquake actions and their distribution on regular high-rise buildings [2]. They have considered shear type, shear-bending type and bending type regular high-rise buildings and have used the modal analysis through response spectrum procedure and lumped mass story models. Wilkinson and Thambiratnam (2001) have also proposed a simplified procedure for seismic analysis of asymmetric buildings [3]. Their method is based on modification of the shear beam model, and has been applied to treat the seismic analysis of asymmetric buildings, as well. Their three dimensional procedure accounts for torsional coupling and the bending rotations at beam–column junctions and it can be used with a personal computer to give fast and reasonably accurate results, which compare well with those from comprehensive finite element analysis. They have claimed that their procedure is useful for preliminary seismic analysis and design of buildings.

In 2005 Miranda has proposed a simplified building response analysis for rapid seismic performance evaluation of existing buildings [4]. His simplified seismic analysis tool uses a continuum model consisting of a flexural beam coupled with a shear beam. Expressing that the earthquake response of many buildings can be estimated by considering only the first two vibration modes in the response spectrum analysis (RSA) procedure, Miranda has presented a simplified response spectrum analysis (SRSA) procedure, which provides very similar estimates of design forces for many buildings. With the development of the SRSA, a hierarchy of four analysis procedures to determine the earthquake forces are available to the building designer: code-type procedure, SRSA, RSA, and RHA (response history analysis). Miranda claims that the criteria presented to evaluate the results from each procedure and to decide whether it is necessary to improve results by proceeding to the next procedure in the hierarchy use all the preceding computations and are, therefore, convenient

An alternative way for reducing the volume of input data and output and information is the physical simplification of Multi-Degree-Of-Freedom (MDOF) systems, so that instead of working with $n\times n$ matrices, resulted from the n-Degree-Of-Freedom system, the engineer works with $n_r\times n_r$ matrices ($n_r<<n$), belonging to a physically simplified system which has n_r degrees of freedom. Details of this method are presented in the next section of the paper for shear beam type buildings.

2 PHYSICAL SIMPLIFICATION OF SHEAR BUILDINGS

The main idea for this physical simplification is finding an appropriate reduced n_r-Degree-Of-Freedom system for the original n-Degree-Of-Freedom system in such a way that the modal frequencies of the simplified system are correspondingly equal to the first nr frequencies (the lower modes) of the original system. Obviously, this can be achieved by adjusting the amount of stiffness and mass in various parts of the simplified system. In this way the modal frequencies of the reduced model will be correspondingly equal to the first n_r modal frequencies of the original building. However, the amounts of base shear force and also base moment of the reduced model will be less than that of the original building, and related to them by some specific factors which are functions of n/n_r ratio and story mass and height in both original and simplified models of building.

For multi-story shear beam type buildings finding the equivalent simplified system is not very difficult. In fact, it is possible to introduce an n_r-story building with the same height and story mass as the original n-story building, in which the stiffness values of the stories have been decreased in a specific way to keep the existing proportionality of stiffness and mass of the original n-story building. For this purpose, it is enough to consider the stories with the same story mass m of the original building just in every other story level, or every other two, three, four story level, and so on, while keeping the rotation restraints imposed to columns at story levels.

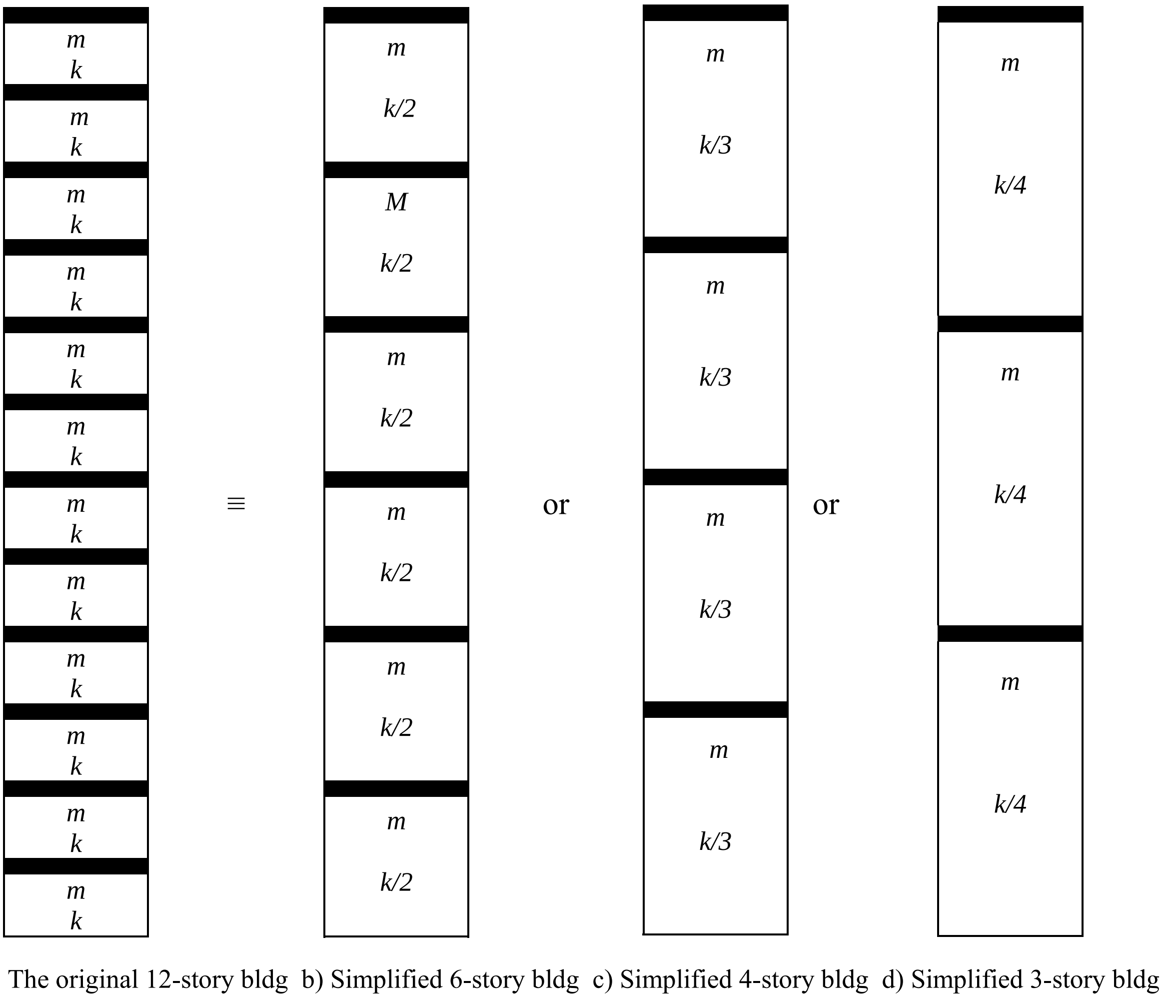

Figure 1: Physical simplification of a 12-story building (a) with total mass of 12m to: b) a 6-story building with total mass of 6m, c) a 4-story building with total mass of 4m, and d) a 3-story building with total mass of 3m

