CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Effect of Different Ground Motion Scaling Methods on Behavior of 40 Story RC Core Wall Buildings

by

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I want to dedicate this investigation entirely to my supervisor and my devoted teacher. He was the person designated for me to build and optimize my skills in the subject of Structural Engineering. Without his kind and strict guidance, this work was never fruitful in the right way. He turned the complex things very easy and motivated me in hard times throughout the research. Whenever I was ready to give up or feel little down, his forever loving strictness commanded me to gear up and retrack my ambitions. I have a lot to write in his honor but the limited space will restrict me to do so. Its my humble pray that he may be rewarded against these ambitious efforts in his never-ending life as well as in this momentarily life. May he get prosperous health, longer and happier life to keep serving brilliantly. I greatly wish him all the success in his future endeavors.

CERTIFICATE OF APPROVAL

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Abstract

Different advanced techniques and guidelines have been formulated for design and construction of high-rise buildings. Designing these structures on the concept of RC core wall has been very eminent at present for its extensive benefits. The non-linear time history analysis (NLTHA) procedure has emerged as the finest design procedure for the design of taller buildings. NLTHA uses synthetic or real recorded ground motions to accurately predict the seismic response of structures at specific locations. The use of real recorded ground motions is preferred over the synthetic or artificially generated records for having original ground motion characteristics. Since these ground motions are recorded at different locations, the characteristics of these ground motions are likely to be modified before using at other specific sites. The compatibility of real recorded accelerogram is usually attained by matching it with the target spectrum of particular site.

Time domain spectral matching (TDSM) and frequency domain spectral matching (FDSM) are mostly preferred for high-rise buildings which comprise their own benefits and drawbacks. The effectiveness of these spectral matching (SM) techniques is usually compared based on characteristics of ground motions. Due to the lengthy process of NLTHA, application of only one technique is conceivable. Based on structural responses on different engineering demand parameters (EDPs) like story drift, story displacements, story shear, story moments etc., no recommendations on best SM method are found in literature for design of high-rise buildings. This research focuses to investigate two different SM techniques particularly for NLTHA of 40 story high-rise RC core wall structures. The results indicate an extensive variation against individual SM intensity measures as well as in different EDPs of building. However, the average EDPs were mostly found identical. Irretrievable to the literature, the FDSM were proved to be a better technique on certain parameters. The use of both SM techniques is acknowledged and the further refinement in displacement drifts of FDSM is suggested to produce more reliable structural responses as compared to the TDSM.

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Abbreviations

BCP	Building Codes of Pakistan
DBE	Design Basic Earthquake
EDPs	Engineering demand parameters
FDSM	Frequency domain spectral matching
G.M	Ground motion selected from PEER Database
MCE	Maximum Considered Earthquake
MPS	Modal Push-over Based Scaling
Mw	Moment magnitude of earthquake
NLTHA	Non-linear Time History Analysis
PGA	Peak ground acceleration
R	Response modification factor
RC	Reinforced concrete
RCCW	Reinforced concrete Core Wall
RSA	Response spectrum analysis
SM	Spectral matching
TDSM	Time domain spectral matching
V30	Shear wave velocity of the respective site
1D	One dimensional
3D	Three dimensional

Symbols

ε	Story shear
$\xi\%$	Damping ratio in percentage
Δ	Story Drift in %age
δ	Displacement in inches
Rj $_{(Rup)}$	Minimum Distance from Rupture Fault to site
$\ddot{u}_g$	Ground acceleration
$\ddot{u}_s$	Story acceleration
u$_g$	Ground displacement
u$_s$	Story displacement
f$_n$	Fundamental frequency
Φ	strength-reduction factor

Chapter 1

Introduction

1.1 Background

In the era of modern science, private and public sector organizations crave to build high-rise structures. The demand of these structures has accelerated more due to limited globe space and advancements in engineering tools. Several seismic codes and guidelines for design and construction of these buildings have been established in the past to achieve more apex within the desired level of safety. Different structural systems have been established to achieve anticipated level of tallness but the RC core wall structural system has been widely spread amongst nations for their extensive benefits. Owing to their flexible architecture, less economy and lesser time to construct, these structures get preference among other sideways resistive systems e.g. dual structural systems [1] [2]. RC core wall systems consists of a middle core wall to act as main load carrying member for whole building. While the gravity load bearing system consists of the boundary columns constructed in core wall surroundings and coupled with the post-tensioned slabs and core wall at each respective floor. Occasionally, core walls also have diagonal bracing of adjacent columns over one or two storied high outriggers to control unusual horizontal displacements arising from strong earthquakes and winds. For having greater stiffness in comparison to the combined stiffness of the peripheral columns, core walls also carry the principal gravity load of building coming from different stories. The building space utilization increases with this structural scheme. Hence, RC core walls resist all lateral loads applied by strong earthquake or winds in a more efficient way as compared to other structural systems.

The traditional seismic codes fail to provide an effective approach for seismic design of high-rise buildings due to their excessive design limitations. The modern analysis tools and developing technologies for conducting seismic analysis have commercialized the performance based seismic design concepts. The Nonlinear Time History Analysis (NLTHA) procedure has been emerged as one of the finest but rigorous procedures for performance based seismic assessment of tall buildings. NLTHA utilizes synthetic or real recorded ground motions to accurately predict the seismic response of structures at specific locations. Due to limited data of real recorded ground motions, earlier techniques mostly used artificial records for seismic evaluations of different structures. By the development of large data storage banks of numerous seismic activities around the globe like COSMOS, USGS and NGA PEER, the real record seismic data has become more accessible for designers at fast and free. Hence, the use of real recorded ground motions is preferred nowadays over the synthetic or artificially generated records for containing original ground motion characteristic.

The real recorded ground motions have different seismic recording locations and the characteristics of these ground motions need modification before using at another specific site. The compatibility of real recorded accelerogram with structure of interest is usually attained by matching it with the target spectrum of their location. The target spectrum is taken through probabilistic or deterministic seismic hazard analysis and usually available in traditional seismic codes like UBC-97 and BCP-07. The use of real recorded earthquakes in seismic assessment led the researchers to develop numerous ground motion modification methods in the past few decades globally. All these methods have two categories, the amplitude scaling or magnitude scaling and the spectral matching. The amplitude scaling method uses a single factor multiplier to linearly scale ground motion records up or down with target spectrum. The frequency contents of scaled records are not changed in this method [3, 4, 5, 6, 7, 12]. While in the Spectral Matching (SM), the time histories are modified over the range of interest of time period to match with the target spectrum. The non-stationary components of ground motions like accelerograms, velocity, displacement amplitude and the frequency content of ground motions may observe alteration in this approach. [8, 9, 10].

The research on several ground motion modification methods has established different consensus whether to choose scaling or spectral matching. The Spectral Matching (SM) process has been preferred over linear scaling for giving relatively unbiased Engineering Demand Parameters (EDPs). The use of Amplitude Scaling Method (ASM) has also been suggested by some authors for different structural systems. However, for high-rise buildings where greater modes of vibrations are expected to contribute, feasibility of amplitude scaling method was questioned by different researchers. It is further elaborated in literature review section with references. As NLTHA procedure is very extensive and time taking so use of only one technique is feasible. The goal of this investigation is to provide an overview of existing ground motion modification techniques and to provide the best spectral matching procedure for design of taller structures. The response of 40-storey RC core wall building against seven site specific ground motions is compared by applying Time Domain Spectral Matching (TDSM) and Frequency Domain Spectral Matching (FDSM). The effectiveness of SM was assessed on the bases of five different characteristics of ground motions and eleven Engineering Demand Parameters (EDPs). These EDPs include story drift, story displacement, story shear, story overturning moments and the story response against the applied time histories. The input and output responses of building were compared for two methods and a final consensus was made based upon these results.

1.2 Research Motivation and Problem Statement

NLTHA is preferred over other analysis techniques for site specific analysis of high-rise structures. Ground motion modification is a core step of NLTHA which mainly scales the selected ground motions to match with the target spectrum of the site of interest with some acceptable accuracy levels. Different modification techniques have been investigated in the past but no harmony or consensus for the use of best technique for ground motions modification exists in literature and multiple techniques are in practice by Engineers. Seismic codes are also unsuccessful to provide the clear stance for the use of scaling or spectral matching and it still sets aside to designers choice. This may lead to provide unrealistic behavior based upon choice of different methods. Although a comprehensive investigation on scaling methods was done in PEER review report but these scaling methods were restricted up to the 30 story buildings and spectral matching was excluded from this investigation. The high-rise building design codes that include TBC and NGA PEER usually support the use of spectral matching over the scaling. The effectiveness of spectral matching techniques for seismic response of high-rise RC core wall buildings need to be explored which yield uniform seismic behaviors and minimum dispersion's in EDPs to satisfy the true seismic behavior of structure.

1.3 Overall objective and specific aim

Different ground motion modification techniques have been investigated by different researchers to perform NLTHA. Building codes and different building design regulating agencies still failed to provide the best modifications approach. TDSM and FDSM methods for ground motions modification are prominent in practiced techniques. The core objective of this research was to investigate a simple yet practicable procedure for performance-based assessment of high-rise RC core wall buildings using NLTHA. Following were the break down objectives and specific aims of this research.

- Assessment of different spectral matching techniques considering multiple ground motion characteristics.
- Seismic evaluation of 40 story RC core wall building using different spectral matching approaches.

- Recommendation of conservative spectral matching technique to perform NLTHA on high-rise RC core wall buildings.

1.4 Scope of work and study limitation

Due to rigorous process of NLTHA, the following principal limitations were imposed on this research:

- The numerical modeling and seismic analysis were performed in modeling software and no experimental evaluations were made.
- The building was analyzed for soil types SD (stiff soil), Seismic Zone 4 and Design Basis Earthquake Level (DBE) only.
- The Structure was assessed for single horizontal component of real recorded ground motion.
- The study was limited to RC core wall buildings and spectral matching in ETABS V17.0.1.

1.5 Methodology

A realistic 40 storied RC core wall structure having seismic zone-4 for soil types SD was modelled in ETABS version 17.0.1. The seven different site-specific ground motions were taken from PEER database. [13]. All PEER database guidelines were followed for selection of suitable ground motion records. The building was first designed by using equivalent static analysis procedure and Response Spectrum Analysis (RSA). The reinforcement of wall and coupling beams were calculated. A non-linear static analysis was performed before initiating NLTHA on site specific ground motions. These ground motions were imported in CSI EATBS V17.0.1 and SM was separately done in time domain and frequency domain methods [14]. After that NLTHA was performed for these ground motions, the seismic response of building against NLTHA was compared against multiple EDPs for seven different spectrally matched ground motions. These EDPs were base shear, story displacements, story shear, story drift ratio, story overturning moment, top displacements, top story drifts and response of building at selected stories against time histories. Finally, a consensus was made for the best spectral matching method based upon these seismic behaviors. A brief overview of the methodology is also mentioned in figure 1.1.

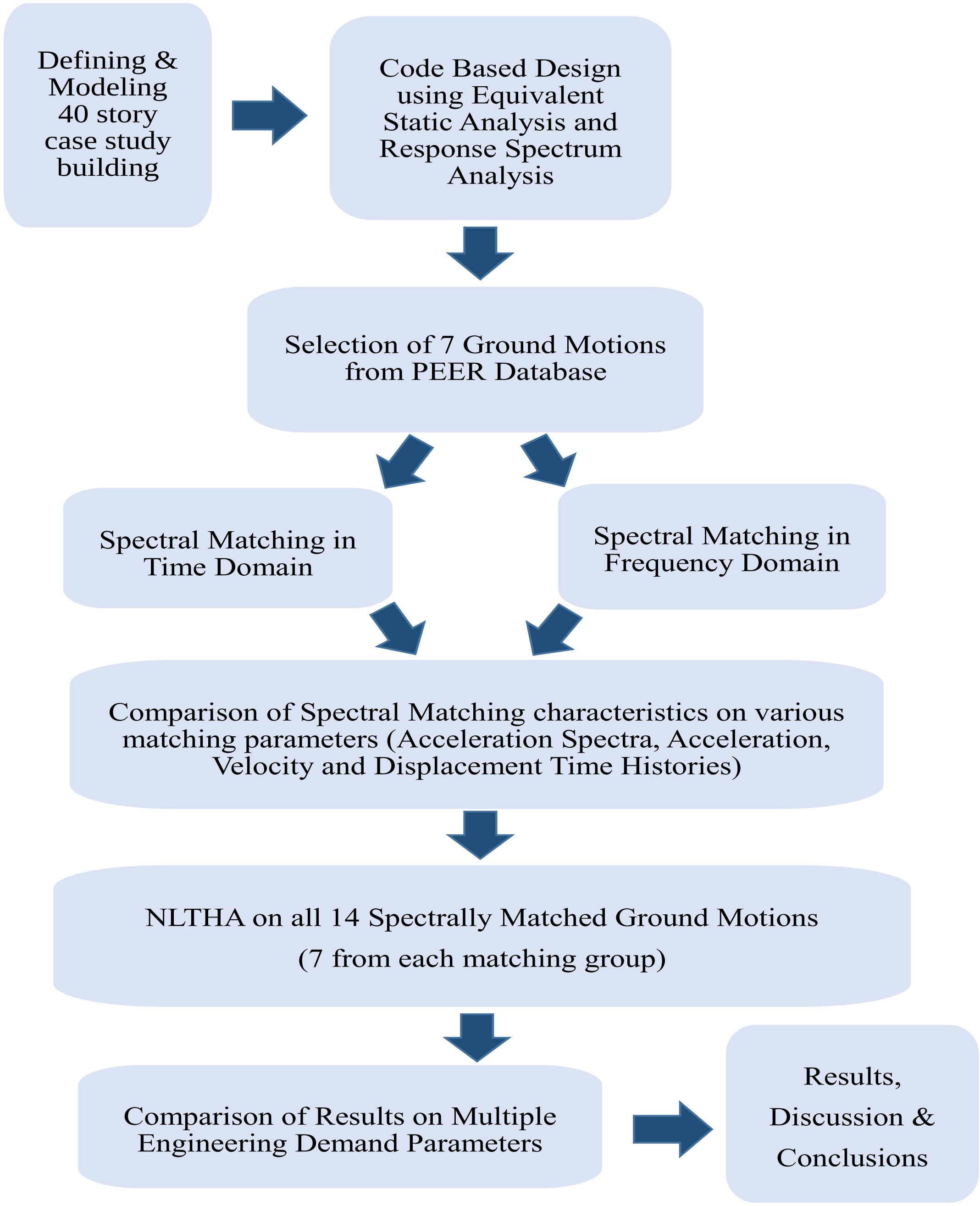


FIGURE 1.1: Research Methodology

1.6 Thesis Outline

The summary of all the five chapters in this thesis is given below: CHAPTER 1: INTRODUCTION: In this section research gap and motivation for conducting this research described. The objectives, limitations and methodology has also been outlined.

CHAPTER 2: LITERATURE REVIEW: This chapter consist of a detailed assessment about existing research on high-rise RC core wall buildings, NLTHA techniques, existing ground motion modification techniques, frequency domain spectral matching and time domain spectral matching.

CHAPTER 3: MODELING AND DESIGN METHODOLOGY: It has detailed description of different aspects of modeling, selection and interpretation of ground motions data, time domain spectral matching, frequency domain spectral matching, and elaboration of spectral matching results in graphical form.

CHAPTER 4: RESULTS AND DISCUSSION: In this chapter the outcomes of NLTHA from different spectral matching techniques analyzed and described in detail. The seismic responses of structure on different EDPs were shown in graphical form and explained in writing as well. These EDPs include story shear, story displacements, story drifts, story moments and plot of these EDPs against time series.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS: The conclusion statements of responses arising from different spectral matching techniques, and recommendations are mentioned in this section. References are furnished at the end of Chapter 5.

Annexures are placed at the end.

Annexure-A has detailed description of spectral matching peak misfits with original G.Ms on varied parameters.

Annexure-B describes the results of spectral matching outputs on varied parameters.

Annexure-C explains the Story Shear plots against time history for Level-20 and Level-30, Story Moment (M3-3) plots against time history for Level-20 and Level-30, Acceleration plots against time history for Level-20, Level-30 and Level-40, Velocity plots against time history for Level-20, Level-30 and Level-40, Displacement plots against time history for Level-20, Level-30 and Level-40.

Annexure-D illustrates Static Load Combinations for Equivalent Static and RS Analysis.

Chapter 2

Literature Review

2.1 Background

There is a fast insurgence of high-rise and ultrahigh-rise buildings around the globe. In the past few decades, there was a rapid growing ratio due to over growing population. Current high-rise structures were mostly designed on existing seismic codes at their construction time. These designs may not fulfill the different ongoing strict seismic requirements around the globe. At present, based upon current seismic regulations, different advanced techniques have been formulated to design and construct high-rise buildings. Design of these buildings on the concept of RC core wall have been widely spread due to its extensive benefits. These structural systems get preference over the other existing sideways force resistive systems e.g., dual structural systems [1, 2]. The Uniform Building Code (UBC) classifies these structural systems as a building frame system [15]. In high-rise structures, controlling structural deformation on account of the lateral load has been very challenging for designers. Different researchers have proved the effectiveness of RC core wall system to efficiently resist these lateral loads of extreme earthquakes and strong winds. The high-rise structures above thirty-five to forty stories generally depend exclusively on the core-wall structures [16, 17, 18]. RC core-wall has proven to be a good structural system to design high rise buildings [19]. Since RC core wall has greater stiffness in comparison to the combined stiffness of the peripheral columns, the core wall gives central contribution to resist all these lateral loads [20].

2.2 NLTHA for High-Rise RC Core Wall Buildings

By progressing speedy refinements in seismic design regulations, numerous guiding principles and evaluation procedures to design high-rise buildings have been reproduced during the past decades. These guidelines not only provide the procedures for conventional code-based design but also gives the guidelines for the performance based seismic assessment of high-rise structures. Prominent reports for performance-based assessment but not limited to the mentioned studies have been published [2, 21, 22]. These reports allow structures to be designed beyond elastic limit for economical design using either the DBE or MCE level. The flexural and plastic hinges were usually permitted to generate at the bottom of core wall for these strong earthquake levels. As per code provisions, remaining wall portions over the hinge region were predicted to behave elastic. The plastic rotation for these plastic hinges must be complying with the code requirements, as the development of plastic hinge necessarily be preferred to locate near the base area of the core wall [23, 24].

The RSA process was considered to be an effective approach in the past decades to design taller RC core walls. To perform this process, the elastic behaviors of different vibrational modes is decreased by a response modification coefficient R to estimate the anticipated design level response for each mode. Usually the design demands are decreased by a same R coefficient for each mode. Numerous investigators have illustrated that the development of plastic hinge at cantilever wall bottom essentially decreases seismic response of the first mode, whereas greater vibration modes were not linked to decrease the identical amount as in the first mode [25]. Hence, the RSA process has not been believed to be an effective method to design cantilever RC walls having plastic hinge at the wall base [26]. New researches on the sixty-storied and the forty-storied RC core wall structures in highly active seismic regions also investigated that the RSA gives significant under estimation of seismic response across the full elevation of core wall for both the DBE and MCE levels [27].

The NLTHA has been one and only extensively recognized and precise process at the times for seismic assessment of high-rise structures. The design regulations permit NLTHA procedure for design of RC core wall structure systems and also provide the modeling requirements for performance assessments of their discrete elements including walls, coupling beams, slab-column connections etc. The NLTHA process requires an extensive level of practice to get the real non-linear seismic demands. The frequent NLTHA investigations have been done for performance evaluation of various high-rise RC core wall structures against different seismic hazards and were not limited to these prominent investigations [19, 28, 29, 30]. The NLTHA has also been proven to be utmost rigorous, time taking but the most accurate technique for seismic assessment of structures [31, 32]. The lengthy and time taking computation process of NLTHA replicate the real performance of structures against the application of site-specific ground motions [33]. The real recorded ground motions are collected from different earthquake databases and require prior modification to use in NLTHA. The modification of site-specific time histories to match with the target spectrum calls for an evaluation of existing scaling and spectral matching practices [34]. By the growing research on NLTHA, different techniques have been established for modification of real recorded ground motion histories. A summarized overview of these developments has given in the succeeding paragraph.

2.3 Overview of the Existing G.M Modification Methods

In order to use real records for performance evaluation of diverse structures, lots of ground motion modification methods have been investigated in the past few decades. In order to apply suitable method for the structure of interest, these methods have been further refined by different investigators. The findings of these investigations varied significantly from one investigator to another in a few cases. All of these methods are mainly divided into two principal groups. The first type is named as amplitude or magnitude scaling and the second one is termed as Spectral Matching (SM). The amplitude scaling is used as a single factor multiplier to linearly scale ground motion records with the target spectrum. The frequency content of scaled records does not change in this method [35, 36, 37, 38].

While in the SM method, the time histories were modified over the range of interest of time period to match with the target spectrum. The frequency component as well as the amplitude of the ground motion observe alteration in this approach. [39]. These components include accelerogram velocity, displacement and frequency contents. It was investigated that the standard deviation may be reduced up to a factor of 2 by using spectral matching technique instead of linear scaling [40]. In another study it was observed that the scaled records decreased the response inconsistency by 20% to 75%. On the other hand, spectrally matched records decreased the response inconsistency by 60% to 80%, which increased the accuracy of the median response with same or reduced number of ground motions. It was observed that the scaling procedure could convert records a little more aggressive than those in nature [41]. A published study proposed a procedure to estimate bias in projected structural response due to amplitude scaling of ground motions. It was alleged that earlier investigations may not have distinguished the scaling bias when records were scaled to match target spectrum at Sa (T1) scaling.

The ground motions scaling was observed to have the unbiased median max inter story drift ratios. [39]. In a study the selection parameter of seed ground motions for spectral matching were investigated. Spectral matching was described better ground motion modification technique over the scaling methods due to consideration of multiple vibration modes, which contribute remarkably towards seismic response of taller buildings. A Modal Push-over Based Scaling (MPS) technique was designed to scale records in order to implement NLTHA for bridges and buildings [33]. For the high-rise buildings of 19 as well as 52 story heights, bias (underestimation or overestimation) reached over 25% when related to the ASCE 7-05 scaling technique. It was observed that overestimation of bias by using ASCE scaling has increased with the increase of the building height. Another published study further applied MPS technique on steel high-rise revealed that the MPS technique was modified procedure over existing ASCE 7-05 procedure because of considering its higher mode effects and strength features of structure [43]. A PEER report published in 2009 explored the effects of 16 out of 40 different scaling procedures with the goal of precisely estimating the median peak structure demand related to ground motions selection and modification [44]. It was observed that when proper inelastic parameter or proper spectral shape were not considered in different scaling methods (e.g. ASCE SaT1 scaling, matching to a UHS), the peak inter story demand was consistently over predicted. A research gap was highlighted for an additional investigation to compare other EDPs like peak floor accelerations in the conclusions of this report [44]. Another study investigated that the practicability of present fragility evaluations on the basis of scaled seismic ground-acceleration histories was uncertain, and scaling of ground motions need to be avoided [79].

An experiment was conducted to compare feasibility of amplitude scaling at fundamental structure period with the spectral matching. The results showed that spectral matching has greater stability in bias and dispersion of EDPs when compared with amplitude scaling. [45]. An investigation of four different ground motion modification procedures was done. These scaling methods were named as geomean scaling, spectral matching, first-mode-period scaling Sa (T1) and spectral demand distribution scaling [80].

The first method of geomean scaling gave better preservation of uneven spectral plots of actual ground motions and little dispersion of EDPs. The second method of spectral matching showed underestimation of median displacement but the dispersions in the EDPs were smaller because the scattering of spectral peaks were eradicated through the matching process. The third method also produced greater dispersions as compared to geomean scaling for nonlinear systems. The last method named as distribution scaling, produced unbiased evaluations of median displacement responses. Conventionally, it estimated the scatterings in the displacement demand parameters. It was concluded that these all methods were investigated for first mode dominant structures with minute inelastic deformations. For higher mode dominant assemblies, these methods may be given a conservative EDPs and other methods needed to be investigated. The study was also performed to evaluate MPS for taller buildings using one component ground motions. The requirement of an additional step was proposed wherever seismic response was expected to occur as a result of higher vibration modes [46]. ASCE 7-05 scaling was referred as fully deficient for predicting over estimation of EDPs [46]. In another study precision of six different scaling methods for spectrum compatible records using soilstructure interaction analysis was investigated.

It was found that choice of an appropriate scaling procedure for specific structural demand parameter vary from method to method and place to place. A further investigation was proposed by choosing diversified EDPs and scaling methods. [47]. The effects of spectrally matched ground motions were also investigated to assess consequence of bi-directional movements in plan-asymmetric systems. Spectral matching was performed by using seismo-matching software. The use of spectral matching was justified to be the best ground motion modification method for reducing number of required records. A consensus for practicality of spectral matching was developed. However, it was said to be still a conjecture as to what extent spectral matching is pragmatic [48].

