THE USE OF LINEAR TIME HISTORY ANALYSIS (LTHA) INSTEAD OF RESPONSE SPECTRUM ANALYSIS (RSA) FOR THE SEISMIC DESIGN OF HIGH-RISE RC SHEAR WALL BUILDINGS

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ABSTRACT

An efficient and economic seismic design of high-rise RC buildings requires an accurate estimation of their true inelastic seismic demands. The most common analysis procedure used for this purpose is the standard Response Spectrum Analysis (RSA) procedure. As prescribed in various seismic codes and guidelines, the individual modal responses are first determined in this procedure and then combined using a suitable modal combination rule (usually SRSS, if the natural periods are well-separated) to get the overall elastic seismic demands. The inelastic force demands are then determined by directly reducing the linear elastic forces by a response modification factor (R). Various studies, however, have argued that the use of SRSS rule to combine the peak modal responses may result in overestimation of the true dynamic responses anticipated during a design-level earthquake, and the dynamic responses can be more accurately determined using the Linear Time History Analysis (LTHA) procedure. This study proposes and evaluates the use of LTHA procedure instead of code-based RSA procedure for determining the design seismic demands of high-rise RC shear wall buildings. Using a 32-story case study building located in a seismically active region, it is shown that the standard RSA procedure results in a costly design compared to the LTHA procedure. The use of LTHA for an accurate determination of design seismic demands should be encouraged among the practicing engineers.

Keywords: Linear time history analysis, RSA, SRSS, code-based design, RC shear wall buildings.

1. INTRODUCTION

Since the last couple of decades, tall buildings are gaining popularity and are being constructed around the metropolitan areas due to their economic advantages as well as sustainability considerations. The need for their efficient and economical design is also increasing in this scenario. For the design purpose, the most commonly used analysis procedures are the equivalent lateral force (ELF) analysis and the standard response spectrum analysis (RSA) procedure. The RSA is an approximate analysis procedure which provides a convenient way of estimating the inelastic seismic force demands by simply reducing the corresponding elastic force demands (combined for each vibration mode using a modal combination rule e.g. SRSS) by a response modification factor, R (ASCE 7-10 2010). The displacement and drifts demands corresponding to these reduced forces are also calculated and multiplied with a displacement amplification factor (C_d) to obtain the inelastic demands.

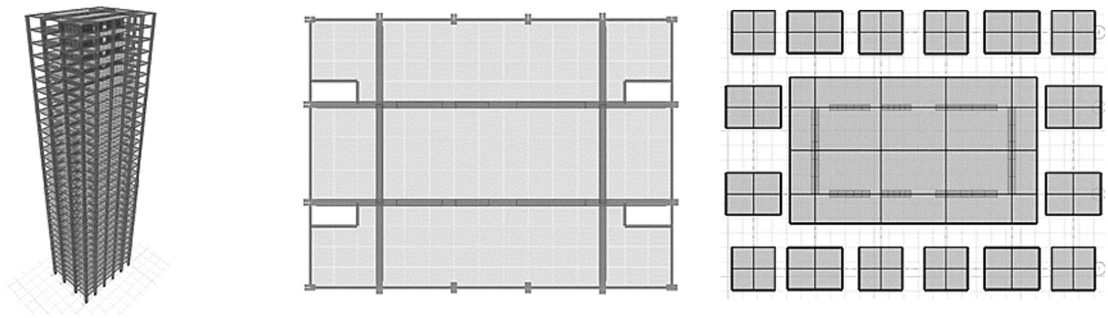
Various studies have shown that the seismic demands obtained from the linear time history analysis (LTHA) procedure are significantly lower than those obtained from the code-based RSA procedure. For example, using a 35-story case study building, Bonita (2015) compared the seismic demands from the RSA procedure with those of LTHA procedure using a set of seven input ground motions. This study concluded that the demand-to-capacity (D/C) ratios of shear walls and column PMM values were reduced by approximately 30% when the LTHA procedure was used. Therefore, for a more cost effective design, this study recommended to use the LTHA procedure instead of the RSA procedure. Charney (2015) analyzed a 6-story moment resisting frame with equivalent lateral force analysis, the RSA and the LTHA procedures according to ASCE 7-10. It is found that the story forces and base shear results of the LTHA procedure are lower than those obtained from the ELF analysis and the RSA procedure. Islam et al. (2011) evaluated 6-story case study building and concluded that the base shear from the LTHA procedure is 26% lower than that of the RSA procedure.

