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Effects of Material Nonlinearity on Seismic Responses of Multistoried Buildings with Shear Walls and Bracing Systems

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Abstract Scads of earthquake-resistant systems are being invented around the globe to ensure structural resistance against the lateral forces induced by earthquake loadings considering structural safety, efficiency, and economic aspects. Shear wall and Bracing systems are proved to be two of the most viable solutions for seismic strengthening of structures. In the present study, three numerical models of a G+10 storied building are developed in commercial building analysis software considering shear wall and bracing systems for earthquake resistance. Material nonlinearity is introduced by using plastic hinges. Analyses are performed utilizing two dynamic methods: Response Spectrum analysis and nonlinear Time-history analysis using Kobe and Loma Prieta earthquake data and results are compared to observe the nonlinear behavior of structures. The outcomes exposed that a significant increase in the seismic responses occurs due to the nonlinearity in the building systems. It was also found that building with shear wall exhibits maximum resistance and minimum nonlinearity when subjected to dynamic loadings.

Keywords: shear wall frame system, steel bracing frame system, Material nonlinearity, Response Spectrum analysis, Nonlinear Time-history analysis

1. INTRODUCTION

The lateral load resisting system becomes more important than the structural system that resists the gravitational loads with increasing height. There are numerous systems that are used to reduce the damage quantity of the structure such as rigid frame, shear wall, wall-frame, braced tube system, dampers, outrigger system, and tubular system. Due to the simple construction and installation process of the shear wall and bracing systems, these are much popular and widely used throughout the world (Nandeesh & Geetha 2016). Some previous studies regarding shear walls and bracing systems are discussed below.

Jani & Patel (2013) analyzed and designed 36, 50, 60, 70, and 80 storied diagrid steel buildings with a floor plan of 36 m × 36 m size considering dynamic along the wind and across wind loads through ETABS as per IS 800:2007. Upadhyay & Jamle (2020) and Patidar & Jamle (2020) studied and modeled 12 shear wall stability case residential apartment buildings for demonstrating the stability issue of the tall structure considering different thickness of shear wall combined with M20, M30, and M35 grades of concrete and stated that structures will be safer and more stable by using a higher thickness of shear wall members and concrete grade.

Dharanya et al. (2017) analyzed a G+4 storied residential RC building with cross bracings and shear wall as per IS 1893:2002 utilizing equivalent stiffness method using ETABS software to evaluate the seismic performance. Linganna (2019) described the dynamic analysis of residential G+11 storied building structure and geopolymer concrete structure using response spectrum method considering seismic zone-III through ETABS. Alashkar et al. (2015) and Ahmad & Talwar (2021) conducted a comparative study on dynamic analysis of H and T-shaped G+13 storied frame systems consisting of shear wall and composite bracings at different locations considering seismic zone III and V through response spectrum method.

Madan et al. (2015) and Azad & Abd Gani (2016) introduced shear wall and steel bracing systems in multistoried RC buildings to show dissimilarities between them using ETABS software. Chavan & Jadhav (2014) studied 7 storied RC buildings with different types of bracing (Diagonal, V type,

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inverted V type, X type) at seismic zone III by equivalent static analysis as per IS 1893:2002 using Staad Pro V8i software and found that the X type of steel bracing significantly contributes to the structural stiffness and reduces the maximum inter-storey drift of R.C.C building than other bracing systems. Chandiwala (2012), Chandurkar & Pajgade (2013), Sengupta (2014), Baral & Yajdani (2015), Soni et al. (2016), Bongilwar et al. (2018), Fares (2019) and Islam et al. (2022) showed the effect of shear walls considering multistoried building system for various parameters like base shear, story drift ratio, lateral displacement, bending moment and shear force using equivalent static method through FEM based software ETABS. Nandeesh & Geetha (2016) examined the seismic reaction and wind analysis of a hyperbolic circular diagrid structure rehabilitated with shear wall and steel braced frames at two distinctive seismic zones 2 and 3 utilizing ETABS according to IS codes.

Abhinav et al. (2016), Kumar (2018), and Patel & Jamle (2019) conducted numerical analysis on a 25-storied high-rise residential building with a plinth area of 825 m2 considering several cases with shear belts on different floors utilizing response spectrum method with SRSS combinations to determine various parameters such as base shear, maximum nodal displacement in the longitudinal and transverse direction, drift values and load cases that creates maximum drift through Staad pro software. Tuppad & Fernandes (2015) introduced Genetic Algorithms for optimum positioning of shear wall in multi-storied structures subjected to seismic loadings, which is coded in MATLAB and analyzed

in ETABS. Khan et al. (2020) performed a comprehensive study on the performance beam column system, shear wall system, and tube system of 12 storied RCC buildings with a plan size of 18 m × 18 m using ETABS, design characteristics, and all the load combinations of seismic forces are considered as per IS 456:2000 and IS 1893(Part 1): 2002; respectively.

2. MODELLING OF BUILDINGS

G + 10 storied residential building frame system was analyzed in the current study considering the seismic zone-III utilizing the Response Spectrum Method (RSM) and Time-History Analysis (THA) through ETABSv18 software as RSM is recognized for conducting linear dynamic statistical analysis. Earthquake analyses were also performed by inputting 1995 Kobe and 1989 Loma Prieta earthquake record data obtained from the Pacific Earthquake Engineering Research Center (PEER) ground motion database developed by UC Berkeley, and these analyses were executed by following the code of ASCE 7-05. As per ASCE 7-05 Complete Quadratic Combination (CQC) was utilized as the modal combination method while Square Root of Sum of Square (SRSS) was used as directional combination type in ETABS to conduct the RSM. Fast Nonlinear Analysis was selected in ETABS for performing nonlinear THA and the Fundamental Equilibrium equation of FNA was followed is given in equation 1, where M- moment (N-m), a- accelerations (m/s2), C- damping factor, v-velocity (m/s), K- Stiffness (N/m), d- Displacement (m), Rnl- Nonlinear object force vector, and R- Force.