A study was also conducted to reveal accurateness and effectiveness of spectral matching procedures. These values were compared to a benchmark and ASCE-7 scaling method. The use of spectrally matched records for NLTHA was proven to be an accurate and precise method for high-rise buildings. It was claimed that at elastic modal periods of system, the spectral accelerations of ground motions are not essentially reliable ground motion intensity measures. Therefore, accurate number of spectrum-matched records were subjected to reduce the higher inelastic response. [49].

A PEER report that was published in 2015 considered four to twenty story models to investigate competency of 14 ground motion selection and modification techniques. It was observed that the fundamental behavior does not change instantly for structures of other elevations. A peak inter story drift ratio was considered and other EDPs were supposed to be investigated in future. The use of two techniques for ground motion modifying were documented and the investigations of spectral matching method were intended to reproduce in the future. It was recommended to restrict the use of all these scaling methods up to 30 stories height and a further research gap was highlighted. Another experiment was performed by using matching sets of selected and modified records on the first mode, and one general matching set for spectral matching of records ground motions to evaluate the seismic demand of nonlinear and fundamental mode dominant systems to explicate the inconsistency in the intermediate structural response [50]. It was disclosed that procedure of Spectral Matching was not mainly controlling the observed bias among Engineering demand parameters resulting from the two considered methods. [50].

A study on the two approaches named weightage scaling (which was also named as amplitude scaling) and the spectral matching revealed that the the existing consensus for choice between these two methods were still uncertain. [51]. Another article explained that the records selected outside the location of structures of interest needed to be matched with the target spectrum of that specific site using frequency domain or time domain spectral marching. The visual comparison of traces of acceleration, velocity, displacement, and possibly Arias Intensity were frequently used to assess spectrum-matched motions, before and after matching. Thus, a judgment is made whether the applied changes are significant or not. [52].

Although there was a variety of researches on implementation and effectiveness of spectral matching methods. The Spectral matching was neither included in ASCE-7-05 nor in ASCE-10. However, the choice between spectral matching and scaling method was allowed by other seismic regulating councils including LATBSDG 2008, PEER TBI 2009 and FEMA 2010. Among all, two of the spectral matching methods were considered utmost reliable at the time which were time domain and frequency domain spectral matching. In an investigation the FDSM and TDSM for seismic assessment of bridge structures were considered through two spectral matching softwares namely SYNTH for FDSM and RSPMATCH for TDSM. It was observed that both methods were capable of producing similar profiles for matched ground motions with minimum dispersions in seismic responses [81]. The background and development of these procedures are described in the following sections.

2.4 Time Domain Spectral matching

The Spectral matching in time domain was first adapted by Lilhanand and Tseng in 1988. They proposed an algorithm that modified the initial time histories by using reserve impulse wavelet function in a way that the targeted spectral becomes well-suited to a response spectral. This method has a fundamental assumption that adjustment of wavelet does not result in a change in peak response time. This assumption may not always be valid as the time of peak response may be shifted by addition of wavelet adjustments to acceleration time history. The time-domain ground motion Spectral matching does not change the character of a real ground motion, hence considered an excellent method of spectral matching [53]. Spectral matching technique was described by highlighting the time domain approach. It permitted to use the real recordings from active regions, and was also eye-catching in the CEUS, although CEUS conditions were matched by enabling high frequency [54, 55]. There was no major issue in addition of high frequency motions into record because these were usually stochastic [56, 57].

A data of CEUS ground motion record was developed by using this process in NUREG/CR 6728 report. A vital phase in evaluating the spectral-matched record is the comparison of initial and final history of displacement, acceleration and velocity, ensuring that they rationally represent the original time series (i.e. indicating the changes which were acceptable physically without unintentional time-domain characters). Perhaps, this was the most significant stage of spectral matching. The time-domain spectral matching algorithm comprises of repeated addition of sets of compact arrangements of wavelets (i.e. discrete length sinusoid-like functions) to acceleration histories [58].

The algorithm developed by N. A. Abrahamson in 1993 was modified for application to preserve mobile parts of initial ground motion at longer periods [53]. It was applied in RSP-Match software with the modified cosine wavelet base, preserving the non-stationary ground motion characteristics [59]. The consequences of these wavelets on spectral ordinates resulted in a linear system of equations to calculate the amplitudes for wavelet modification function. This technique provided a spectral-matched time history in distinct phase if the added wavelet had a direct consequence on sets of spectral ordinates. Different studies have revealed that when wavelet functions were added to acceleration histories, it has a non-linear consequence on spectral ordinates. These were the result of alteration in peak response time of single degree of freedom oscillators which were used to compute spectral ordinates. The peak response fluctuated in time or formerly smaller peaks became amplified to outstrip the original maximum due to addition of wavelet set adjustment function to acceleration record. Hence, Time Domain Spectral Matching Algorithms were frequentative likewise Newton algorithms or Modified Newton algorithms to anticipate non-linear behavior. After that the researchers used broyden updating to investigate the time-domain spectral matching of earthquake ground-motions. [60].

Improvements were first time made in the previous algorithm, to further discourse non-linearity related to the shifting time of ultimate response which included addition of supplementary compensating wavelet modifications or dropping those amplitudes which can cause problems in wavelet alteration function [61]. An upgraded tapered cosine wavelet basis was produced to preserve an efficient form which have the ability to instantly fit in zero displacement and velocity, and need no baseline correction [62]. Investigators have also explored further characteristics linked with usage of wavelets to Time Domain Spectral Matching. Spectral matching by different procedures is anticipated to associate wavelet analysis with neural networks [63]. Various wavelet alterations and damage index were used to investigate inelastic spectral matching [64]. The use of different mother wavelets in spectral-matching was explored such as adjusted tapering cosine wavelet were described and use of wavelet termed as an effective method that was also revealed by various scientists [62, 65].

2.5 Frequency Domain Spectral matching

The frequency domain spectral matching was reported in 1984 along with other spectral matching procedures at the times. This method was first commercialized by Silva and Lee by developing a software named RASCAL [66]. This technique used Fourier transform to make the actual ground motion records compatible with target spectrum of site of interest. To do this, filtering of actual ground motions was done through the spectral ratio of the target response spectrum to the actual response spectrum of selected record. In primary iteration, the ratio of the target spectrum accelerogram of site to the spectral accelerogram of selected ground motion were calculated for the desired range of periods. These ratios were used to modify the frequency content and the amplitude of primary accelerogram so as the modified accelerogram was approximately compatible with the target spectrum. An average error and the misfit between the spectrally matched accelerogram and target spectrum's were calculated. If results are not satisfactory, further iterations are carried out and previously modified accelerograms are utilized. This procedure is iteratively repeated for getting spectral matching up to the desired level of acceptance and period range. The increased number of iterations are used to refine the compatibility of ground motions with the target spectrum.

This technique only modifies Fourier spectral amplitudes of input ground motions and keeps the Fourier phases (sinusoids) of original record constant. The preservation of ground motion phase characteristics is significant as the nonlinear analysis ignites as a result of phasing. To preserve the Fourier phase, a zero only imaginary component transfer function was applied to the signal amplitudes and re-scaled. [67, 68, 69]. The FDSM has been considered very simple and straightforward process but some downsides of this methods are also reported in literature. In 1995, it was investigated that this method expressively modifies nonstationary characteristics of original ground motions and has tendency to enhance its overall energy [70]. The two main downsides of this method were also reported. Firstly, the produced acceleration time histories do not have convergence properties. Secondly, the drift was also produced in the resultant displacement and velocity time series. [62]

A modification in FDSM using random vibration theory was proposed to adjust the Fourier Amplitude Spectrum. In this technique, power spectral density functions were computed by using sinusoidal signals and smoothened response spectrum alongside random amplitudes and phase angles. These functions were practiced repetitively to develop distinct matching levels with recorded acceleration response and target response spectrum. By using this technique, results were obtained through considering velocity and acceleration time history records only. Even if various base line correction methods were followed, the characteristics of displacement time series was changed [62]. FEMA chapter three section 3.3.1.4 allowed the transformation of the time-acceleration spectra using fast Fourier transform using Frequency Domain Spectral Matching (FDSM).

In order to get precise match of the target spectrum, amplitude modifications at particular frequencies were done and then transformed back into the time domain. This process interrupted frequency content, amplitude and phasing of the ground motions which may lead to enhance the total input energy of the ground motions. This technique was designated effective for estimating mean structural response with lesser number of ground motions. However, it was slightly doubting the potential inconsistency of that response. The application of this technique has been allowed by the seismic codes, but reduction of number of records as used for time-domain scaling is not yet allowed. It was also investigated that spectral matching in the frequency domain produce unexpected interruption in velocity and displacement after the matching process. This interruption produced a drift at the end of the velocity time histories and constantly enhancing or reducing displacement time histories in matched ground motions. In order to overcome this interruption a baseline modification was proposed [71]. A step by step procedure of spectral matching in frequency domain is summarized in Figure 2.1.

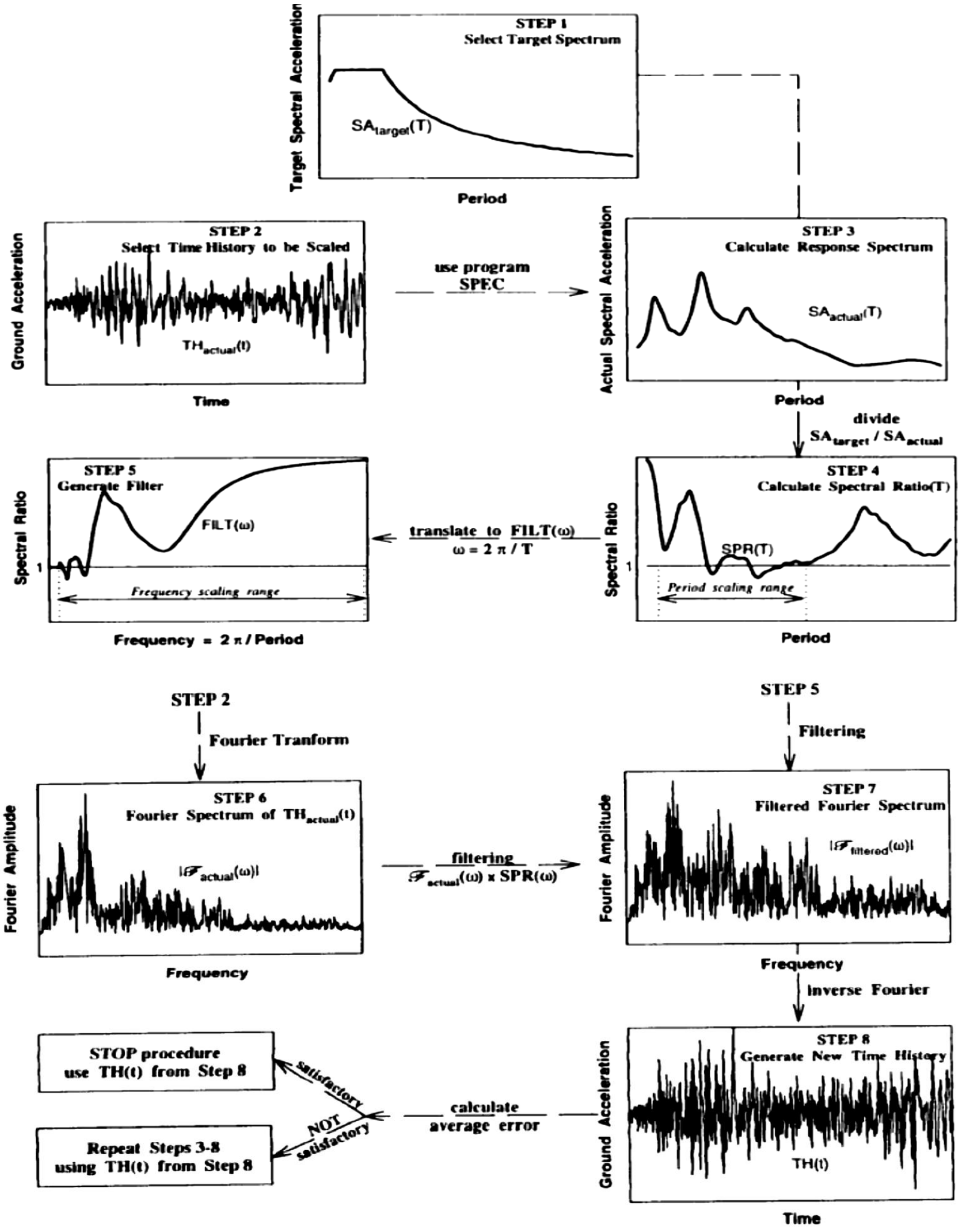


FIGURE 2.1: Frequency Domain Spectral Matching Procedure (Nikolaou 1998)

2.6 Summary

Different techniques have been used to design the high-rise buildings, the Non-Linear Time History Analysis (NLTHA) has been accepted as one of the finest but most rigorous techniques at present. The NLTHA utilizes artificial generated and real recorded ground motions to estimate seismic response of buildings at representative of specific site locations. The real recorded ground motions are preferred nowadays because of ease of global access to ground motion databanks and for comprising original ground motion characteristics (COSMOS, USGS, NGA PEER database etc.). These real recorded ground motions, selected from seismic databanks, require prior modification before using at structures representative site of interest.

There are mainly two types of these ground motion modifications, the spectral matching and the amplitude or magnitude scaling. A single factor is multiplied in typical amplitude scaling to linearly scale up or down the ground motion records with the target spectrum which provides unchanged frequency content of scaled ground motions. While the spectral matching involves the modification of time histories over the range of interest of time periods which may yield a little change in the frequency content and amplitude of ground motions. However, the spectral matching has been proved to give lesser dispersion's in EDPs as compared to amplitude scaling and henceforth preferred for high-rise buildings.

In previous explorations, the spectral matching was done using external source softwares and modeling in same softwares (i.e. ETABS) was not done for spectral matching comparison. The spectral matching is mainly divided into two categories, the Time Domain Spectral Matching (DSM) and Frequency Domain Spectral Matching (FDSM). The TDSM is considered a better spectral matching approach that utilizes the addition of wavelets in initial time histories by using latest softwares. The FDSM is also a commercially available technique in latest software's which uses Fourier transform but it upsurges the frequency content. As both spectral matchings are available in numerous softwares including but not limited to RSPMatch09, Seismosoft TARSCTHS or SIMQKE and ETABS17, the practicability of spectral matching and choice of matching software turn out to be a fundamental question for designers. Hence, there is a need to investigate the behavior of high-rise buildings against these spectral matching techniques.

Chapter 3

Modeling and Design Methodology

3.1 Introduction

A 40 storied RC core wall structure having seismic zone-4 for soil types SD has been modelled in ETABS version 17.0.1. This is an extension of previous investigations conducted on this structure for various objectives [69, 70, 71, 72]. The building was first analyzed using Equivalent Static Analysis (ESA) and Response Spectrum Analysis (RSA) procedures and the reinforcement of core wall was calculated. Seven different site-specific ground motions were then taken from PEER database by using BCP-07 faulting map as a reference. These ground motions were imported in CSI EATBS V17.0.1 and spectral matching was separately done in time domain and frequency domain methods. These spectrally matched ground motions were than compared on five different ground motion characteristics. A non-linear static analysis was performed before initiating NLTHA. NLTHA was then performed against these fourteen spectrally ground motions and seismic response of building was compared on eleven different EDPs. Finally, a consensus was developed for the best spectral matching method based upon matching characteristics and response of building on these EDPs.

3.2 Description of the Case Study Building

The figure-3.1 and figure-3.2 represents the buildings typical floor plan and the elevation, respectively. Three-Dimensional (3D) view is also given in Figure-3.3. This is a typically constructed high-rise RC core wall structural system. There are 40 stories above ground and three stories for a basement below the ground. Total height above ground is 415 for 40 stories having a typical story height of 10-0. The height of ground floor lobby and top story was kept at 20 and 15 respectively. Three basement stories consist of a typical 100 height. The base slab stays on the stiff rocky soil which have a bearing capacity of 1.2 KSf.

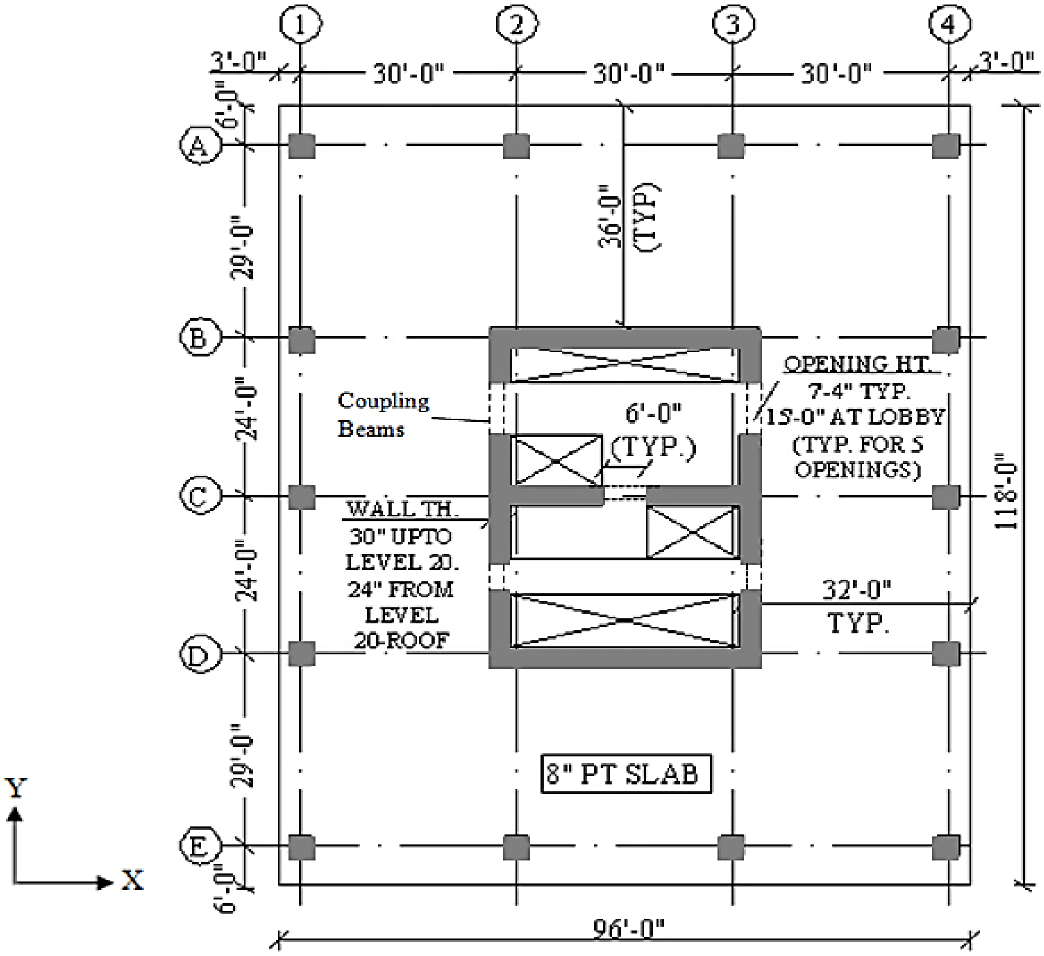


FIGURE 3.1: Building Plan View (Typical)

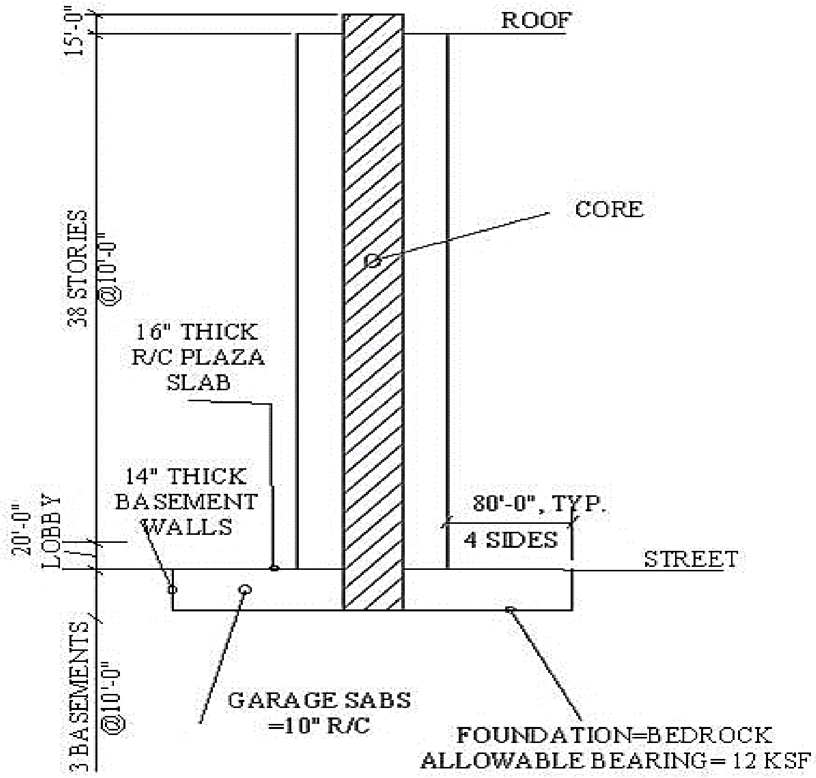


Figure 3.2: Building Elevation View

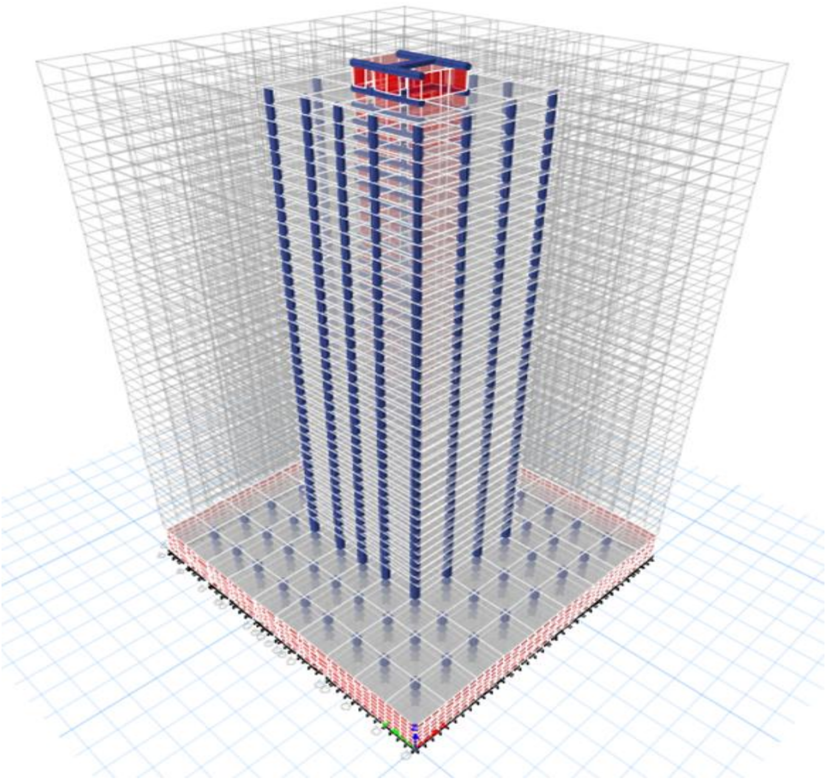
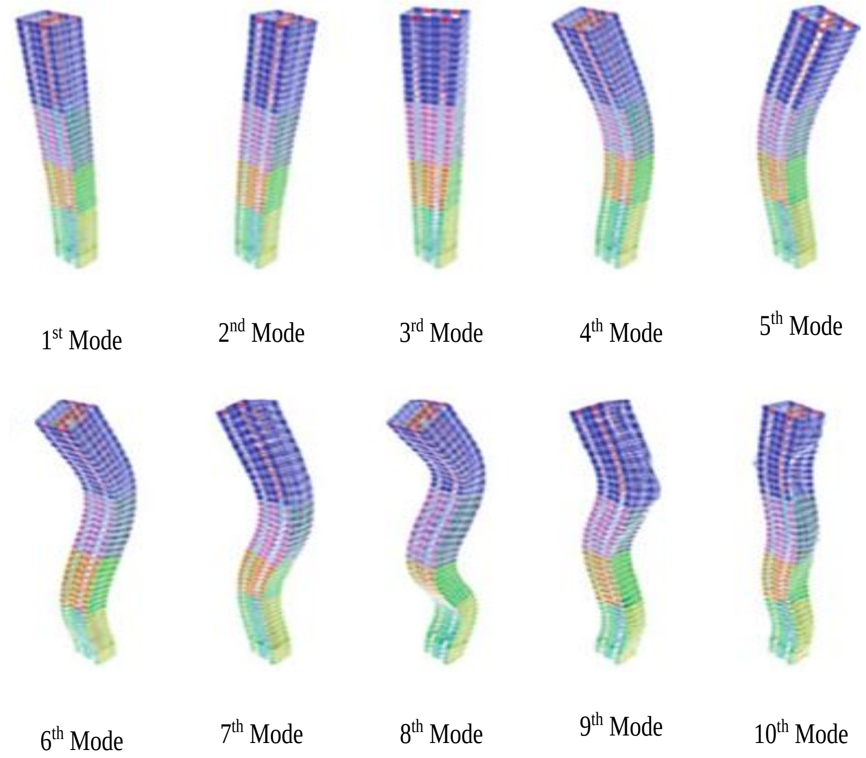


Figure 3.3: Building 3D View

The lateral force resistance system of building consists of the middle core wall and the boundary columns. While the gravity system comprises 8 thick post tensioned concrete flat slabs staying on the boundary columns and the middle RC core wall. The width of the core wall was kept at 30 inches and 24 inches up to the story 20 and story 20 to roof respectively. Four variable dimensions of the columns 36x36, 32x32, 28x28 and 24x24 were used along the entire elevation of the structure. The sizes of coupling beams for openings are kept 60 x 32 over the lobby-level, typical 30x 32 up to the story 20 and typical 24x 32 from story 20 to the rooftop equally in X and Y planes. Since in-plane stiffness of concrete slabs were very enormous and considered as rigid diaphragms in the analysis. It was supposed that structure is situated in a highly active seismic region corresponding to the UBC-97 and zone-4. The soil type was assumed as type SD of UBC-97 which designates stiff soil having a typical shear wave velocity fluctuating between 600 to 800 ft/sec at a depth of 30 m below ground (i.e. Vs 30). The design of this structure was completed by following LATBSDC alternate design procedure.