In this way the stiffness of each column in the simplified model of the building, which the height of $2h$ (h being the story height), $3h$, $4h$ and so on, depending on the number of deleted stories, will be obtained based on the formula of springs in series, that is:

$$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \ \dots \tag{1}$$

where k_{eq} is the stiffness of the equivalent column in the simplified model of the building, and k_1, k_2, k_3 and so on are the stiffness values of the successive columns in one vertical line. Considering the same stiffness value of k for the successive columns, Equation (1) leads to a value of $k/2$, $k/3$, $k/4$ and so on, corresponding to deletion of, respectively, every other one story, every other two, three, four stories, and so on, as shown in Figure 1.

As shown in Figure 1, the original building (a) has a total mass of $12m$, while in case (b) the simplified model has a mass of $6m$, which is as half of the original building, and proportionally the stiffness of stories is k/2. In cases (c) and (d) the total mass of the simplified model is, respectively, $1/3^{rd}$ and $1/4^{th}$ of the original building, and accordingly the stiffness of stories in these two cases is, respectively, $1/3^{rd}$ and $1/4^{th}$ of the original building as well.

Based on this logic, the modal frequencies of the reduced model of an n-story building will be correspondingly equal to the first n_r modal frequencies of the original building. However, the amounts of base shear force and base moment of the simplified model, subjected to any accelerogram of a horizontal component of an earthquake ground motion, will be obviously less than that of the original building, due to the lower mass of the simplified model. Paying attention to the ratios between the masses and story heights of the simplified model and the original building, in case of buildings with the same story masses and equal story heights, the modification factors for the base shear force and the base moment, by which the values obtained for the simplified model should be multiplied, to give the values of base force and base moment of the original building, are respectively:

$$Base\ Shear\ Modification\ Factor = \frac{n}{n_r} \tag{2}$$

and

$$Base\ Moment\ Modification\ Factor = \frac{\sum_i^n H_i}{\sum_j^{n_r} H_j} \tag{3}$$

where H_i and H_j are height of, respectively, the i^{th} floor of the original building, and the j^{th} floor of the simplified model above foundation level. For buildings with unequal story masses and heights the given modification factors will have some errors. However, the amount of error will not be remarkable for most of actual cases, as shown in the next section, in which some numerical examples are presented.

3 NUMERICAL EXAMPLES

Several examples of response time histories calculated for a series of multi-story buildings and their simplified (reduced) models, obtained by using the proposed method have been worked out, of which some are presented in this section of the paper to show the efficiency of the proposed simplification technique. These examples include a 10-story building simplified as a 3-story model, a 21-story building, simplified once as a 3-story and once again as a 5-story model, a 40-story building, simplified as a 10-story model, and finally a 60-story building, simplified as a 15-story model. The original buildings have been assumed to be regular in both plan and elevation to avoid the torsion effects. The buildings have been designed by considering the drift limitation of the seismic design code, and therefore, their fundamental period values are close to the code value. Results of the 40-story and 60-story buildings are shown in this section. These results include the time histories of roof displacement, roof acceleration, base shear, and base moment of the original and the simplified buildings. Table 1 shows the modal periods of the original 40-story building and the simplified 10-story model for their first ten modes.

Table 1: Modal periods (in seconds) of the original 40-story building and its simplified 10-story model

Mode No.	40-Story Original Building	10-Story Simplified Building	Accuracy (%)
1	3.06	2.91	95
2	2.81	2.78	99
3	2.49	2.41	97
4	1.01	1.09	92
5	0.93	1.05	88
6	0.83	0.93	89
7	0.57	0.63	91
8	0.55	0.61	88
9	0.50	0.54	91
10	0.41	0.43	95

As it is seen in Table 1 the modal periods of the simplified model match very well with those of the original building. This shows that the proposed simplification technique has a very good precision. For the THA the accelerograms of two well-know earthquakes of Kobe (1996 - FUK090_AT2 Component) and El Centro (1940 - Imperial Valley Station, I-ELC180_AT2 Component) have been used, which have different frequency contents. Figures 2 to 5 respectively show the time histories of roof displacement, roof acceleration, base shear, and base moment of the original and the simplified buildings for the case of 40-story building subjected to Kobe accelerogram.