2. METHODOLOGY

In this study, a 32-story case study core wall building is selected for the detailed analysis. It is located in a seismically active area in Philippines. Its seismic design is based on the design-basis earthquake (DBE) level which is defined as the earthquake with a 10% probability of exceedance in 50 years. The design seismic demands are first determined using the code-based ELF analysis and the RSA procedures following the guidelines prescribed in ASCE 7-10 (2010). The structure is then subjected to the LTHA procedure and the peak seismic demands are compared with the design demands. For this purpose, a linear elastic model of the case stud building is created in ETABS (CSI 2015). The Ritz vectors are used to get the mode shapes, mass participation ratios and the natural periods of all significant vibration modes. For the RSA procedure, ASCE 7-10 (2010) prescribes that the number of significant modes participating in the combined response should capture at least 90 % of the total mass of the building. The individual modal responses from the linear elastic model are determined and combined using SRSS to get the total responses. The LTHA procedure is performed using a set of seven ground motions records spectrally matched to DBE-level response spectrum (ASCE 7-10 2010). The individual structural components are designed based on the maximum demands obtained from all the load combinations.

2.1. Description of the case study building

The lateral load resisting system of the case study building is a combination of RC core wall and the moment resisting frame. The gravity load resisting system has slabs and beams that rest on the columns and core wall. The concrete compressive strength, f_c' is different for different structural components. The column sizes are varied in three groups (i.e. ground to 15th floor, 16th to 25th floor and 26th to 32th floor). Table 1 shows the salient features and the dimensions of the building while Figure 1 illustrates the 3D view, floor plan and the foundation plan of the building.



3D view of tower   Typical floor plan   Plan view of foundation

Figure 1: The case study building

Table 1: The basic features and dimensions of the case study building

Details	Dimensions
No. of stories	32
Total height (m)	124
Typical story height (m)	3.875
Core wall thickness (mm)	Base to 6^{th} = 750 mm and 7^{th} to 32^{th} = 600 mm
Coupling beam sizes (mm)	600×700
Girder size (mm)	600×800
Column size (mm)	Base to 15^{th}, C1 1100×1200, C2 600×1600, C3 600×1400, C4 1600×600 16^{th} to 25^{th}, C1 1200×600, C2 600×1400, C3 600×1000, C4 1400×600 26^{th} to 32^{th}, C1 1000×600, C2 600×1200, C3 600×1000, C4 1200×600
Slab thickness (mm)	Outside core wall = 200 mm, Inside core wall = 150 mm
Yield strength of steel, $\boldsymbol{f_y}$ (MPa)	Ground to 32^{th} = 400
Concrete $\boldsymbol{f'_c}$ (MPa) Columns, Shear walls, Coupling beams	Base to 15^{th} = 58.6, 16^{th} to 25^{th} = 48.3, 26^{th} to 32^{th} = 41.4
$\boldsymbol{f'_c}$ (MPa) Girders, Beams, Slabs	Base to 15^{th}= 41.4, 16^{th} to 25^{th} = 34.5, 26^{th} to 32^{th} = 31
Live load ($\boldsymbol{KN/m^2}$)	Inside core wall = 4.79, Outside core wall = 1.92
Superimposed dead load ($\boldsymbol{KN/m^2}$)	Inside core wall = 1.44, Outside core wall = 3.11