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) + Rnl(t) = R(t) \quad (1)$$

In this study, three types of frame systems were adapted for the model analysis as- building with Special Moment Resisting Frame (SMRF) system, building with special shear wall frame (SSWF), and special concentrically braced frame (SCBF) system and compared their results. The response spectrum graph plotted between the time period and spectral acceleration coefficient (Sa/g) for E-type soil is depicted in Figure-1. The damping ratio is usually taken as 5% and this study followed the same. M40 and HYSD Fe550 grade concrete and reinforcing steel were considered for the design of the RCC frame building structure. A 34 m height of the building was considered which consisted of 4m of bottom story and the remaining story heights were 3m. Beam and column dimensions were adapted as 230×460 mm and 230×690 mm; respectively, whereas 150 mm slab and shear wall thickness were considered for the analysis. Several types of loads were picked here in this study- Live (5 kN/m2), dead (2 kN/m2), floor finish (5 kN/m2), earthquake, and wind load; respectively. The important and rudimentary parameters for the analysis purposes are presented in Table-1. Regarding bracing materials UPN-220, S-235 grade steel section along with EN-10025-2 standard was used for designing the bracing system. To observe the nonlinear behavior of the structures, plastic hinges are added to both ends of the beam and column of SCBF and SSWF systems as material nonlinearity. The whole procedure is described through a flowchart for getting a crystal-clear view of this research study as illustrated in Figure 2. The 3D view of three models developed in ETABS Software is depicted in Figures 3 to 4.

Table 1. Parameters considered for the Model analysis

Structure type	B (SSWF & SCBF) & C (SMRF)	Soil type	E (SCS), V_s<600 ft/s, N´<15. USS, Su´<1000 Psf
BWS	45 m/s	SAP1, S_1	0.28
IF, I	1	ZC, Z	0.22
RRF, R	8 (SMRF) 6 (SSWF & SCBF)	PMF, λ	0.12
SOSF, Ω	3-(SMRF), 2.5-(SSWF) & 2-(SCBF)	TP, T	1.11 sec
DAF, C_d	5.5 (SMRF) & 5 (SSWF & SCBF)	S	1.35
ORSPP, S_{D1}	0.504	F_a	1.35
SRSAP, S_{DS}	0.63	F_v	2.7
SAPSP, Ss	0.7	LTP	2 sec

BWS-Basic Wind Speed, **IF**-Importance Factor, **TP**-Time period, **RRF**-Response Reduction Factor, **SOSF**-System over strength factor, **DAF**-Deflection Amplification Factor, **ORSPP**-One-second response spectral acceleration parameter, **SRSAP**-Short-period response spectral acceleration parameter, **SAPSP**-Spectral acceleration parameter at short periods, **SAP1**-Spectral acceleration parameter at a period of 1 sec, **ZC**-Zone Coefficient, **PMF**-Property Modification Factor, **LTP**-Long transition period **SCS**- Soft clayey soil, **USS**-Undrained Shear Strength

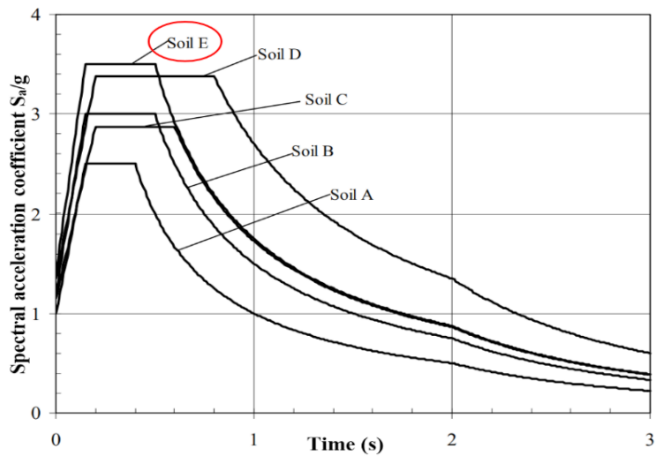


Figure 1. Response spectrum for medium soil type for 5% damping as per Kappos (2009).