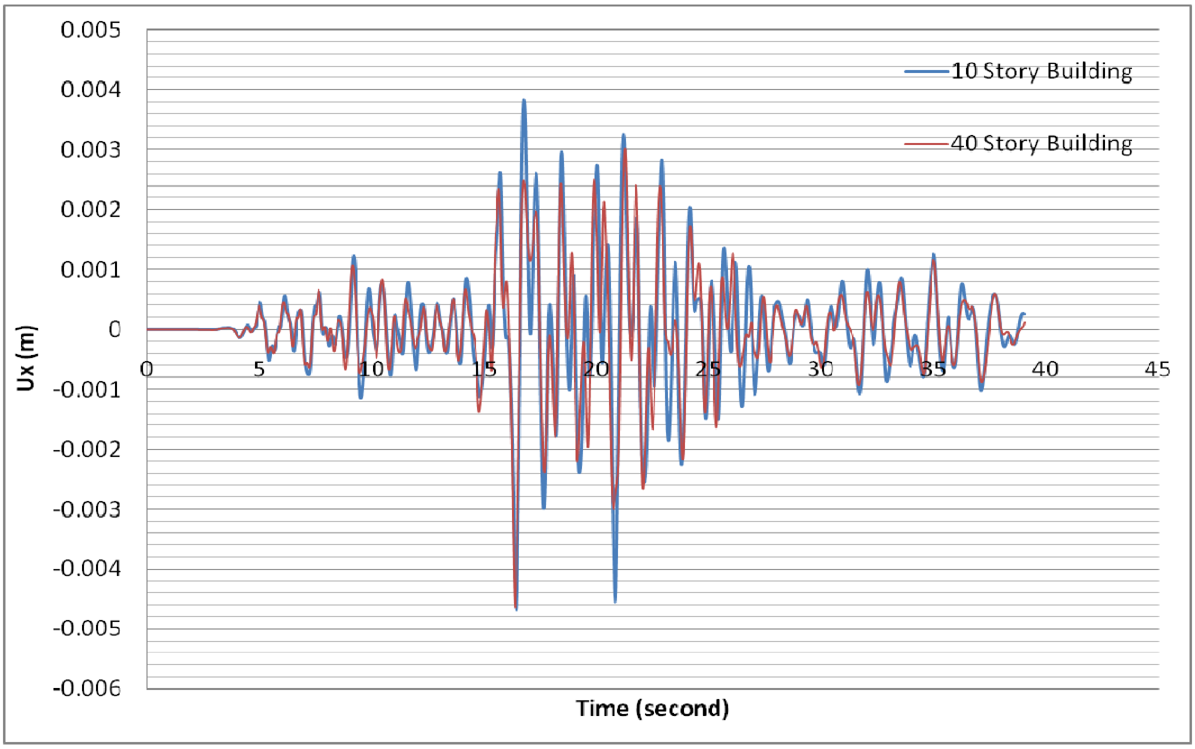

Figure 2: Roof displacement time histories of the original and simplified models for the case of 40-story building subjected to Kobe earthquake accelerogram

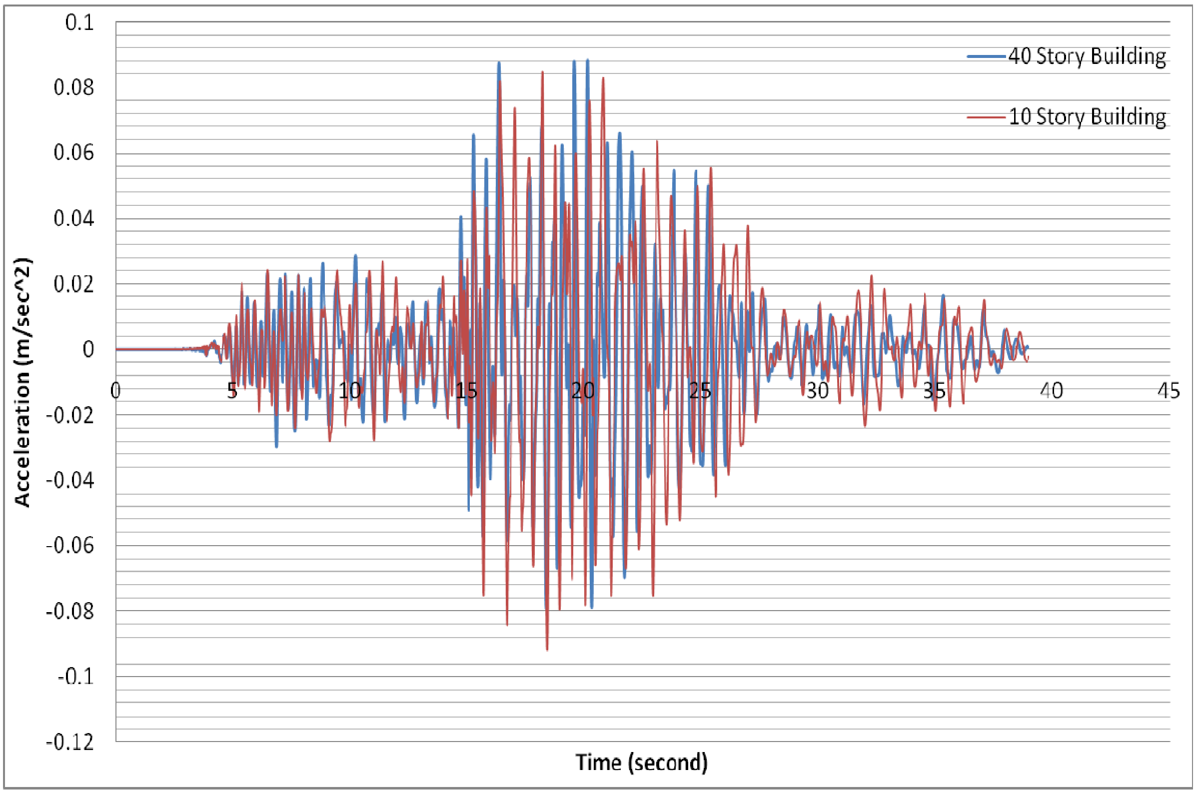

Figure 3: Roof acceleration time histories of the original and simplified models for the case of 40-story building subjected to Kobe earthquake accelerogram