2.2. Selection of seismic loading and ground motions

The uniform hazard spectrum (UHS) for the actual site of case study building in Philippines is used as the design response spectrum. Table 2 shows the seismic design parameters for the RSA procedure. For the LTHA procedure, a set of seven ground motions are carefully selected from the Pacific Earthquake Engineering Research Center (PEER) strong motion database (2017). These ground motions are spectrally matched with the target response spectrum. Figure 2 presents the spectra of seven pairs of ground motions along with the target spectrum. The design load combination for the LTHA and RSA procedures are based on ASCE 7-10 (2010). For the RSA procedure, 100% of the scaled X direction and 30% of the scaled Y direction loads are used for load combination. For the LTHA procedure, 100% of the ground motions in both X and Y directions are simultaneously used. ASCE 7-10 section 16.1.4 (2010) prescribes that if the time history procedure is carried out using seven or more records, the average values of seismic demands can be used, for fewer than seven ground motions, the maximum seismic demand values should be used for the design or evaluation.

Table 2: The seismic design parameters for the RSA procedure

Parameters	Value
Code	ASCE 7-10
Earthquake	DBE level
Mode Shapes	Ritz vector
Occupancy category	II
Importance factor	1
Spectral response	S_S=1.087,
acceleration parameters	S_1=1.056
Design spectral response	S_{DS}=0.731,
acceleration parameters	S_{D1}=0.704
Response modification, R	6
Seismic design category	D

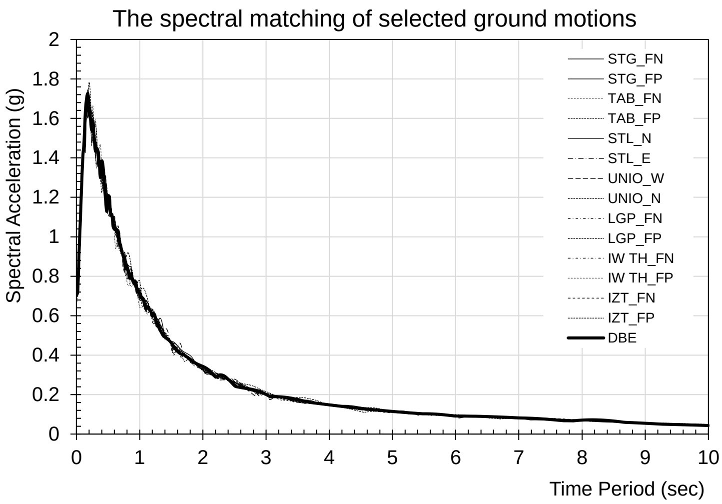


Figure 2: The selection and matching of ground motions for the LTHA procedure

2.3. Scaling of responses

The response scaling for the design using the RSA procedure is based on ASCE 7-10 section 12.9.2 (2010). The elastic member forces will be multiplied by I_e/R where I_e is the importance factor prescribed in section 11.5.1 (2010) and R is the response modification factor used in accordance with section 12.2.1 (2010). The story drifts and displacements corresponding to the reduced forces are multiplied by the displacement amplification factor, C_d. If the modal base shear (V_t) obtained from the RSA procedure is less than $0.85C_sW$ (where C_s is determined in accordance with Equation 12.8-6 of ASCE 7-10 (2010)), the drifts and forces should be scaled by a factor of $0.85C_sW/V_t$ and $0.85V/V_t$, respectively. The response scaling for the LTHA procedure is based on ASCE 7-10 section 16.1.4 (2010). The force responses are multiplied by the factor I_e/R. The drifts and displacements scaling is same as the RSA procedure. For each ground motion, if the maximum scaled base shear in the analysis V_i is less than the value of V determined using equation 12.8.5 or 12.8.6 of ASCE 7-10 (2010), the member forces should be multiplied by V/V_i where V is the minimum base shear. These equation 12.8.5 and 12.8.6 (2010) are shown below.

$C_s = 0.044S_{DS}I_e \geq 0.01$, (Equation 12.8.5, ASCE 7-10),

$C_s = 0.5S_1/R/I_e$, (Equation 12.8.6, ASCE 7-10)

3. RESULTS AND DISCUSSION

The linear elastic model of the case study building is subjected to the RSA and the LTHA procedures. Various global and local response quantities are compared and presented in this section. Table 3 shows the natural periods for first three vibration modes in both translational directions and for torsion. It can be observed that the X direction is stiffer compared to Y as also indicated by the higher base shear demand shown in Figure 3.