3.3 Equivalent Static Analysis (ESA)

ESA is a simplified procedure extensively used in seismic design businesses. This procedure is considered a better approach to design first mode dominant building. Due to higher modes contribution in midrise and high-rise buildings, this approach is not thought a better technique but still provide a design basis for other seismic design procedures like RSA. An equivalent static analysis and modal analysis were first executed to estimate the mode shapes, modal mass contribution coefficients and natural periods for all the governing translational modes in both primary horizontal directions (X, Y). In this study both the equivalent static and Response spectrum analysis were performed by using CSI ETABS, version 17. All seismic design practices given in BCP-07 and UBC-97 were followed. The Near Source factor was taken as 1, as the ground motions were selected from the fault lines which contain a varying distance of 15 to 110 Kilometer. The seismic zone type of selected site was considered to be zone-4 from BCP-07 and the soil type was assumed as Sd. Seismic load of structure consists of the dead load, partition load and finishes load and an additional 25% live load for retail floors as prescribed by the BCP-07 section 5.30.1.1 and UBC-97 section 1630.1.1. Table 3.2 presents the manual results of base-shear calculated through ESA and RSA for the subject building. The structures mode shapes plotted along height are shown in figure 3.4. The fundamental period of the structure as found from model analysis was 3.76 seconds in x direction and second mode period was found 0.808 seconds in the same direction.



1st Mode 2nd Mode 3rd Mode 4th Mode 5th Mode

6th Mode 7th Mode 8th Mode 9th Mode 10th Mode

Figure 3.4: The vibrational mode shapes of structure along height

3.4 Response Spectrum Analysis (RSA)

RSA is a linear-dynamic statistical analysis procedure that capture the involvement of all respective natural vibrating mode to designate the peak seismic response of a building. The RSA technique as per UBC-97 was implemented in this investigation to estimate initial response of structure. RSA was helpful to make design basis because it reflects structural element choice against dynamic reciprocation. The short period structures get a larger acceleration, while long period structures get larger displacements. The mass and stiffness dispersion of structures regulates the seismic response of structures. A response spectrum is mainly a graph for the steady state or ultimate response (accelerations, velocities or displacements) of a succession of oscillators of fluctuating natural frequencies which are carried in the form of waves by the same base shaking or tremor.

It was necessary to get more than or equal to 98 percent of the modal mass contribution of the structure in both respective planes. It was restricted to only X plane that was adequate for the intention of this investigation. The Response Combinations in accordance to UBC-97 were used for both analysis and presented in annexure D. The design spectrum considered in this RSA process was the elastic response spectrum at 5% damping ratio (ξ). Using this process, elastic responses of all dominant vibration modes were calculated from the design spectrum at first, followed by calculation of total responses, and then decreased to the seismic demands for designing through the response modification factor ‘. The ‘R’ factor of 5.5 was designated as the investigated structure may be classified as a building frame system with concrete shear wall’s.

Table 3.1: Calculation of seismic demands by ESA and RSA procedures of UBC-97

Parameter	Value
Seismic zone factor (zone-4)	Z = 0.4
Soil type	SD
Seismic coefficient (acc.)	Ca = 0.44
Seismic coefficient (vel.)	Cv = 0.64
Response modification factor	R = 5.5
Importance factor	I = 1.0
First-mode natural period (by method B) Tb=1.3*Ta*Ct *Hn$^{3/4}$	T= 1.3x0.03x415$^{3/4}$ = 3.58 sec
Total seismic dead load	W = 89,700 kips
Equivalent Static Force Procedure	
Design base shear (Eq. 30-4) V=C v*I *W/ (R*T)	V = 0.032 W = 2,911 kips
Minimum design base shear (Eq. 30-6) V=0.11 Ca I W	V = 0.048 W = 4,312 kips
Minimum design base shear (Eq. 30-7) V=0.8 Z Nv I/R W=0.8*0.4*1*1/5.5W=	V = 0.058 W = 5,220 kips (Governed)
Response Spectrum Analysis Procedure	
Elastic base shear	VE = 0.21W = 18,457 kips
Elastic base shear/ R	VE /R = 18,457/5.5 = 3356 kips
1/Reff = Greater of 1/R and 0.9V/VE	1/Reff = 0.9x5,220/18,457=1/4 (Governed)

3.5 Selection of Ground Motions

As described by different Building Codes and as stated in LATBC, a minimum of seven record accelerogram sets are required to do NLTHA. Peer database guidelines for selection of records were followed to search site compatible ground motion records. This section describes the procedure for selection and spectrum matching of seven different ground motions for NLTHA for a site-specific structure. The subjective structure was assumed to be located in Muzaffarabad which is classified as seismic zone 4 of UBC-97. The soil type was also assumed to be Sd. In order to get the site geology and inputs for ground motion record search from peer database, the faulting map provided in Building Codes of Pakistan (BCP) was used. The site location is marked on faulting map of BCP as shown below in figure 3.5. A close view of the fault lines for site location on Fault Map is shown in Figure 3.6. The table 3.3 shows the input data for peer ground motion record search. The fault type and distance to the respective site was also taken from BCP. Whereas the table 3.4 shows the characteristics of the selected ground motions taken from peer database against these inputs.

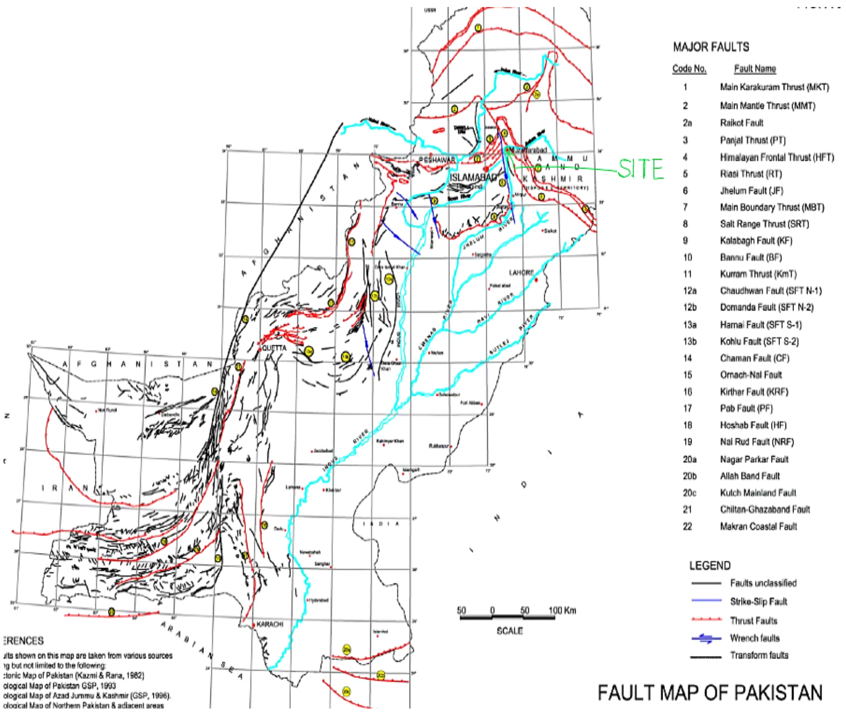


FIGURE 3.5: The site location on Fault Map of Pakistan (BCP)

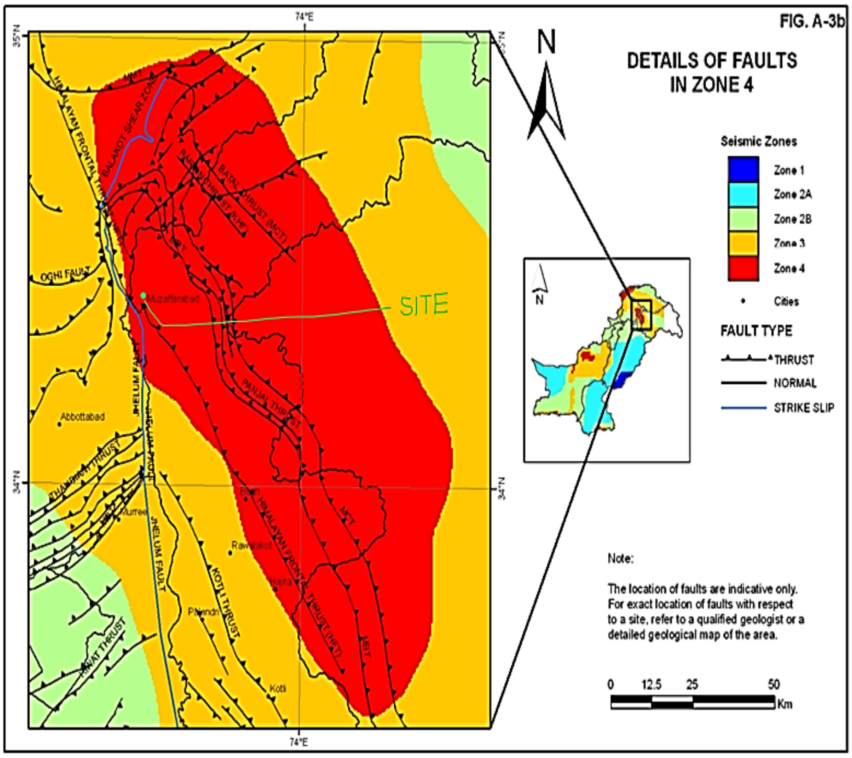


FIGURE 3.6: A close view of the fault lines for site location on Fault Map

TABLE 3.2: Input data for ground motion record search for PEER database

No	Fault Name	Fault Number on Map	Mw Fault (BCP)	Fault Type	R_j (Rup) (km)
1	Himalayan Frontal Thrust (HFT)	4	7.0, 7.2	Reverse	15, 18
2	Jhelum Fault (JF)	6	7.0, 7.9	Strike Slip	18, 20
3	Panjal Thrust (PT)	3	6.8, 8.2	Reverse	20, 25
4	Main Boundary Thrust (MBT)	7	6.7, 8.0	Reverse	25, 30
5	Riasi Thrust (RT)	5	7.6, 7.8	Reverse/Thrust	33, 40
6	Main Mantle Thrust (MMT)	2	7.5, 7.9	Reverse	95, 100
7	Salt Range Thrust (SRT)	8	7.7, 8.0	Reverse	100, 110

Note: Mw = Input moment magnitude, Rj (Rup) = distance from selected site to fault line

Table 3.3: Selected ground motion records from PEER database

Sr. No	PEER Record No.	Location	Year	Fault Mechanism	Mw	Rjb, Rrup (km)	Vs30 (m/sec)	PGA (g)	Duration (sec)
1	803	Loma Prieta	1989	Reverse Oblique	6.93	8.48, 9.31	348	0.248	32
2	6908	Darfield New Zealand	2010	Strike Slip	7.0	13.64, 13.64	293	0.190	110
3	1498	Chi-Chi Taiwan	1999	Reverse Oblique	7.62	17.11, 17.11	273	0.150	72
4	1481	Chi-Chi Taiwan	1999	Reverse Oblique	7.62	25.42, 25.42	298	0.145	72
5	1186	Chi-Chi Taiwan	1999	Reverse Oblique	7.62	33.19, 34.18	348	0.250	150
6	1308	Chi Chi Taiwan	1999	Reverse Oblique	7.62	95.58, 97.58	220	0.070	93
7	1354	Chi Chi Taiwan	1999	Reverse Oblique	7.62	100, 110	291	0.024	72

Note: Mw = moment magnitude of earthquake, PGA = peak ground acceleration, Duration = Duration of strong ground motion, V30 = Shear wave velocity of the respective site.

3.6 Modification of Selected Ground Motions

Both the FDSM and TDSM approaches are considered utmost reliable as proficient of creating design time histories that not only have closely matched spectra but do preservation of the principal characteristics of the original ti me histories with respect to the amplitude and frequency content of the time series over the time history interval. These two methods are also available in CSI ETABS V17.01 and succeeding versions. Seven sets of ground were selected from PEER NGA database site and elaborated in section 3.3.1. The PEER database selected ground motions were imported in ETABS for Spectral matching in both of the methods. These ground motions were spectrally matched to the DBE target spectrum through time domain and frequency domain spectral matching technique. It is noteworthy to mention that only acceleration spectra were imported for spectral matching purpose. Other ground motion characteristics were derived from numerical integration of this acceleration time history by ETABS software. Base line corrections were not performed separately and it was reliant to ETABS. Further steps of spectral matching and methodologies are described in the subsequent sections.

3.6.1 Spectral Matching in Time Domain

The time domain spectral matching includes the addition of wavelets to initial time series to modify it in the time domain. The wavelet is a mathematical function which effectively describes the limited duration waveform with a zero average and its amplitude starting from zero, starts increasing first and then goes back to zero. The primitive time domain spectral matching algorithm was different from modern mechanism, using a wavelet adjustment function providing numerical strength. However, this process may not reserve the non-stationary characteristics of the initial acceleration time series and leads to drifts in resulting displacement and velocity time series. The following procedure is performed by the software:

- Generates the response spectrum for the reference time history using the damping specified for the target response spectrum.
- Compares the resulting response spectrum ordinate (peak response of the SDOF oscillator) with the target value.
- Determines the mismatch for each period and damping ratio (ξ), Sa misfit.
- Calculates the spectral sensitivity matrix C, whose elements Cij describe the amplitude of acceleration response at peak time ti of SDOF oscillator with period Ti due to wavelet adjustment with period Tj.
- Calculates the set of wavelet magnitudes, b, by solving the linear set of equation Samisfit = C b.

- Adds wavelets to the acceleration time histories with the appropriate phase and amplitude with the objective of modifying the spectral ordinates.
- One wavelet is added for each period to be matched.
- Iterates by repeating the above steps until the largest spectral mismatch is below at the given tolerance.
- The spectral matching using TDSM method are shown below in Figure 3.7 for all seven ground motions.

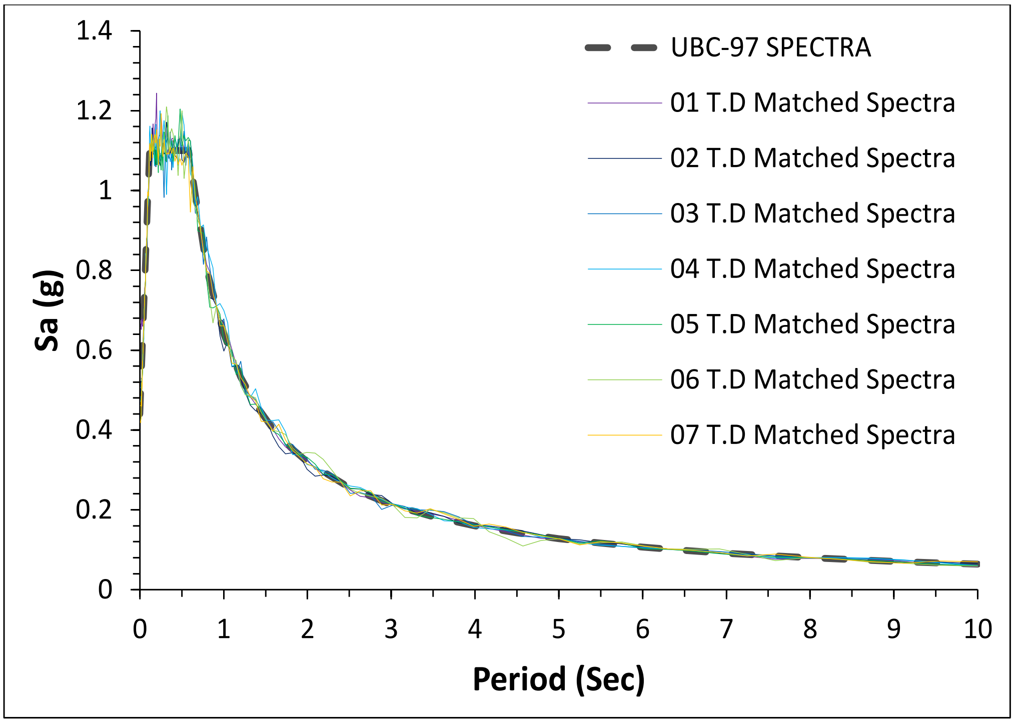


Figure 3.7: Time domain Matched Spectra for seven ground motions

3.6.2 Spectral Matching in Frequency Domain

Frequency domain spectral matching use Fourier transform to make the actual ground motion records compatible with target spectrum of site of interest. To do this, filtering of actual ground motions is done through the spectral ratio of the target response spectrum to the actual response spectrum of selected record.

In primary iteration, the ratio of the target spectrum accelerogram of site to the spectral accelerogram of selected ground motion are calculated for the desired range of periods. These ratios are used to modify the frequency content and the amplitude of primary accelerogram so as the modified accelerogram are approximately compatible with the target spectrum. Average error and the misfit between the spectrally matched accelerogram and target spectrums are then calculated. If results are not satisfactory further iteration are carried out. Further iterations use previously modified accelerograms. This procedure is iteratively repeated for getting spectral matching up to the desired level of acceptance and period range. Increased number of iterations further refine the compatibility of ground motions with the target spectrum. The disadvantages of frequency domain methods are reported by some authors for having disturbed non-stationary characteristics [52]. In order to generate a target spectrum compatible time series using FDSM, the following procedure is performed in ETABS software:

- Generates the response spectrum for the reference time history using the damping specified for the target response spectrum.
- Generates the Fourier amplitude spectrum of the reference time history through a Fast Fourier Transform (FFT).
- Determines the scale factor for all frequencies in the specified range. The scale factor is computed as:
- Getting a Scale Factor for a given frequency = RSATS/RSARTH, Where,
- RSATS = Acceleration of the target response spectrum at the given frequency
- RSARTH = Acceleration of the response spectrum for reference time history at the given frequency
- Multiplying the Fourier amplitudes by the computed scale factors for all frequencies in the specified frequency range

- Doing an inverse FFT on the scaled Fourier amplitude spectrum to obtain the modified time history.

- The spectral matching using FDSM method are shown below in Figure 3.8 for all seven ground motions.

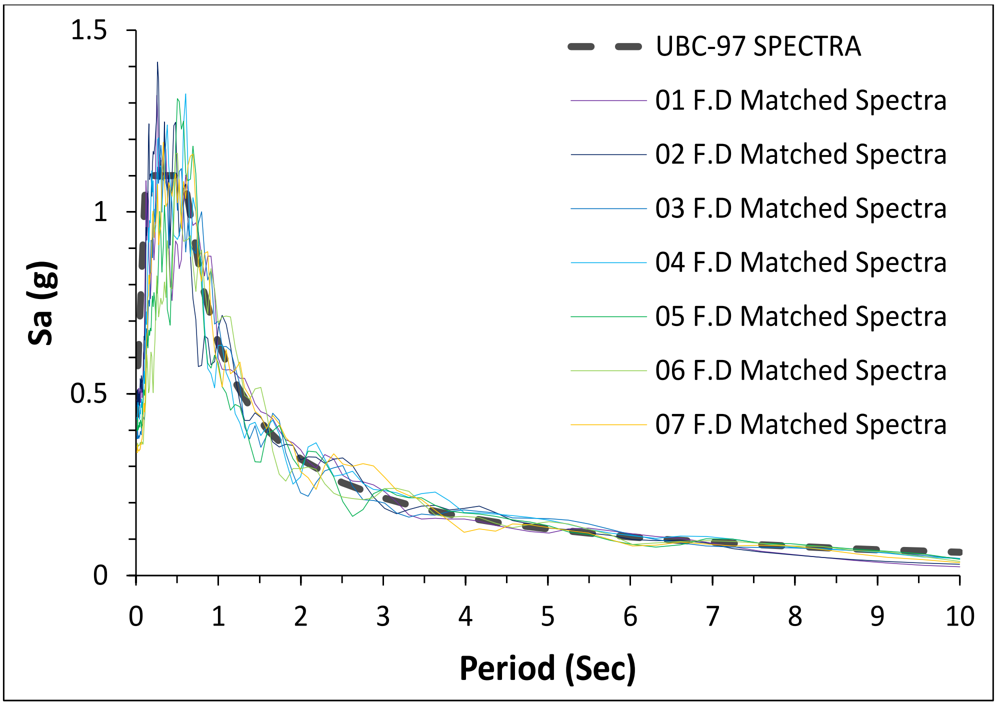


FIGURE 3.8: Frequency domain Matched Spectra of seven ground motions

3.7 Comparison of Spectral Matching Characteristics

In this section, the characteristics of FDSM and TMSM on five selected parameters are compared. These parameters include acceleration spectra and acceleration, velocity and, displacement time histories. The spectrally matched characteristics of ground motions against their originals are presented in Figure B-1 to Figure B-7 of Annex B. All these characteristics are plotted side by side for both spectral matching parameters to get better comparison. Since there are no assessment formulas at present to evaluate spectral matching, it solely depends upon visual inspection of various matching parameters. In order to do Intra-comparison and Inter-compression between these two spectral matching approaches, a ranking table has been prepared as shown in Table A-1 of Annex-A. The spectral matching peak misfits have also been compared and shown in Table A-2 of Annex A. The scoring points were assigned on the following assumptions. The matched ground motion that follows the pattern and characteristics of original ground motion gets maximum score. Secondly, a ground motion with closest spectral matching gets greater score. Thirdly, higher score was given to a spectrally matched ground motion based upon maximum preservation of frequency contents of original ground motions.

While comparing the matching characteristics, it was observed that TDSM closely matched the acceleration spectra as compared to the FDSM but some other characteristics of original ground motion were better preserved in FDSM. The matched ground acceleration time history and ground velocity time history in FDSM gave much better results as compared to TDSM. The behavior of matched ground displacement time history was observed better in TDSM and it infrequently preserved the characteristics of original ground displacement in FDSM. The TDSM gets slightly higher rank as compared to the FDSM. The frequency contents for original, FDSM and TDSM are shown in figure B-8 and B-9 of Annex B. It was observed that the TDSM considerably disturbs the frequency content of originally recorded ground motions. Slightly upshift of the frequency content was also observed in both SM techniques. This correlates the statement of literature that the frequency content and energy of the original ground motion slightly increase due to spectral matching. Irrespective to the literature, it can be observed that FDSM better preserves the frequency content of original ground motions as compared to that of TDSM. In conclusion, both spectral matching techniques have been found alike by observing five matching characteristics, ranking table and comparison of peak misfits was also found identical. Henceforth, the superiority of one technique was not conceivable based upon these spectral matching characteristics and an assessment of structures response against these spectrally matched ground motions was further required.

3.8 NLTHA Procedure

After doing response spectrum analysis and getting the spectrally matched results in ETABA, the NLTHA was then performed for the capacity design of the building. It was to make sure that all the designed sections fulfil the ACI-318 minimum and maximum reinforcing requirements. NLTHA implemented for this structure meets the requirements of Section 1629.10 of UBC-97. A kinematically permissible plastic behavior suitable for taller structures having core walls was then needed to be designated. For achieving that, the ductile plastic hinges were allowed to create only at the bottom part of the core walls. The extent and dispersion of longitudinal steel reinforcement of the core wall in the base region were calculated in a way that the nominal flexural strength times the strength-reduction factor (ϕ) of 0.9 nearly corresponds to the design base moment.