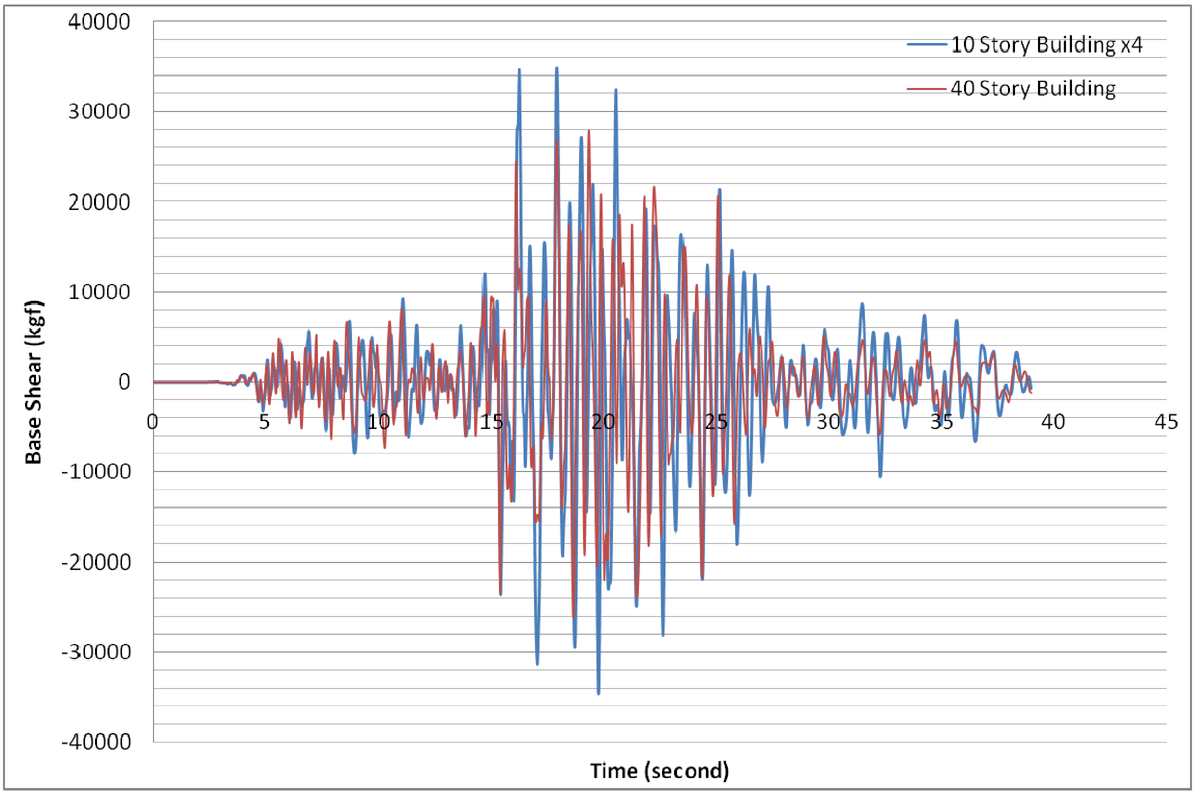

Figure 4: Base shear force time histories of the original and simplified models for the case of 40-story building subjected to Kobe earthquake accelerogram

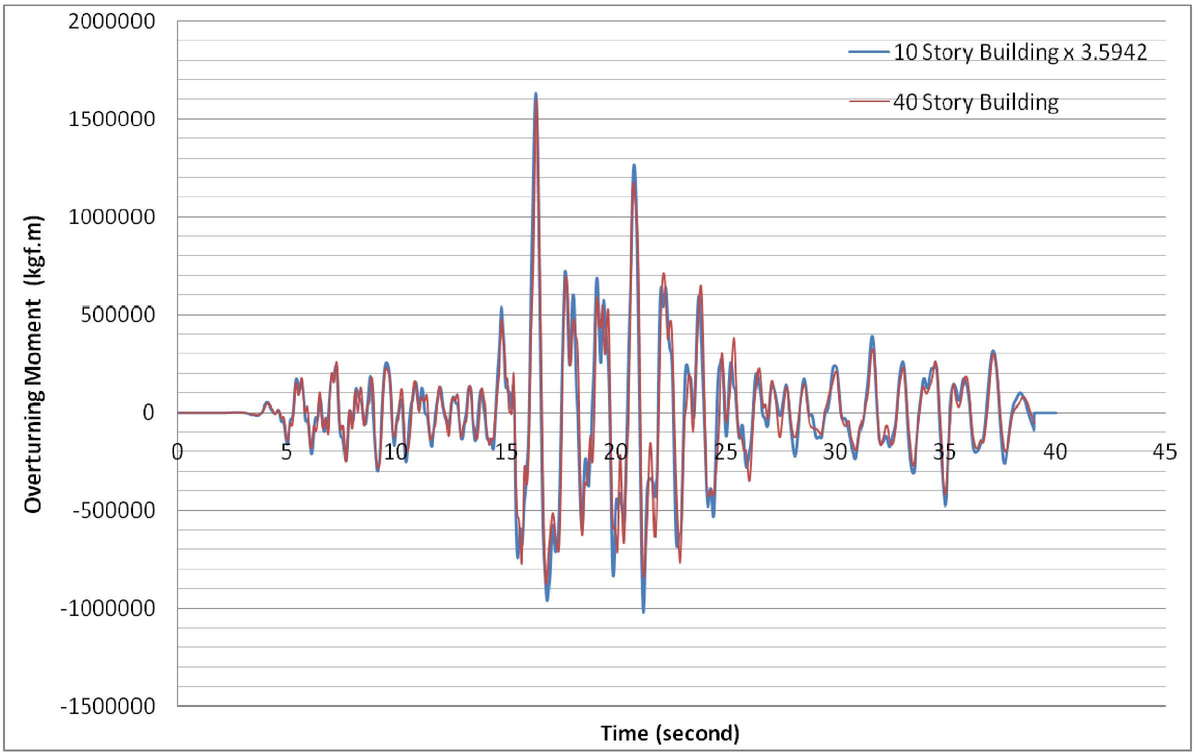

Figure 5: Base moment time histories of the original and simplified models for the case of 40-story building subjected to Kobe earthquake accelerogram

Figures 6 to 9 show the same four set of results of the 40-story building and its 10-story simplified model subjected to El Centro earthquake.