Table 3: The natural periods of vibration modes

Direction	Time Period (sec)		
	Mode 1	Mode 2	Mode 3
Translation in Y	4.403	1.075	0.486
Translation in X	2.967	0.869	0.438
Torsion	2.585	0.688	0.284

Figure 3 represents the comparison of elastic and scaled base shear (V_b) computed using the RSA and LTHA procedures. The comparison is shown in the form of absolute base shear values (V_b) as well as the base shear coefficient (V_b/W, the base shear normalized to the total seismic weight of the building). It can be seen that the base shear scaled according to ASCE 7-10 (2010) for the RSA procedure are higher than the LTHA procedure in both directions. The base shear computed using the RSA procedure for X direction (15860.80 KN) was lower than 85% of that obtained from ELF analysis procedure (27595.36 KN). Similarly, for each ground motion analyzed, the base shear of LTHA procedure for X direction (14056.37 KN) was lower than that obtained from the ELF analysis procedure using Equation 12.8.6 (32465.12 KN). Therefore, the RSA results are scaled to 85% of the values obtained from the ELFA procedure (Equation 12.8.6), while the LTHA results are scaled to 100% of the values obtained from the ELFA procedure (Equation 12.8.5) according to ASCE 7-10 (2010). It can be seen that the scaled base shear is approximately 3 to 3.5 times smaller than the corresponding linear elastic base shear in both X and Y directions. The scaled values of base shear in both X and Y directions are same due to the scaling up to the same level.

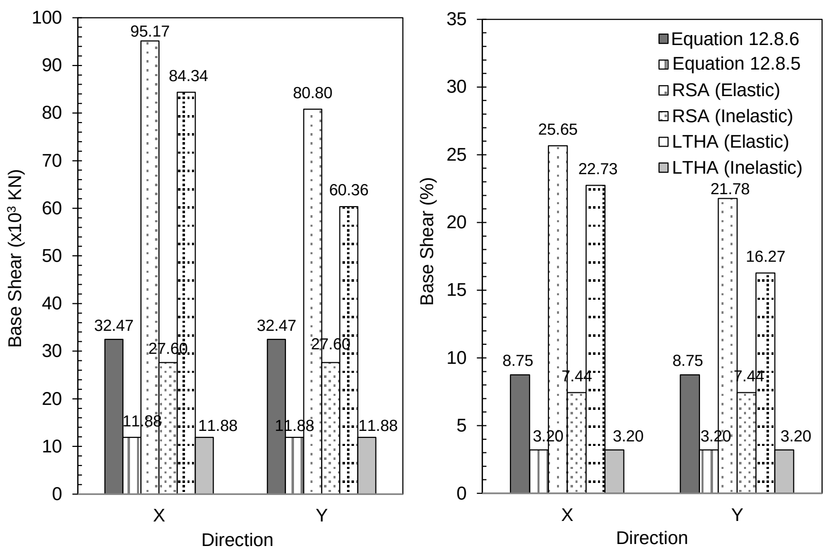


Figure 3: The base shear (V_b) and the base shear coefficient (V_b/W, base shear normalized to the total seismic weight of the building) computed using the RSA and LTHA procedures