Plastic hinges were allowed over ground floor lobby having double height (i.e. 20 feet). There were two concrete strengths in this model including 8000 psi and 6000 psi up to story 20 and story 20 to rooftop respectively. The steel Grade 60 was selected as a reinforcement rebars. Similarly, the longitudinal steel reinforcement at each end of coupling beam joining this segment of wall was also estimated such that its nominal flexural strength times the strength reduction factor nearly equivalates to the design moment at that location. The crosswise and other reinforcement details for these plastic hinge segments were set as described in UBC-97 detailing provisions. The remaining portion of coupling beams and the core wall and different structural elements such as slabs, columns, etc., were expected to have adequately high strengths to keep on elastic range. It requires to be distinguished that apart from core walls at the base, the coupling beams in the high-rise core walls were usually aimed to exhibit ductility. The structure was analyzed for X-direction only in this research. It was well thought out because the core walls in the X-direction did not provide sufficient energy dissipation phenomena as of coupling beam. This was expected to be more prone to a dynamic exaggeration of seismic response. Various published articles confirmed such results in their previous research on this core wall [72, 58].

The traditionally assumed modal damping ratio (ξ) of 5% was too high according to recent recommendations for the seismic design of high-rise buildings, and was not realistic for taller buildings. A damping ratio (ξ) of 1-2% for fundamental translational modes having frequency (fn) looks rational for 160-82 ft. high buildings [19]. The modal damping ratios () for two translational modes were fixed to 1.0% for the 1st mode and 1.2% for the 2nd mode in x direction. The model damping was given through load case function between two specified points in ETABS software. The software linearly interpolates the damping between these two specified periods. While outside this range of periods, a constant value of damping is saved as per the nearest specified point. The performance-based seismic designs were used to ensure the entire structural response at least one stated performance objective at descriptive seismic levels. The particular performance objectives as described in seismic codes for the structural design using performance-based mechanism are given in Table 3.1.

Table 3.4: Performance objectives

Level of earthquake	Performance objectives
Frequent: Currently not to be considered for analysis	Serviceability: Minimal structural damage; repairable
DBE: 10% possibility of exceedance in 50 years (475-year return)	Code level: Moderate structural damage; extensive repairs may be required
MCE: Rare Earthquakes, currently not to be considered for analysis, MCE (2% possibility of exceedance in 50 years) and the deterministic MCE (calculated as 150% of the largest median, 5% damped spectral response acceleration computed at that period for characteristic earthquakes on all known active faults within the region)	Collapse prevention: Extensive structural damage; repairs are required and may not be economically feasible

Several plane layers of 10 ft. height were formed by core wall divisions. Each layer contained 22 shear wall elements. Each shear wall component was a non-linear element for the plastic hinge region (levels 0-2), consisting of 8 vertical segments of concrete and steel, and forming a total of 352 fiber sections per layer. The post-yield stiffness was adjusted to 1.2% of elastic stiffness. The yield strength of grade 60 steel bars was supposed to be 70.2 psi, which is 1.17 times more than its nominal yield strength. This explains the fact that actual material strengths are usually higher than nominal strengths defined by design codes. Slabs and columns were demonstrated by elastic column and shell/slab elements, correspondingly.

The flexural strength at the plastic hinge place was based on the DBE design moment demands. There are primarily two clarifications for locating flexural strength through such means. At first, it follows the ordinary code-based design process, Secondly, the progressive codes like LATBDC-2008 endorse capacity design as a first stage of the performance-based design, and investigators are applying the code. The providing strength was more as compared to the design demands as of satisfaction of least needs of reinforcement for serviceability in the wall. The serviceability requirement was satisfied by using at least 0.25% longitudinal reinforcement ratio, as described in ACI-318-18. In addition to the non-linear building model, NLTHA was performed for 14 spectrally matched ground motions at DBE level in the X-direction. The 14 different Nonlinear cases were defined and a single case took nearly 24 hours to complete. The seismic response of structure against all these input motions were then extracted and plotted for comparison on eleven different EDPs as explained in the next chapters.

Chapter 4

Results and Discussion

4.1 Background

In previous chapters, two of the spectral matching techniques, Time domain spectral matching and Frequency domain spectral matching has been discussed and the comparison of matched ground motions on five selected ground motion characteristics was presented. These spectrally matched ground motions were then applied on the selected RC core wall building through NLTHA and seismic response of structure was compared on eleven different engineering demand parameters (EDPs). Seismic response of selected building against each matching technique was further required to compare the superiority or equivalency of each matching technique. The following EDPs have been considered for this investigation.

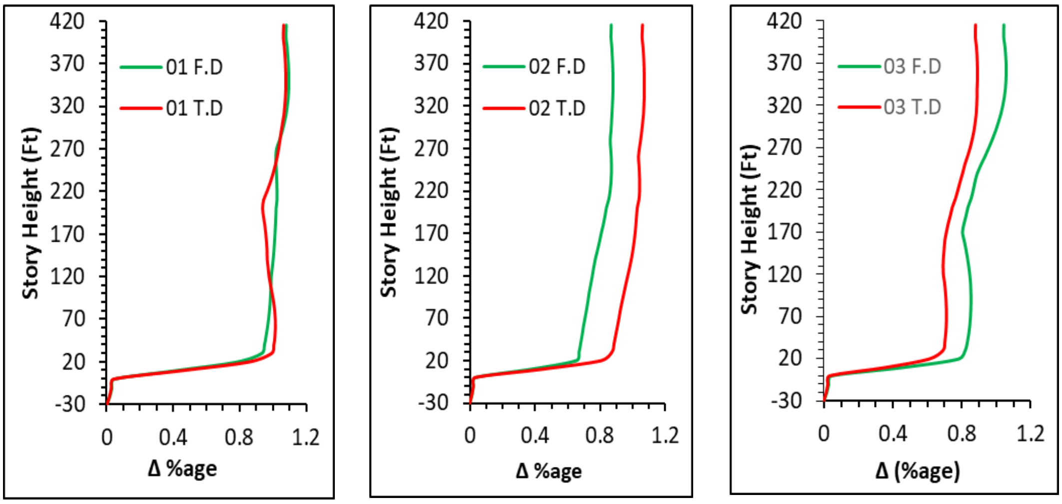
- Maximum story Drift Ratios
- Maximum Story Displacement
- Maximum Story Shear
- Maximum Story Moment
- Maximum Story Accelerations

- Hysteresis Curves
- Maximum Story shear Plots versus Time Histories (Fx-2-2)
- Maximum Overturning Moment (M3-3) versus Time Histories
- Maximum Acceleration plots versus Time Histories
- Maximum Velocity plots versus Time Histories
- Maximum Displacement plots versus Time Histories

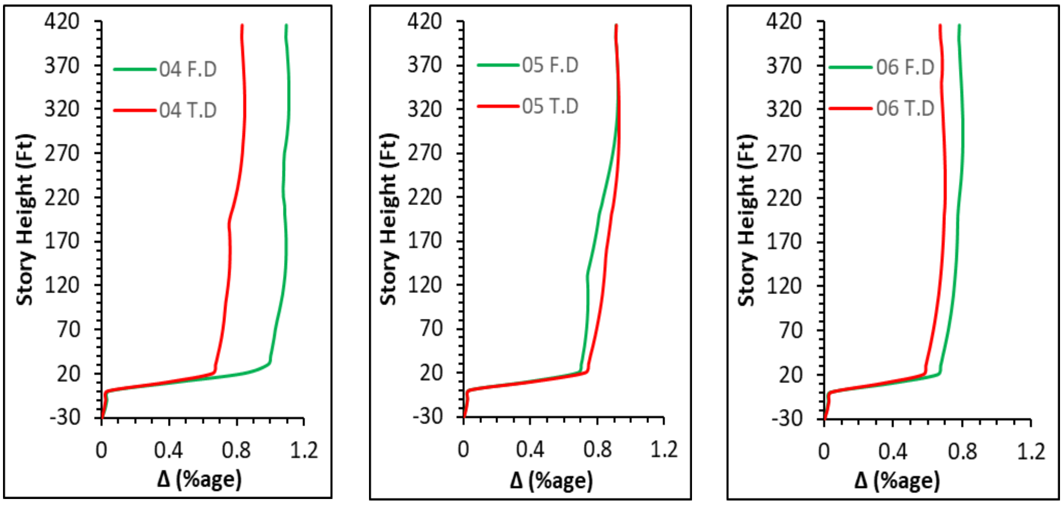
4.2 Maximum story Drift Ratios

Story drift ratio is one of the most important EDPs in structural engineering and is defined as the difference of displacements between the two successive stories divided by the in-between height of stories in consideration. To compare the maximum story drift ratios for FDSM and TDSM, maximum story drift ratios were plotted for all individual ground motions and then converted into a single graph for average response as shown in Figure 4.1. As per UBC-97 section 1630.10.2, the maximum story drift ratio permitted for shorter period structures shall not exceed 0.025 times the story height. Thus, for this structure the calculated value is 0.0025 times the story height i.e. 0.0025 x 10 x 100 = 2.5% for all stories except the ground floor. For ground floor the allowable story drift is found to be 0.0025 x 20 x 100 = 5%. Hence, the story drift for all the floors has been observed within the allowable code restrictions. While comparing the story drift ratios of two spectral matching in consideration, it was observed that story drift ratios have similar pattern and alike values for all individual responses with minute differences.

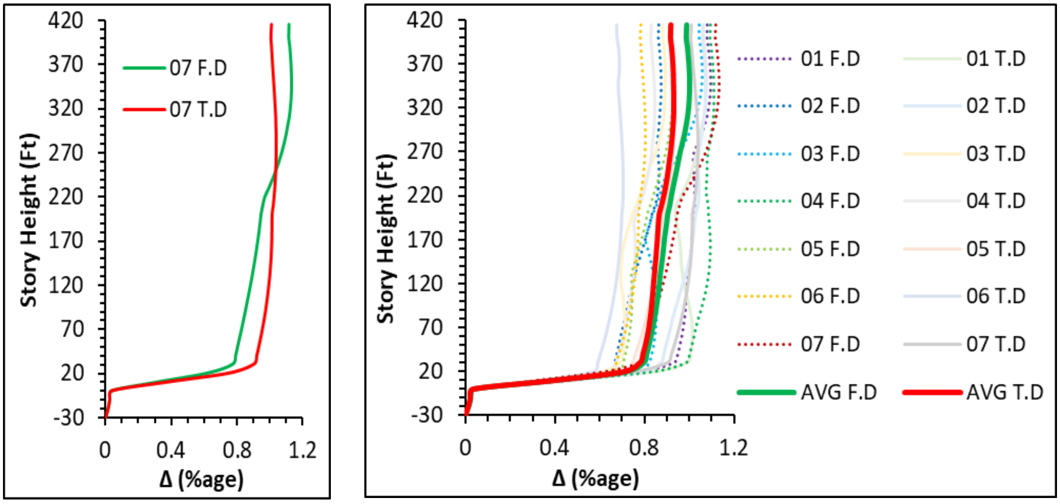
The story drift ratio pattern calculated by FDSM considerably followed the pattern of average plot and gave the maximum value at ground floor possibly due to plastic hinge development. The average inter-story drift ratio of FDSM was found slightly higher as compared to TDSM. However, the average story drift ratios for both spectral matching were found identical and almost equal in magnitude.



a) Max Story Drift Ratios for G.M-01 b Max Story Drift Ratios for G.M-02 c) Max Story Drift Ratios for G.M-03



d) Max Story Drift Ratios for G.M-04 e) Max Story Drift Ratios for G.M-05 f) Max Story Drift Ratios for G.M-06

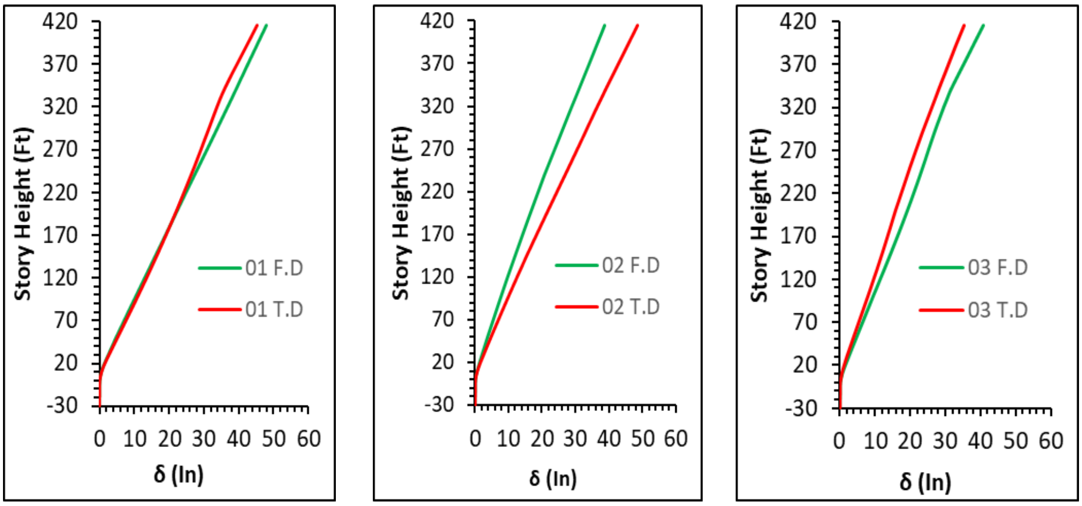


g) Max Story Drift Ratios for G.M-07 h) Average of Max Story Drift Ratios (Avg.)

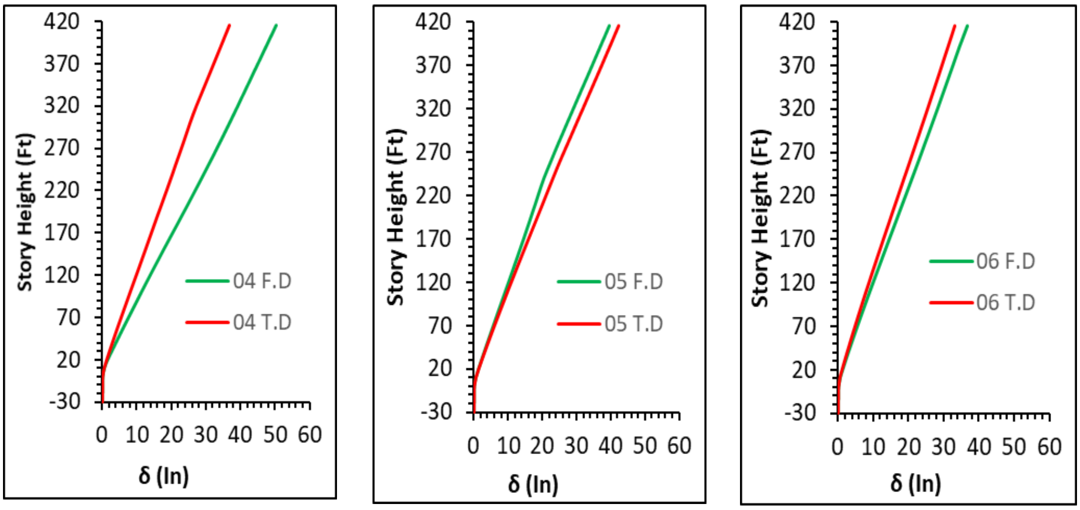
Figure 4.1: Maximum Story Drift Ratios (Δ) plots

4.3 Maximum Story Displacement Plots

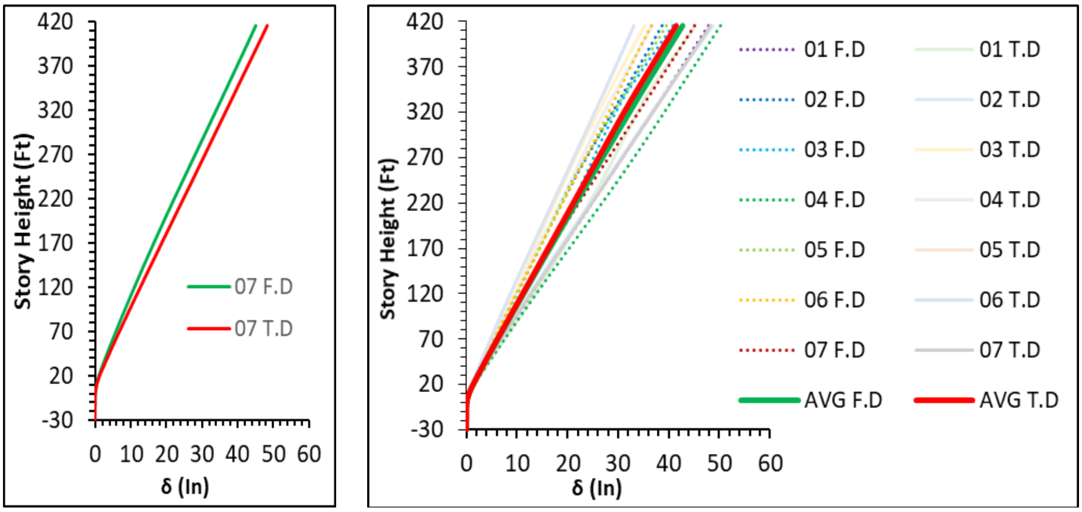
The absolute story displacement because of the lateral forces is called the story displacement. The story displacements against all individual and average spectrally matched ground motions were plotted as shown in Figure 4.2. It was observed that the story displacement has linear increase from bottom to top against both spectral matched ground motions. The displacement demands have almost similar behavior as of story drift ratios. The displacement at ground floor was observed maximum as predicted due to plastic hinge development and the average displacement of FDSM was found slightly greater but significantly closer to TDSM.



a) Max story Displacements for G.M-01 b) Max story Displacements for G.M-02 c) Max story Displacements for G.M-03



d) Max story Displacements for G.M-04 e) Max story Displacements for G.M-05 f) Max story Displacements for G.M-06

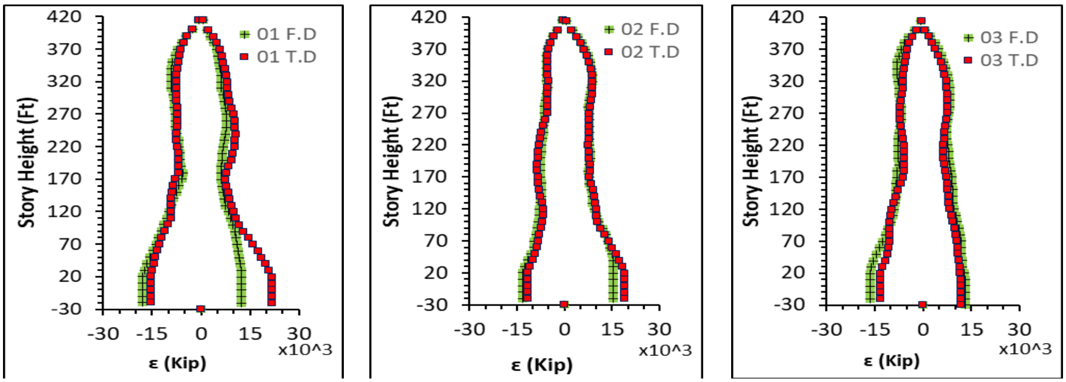


g) Max story Displacements for G.M-07 h) Average of Max story Displacements (Avg.)

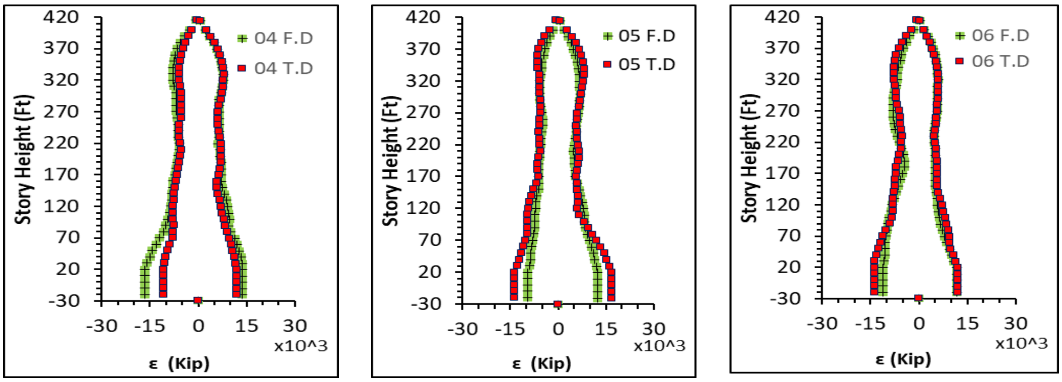
Figure 4.2: Maximum story Displacement (δ) plots against different ground motions

4.4 Maximum Story Shear

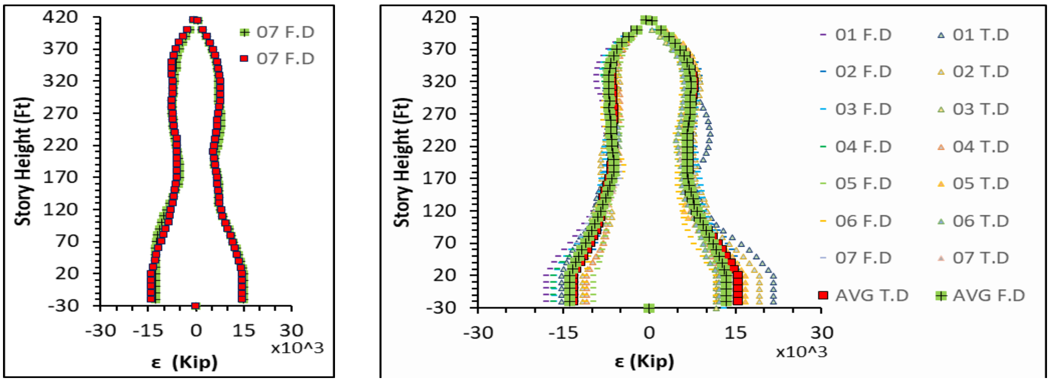
The story shear is the graph to present lateral seismic forces acting on each story level. The comparison of story shear for frequency domain spectrally matched and time domain spectrally matched ground motions are shown in Figure 4.3. The story shear force was found to be maximum at ground floor lobby as predicted due to plastic hinge development. Average of story shear for FDSM was observed to be slightly greater as compared to TDSM. The overall similar pattern was similar to the story drift ratios and story displacements.



a) Max story Shear for G.M-01 b) Max story Shear for G.M-02 c) Max story Shear for G.M-03



d) Max story Shear for G.M-04 e) Max story Shear for G.M-05 f) Max story Shear for G.M-06

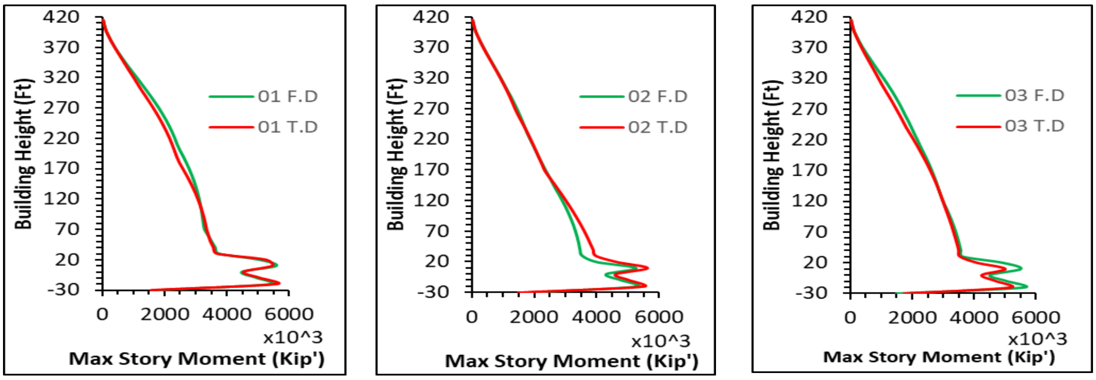


g) Max ε for G.M-07 h) Average of Max story Shear (Avg.)