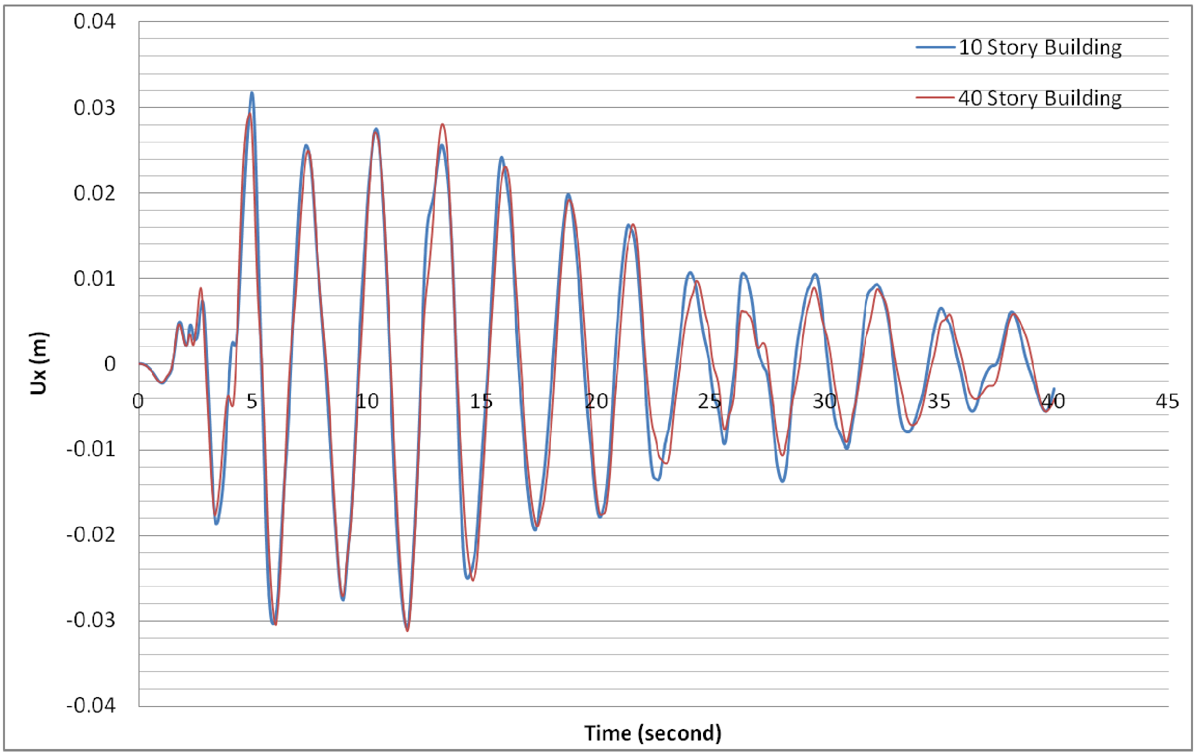

Figure 6: Roof displacement time histories of the original and simplified models for the case of 40-story building subjected to El Centro earthquake accelerogram

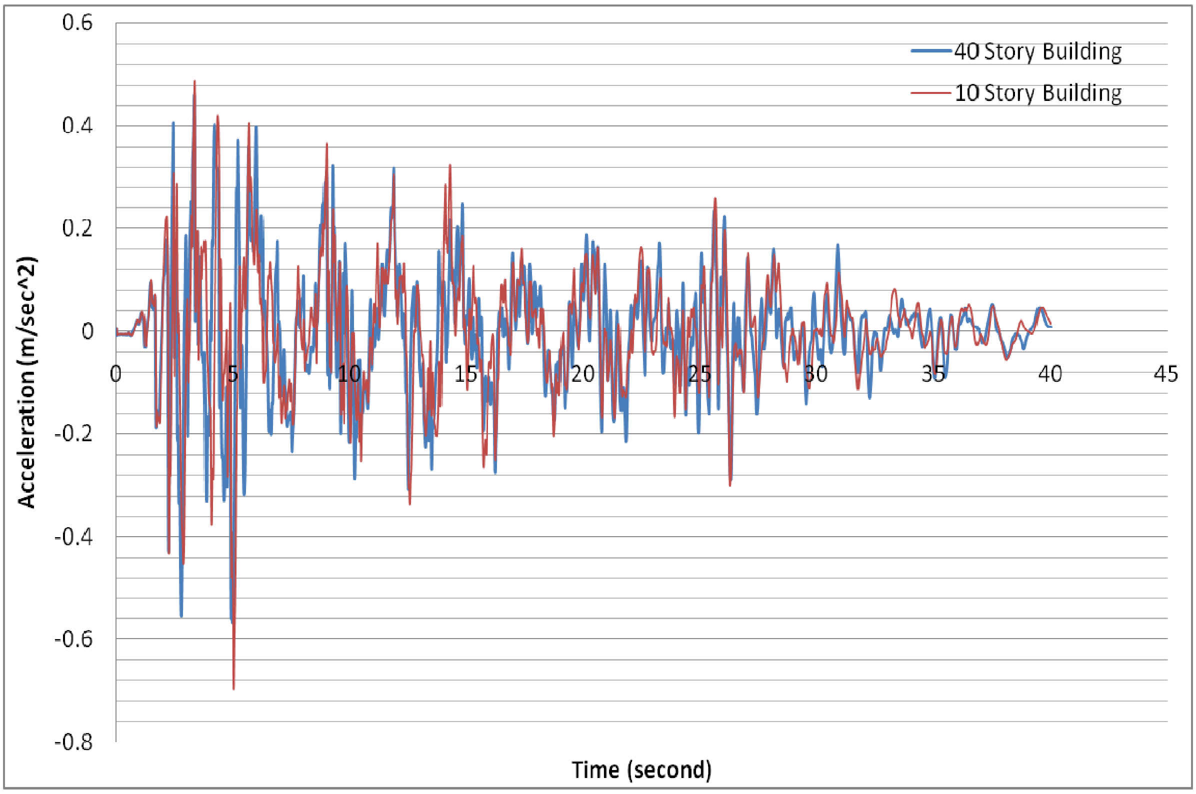

Figure 7: Roof acceleration time histories of the original and simplified models for the case of 40-story building subjected to El Centro earthquake accelerogram