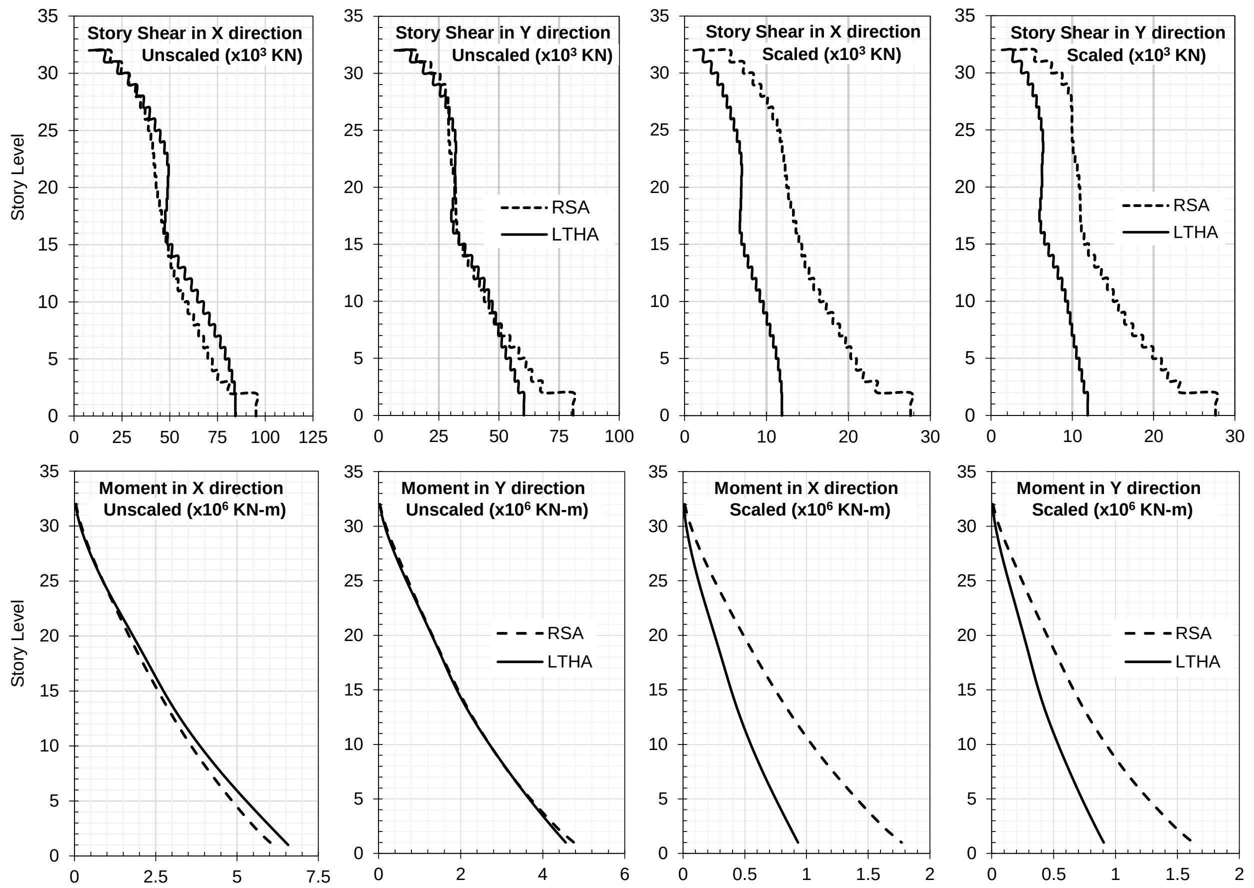


Figure 4: The comparison between the seismic demands (both unreduced elastic and scaled shears and moments in both directions) obtained from the RSA and LTHA procedures.