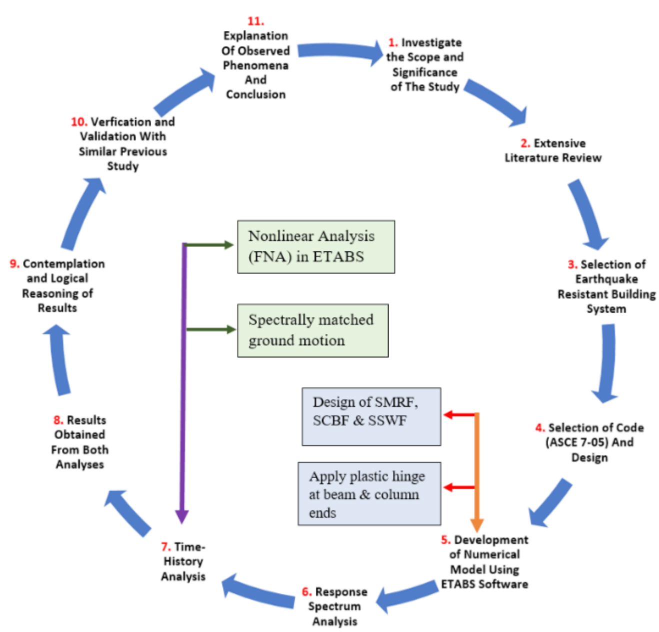
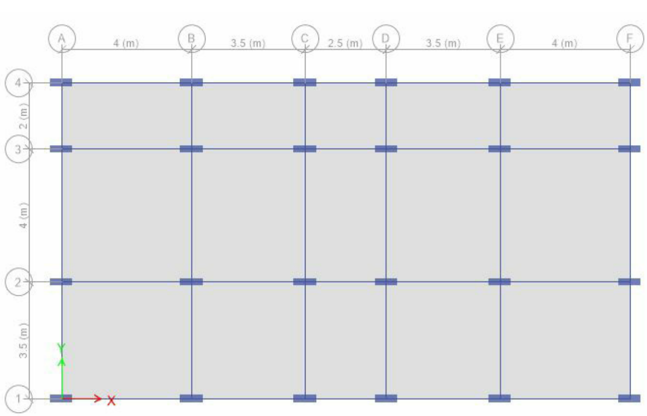
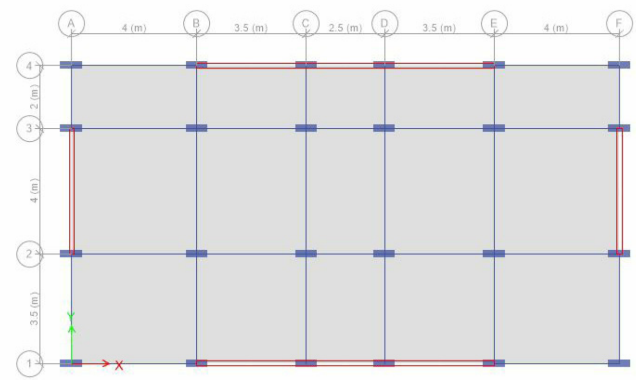


Figure 2. Schematic flow diagram of the current study.

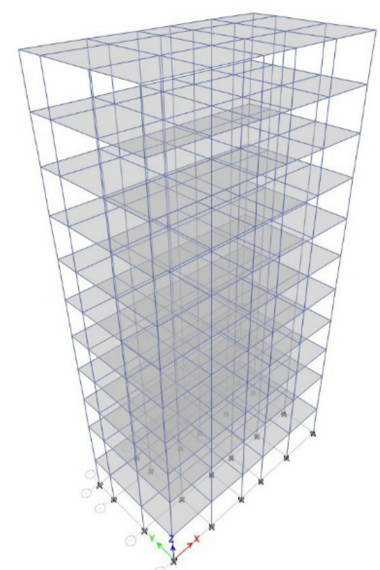


(a) SMRF & SCBF systems

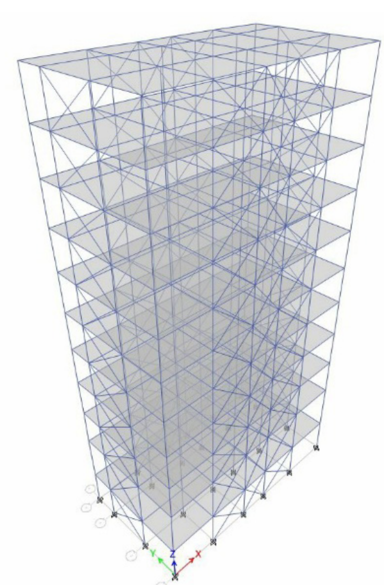


(b)) SSWF system

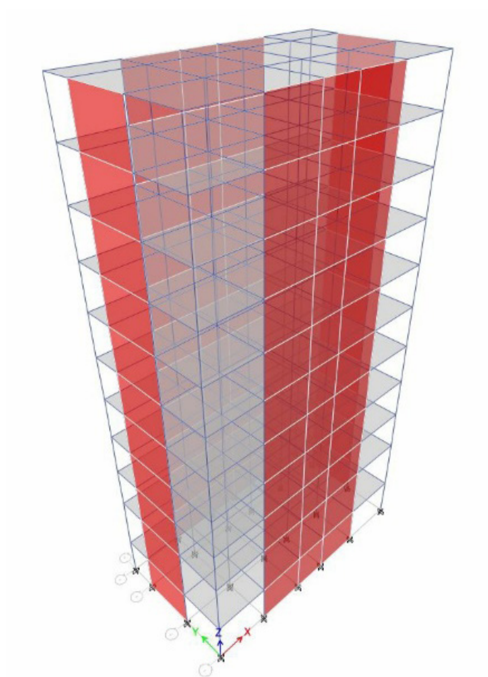
Figure 3. Plan view of building systems



(a) SMRF systems



(b) SCBF systems



(c) SSWF system

Figure 4. Three-dimensional view of three models.

3. ANALYSIS AND RESULTS

Three types of structural frame systems with G+10 stories were numerically analyzed in this study through ETABS software considering RSM and nonlinear THA. Two types of earthquake loads were used in this research such as Kobe and Loma earthquakes, the time history curves for these quake loads are depicted in Figure 5. The results obtained from the analysis are discussed in the following sections.