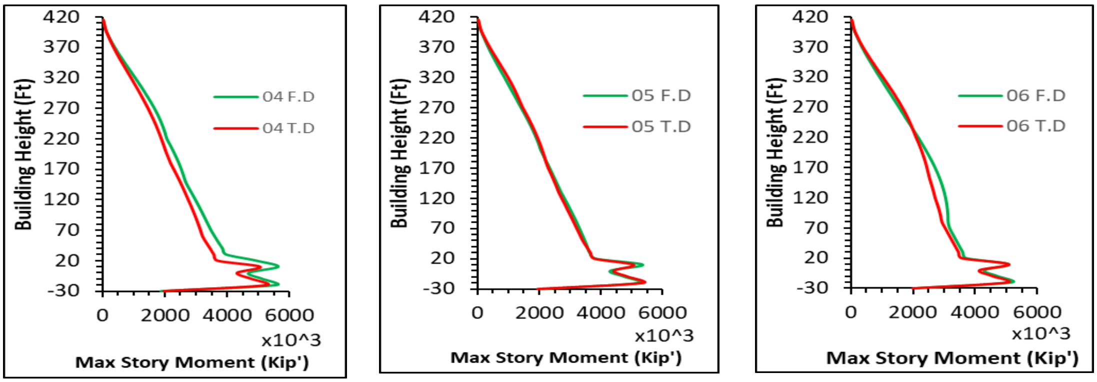
FIGURE 4.3: Maximum story Shear (ϵ) plots against different ground motions

4.5 Maximum Story Moment Plots

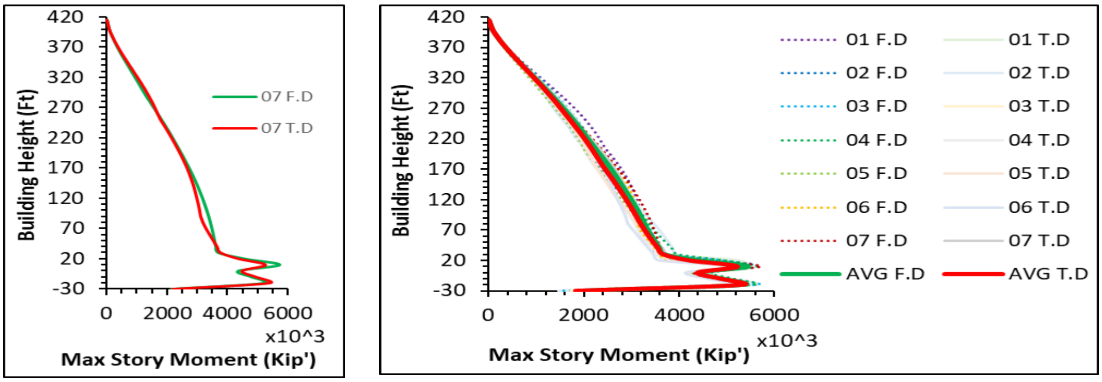
The story moment responses against FDSM and TDSM are plotted in Figure 4.4. The story moment at ground floor was observed to be maximum as predicted due to plastic hinge development. Average story moment of FDSM was greater but significantly closer to that from TDSM. An overlapping in individual and average story moment responses against both spectrally ground motions also indicate the similarity of both story responses. The overall similar pattern as of story drift, displacements and shear was observed.



a) Max story Moment for G.M-01
b) Max story Moment for G.M-02
c) Max story Moment for G.M-03



d) Max story Moment for G.M-04
e) Max story Moment for G.M-05
f) Max story Moment for G.M-06

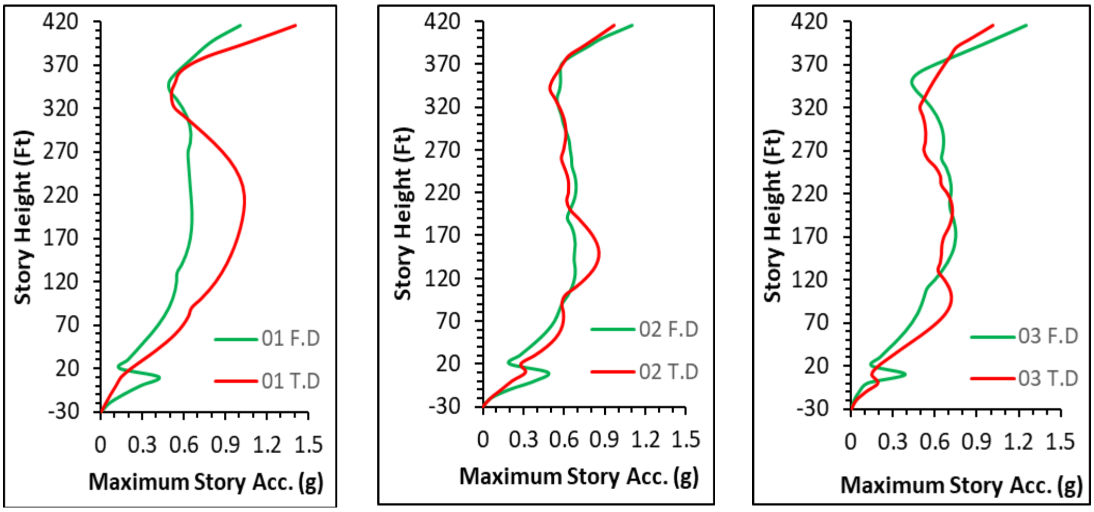


g) Max story Moment for G.M-07
h) Average of Max story Moment (Avg.)

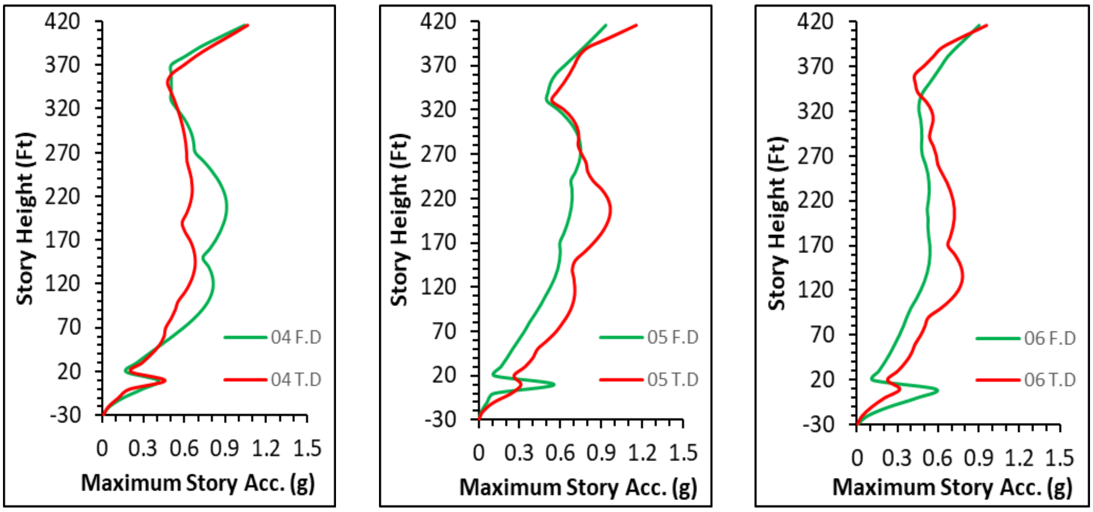
FIGURE 4.4: Maximum story Moment plots against different ground motions

4.6 Maximum Story Acceleration Plots

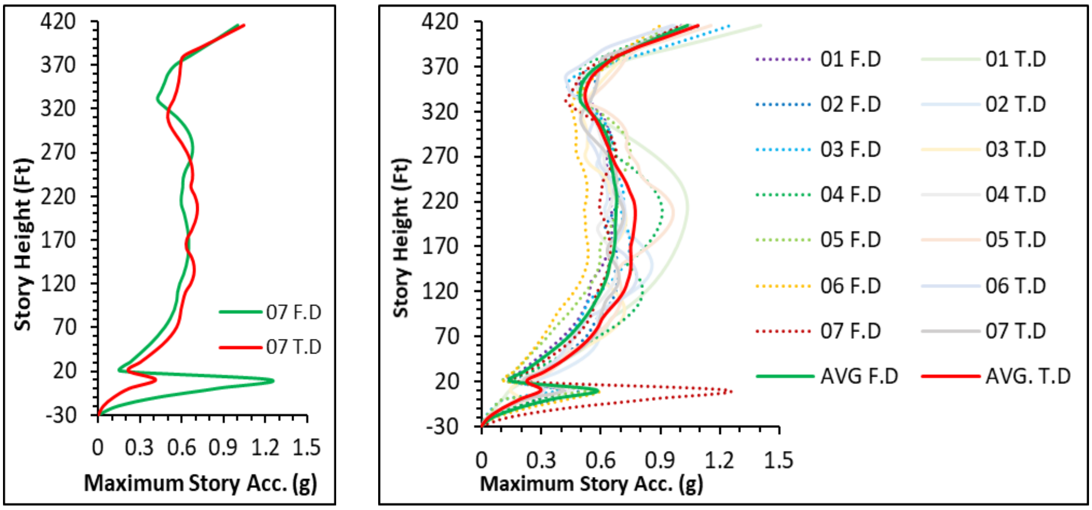
The acceleration is usually considered more sensitive EDP as compared to other parameters. The story acceleration response of structure against FDSM and TDSM are plotted in Figure 4.5. The response of individual ground motions for acceleration was found little different as compared to other EDPs considered so far. It was observed that story acceleration of TDSM has greater dispersions in individual responses from average values as compared to FDSM. It can be seen that the input acceleration mainly controls the story acceleration demands. The story acceleration has a notable dispersal of acceleration at ground floor for both spectral matching ground motions due to plastic hinge development as observed in other EDPs. This acceleration fluctuated more for FDSM possibly due to some matching deficiencies. Further explanation and insight of this phenomena is presented in the subsequent segments (i.e. section 4.10). It can also be observed that the ground motions spectrally matched from very low bias presented more deviations in acceleration response. The average story acceleration of FDSM was also found slightly higher as compared to TDSM. However, the average of story acceleration was identical and nearly equal in magnitude for both spectral matching.



a) Max story Acceleration for G.M-01 b) Max story Acceleration for G.M-02 c) Max story Acceleration for G.M-03



d) Max story Acceleration for G.M-04 e) Max story Acceleration for G.M-05 f) Max story Acceleration for G.M-06

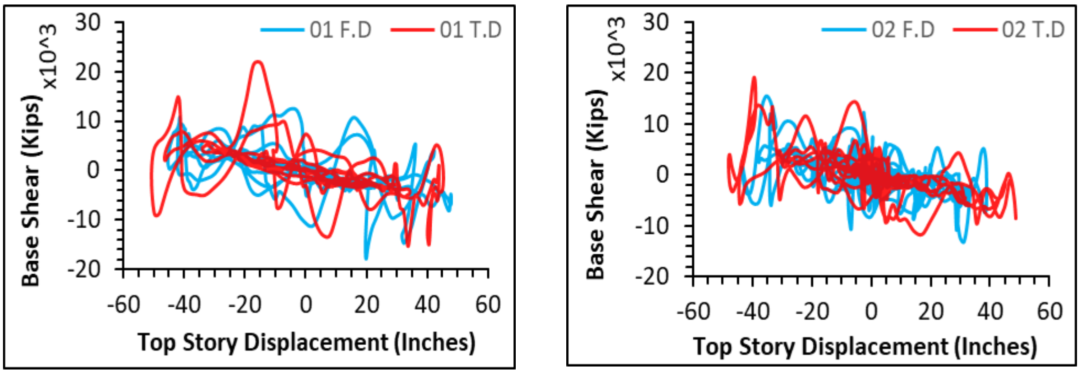


g) Max story Acceleration for G.M-07 h) Average of Max story Acceleration (Avg.)

FIGURE 4.5: Maximum story Acceleration plots against different ground motions

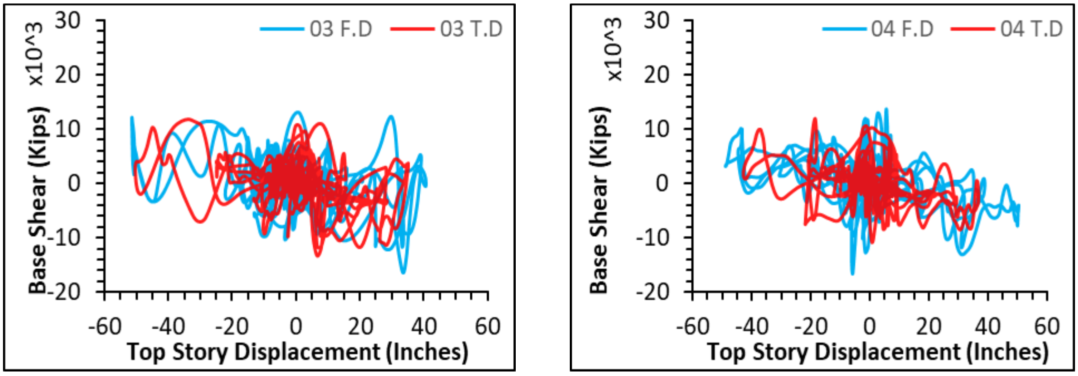
4.7 Hysteresis plots

In order to assess the seismic response of structure under the action of cyclic loading, the hysteresis curves give a good EDP. The hysteresis curves of all individual ground motions were plotted and then converted into a single graph for average response as shown in Figure 4.6. The energy absorption of building was then compared for both spectral matching techniques. Hysteresis curve of this plot comprises of base shear versus top story displacements. It was observed that hysteresis loop area of FDSM was stretched out as comparison to that of TDSM. It can be remarked that the FDSM absorbs more energy as compared to that of TDSM. However, this hysteresis expressively presented the pattern of previously selected EDPs. The overall pattern and magnitude of energy absorption can also be said identical and approximately equal for both the hysterics.



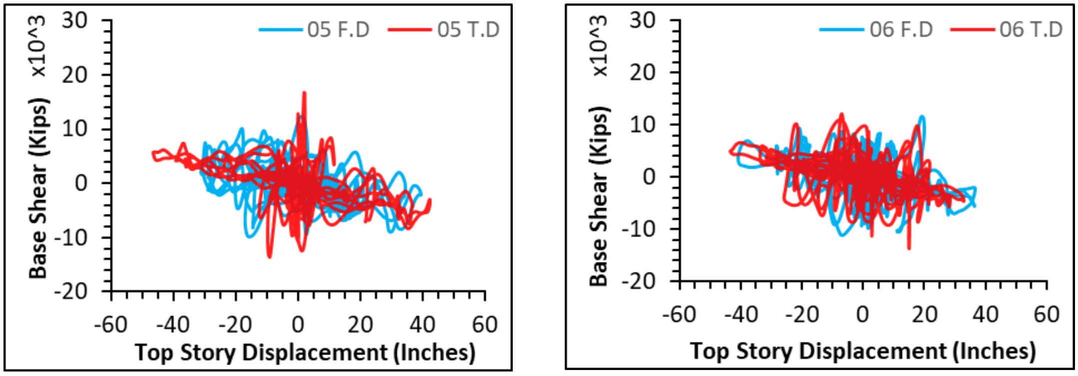
a) Hysteresis Curves for G.M-01

b) Hysteresis Curves for G.M-02



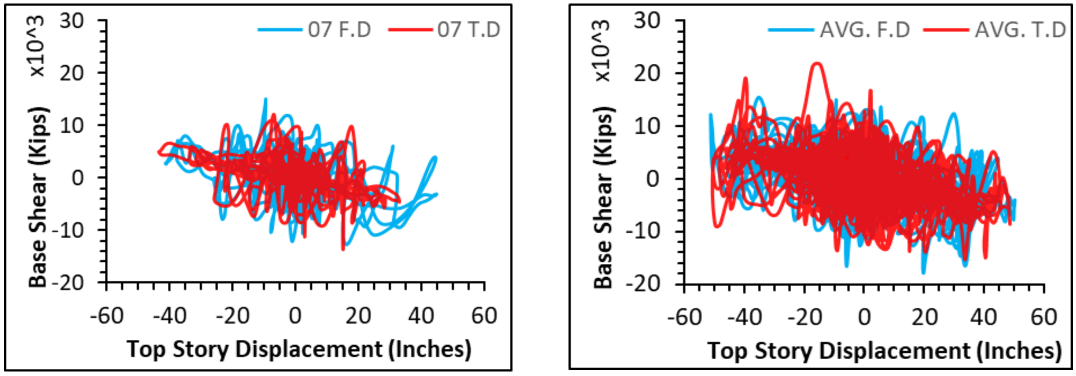
c) Hysteresis Curves for G.M-03

d) Hysteresis Curves for G.M-04



e) Hysteresis Curves for G.M-05

f) Hysteresis Curves for G.M-06



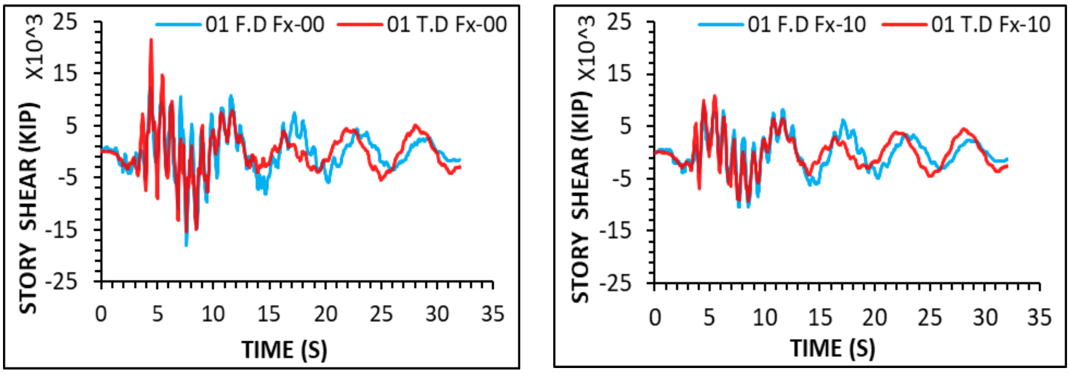
g) Hysteresis Curves for G.M-07

h) Comuative Hysteresis Curve (G.M-1 to G.M-7)

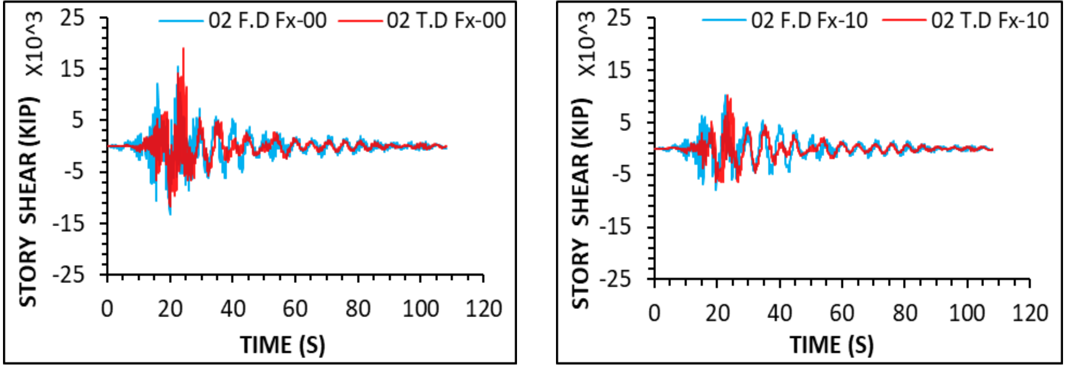
FIGURE 4.6: Hysteresis curves for base shear against top story displacement

4.8 Story Shear Plots against Time Histories (Fx-2-2)

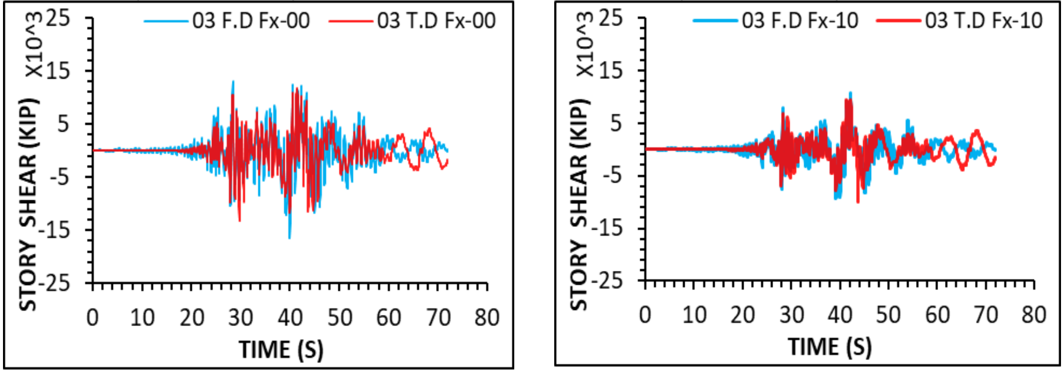
In order to assess the story shear behavior of structure throughout the height, the story shear responses of TDSM and FDSM were plotted against time histories at story level 0, 10, 20 and 30 respectively. Figure 4.7 and Figure 4.8 shows these plots at story level 0 and 20 respectively. While the remaining plots are given in Figure C-1 and Figure C-2 of annexures C. It can be observed that shear force has an identical shape with minimum variations at all stories. The smaller duration earthquake (i.e. G.M-1) also produced more consistent and identical patterns for both spectral matching methods as compared to that of longer duration earthquakes (i.e. G.M-5). However, overall story shear response found to be identical and equal in magnitude for both spectral matching time histories.



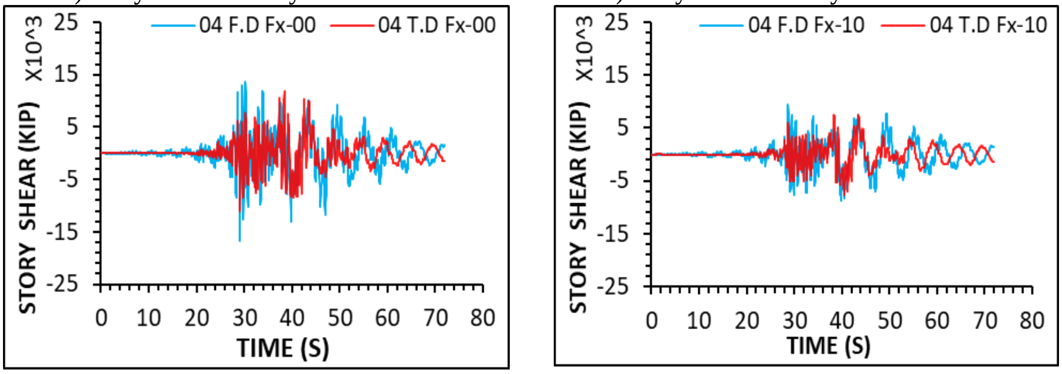
a) Story Shear at Story-0 for G.M-01 b) Story Shear at Story-10 for G.M-01



c) Story Shear at Story-0 for G.M-02 d) Story Shear at Story-10 for G.M-02

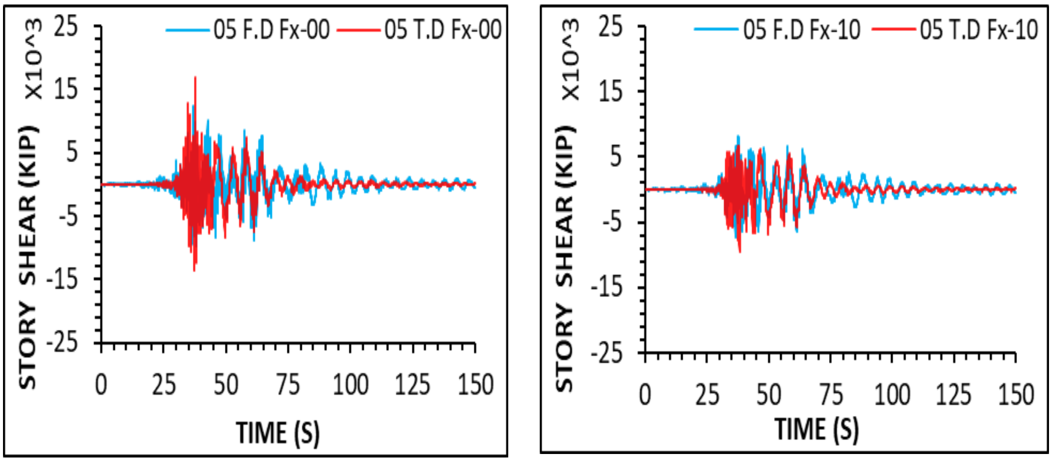


e) Story Shear at Story-0 for G.M-03 f) Story Shear at Story-10 for G.M-03

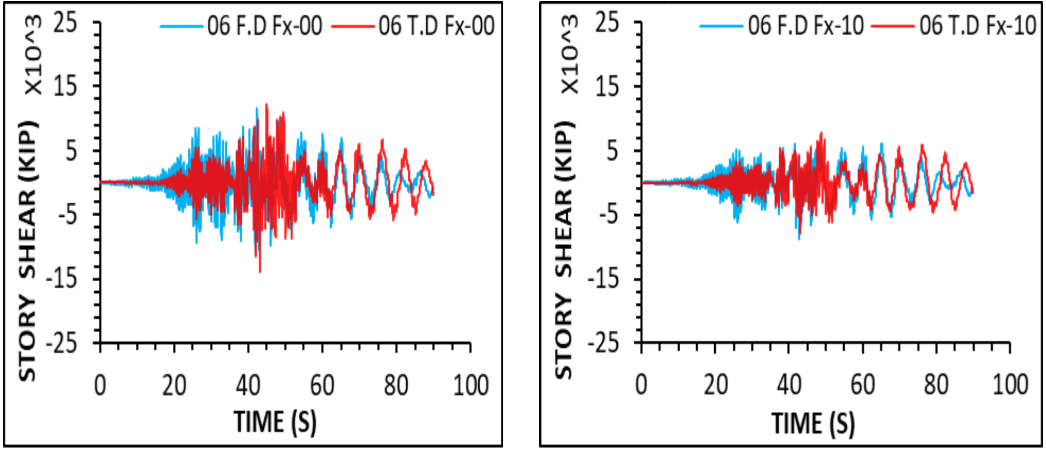


g) Story Shear at Story-0 for G.M-04 h) Story Shear at Story-10 for G.M-04

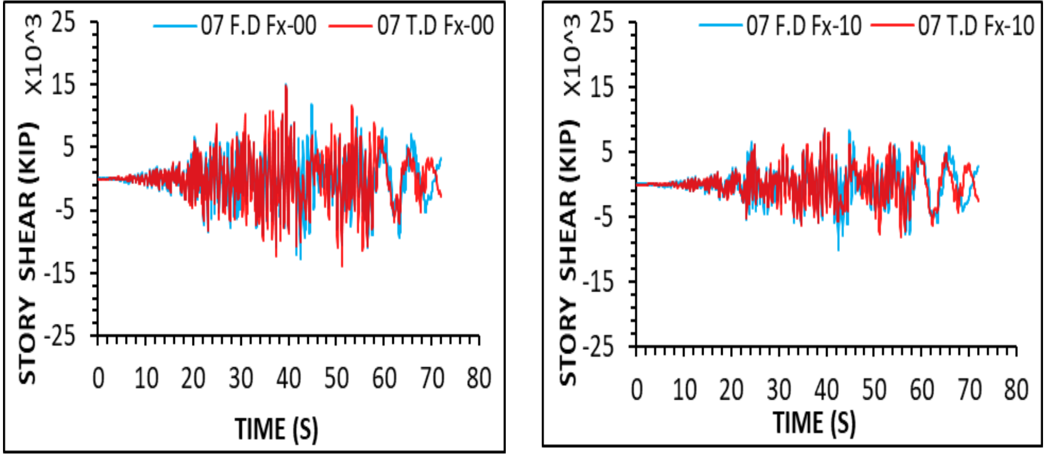
Figure 4.7: Story Shear versus Time History (Story Level-00 and Level-10, G.M-1- G.M-4)