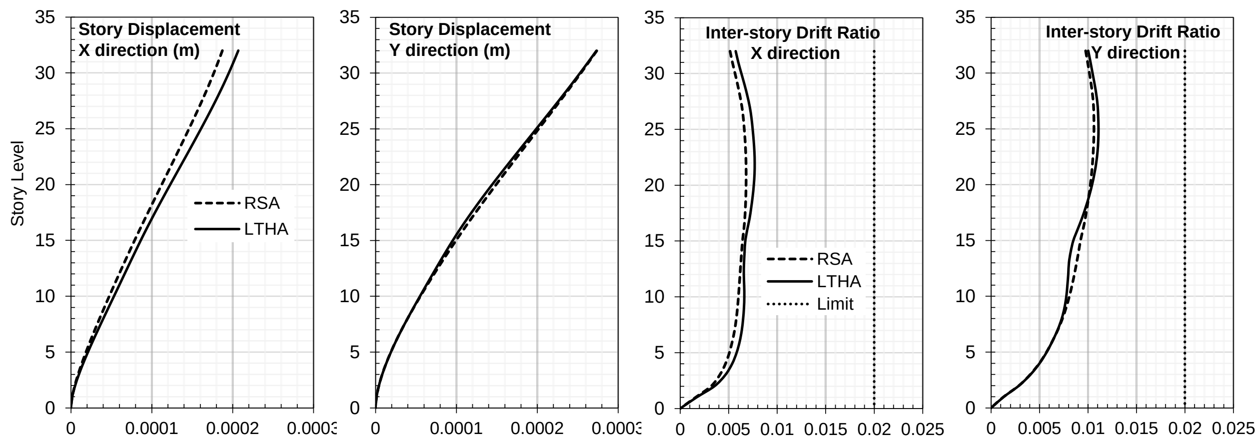


Figure 5: The comparison of story displacements and the inter-story drift ratios for both directions computed by using the RSA and LTHA procedures

Figure 4 presents the comparison of the story shears and overturning moments in both X and Y directions obtained from the RSA and LTHA procedures, respectively. The unscaled elastic values for both procedures are almost same for both directions as well as for both story shear and overturning moment. However, the difference among the scaled values is mainly due to the use of different scale factors for both analysis procedures, as mentioned in section 2.3. As an overall observation, the scaled results from the RSA procedure are 50% to 60% larger than those obtained after scaling the LTHA results. Figure 5 shows the comparison of story displacements and the inter-story drift ratios for both directions computed by using the RSA and LTHA procedures. The story drifts for both procedures is same and are within the allowable limit of 2%. The story displacements obtained from the LTHA procedure are higher than those obtained from the RSA procedure. As an overall observation, the story displacements and drifts for X direction are lower than Y direction.

Figure 6 shows the predictions of local responses by the RSA and LTHA procedures. The shear and moments in the core wall and a selected column are shown. It can be seen that similar to the global response, the RSA procedure is overestimating the component-level response as well. This would result in an uneconomical design by the RSA procedure.