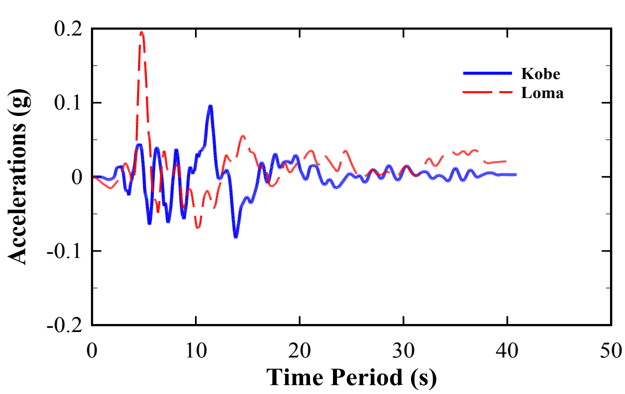


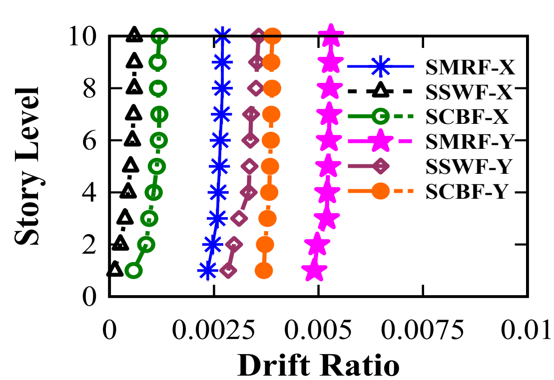
Figure 5. Time history curves for Kobe and Loma

(1) Story Drifting

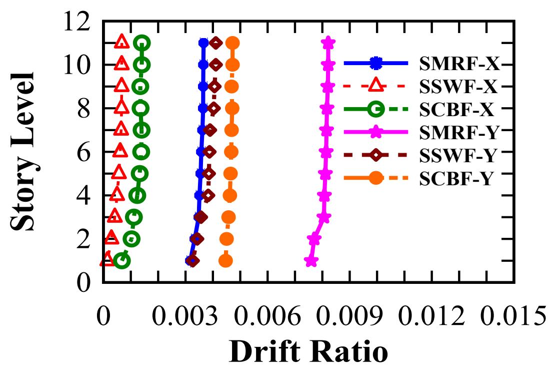
The drift ratio is defined as the ratio of maximum lateral drift to the total height of the specimen. The drift ratio is defined as the ratio of maximum lateral drift to the total height of the specimen and the procedure developed by Priestley [4] relies on the ductility ratio () to calculate the reduction in shear strength that occurs under cyclic loading and lateral drift increase. As per IS 1893, Story drift shall not exceed 0.004 times story height. It can be seen from Figures 6a, 6b, and 6c that, the drift ratio is higher at Y-axis than X-axis and all the curves are following same linear trends. Accept the drifting ratio magnitude in the Y-axis for SMRF and SCBF systems, the rest of the ratio magnitudes were less than 0.004 for all the structural systems both for the X and Y axes. Concerning drift ratio, the SSWF system exhibits the best performance, as the drifting ratio is less for this system than all other systems analyzed for both axes in RSM and nonlinear THA procedures.

Displacement in each story level is discussed in Figures 7a, 7b, and 7c. It was observed that the system with shear wall provides less displacement or drift than the structure incorporating bracing. The current study is compared only with RSM method with previous research conducted by Saikumar and Mandava (2022), they also analyzed an 11-storied building considering shear wall and bracing by utilizing RSM. They modeled three types of building, denoted here in this manuscript as general building (GB), building with shear wall (BWSW), and building with bracing (BWB); respectively. No similarity was found between the current and previous studies comparing drifting, as the results obtained from both axes of the present research were showing the same patterns whereas in the case of the previous study the results were not the same for the two axes. According to Figures 6 and 7, the current study exhibits common results both for drift and displacements in both analysis and axes like SMRF < SSWF < SCBF, while in the previous study X-axis were showing GB < BSW < BSW whereas Y-axis were showing GB < BSW < BWB. One important thing was that the drift value found in the previous study was much less than in the current research. These discrepancies occurred mainly due to the difference in code provisions used in the two studies.

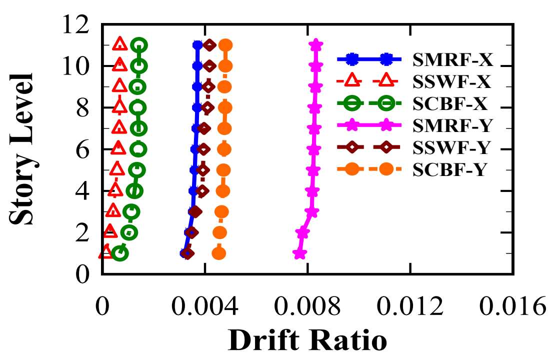
Comparing Figures 6 and 7, both for drift ratio and displacement, higher magnitudes were found at the higher story level and values decreased as the story level was decreased by following a linear pattern, indicating that these factors tend to ascend with increase in the height of the story.