i) Story Shear at Story-0 for G.M-05 j) Story Shear at Story-10 for G.M-05



k) Story Shear at Story-0 for G.M-06 l) Story Shear at Story-10 for G.M-06

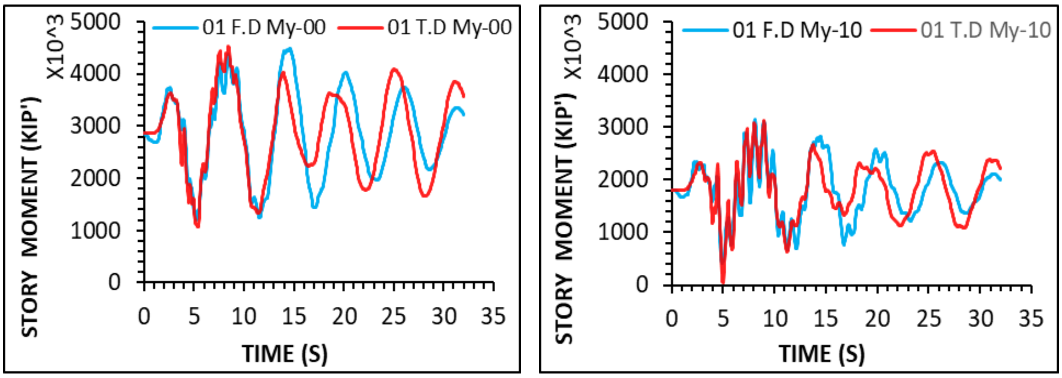


m) Story Shear at Story-0 for G.M-07 n) Story Shear at Story-10 for G.M-07

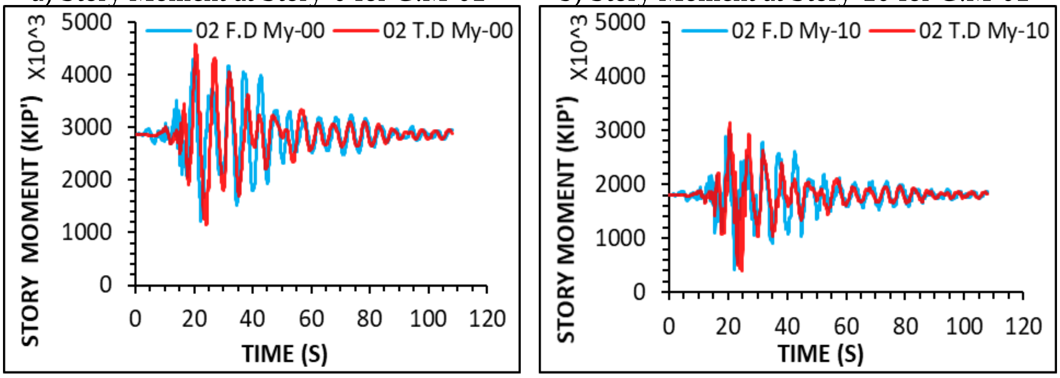
Figure 4.8: Story Shear versus Time History (Story Level-00 and Level-10, G.M-5 -G.M-7)

4.9 Overturning Moment (M3-3) against Time Histories

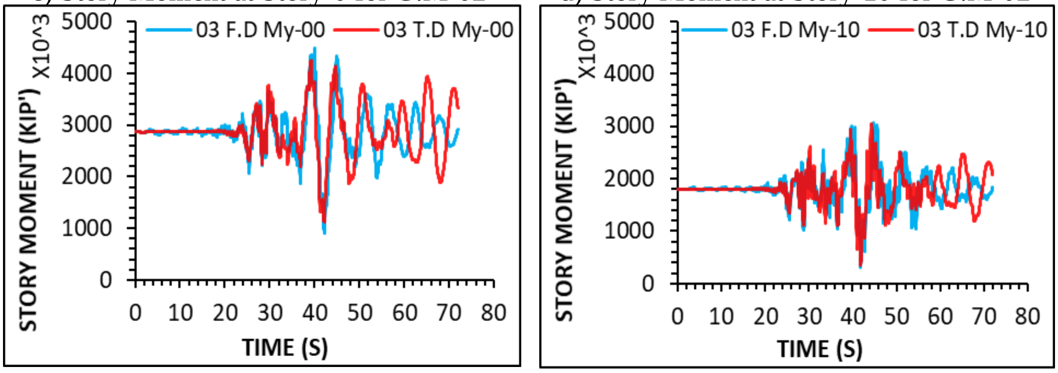
The story responses of TDSM and FDSM were plotted for Overturning Moment (M3-3) against each time history at story level 0, 10, 20 and 30 respectively. Figure 4.9 and 4.10 shows these plots at story level 0 and 20 respectively. The other plots for story level 20 and 30 are presented in Figure C-3 and Figure C-4 respectively. It can be observed from these plots that the overturning Moment (M3-3) have an identical shape with a smaller variation at different levels. The overturning moment decreases towards higher story levels but its pattern for both spectral matching is observed to be more consistent towards the top story as expected due to plastic hinge development at ground floor and elastic behavior at top stories.



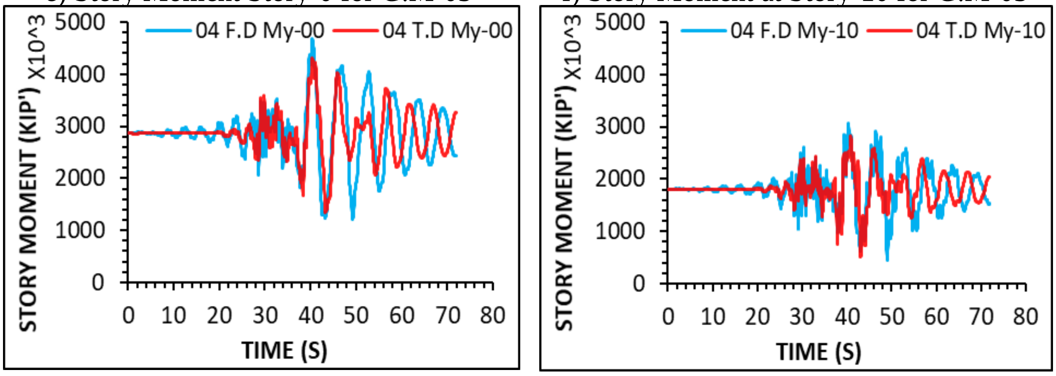
a) Story Moment at Story-0 for G.M-01 b) Story Moment at Story-10 for G.M-01



c) Story Moment at Story-0 for G.M-02 d) Story Moment at Story-10 for G.M-02

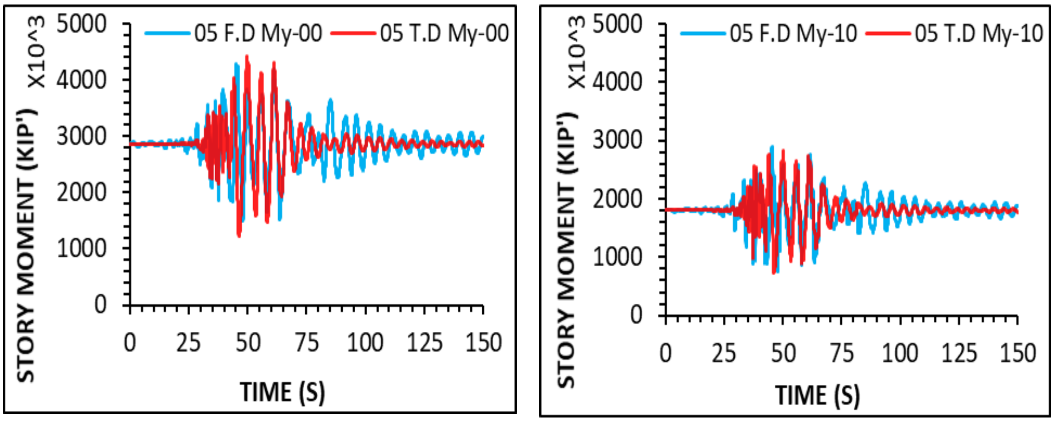


e) Story Moment Story-0 for G.M-03 f) Story Moment at Story-10 for G.M-03

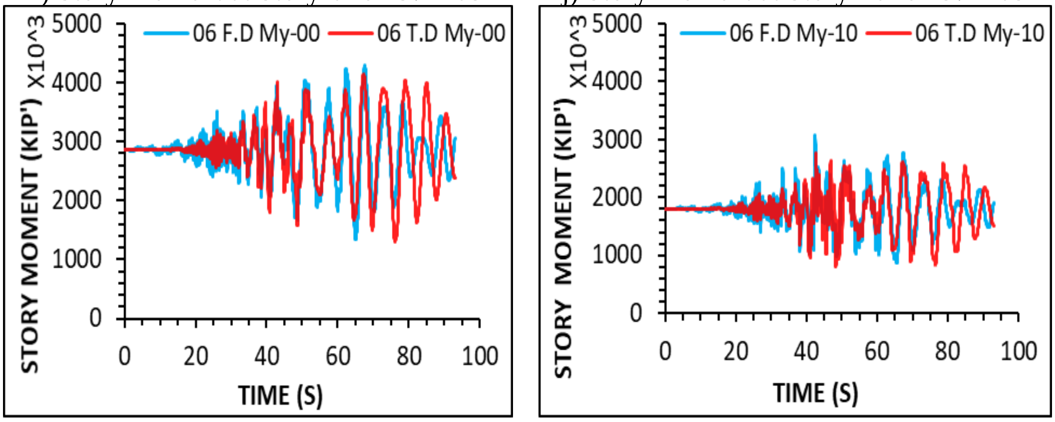


g) Story Moment at Story-0 for G.M-04 h) Story Moment at Story-10 for G.M-04

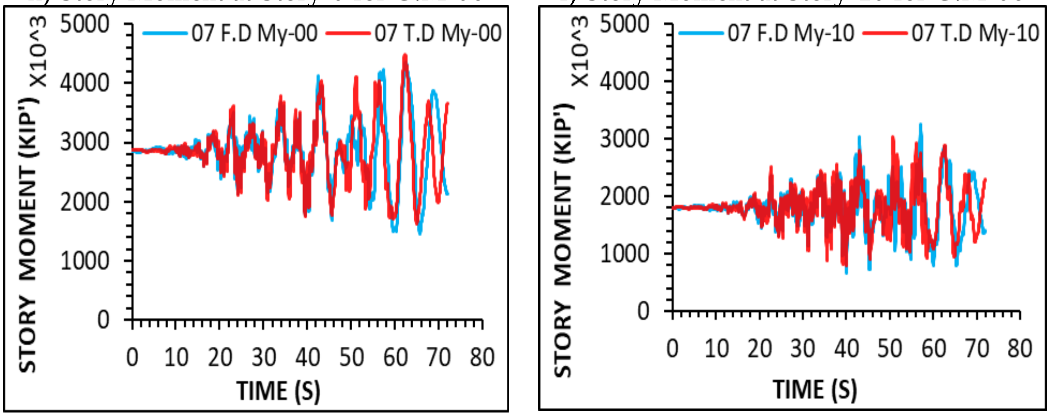
FIGURE 4.9: Moment (M3-3) plots against time history for story Level-0 and Level-10



i) Story Moment at Story-0 for G.M-05 j) Story Moment at Story-10 for G.M-05



k) Story Moment at Story-0 for G.M-06 l) Story Moment at Story-10 for G.M-06

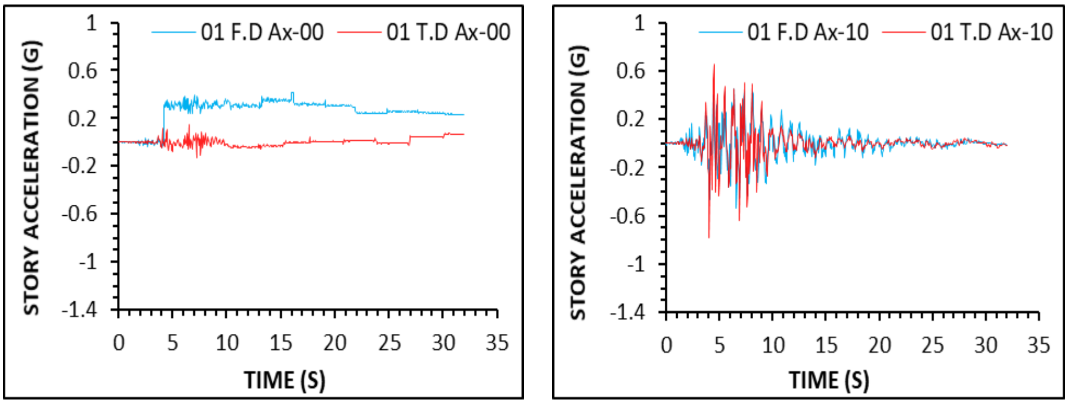


m) Story Moment at Story-0 for G.M-07 n) Story Moment at Story-10 for G.M-07

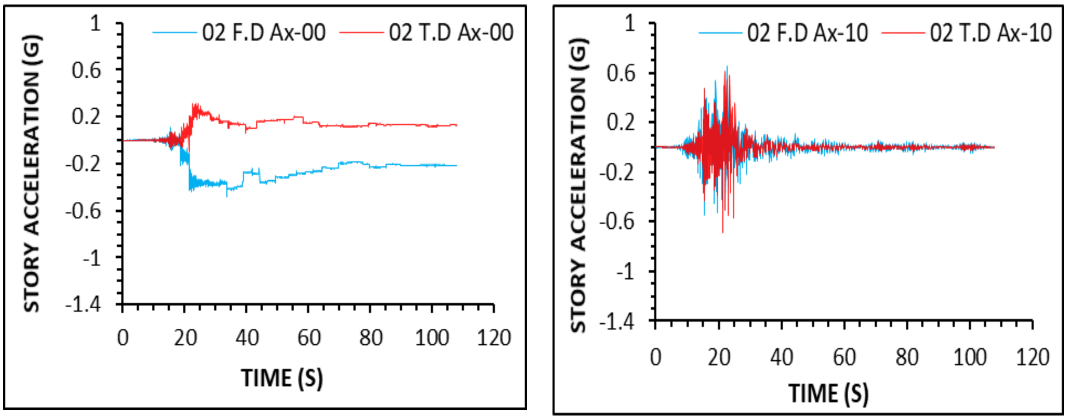
FIGURE 4.10: Moment (M3-3) plots against time history for story Level-0 and Level-10

4.10 Acceleration plots against Time Histories

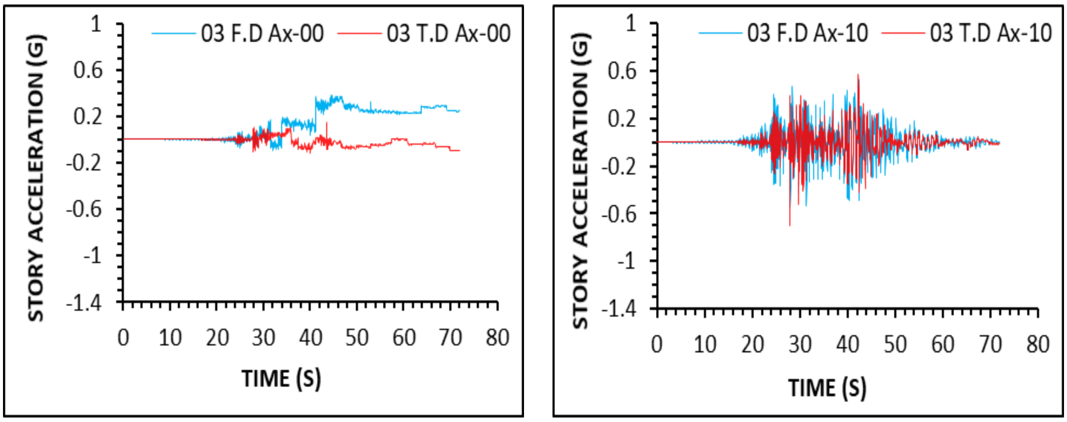
As described previously, acceleration is usually considered utmost sensitive as compared to other EDPs. The consequences of TDSM and FDSM have been plotted for acceleration against each time history at story level 0, 10, 20, 30 and 40 respectively. Figure 4.11 and Figure 4.12 show these plots at story level 0 and 20 respectively. The other concerned plots are given in Figure C-5, C-6 and C-7. It can be observed from story acceleration plots at different levels that the story acceleration has overall identical pattern with and minimum variation when it moves towards greater height. However, story acceleration at level-0 was found to be a little different. While investigating the reason for this variation, several options were considered. Firstly, it was predicted to happen due to confinement of bottom stories with retaining walls and plastic hinge formation at ground floor area and the energy dissipation at plastic hinge location may lead to provide variation in acceleration response. Second and more realistic reason was found due to matching inconsistencies at smaller period of structure. It can be seen that frequency domain spectrally matched acceleration spectrum has jump in spectral acceleration at initial periods. Since higher modes of vibration are expected to contribute, this jump created variation in acceleration time histories. As acceleration is more sensitive, this variation was not equally affected to other EDPs. Similar to the previous responses on selected EDPs, the story acceleration from FDSM also found slightly higher as compared to that of TDSM. However, overall acceleration was found alike for other stories with smaller variations due to expected release of energy at plastic hinge.



a) Story Acceleration vs T.H at Story-0 for G.M-01 b) Story Acceleration vs T.H at Story-10 for G.M-01

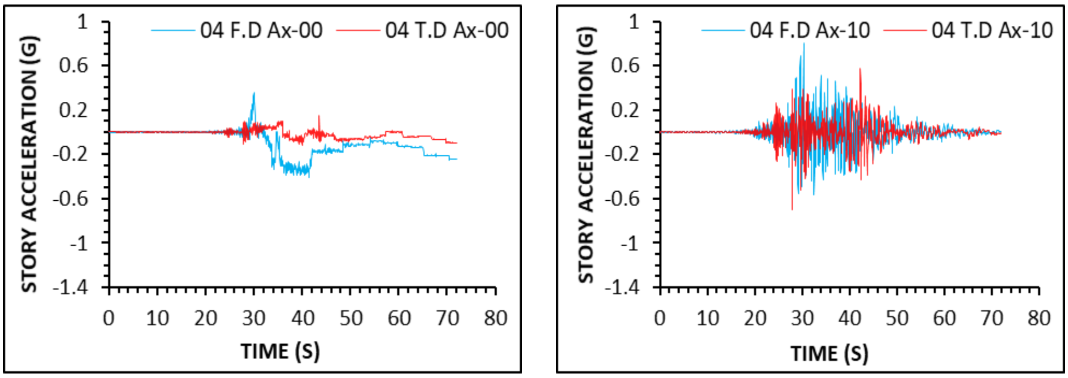


c) Story Acceleration vs T.H at Story-0 for G.M-02 d) Story Acceleration vs T.H at Story-10 for G.M-02

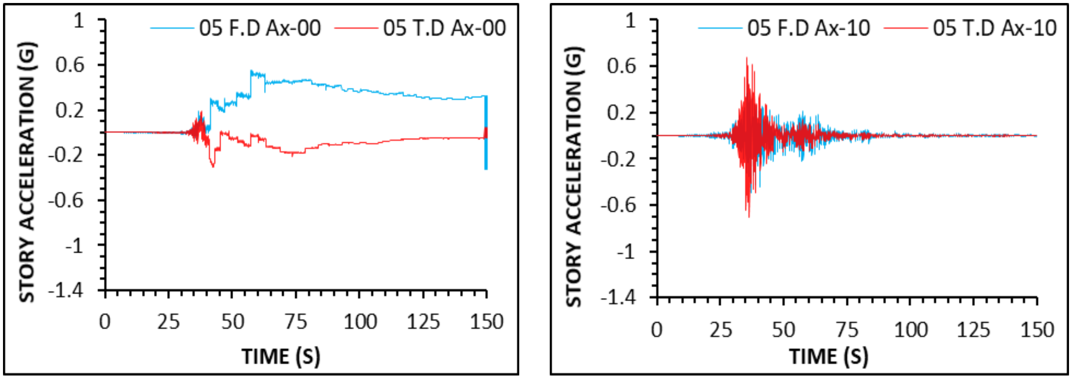


e) Story Acceleration vs T.H at Story-0 for G.M-03 f) Story Acceleration vs T.H at Story-10 for G.M-03

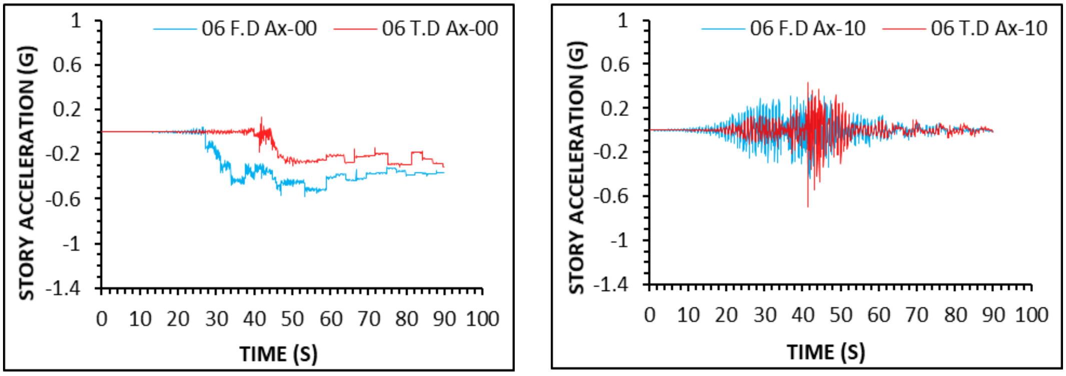
FIGURE 4.11: Acceleration plots against time history for Level-00 and Level-10



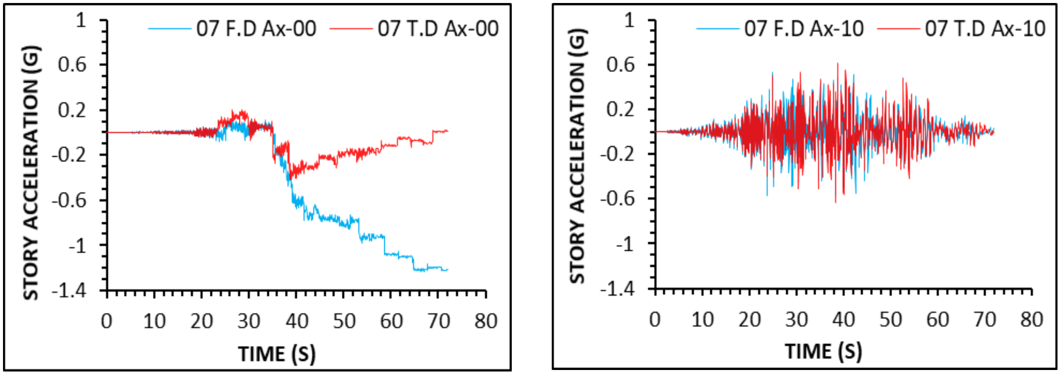
g) Story Acceleration vs T.H at Story-0 for G.M-04 h) Story Acceleration vs T.H at Story-10 for G.M-04