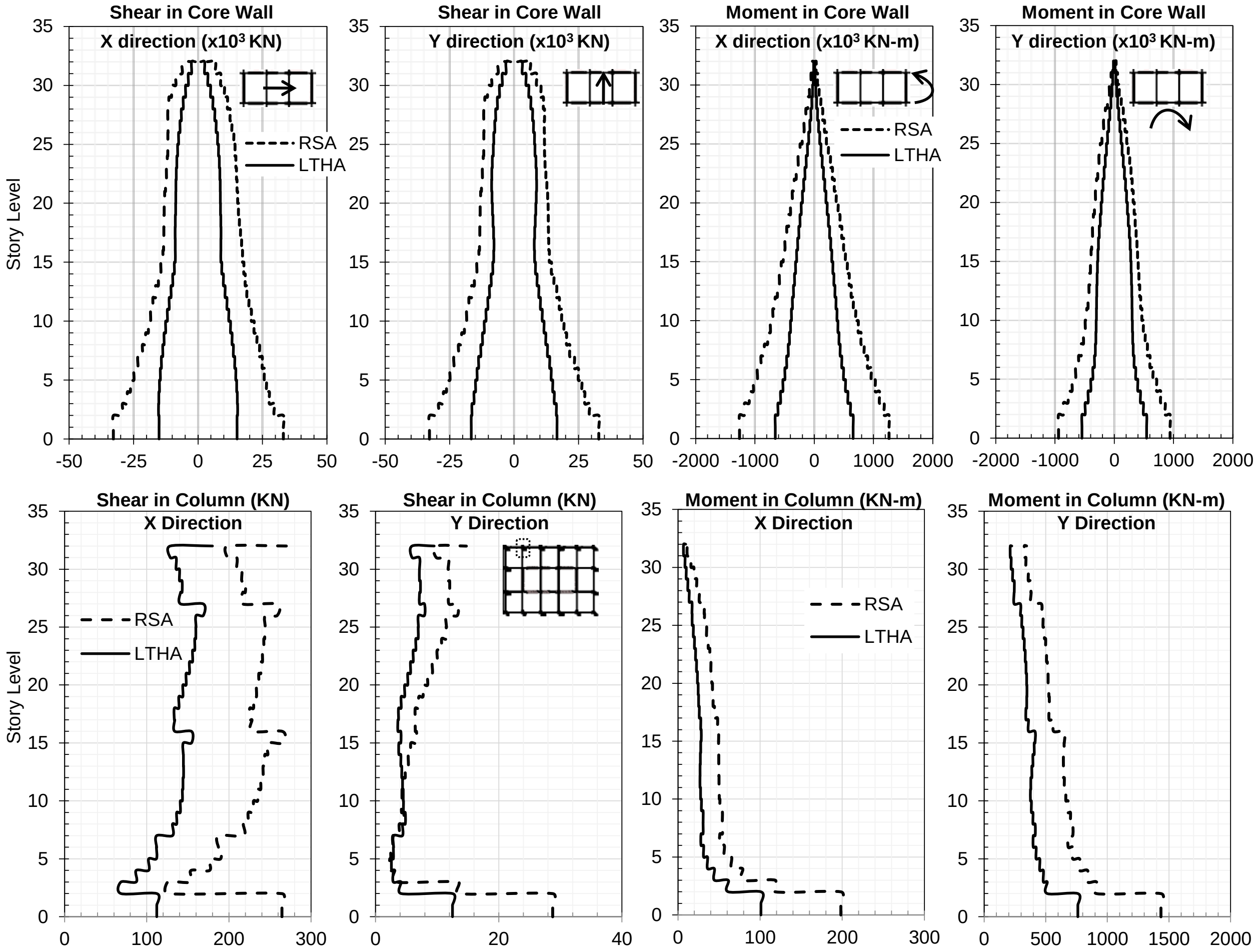


Figure 6: The shear and moment computed in core wall and a selected column computed from the RSA and LTHA procedures for both directions.

Figure 7 shows shear demands determined from both the analysis procedures for a two shear wall legs and two coupling beams. The corresponding shear capacity provided as part of design is also shown for both cases. On average, the shear demands obtained by the RSA procedure are around 30% higher than those obtained from the LTHA procedure. Therefore, the RSA is resulting in a costly design compared to the LTHA procedure.

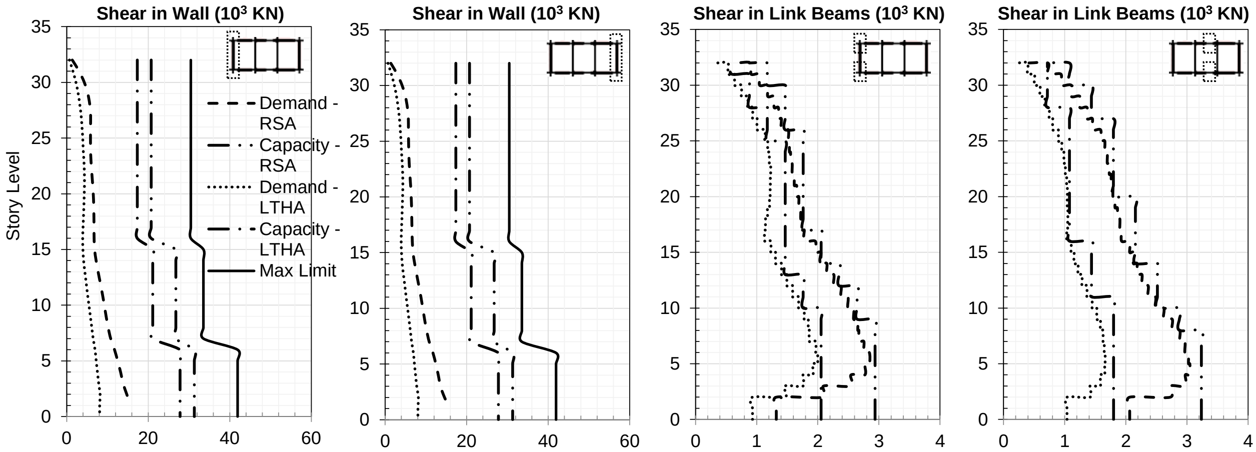


Figure 7: The comparison of shear demands and capacity of shear wall and coupling beam computed by using the RSA and LTHA procedures