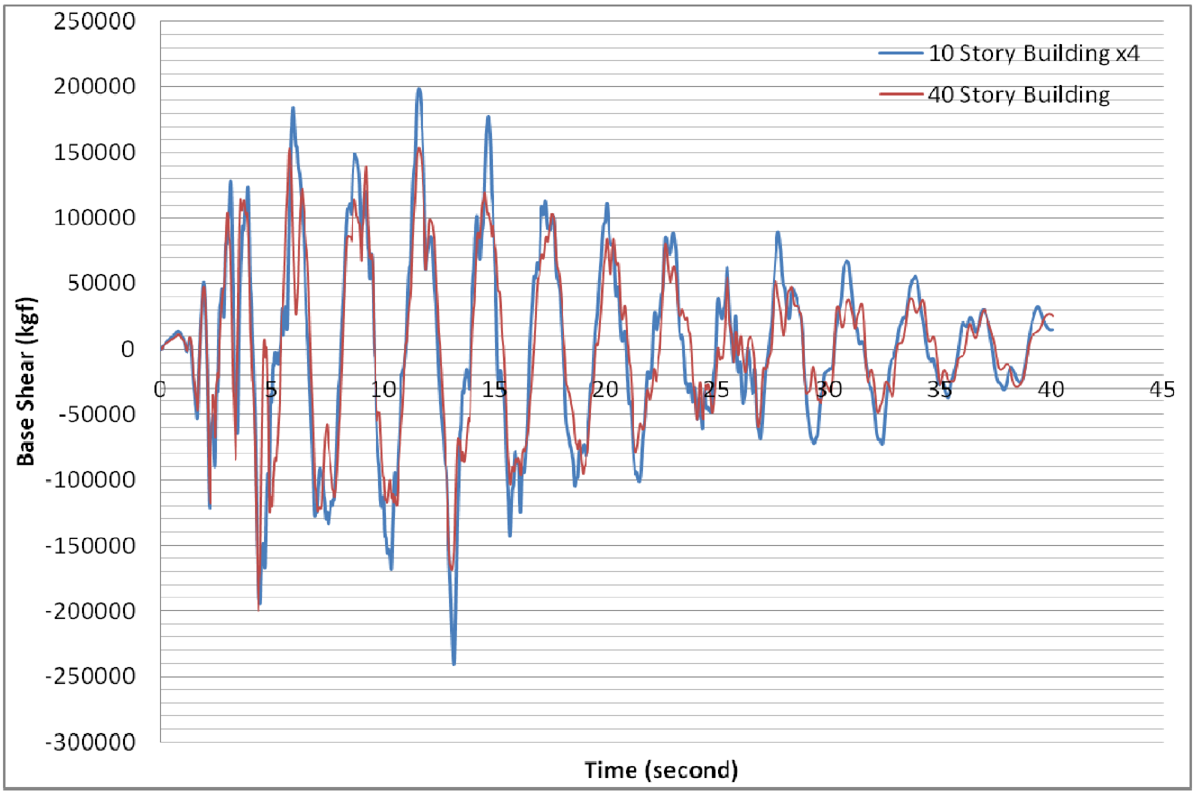

Figure 8: Base shear time histories of original and simplified models for the case of 40-story building subjected to El Centro earthquake accelerogram

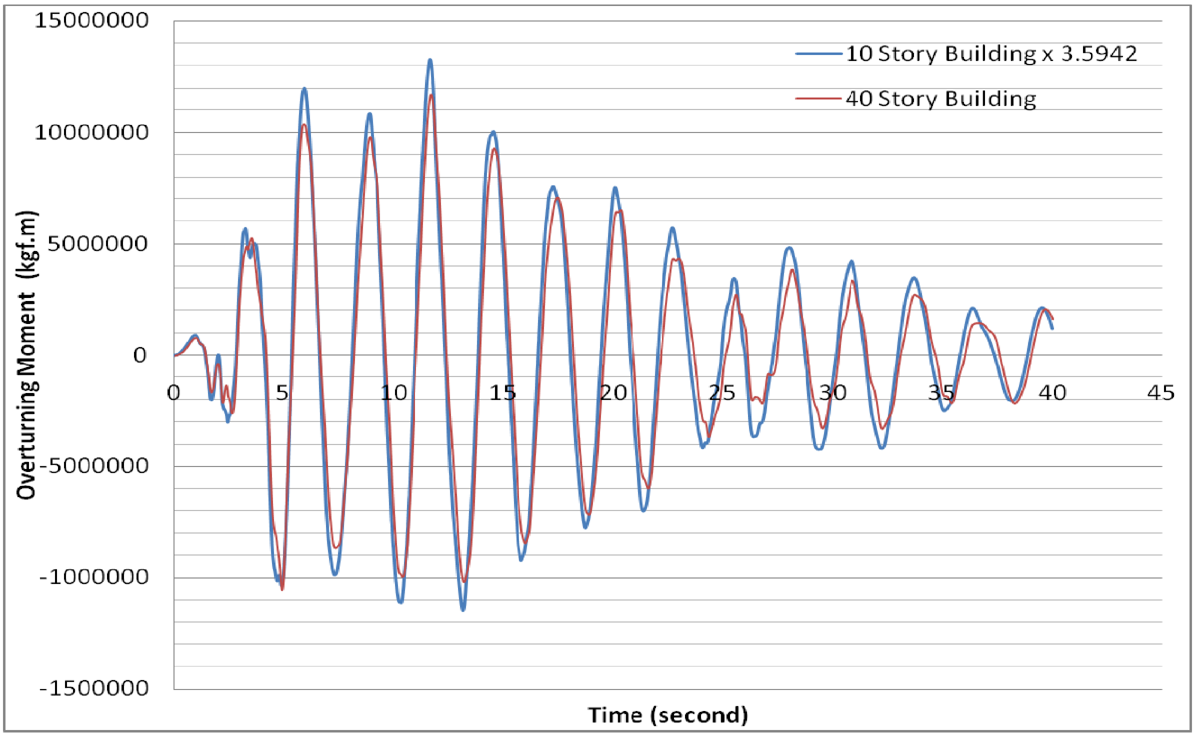

Figure 9: Base moment time histories of original and simplified models for the case of 40-story building subjected to El Centro earthquake accelerogram

Comparing Figure 2 with Figure 3 and also Figure 6 with Figure 7, it can be seen that the agreement between displacement time histories is better than that between acceleration time histories. The reason behind this fact is that the acceleration response is more sensitive than displacement response to high frequency excitations. Better agreement of results in case of El Centro earthquake than Kobe earthquake can be also due to the lower frequency content of El Centro earthquake. Table 2 compares the modal periods of the original 60-story building and its simplified 15-story model, which are again in good agreement .

Table 2: Modal periods (in seconds) of the original 60-story building and its simplified 15-story model

Mode No.	60-Story Original Building	15-Story Simplified Building	Accuracy (%)
1	4.30	4.17	97
2	3.98	3.95	99
3	3.22	2.78	86
4	1.42	1.47	97
5	1.33	1.40	94
6	1.12	1.11	98
7	0.81	0.83	97
8	0.77	0.80	95
9	0.66	0.65	98
10	0.56	0.55	100
11	0.53	0.54	99
12	0.46	0.45	96
13	0.41	0.40	96
14	0.40	0.39	98
15	0.35	0.33	94

Figures 10 to 13 show the four set of results of the 60-story building and its 15-story simplified model subjected to El Centro earthquake.