a) RSM

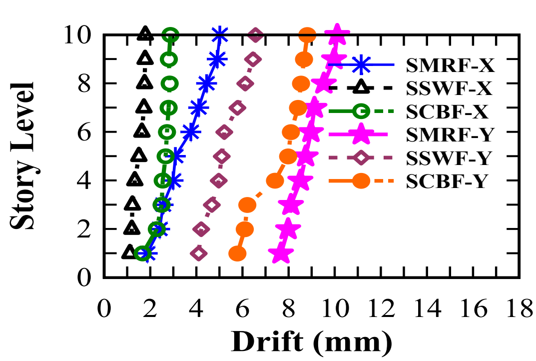


b) Kobe earthquake

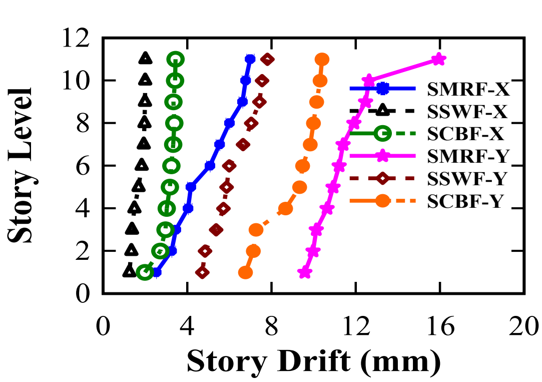


c) Loma earthquake

Figure 6. Story drift ratio in RSM and THA.



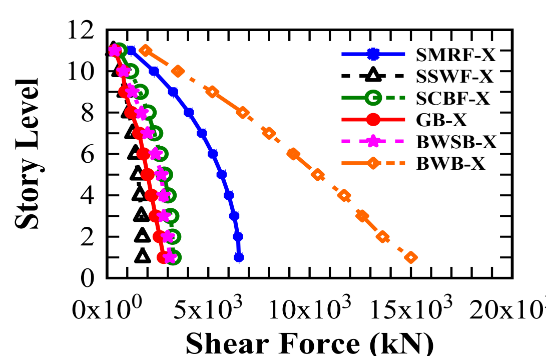
a) RSM (X and Y-axis)



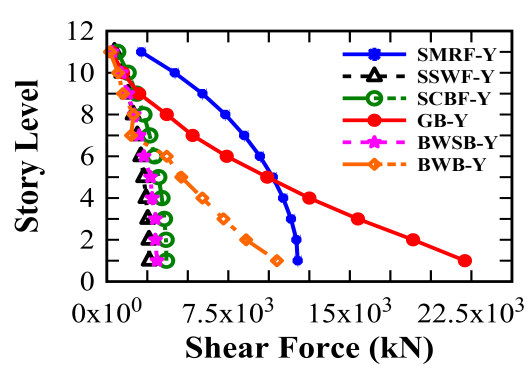
b) Kobe earthquake (X and Y-axis)

(2) Story Shear

Story shear (V) is the reaction that each column, a vertical member of the building, has on each floor level of the building assuming the column is simply supported at the top and bottom of the floor levels. It is the lateral force acting on a story due to the forces such as seismic and wind forces. It is calculated for each story and changes from minimum at the top to maximum at the bottom of the building. In this study, shear forces of the buildings were found applying two methods such as RSM and nonlinear THA as depicted in Figures 8 and 9. In Figure 8, the SMRF system provided maximum shear magnitudes than the other remaining two structural systems, and all the three shear force curves of the three types of structural systems followed the same pattern decreasing with the story level of the shear force values were increased for each three building systems. It was also noticed that the magnitudes of shear force were higher on Y-axis than X-axis. However, the same curve pattern for the shear force at each story level was also witnessed in the previous study conducted using RSM by Saikumar and Mandava (2022), but in their cases, buildings with bracings exhibited maximum shear values at X-axis whereas, in the Y axis, GB provided higher magnitudes than other two building systems. In the case of nonlinear THA considering Kobe and Loma earthquake loads was shown exactly similar kinds of behavior like RSM as presented in Figures 9a and 9b. Maximum value obtained at the base level for both analysis systems in both axes. In terms of shear force, obtained results were like SMRF > SCBF > SSWF.

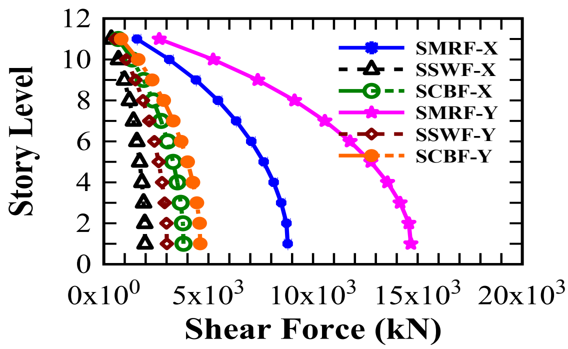


a) RSM (X-axis)

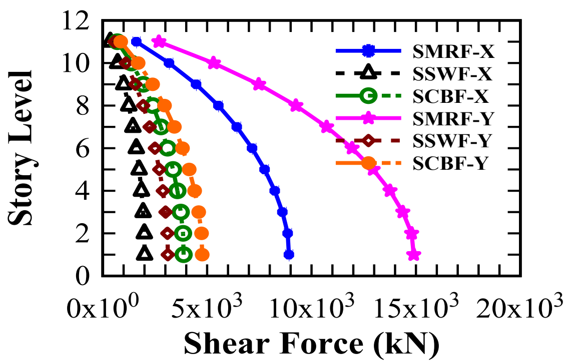


b) RSM (Y-axis)

Figure 8. Shear forces for all structural systems in RSM.