Figure 8 demonstrates the comparison of longitudinal reinforcement ratio required by the RSA and LTHA procedures. One column and girder is used here for the purpose of demonstration. It can be seen that the RSA procedure is resulting a high reinforcement demand for column as compared to the LTHA procedure. For the girder, this difference can be as high as 30% in some cases. Figure 8 also illustrates the demand-to-capacity (D/C) ratios for a given flexural reinforcement in mat foundation. In consistence with all previous results, the RSA procedure is resulting in a higher D/C ratios compared to the LTHA procedure.

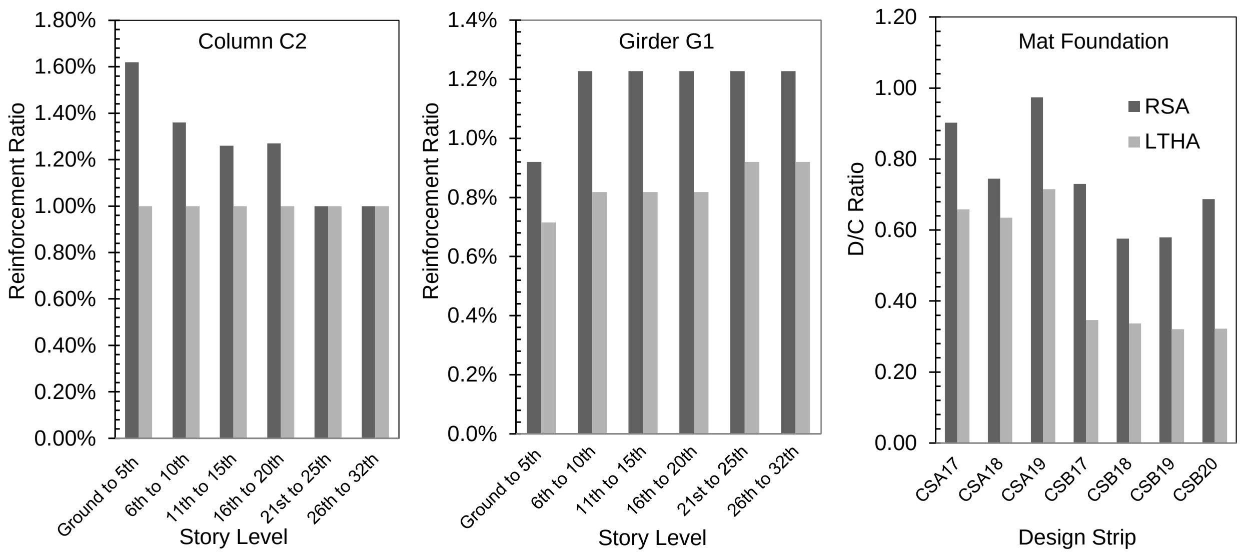


Figure 8: The reinforcement ratios in columns C2, girder G1, and the flexural D/C ratios of mat foundation computed by the RSA and LTHA procedures.

4. CONCLUSIONS

This study evaluates and compares the use of Linear Time History Analysis (LTHA) procedure with the code-based standard RSA procedure for determining the seismic demands of high-rise RC shear wall buildings. Using a 32-story case study building located in a seismically active region, it is shown that the use of LTHA procedure would result in reduced seismic demands (e.g. story shear, overturning moment, component-level shear and moment) by approximately 30% to 35%, mainly due to the difference in scaling factors prescribed by the ASCE 7-10 (2010). Therefore, its use will result in an economic code-based design of new buildings as compared to if the RSA procedure was used. Although the LTHA procedure requires more computational cost, effort and resources compared to the RSA procedure, it can provide a significantly improved and accurate estimate of elastic seismic demands. Therefore, its use should be encouraged among the practicing design engineers.

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