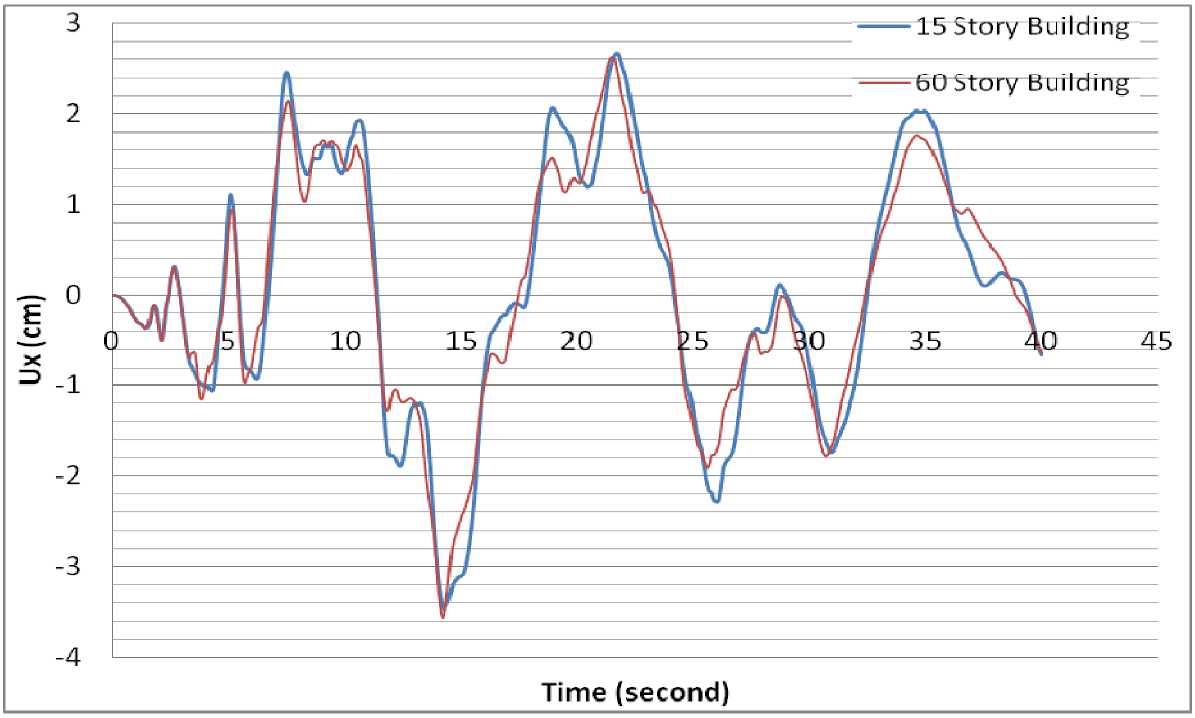

Figure 10: Roof displacement time histories of the original and simplified models for the case of 60-story building subjected to El Centro earthquake accelerogram

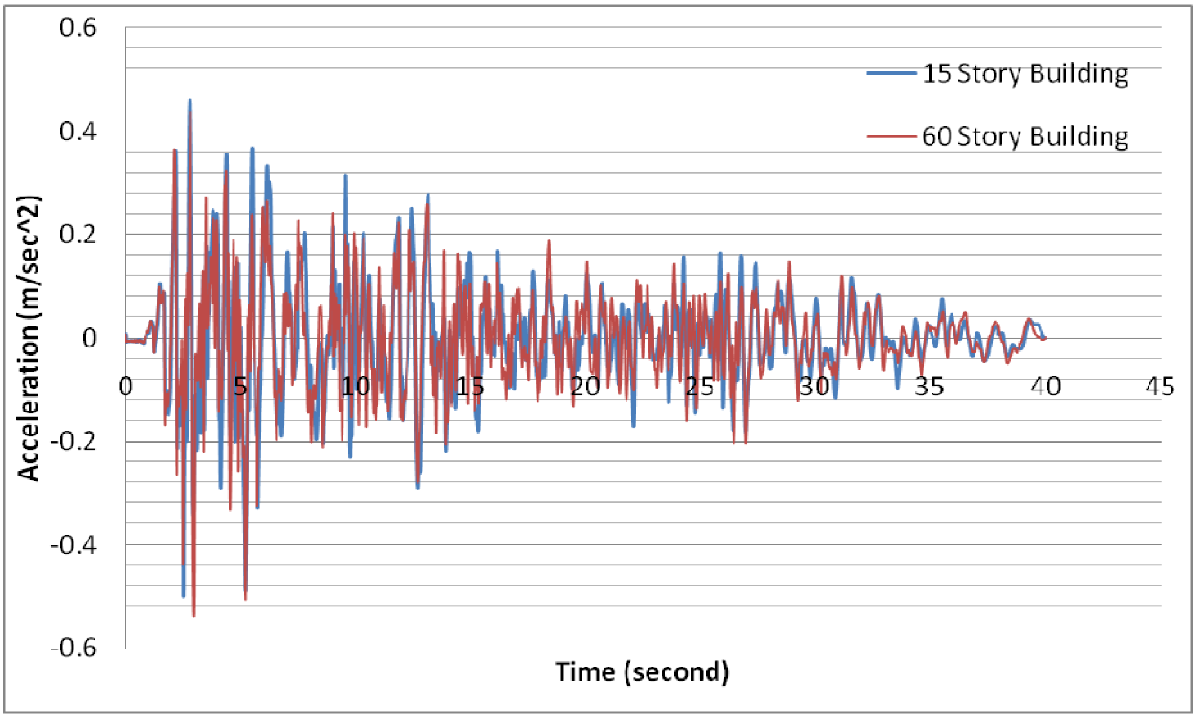

Figure 11: Roof acceleration time histories of the original and simplified models for the case of 60-story building subjected to El Centro earthquake accelerogram