0i) Story Acceleration vs T.H at Story-0 for G.M-05 j) Story Acceleration vs T.H at Story-10 for G.M-05



k) Story Acceleration vs T.H at Story-0 for G.M-06 l) Story Acceleration vs T.H at Story-10 for G.M-06

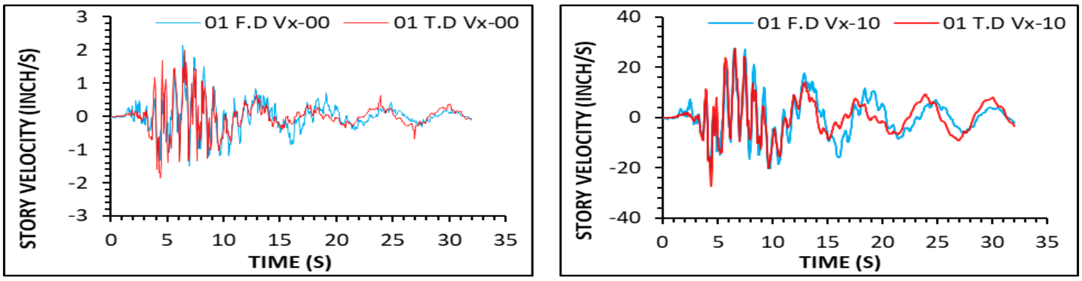


m) Story Acceleration vs T.H at Story-0 for G.M-07 n) Story Acceleration vs T.H at Story-10 for G.M-07

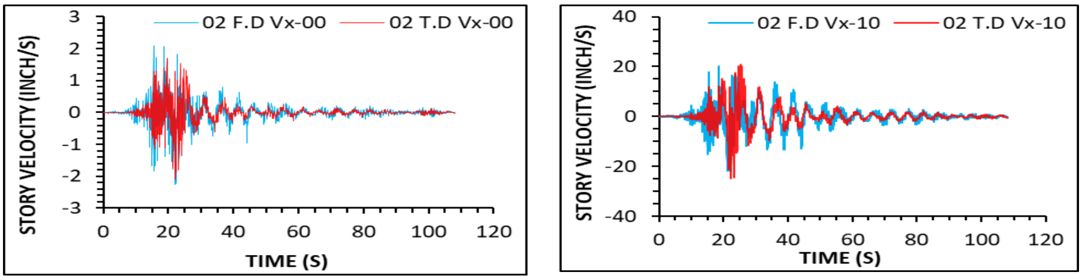
FIGURE 4.12: Acceleration plots against time history for Level-00 and Level-10

4.11 Velocity plots against Time Histories

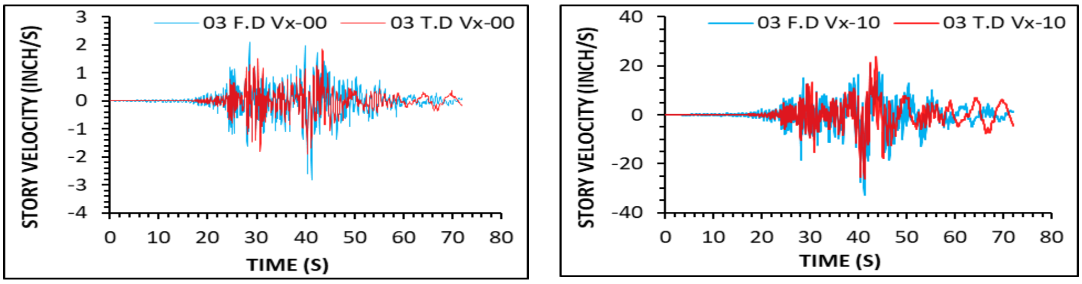
The story velocity response against TDSM and FDSM were plotted against each time history at story level 0, 10, 20, 30 and 40 respectively. Figure 4.13 and 4.14 show these plots at story level 0 and 20 respectively. The other concerned plots are shown in Figure C-8, Figure C-9 and Figure C-10. It can be observed that story velocity has an identical pattern with a little variation. Similar to the acceleration time histories, FDSM gave a little dominant response as compared to TDSM. However, the overall results still found to be identical and equal in magnitude. Similar to the previous trends, story velocity was found more consistent towards higher story levels because of elastic behavior.



a) Story Velocity vs T.H at Story-0 for G.M-01 b) Story Velocity vs T.H at Story-10 for G.M-01

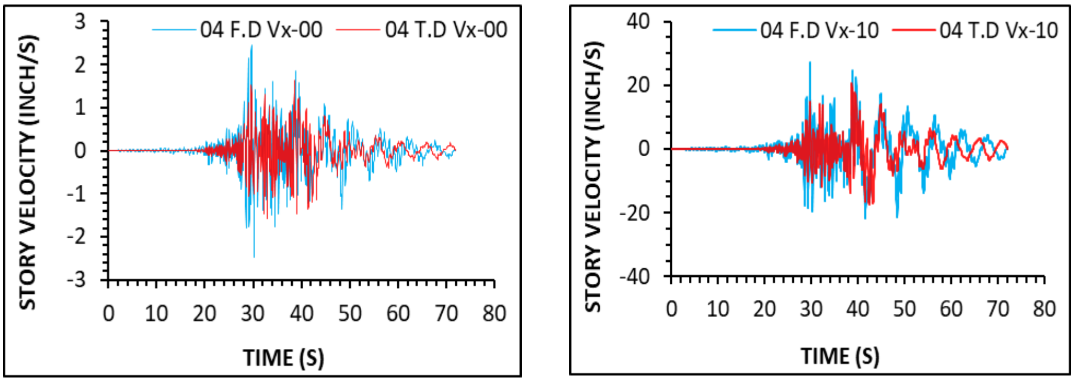


c) Story Velocity vs T.H at Story-0 for G.M-02 d) Story Velocity vs T.H at Story-10 for G.M-02

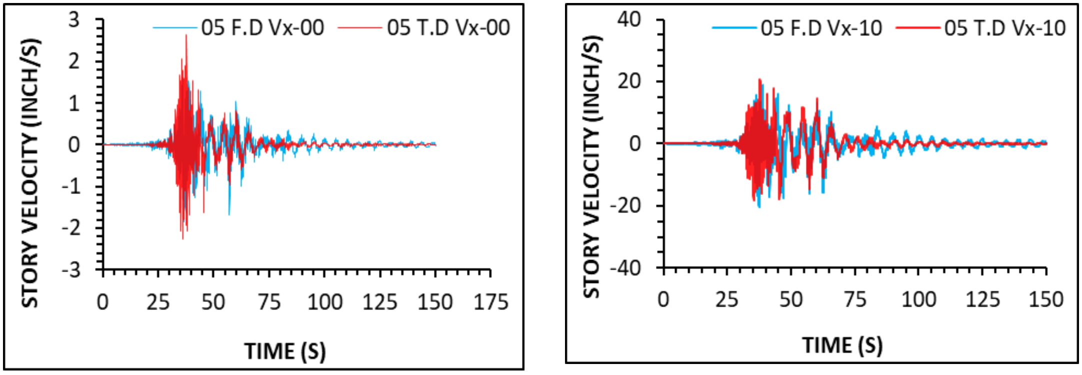


e) Story Velocity vs T.H at Story-0 for G.M-03 f) Story Velocity vs T.H at Story-10 for G.M-03

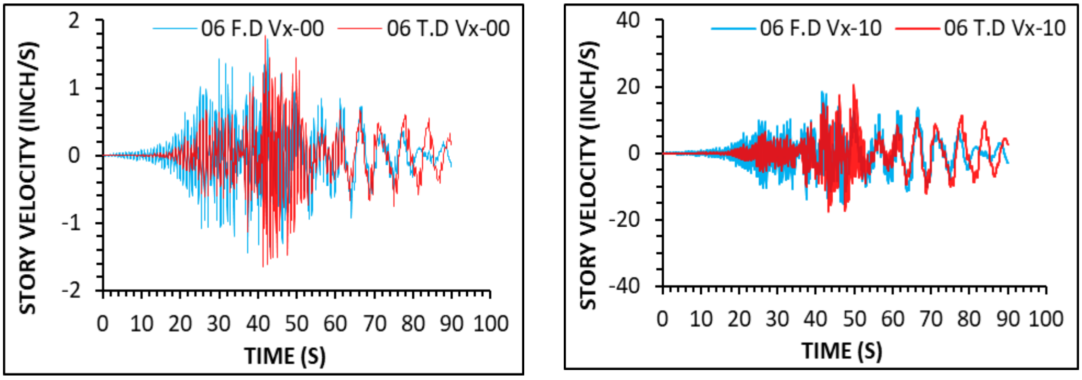
Figure 4.13: Velocity plots against time history for Level-00 and Level-10



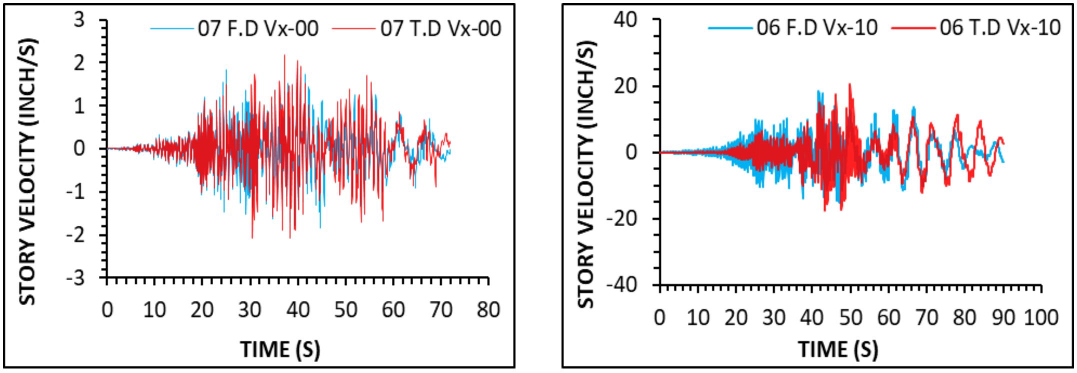
g) Story Velocity vs T.H at Story-0 for G.M-04 h) Story Velocity vs T.H at Story-10 for G.M-04



i) Story Velocity vs T.H at Story-0 for G.M-05 j) Story Velocity vs T.H at Story-10 for G.M-05



k) Story Velocity vs T.H at Story-0 for G.M-06 l) Story Velocity vs T.H at Story-10 for G.M-06

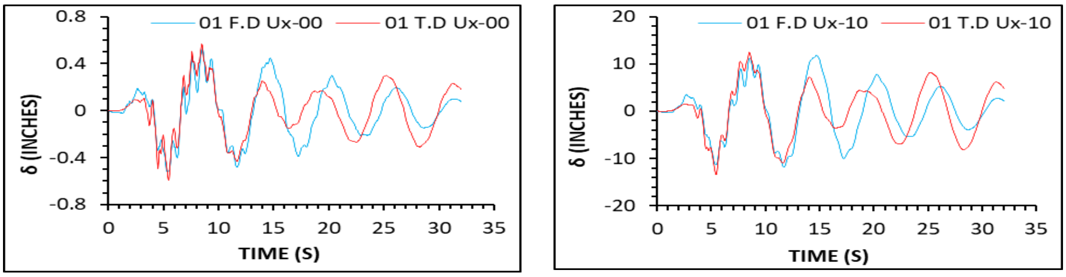


m) Story Velocity vs T.H at Story-0 for G.M-07 n) Story Velocity vs T.H at Story-10 for G.M-07

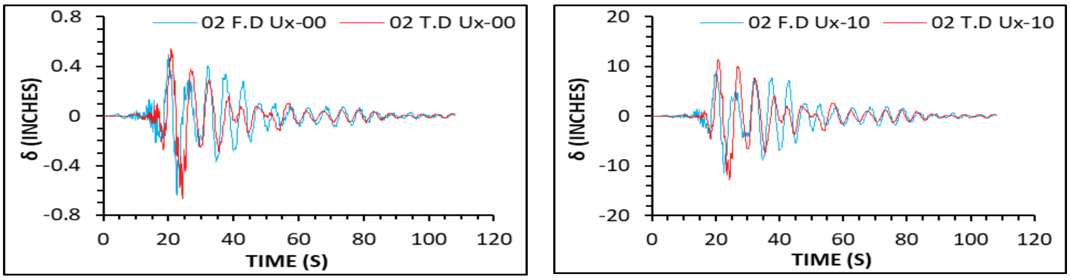
Figure 4.14: Velocity plots against time history for Level-00 and Level-10

4.12 Displacement plots against Time Histories

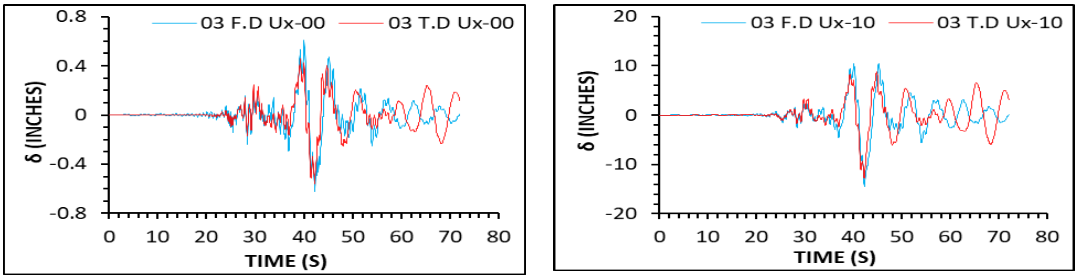
The story displacement responses against TDSM and FDSM were plotted against each time history at story level 0, 10, 20, 30 and 40 respectively. Figure 4.15 and Figure 4.16 shows these plots at story level 0 and 20 respectively. The other plots for story displacement response are given in Figure C-11, Figure C-12 and Figure C-13. The story displacement showed an identical behavior with a minimum difference. Only a little change was observed in longer duration earthquake. Continuing the trend of acceleration and velocity time histories, it was observed that the FDSM provide relatively higher seismic demand at all floor levels. However, no significant difference was still found against both of the matching techniques.



a) Story Displacement vs T.H at Story-0 for G.M-01 b) Story Displacement vs T.H at Story-10 for G.M-01

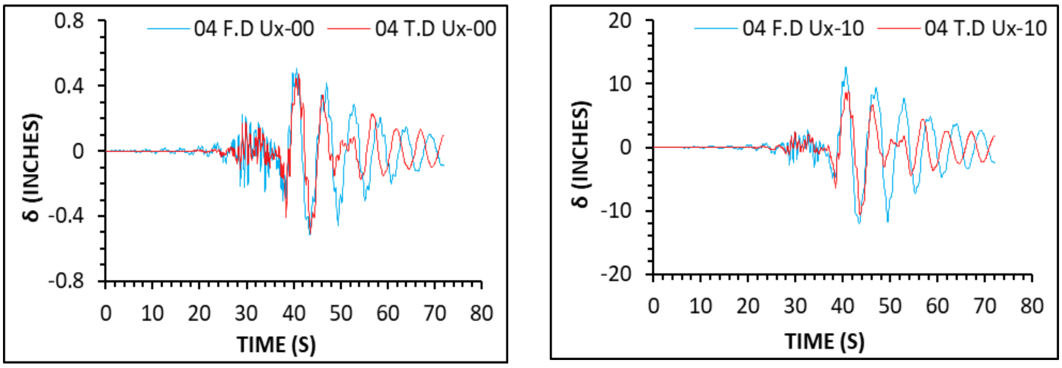


c) Story Displacement vs T.H at Story0 for G.M-02 d) Story Displacement vs T.H at Story-10 for G.M-02

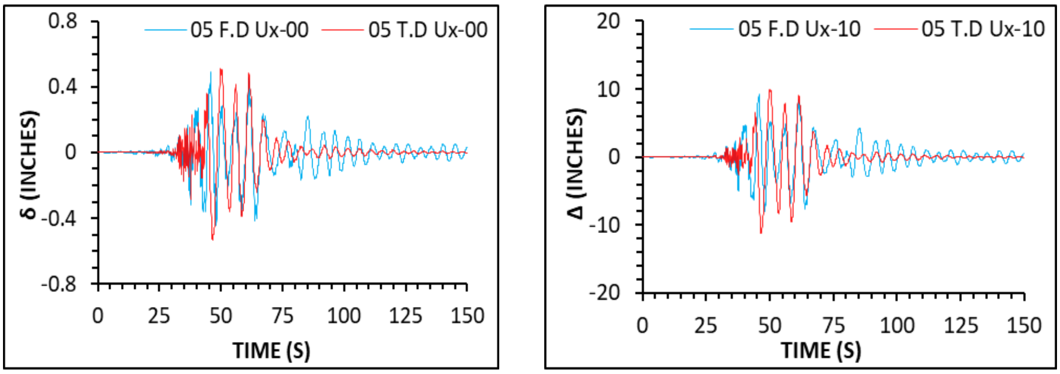


e) Story Displacement vs T.H at Story-0 for G.M-03 f) Story Displacement vs T.H at Story-10 for G.M-03

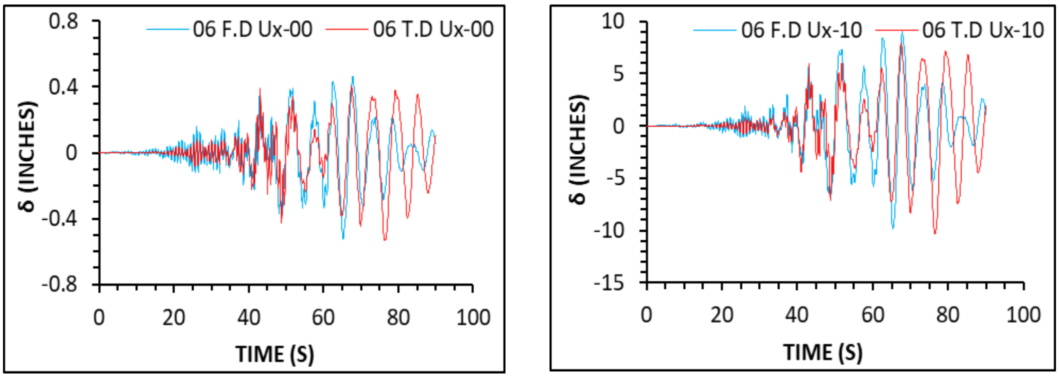
FIGURE 4.15: Story Displacement (δ) plots against time history for Level-00 and Level-10



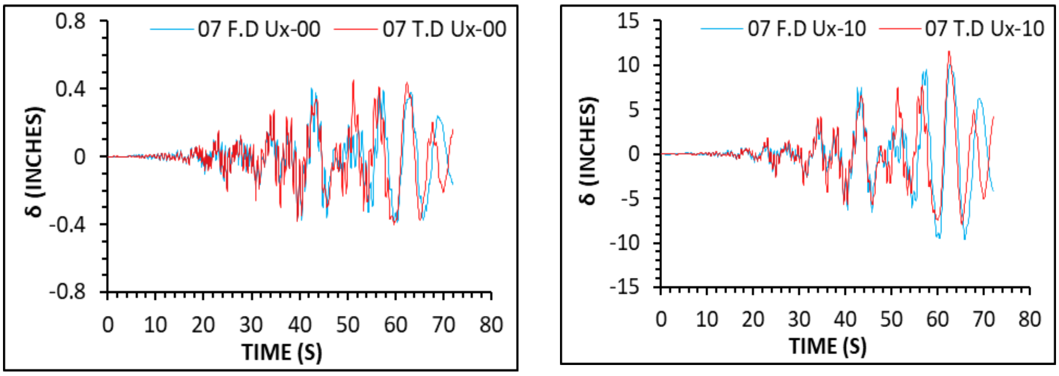
g) Story Displacement vs T.H at Story-0 for G.M-04 h) Story Displacement vs T.H at Story-10 for G.M-04



i) Story Displacement vs T.H at Story-0 for G.M-05 j) Story Displacement vs T.H at Story-10 for G.M-05



k) Story Displacement vs T.H at Story-0 for G.M-06 l) Story Displacement vs T.H at Story-10 for G.M-06



m) Story Displacement vs T.H at Story-0 for G.M-07 n) Story Displacement vs T.H at Story-10 for G.M-07

FIGURE 4.16: Story Displacement (δ) plots against time history for Level-00 and Level-10

4.13 Summary of Results

The seismic behavior of 40 story RC core wall on eleven different EDPs was compared in previous sections. These EDPs include story drift, story displacement, story shear, story moment and story acceleration plotted against building height. The other EDPs include hysteresis curve plotted for base shear against top story displacement, whereas the story moment, story shear, story acceleration, story velocity and story displacements were plotted against time histories at story level 0, 10, 20, 30 and 40 respectively.

While comparing these seismic responses of building, the similar trends were observed for these selected EDPs. Core findings against each EDPs are highlighted in Table 4.1. Seismic behavior of building for individual ground motions fluctuated a little when plotted against height especially when ground motions were spectrally matched from very low intensities. A significant difference was found in acceleration time histories at ground floor lobby due to matching inconsistencies at initial time periods for FDSM. The average acceleration response was yet identical and significantly equal in magnitude for both spectrally matched ground motions. Moreover, the frequency domain spectrally matched ground motions presented slightly higher seismic response and greater energy absorption as compared to that of time domain spectrally matched ground motions and hence can be remarked as a conservative spectral matching approach.

Table 4.1: Summary of Seismic Demands on against selected EDPs

Sr. No	Assessment EDP	Pattern Comparison (FDSM TDSM)	Magnitude Comparison (FDSM TDSM)
1	Story Drifts	Similar pattern observed in Individual and Average Response with smaller differences in some individual responses,	A small variation in individual response found. FDSM gave slightly greater response on average
2	Story Displacement	Similar patterns found in Individual and Average Response	FDSM gave slightly greater response on average with little variations in individual response
3	Story Shear	Similar patterns found for Individual and Average Response	Similar behaviors in Individual and Average Response observed
4	Story Moment	Similar pattern for Individual and Average Response observed	Similar behavior observed for Individual Response. FDSM gave slightly greater response on average
5	Story Accelerations	A small variation observed in individual response but similar pattern seen for Average Response	A small variation in individual response found. TDSM gave slightly greater response on average
6	Hysteresis	Variable hysteresis observed in individual responses but similar pattern for Average/ commutative Response found	A small variation in individual response observed. FDSM gave slightly greater response on average. The cumulative response found more identical
7	Story Shear T.H	Nearly same Pattern observed at all levels, and Similarity increases with height	Nearly same response at all levels found, FDSM gave slightly higher response. Similarity increases along the height

8	Story Moment T.H	Nearly Same Pattern observed at all levels, Similarity increased with the height	Nearly same response found at all levels, FDSM gave slightly greater response. Similarity increased along the height
9	Story Accelerations T.H	Nearly Same Pattern observed at all levels other than ground floor, Similarity increased with the height	Nearly same response found at all levels other than ground floor, FDSM gives slightly higher response. Similarity increased along the height
10	Story Velocity T.H	Nearly Same Pattern observed at all levels, Similarity increased with the height	Nearly same response found at all levels, FDSM gives slightly greater response. Similarity increased along the height
11	Story Displacement T.H	Nearly Same Pattern observed at all levels, Similarity increased with the height	Nearly same response found at all levels, FDSM gives slightly higher response. Similarity increased along the height
12	Overall Results	Similar patterns for Individual and Average Response being observed. The average response found more identical when compared to individual pattern.	Similar behavior for Individual and Average Response observed with a little variation in Acceleration at ground floor. Average results indicate that FDSM give a conservative seismic response of structure for all EDPs as compared to TDSM

4.14 Comparison with Previous Studies

To the best of authors knowledge, no similar studies have been conducted to investigate the seismic response of RC core wall structural system against these spectral matching techniques. However, [34] compared seismic response of 15 story building by using only spectral matching in time domain. Two different softwares namely RSPMATCH and seismsoft were utilized for TDSM. The use of spectral matching using RSPMATCH was recommended to better estimate seismic responses of building for maximum story acceleration, maximum story drift and average spectral acceleration at different stories. Frequency domain spectral matching was not considered for this study.

A development was made in an investigation where FDSM and TDSM were used for seismic assessment of bridge structures using two spectral matching softwares namely SYNTH for FDSM and RSPMATCH for TDSM. It was recommended to use FDSM and TDSM methods for producing similar profile of matched ground motions and for giving minimum dispersions in seismic responses [81]. The results of authors investigations nearly comply with spectral matching characteristics of this investigation. However, the seismic response of bridges under consideration may not be feasible to compare with the seismic response of investigated building. An insights and conclusive comparison of these two methods are further given in the next chapter.