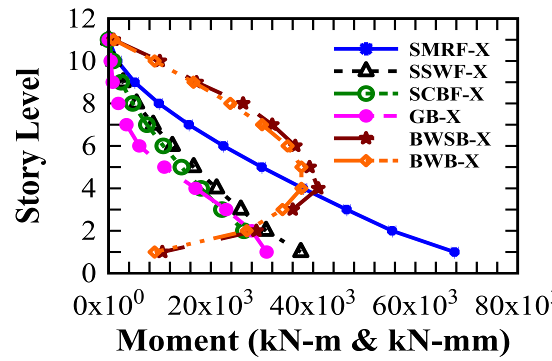


a) Kobe earthquake in both axes

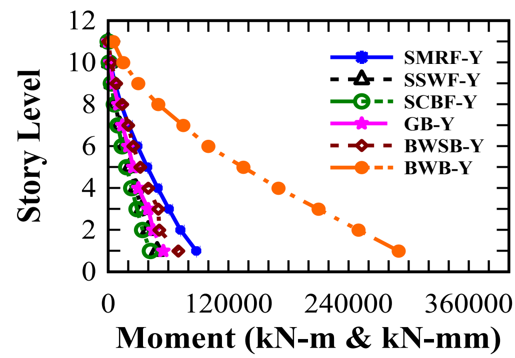


b) Loma earthquake in both axes

Figure 9. Story shear forces for all buildings in THA.



a) RSM at X-axis

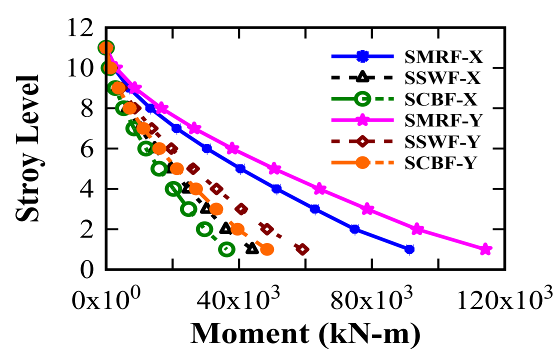


b) RSM at Y-axis

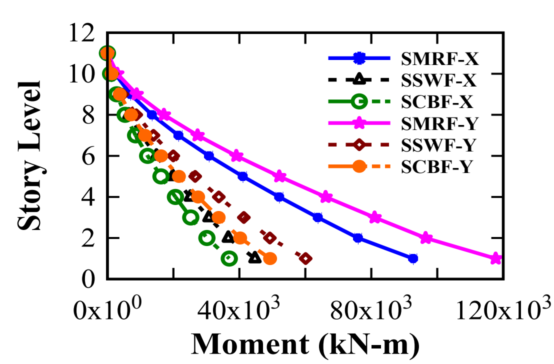
Figure 10. Bending moment for all building systems in RSM at both axes.

(3) Story Moment

From Figure 10, building system with shear wall generated maximum moments than building system with bracing and which is partially similar to the previous study conducted by Saikumar and Mandava (2022) as in their result, shear wall building provided maximum values in the X axis, whereas bracing system exhibited maximum magnitude in Y-axis. It is also noticed that the value of bending moment in both directions increases from story 11 to story 1, which is partially true for the previous study as this incident only coincides with the Y axis. The magnitude of the produced moment was much less than in the current study, different code provision has made this huge dissimilarity. For getting the evidence of the moment generated from the Kobe and Loma earthquake, the obtained result from the analysis is graphically presented in Figures 11a and 11b. It can be clearly understood from Figure 10 that, for both quake loads Y axis produced maximum moments and the structural system with shear wall generated a high amount of momentum than the shear walls structural system. The order is like that, SMRF > SSWF > SCBF in terms of bending moment. Bending moment curves for both RSM and nonlinear THA analysis provides the same pattern of linear trends like moment value increases from the 11th floor to level 1.



a) Kobe earthquake



b) Loma earthquake

Figure 11. Bending moment all structural systems in THA.

(4) Torsion

RSM and nonlinear THA, two types of analysis were performed and maximum torsion was generated in the Y axis in both analysis procedures. In the case of RSM, maximum torsion was generated for the building system with shear wall, and produced torsion following a linear trend with highest and lowest torsion detected at the levels 1 and 11; respectively for all the building systems as presented in Figure 12. The phenomena conspicuous in the current study exactly coincide with the previous research performed by Saikumar and Mandava (2022) except the magnitude of their study was found higher than this present study, maybe this was due to the use of different building codes. However, exactly a similar phenomenon was noticed in the building system while Kobe and Loma earthquakes were applied as depicted in Figures 13a and 13b. According to the torsional values obtained from both analyses, SMRF > SSWF > SCBF this order was found.

(5) Stiffness of Structural System

The value of modal stiffness in RSM and nonlinear THA increases from modes 1 to 33 and the maximum value of model stiffness was acquired for shear wall building than the bracing system as depicted in Figure 14. This phenomenon was partially matched with the previous study done by Saikumar and Mandava (2022), as their modal stiffness values were much higher than the present research. This discrepancy happened as the two analyses were conducted considering different building codes. In terms of modal stiffness, this SSWF > SCBF > SMRF order can be generalized.

(6) Modal Time Period

From Figure 15 the magnitude of the time period in both analysis systems decreases from modes 1 to 33 the maximum value of the time period was perceived for the SMRF system than the other two building systems (SSWF & SCBF). This incident exactly coincided with the previous study performed by Saikumar and Mandava (2022). As per Figure 15, this SMRF > SCBF > SSWF chronological order can be noticed.