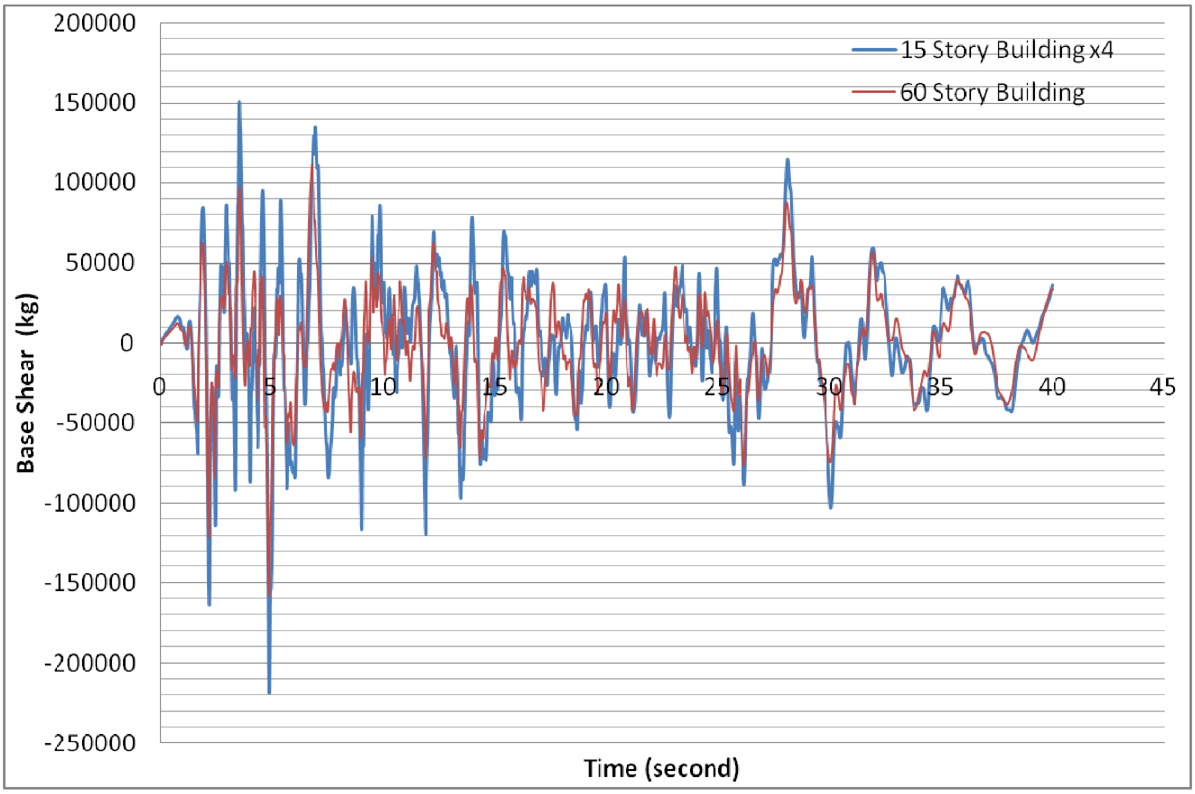

Figure 12: Base shear time histories of original and simplified models for the case of 60-story building subjected to El Centro earthquake accelerogram

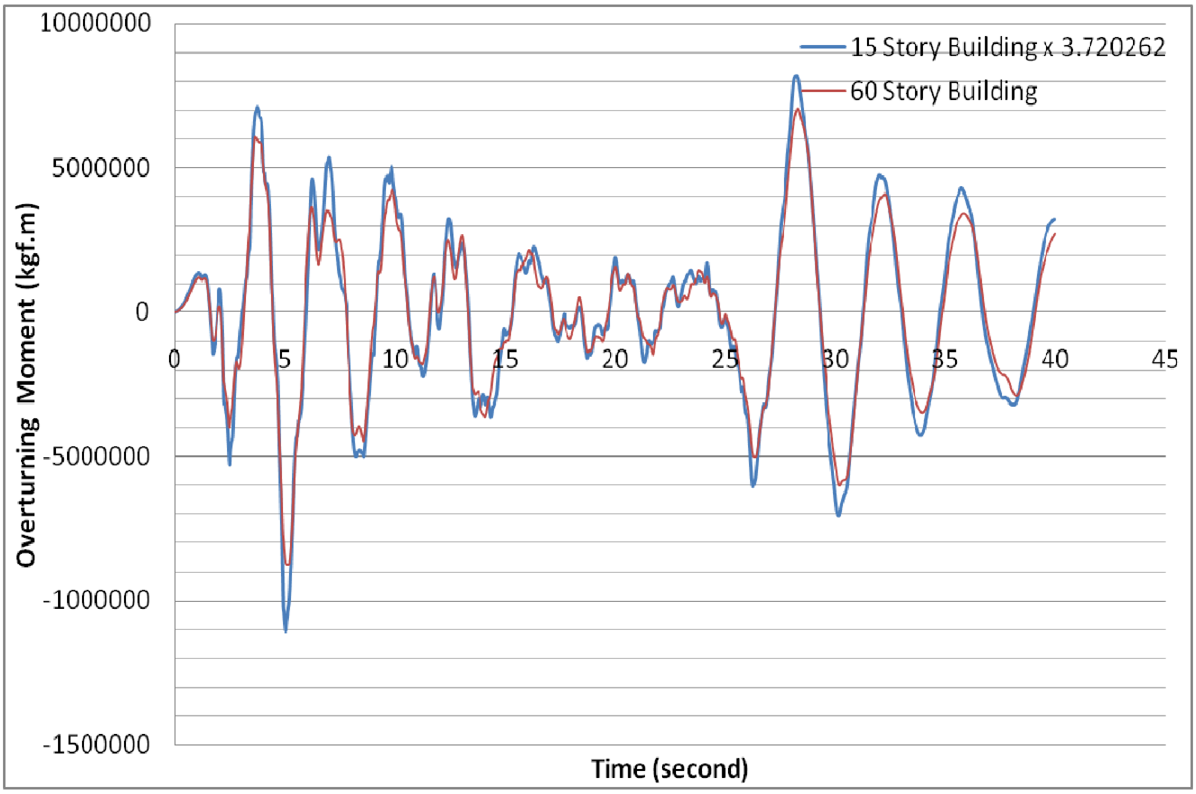

Figure 13: Base moment time histories of original and simplified models for the case of 60-story building subjected to El Centro earthquake accelerogram

Figures 10 to 13 show again that the proposed simplification technique leads to very satisfactory results, and therefore, it can be considered as a high efficiency method for THA of multi-story buildings.

4 CONCLUSIONS

Several examples of response time histories calculated for a series of multi-story buildings and their simplified reduced models, obtained by using the proposed method, show that:

- by using the proposed simplification technique the volume of elaborations needed for THA of building systems are reduced drastically.
- The amount of reduction in the 'required calculation time', and also the achieved level of precision in response values both depend on n and also the n/n_r ratio.
- By using a value of 4 or 5 for n/n_r ratio, the response values can be calculated with negligible error, while the required calculation time for THA is significantly reduced, particularly for buildings with larger number of stories.

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