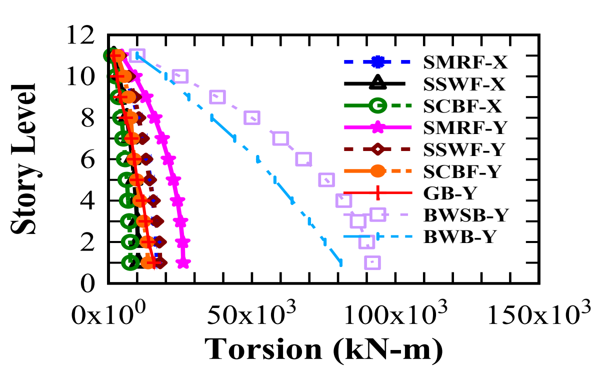
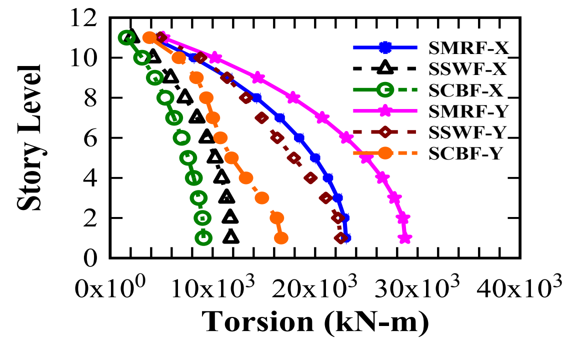
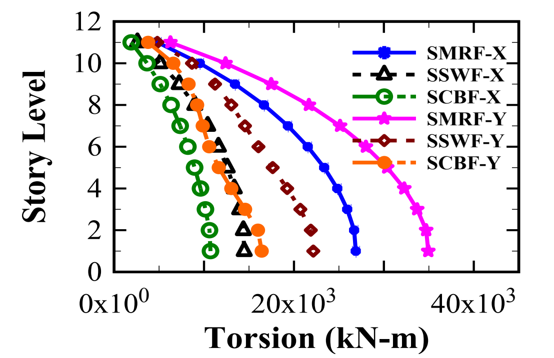


Figure 12. Produced torsion in RSM.



a) Kobe earthquake



b) Loma earthquake

Figure 13. Developed torsion due to earthquake excitations.

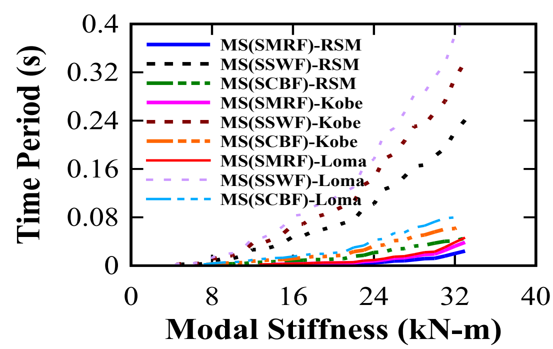


Figure 14. Modal stiffness

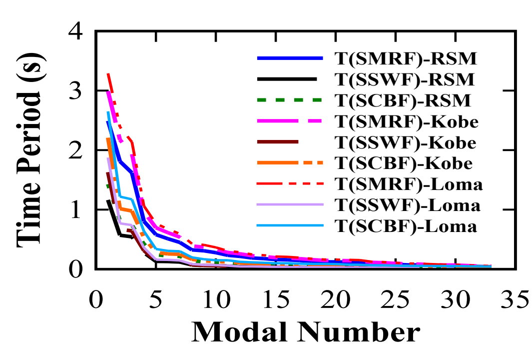


Figure 15. Comparison of modal time periods

(6) Linearity and Non-linearity of Building System

Linear and non-linear performance of three building systems such as special moment resisting building system, and building system with shear wall and bracing were highlighted in this research. In this regard, all the three structural systems were analyzed through linear response spectrum and non-linear time history analysis by implying Kobe and Loma earthquakes. In Figure 16, the magnitude of different parameters obtained from RSM analysis was increased in THA. Values found from the analysis applying Loma earthquake load exhibit maximum results than obtained magnitude manifested while applying Kobe earthquake.

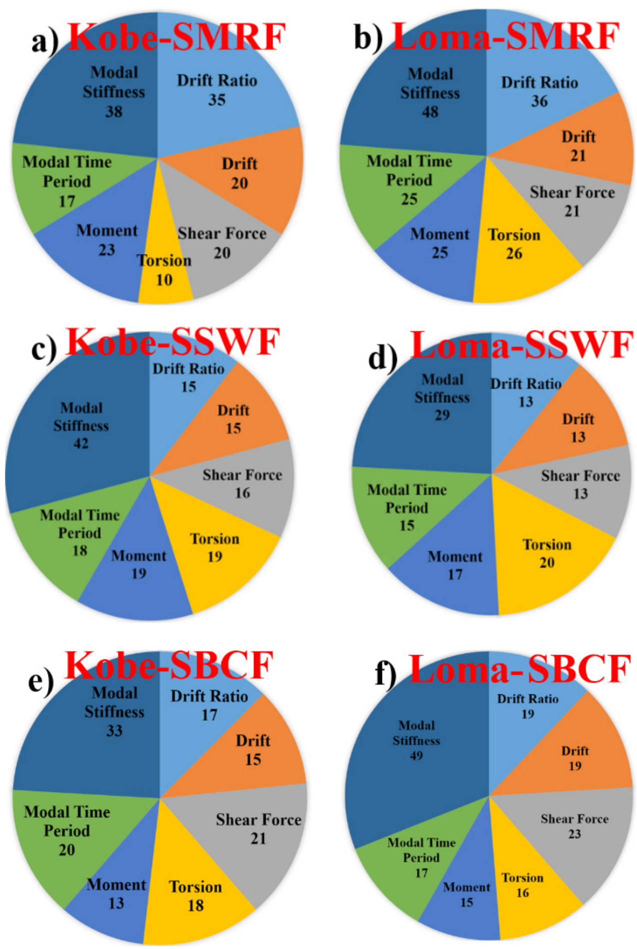


Figure 16. Increment in Different Parameters for Non-linear THA-Kobe and Loma earthquake at SMRF, SSWF, and SCBF Systems.

4. DISCUSSIONS

In both methods, the maximum story drift ratio was found at Y-axis for all three building systems and followed a specific pattern. Generalized coordination was seen for all model structures in two analysis methods such as-maximum drifting ratio value was noticed at the upper story level for all the structural systems. It was also noticed that the drift ratio magnitude for all the building systems didn't exceed 0.004 except for the value of SMRF and SCBF systems at only the Y-axis. Maximum displacement (drift) was provided by the SMRF system as in this system no earthquake-resistant system was applied. Between SSWF and SCBF structural system, building with shear wall exhibits better performance as in this system less displacement was taken place. And the Y-axis value was governed by the magnitude of the X-axis and a specific pattern was noticed for all the structural systems such as maximum displacements at the upper story level. Additionally, maximum amplification in results from RSM to nonlinear THA for drifting ratio, and displacements were found for SCBF systems in both Kobe and Loma earthquakes than in SSWF systems while this amplification was 2% higher in the case of Loma than in the Kobe earthquake.

In both response spectrum and nonlinear time history analysis, the Y axis exhibits maximum shear force and bending moment for all the building systems. Both shear force and bending moment were intensified with decreased story level while the maximum value for the shear force and bending moment was significant at the base. Based on the shear force value, the structural system can be ordered like SMRF > SCBF > SSWF, and this order remained similar in both analyses and axes while significant momentum was achieved for SSWF systems due to the extra load being added as self-weight of the shear wall itself. Similar phenomena also became apparent for torsion as like moment and shear force, because of having interrelationship among them. Maximum torsional value was provided by the SSWF system in both RSM and THA. In the case of story shear, the SCBF system amplified in nonlinear THA more significantly than SSWF systems, and the percentage of amplification of SCBF and SSWF for both Kobe and Loma earthquakes were 21, 23, and 13, 16; respectively. The maximum amplified magnitude for torsional effects was found in SSWF than SCBF systems in RSM to nonlinear THA and Kobe provided around 2% higher increment than the Loma earthquake.

The magnitudes of modal stiffness were amplified from mode 1 to mode 33 and the maximum value of stiffness was found for SSWF systems than in other building systems. The modal time period was decreased with the increase in the modal number and the SMRF system exhibits a maximum modal time period than the other two cases. If the results for the three systems are chronologically arranged, the orders will look like that- SMRF > SCBF > SSWF.

The current study was validated by a previous study and the results and trending phenomena partially coincided with the present study. The discrepancies mainly occurred due to the discrepancies inherent in the building code provisions used in these two studies. It can be concluded that building with shear wall provides better performance than the other two building systems in terms of feasibility.

17% and 19% increase in the moment of the SSWF system whereas, 13% and 15% increment was found in SCBF system; respectively for Kobe and Loma earthquake. Responses in the SCBF system amplified 5% higher than SSWF systems for the Kobe earthquake whereas, for Loma, 1% higher values were seen for SSWF than SCBF system. In terms of modal stiffness, the SCBF system amplified more than the SSWF system and maximum amplification was noticed in the sphere of Loma earthquake. Finally, it can be concluded that, SMRF structural system exhibited significant enlargement in the remaining cases. Furthermore, the building with shear wall system shows the best performance both in linear and nonlinear studies.

5. CONCLUSION

Three types of building systems were considered in the current study as- Special Moment Resisting Frame (SMRF) system, the building with special shear wall frame (SSWF), and the special concentrically braced frame (SCBF) system. Response Spectrum and nonlinear Time History analyses were conducted utilizing ETABS software. Plastic hinges are calibrated at the beams and columns of SCBF and SSWF building systems to obtain the nonlinear response of the structures under dynamic loading. Two types of analysis were performed. The following concise conclusions can be made from this study.

1. Vertical responses (responses found from Y-axis) seem to be the most crucial one while analyzing seismic resistance of building structures.
2. Buildings with shear wall system manifests lower displacement and drift ratio due to the additional stiffness to the building system induced from shear wall.
3. Higher moment was observed for SSWF buildings due to the extra weight appended from shear wall. However, SSWF building systems provided excellent performance in resisting extra torsions originated from nonlinearity of materials.
4. All the engineering parameters (shear force, bending moment, torsion, drift ratio, displacement, modal stiffness etc.) displays a large leap in amplification in case of nonlinear analysis. Thus, it can be stated that nonlinearity plays a vital role in seismic performance analysis of building systems.
5. SSWF building systems demonstrate better performance in both RSM and nonlinear time-history analysis, which indicates its supremacy as a better choice for the design of earthquake resistant buildings.

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