Chapter 5

Conclusion and Recommendations

5.1 Background

Spectral matching is one of the core steps of performing nonlinear time history analysis. It is a procedure to modify real recorded time histories to make them compatible with target spectra of site of interest. Spectral matching is generally done in frequency domain or time domain. This research investigated the effects of these two spectral matching techniques on seismic behavior of 40 story RC core wall building. The results of spectral matching were initially compared on the basis of five characteristics of ground motions which include the acceleration spectra, acceleration, velocity and displacement time histories, and the frequency contents. The seismic behavior of building was then assessed through NLTHA against these target spectrum compatible ground motions. The seismic behavior was compared on 11 different EDPs including story drifts, story displacements, story shears, story moments, story acceleration, hysteresis curves and different time histories at selected floor levels. The precision of spectral matching processes was assessed by comparing seismic response of building against these EDPs. The core findings, conclusions and future works of this research are deliberated below.

5.2 Conclusions

- Time domain spectral matching gives a closer match to the target spectra and produces lesser drifts in matched displacement time history.
- Frequency domain spectral matching on the other hand better preserves the frequency content of original ground motion as compared to time domain spectral matching.
- More interestingly, frequency domain spectral matching provides better matching results of acceleration as well as velocity of matched time history with their original acceleration and velocity time histories.
- While considering all ground motion matching characteristics, it comes very hard to make consensus about the superiority of any technique due to variable matching results and a seismic assessment of designated structure against these ground motions become more viable.
- While modifying ground motion records from very low intensities, both spectral matching produce drifts in displacement time histories.
- The average seismic response of high-rise RC core wall building found identical for both procedures. However, this response in frequency domain spectral matching found slightly higher and said to be more conservative.

5.3 Recommendations

- Since the average seismic response of building under consideration found alike for both spectral matching techniques, both techniques can be practiced for high-rise RC core wall buildings.
- However, for giving conservative seismic response and better matching characteristics, the FDSM may be preferred for these structural systems.

- Moreover, since the average seismic response for this research found marginal on average and a notable difference only in acceleration produced because of higher modes contribution, the designers must be given a freedom to choose between these two methods based upon their target goal and design demands.

5.4 Future Work

The NLTHA on seven different ground motions validates that TDSM and FDSM give minimal variations in ground motion characteristics as well as in multiple EDPs. Effects of base line corrections in spectral matching on seismic behavior of structure need to be explored so as to achieve more reliable results. The seismic responses of both spectral matchings also need to be correlated with improved ground motion scaling methods like model pushover scaling method of Chopra or Conditional mean spectrum. Since this research investigates application of one horizontal component of ground motion, the application of another horizontal component on SM may also be examined. Moreover, this investigation may also be done for other RC structural system and steel structures.

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Annexure A

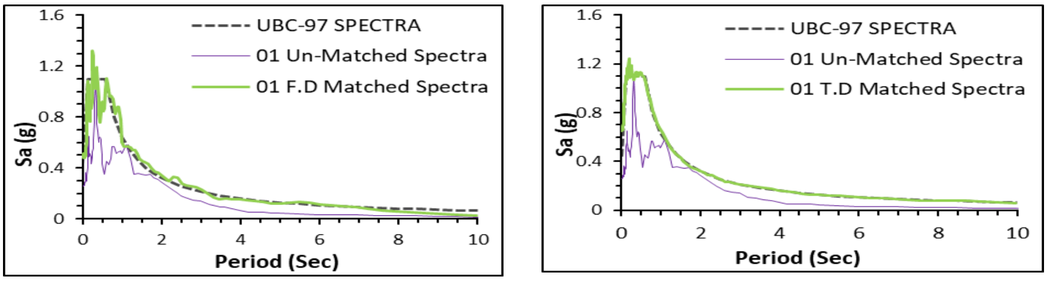
A.0 1: Spectral matching Peak Misfits with original on varied parameters

Assessment Parameter	Acceleration of Matched T.H	—	Velocity of Matched T.H	—	Displacement of Matched T.H	—	Average Misfit	—
Scaling Type	F. D	T. D	F. D	T. D	F. D	T. D	F. D	T. D
Record No	%age Misfit with original	—	%age Misfit with original	—	%age Misfit with original	—	Avg. %age Misfit with original	—
1	85	154	43	25	136	122	88	100
2	145	164	20	4	138	24	101	64
3	135	216	54	44	66	62	85	107
4	196	229	47	46	43	55	95	110
5	54	65	6	15	23	4	27	28
6	397	549	89	91	148	20	212	220
7	1,261	1,609	156	200	266	187	561	665
Average	325	426	59	61	117	68	167	185

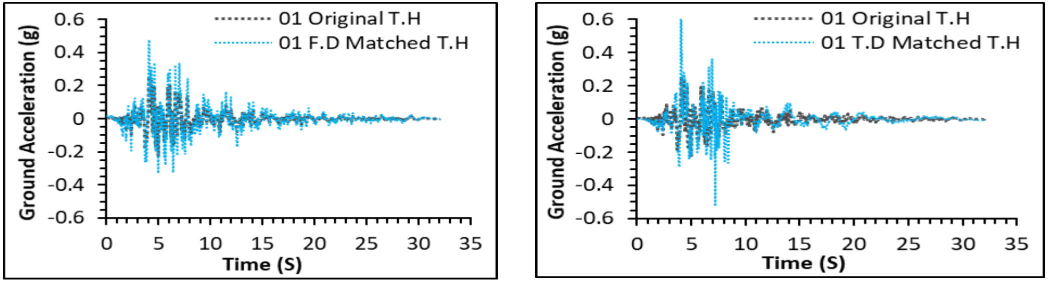
A.0 2: Assessment of Spectral matching plots on varied parameters

Assessment Parameter	Spectrum Matching	—	Acceleration of Matched T.H	—	Velocity of Matched T.H	—	Displacement of Matched T.H	—	Frequency Content of Matched T.H	—	Overall Score	—
Weightage/ Score	20	—	20	—	20	—	20	—	20	—	100	—
Scaling Type	F. D	T. D	F. D	T. D	F. D	T. D	F. D	T. D	F. D	T. D	F. D	T. D
Record No	Score	—	Score	—	Score	—	Score	—	Score	—	Score	—
1	17	19	17	15	18	16	13	16	18	13	83	79
2	18	19	16	18	17	15	11	15	16	18	78	85
3	18	19	16	15	18	17	17	18	18	17	87	86
4	18	18	16	18	18	16	17	19	19	16	88	87
5	18	20	16	19	19	17	15	18	18	16	86	90
6	19	20	16	14	18	15	15	17	18	15	86	81
7	19	20	16	16	16	15	14	18	18	16	83	85
Average	18	19	16	16	18	16	15	17	18	16	84	85

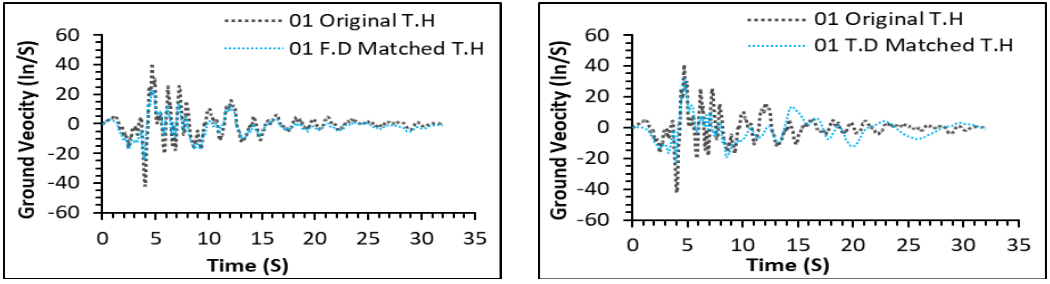
Annexure B



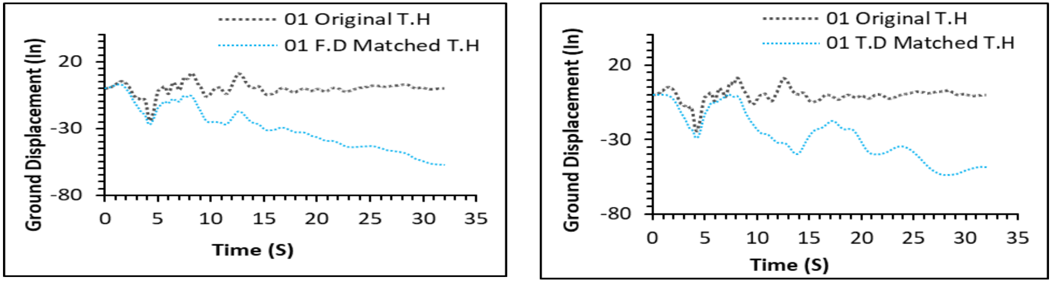
a) FDSM Aceleration Spectra for G.M-01 b) TDSM Aceleration Spectra for G.M-01



c) F.D Acceleration T.H Matching for G.M-01 d) T.D Acceleration T.H Matching for G.M-01

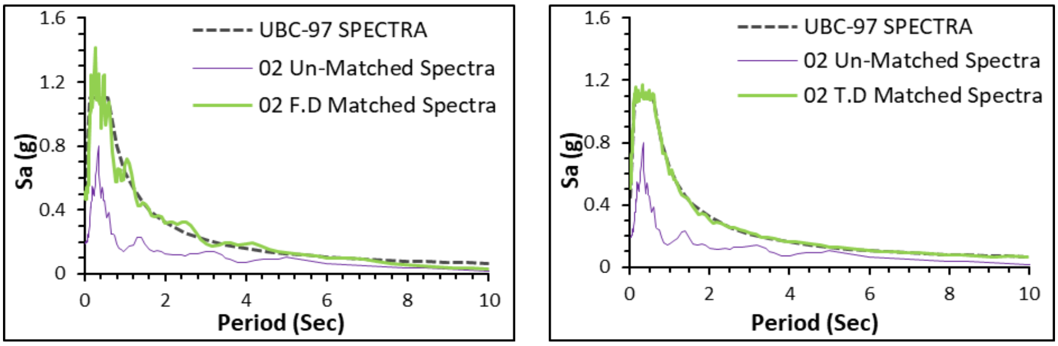


e) F.D Velocity T.H Matching for G.M-01 f) T.D Velocity T.H Matching for G.M-01

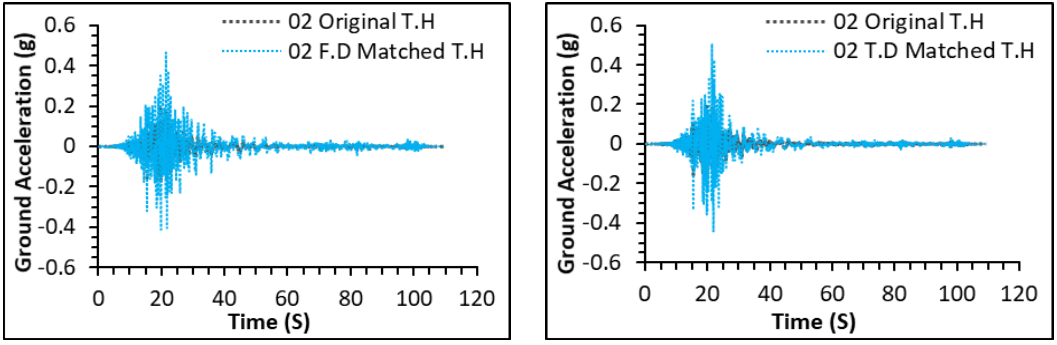


g) F.D Displacement T.H Matching for G.M-01 h) T.D Displacement T.H Matching for G.M-01

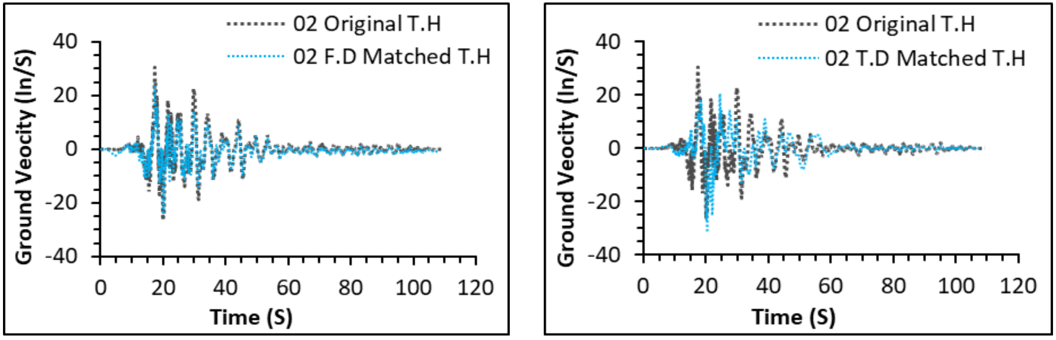
Figure B.1: Spectral matching plots on varied parameters for G.M-01



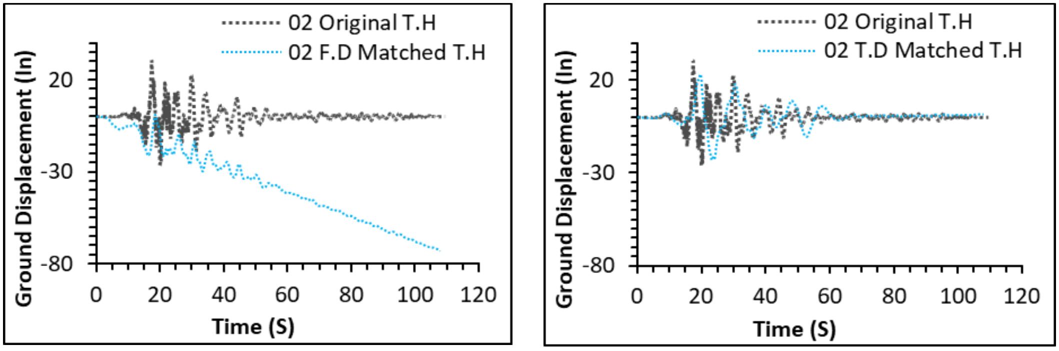
a) FDSM Aceleration Spectra for G.M-02 b) TDSM Aceleration Spectra for G.M-02



c) F.D Acceleration T.H Matching for G.M-02 d) T.D Acceleration T.H Matching for G.M-02

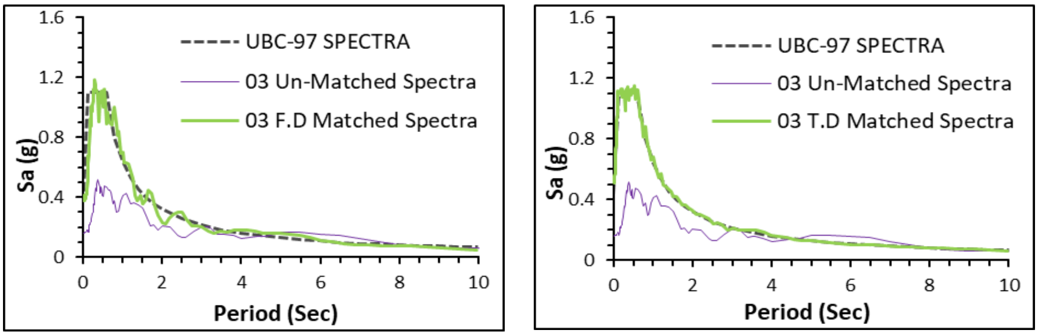


e) F.D Velocity T.H Matching for G.M-02 f) T.D Velocity T.H Matching for G.M-02

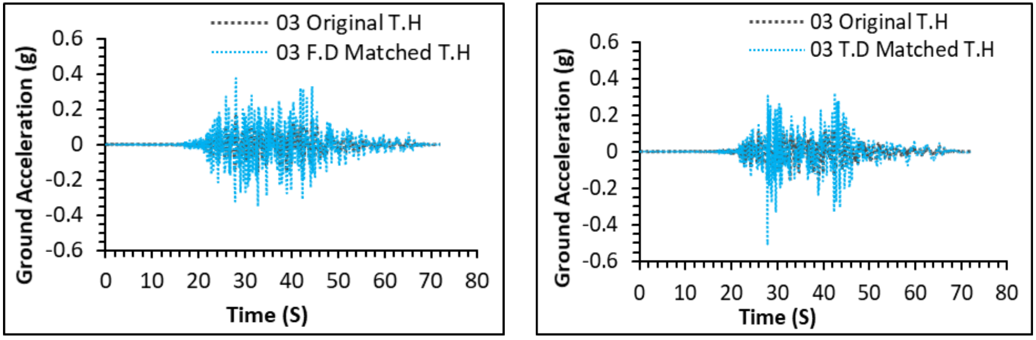


g) F.D Displacement T.H Matching for G.M-02 h) T.D Displacement T.H Matching for G.M-02

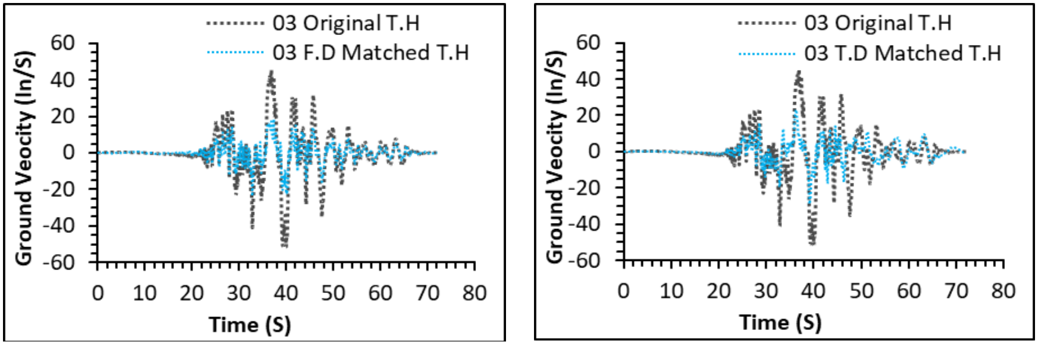
Figure B.2: Spectral matching plots on varied parameters for G.M-02



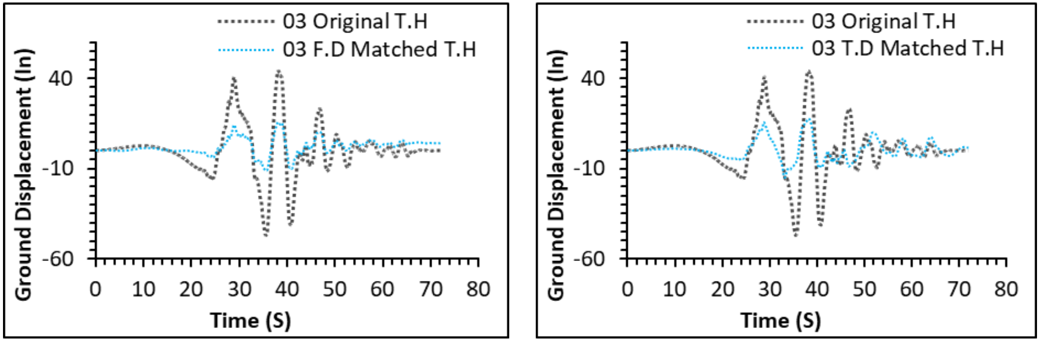
a) FDSM Aceleration Spectra for G.M-03 b) TDSM Aceleration Spectra for G.M-03



c) F.D Acceleration T.H Matching for G.M-03 d) T.D Acceleration T.H Matching for G.M-03

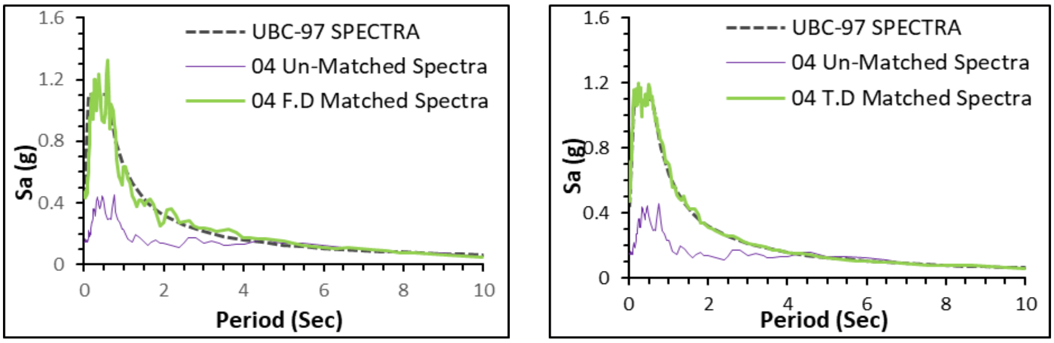


e) F.D Velocity T.H Matching for G.M-03 f) T.D Velocity T.H Matching for G.M-03

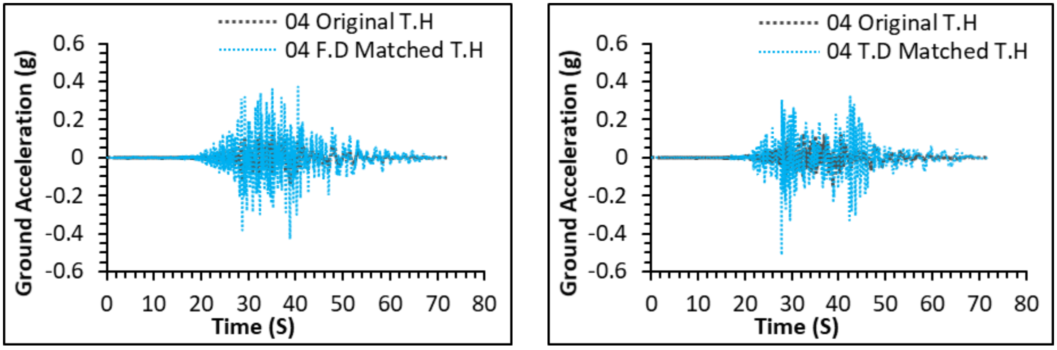


g) F.D Displacement T.H Matching for G.M-03 h) T.D Displacement T.H Matching for G.M-03

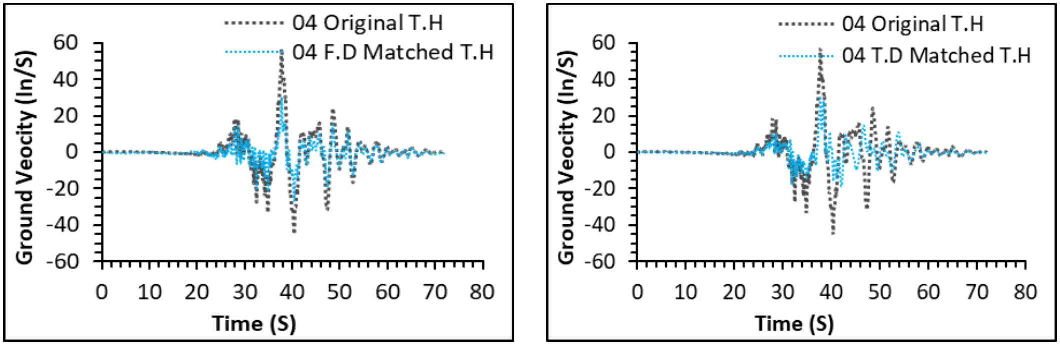
FIGURE B.3: Spectral matching plots on varied parameters for G.M-03



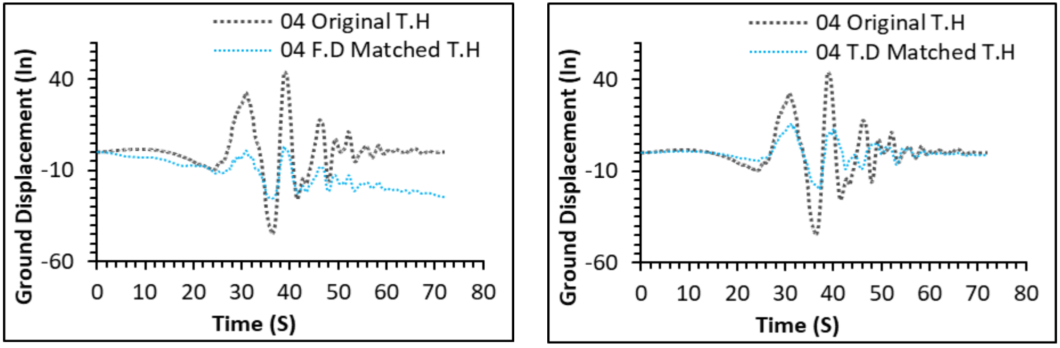
a) FDSM Aceleration Spectra for G.M-04 b) TDSM Aceleration Spectra for G.M-04



c) F.D Acceleration T.H Matching for G.M-04 d) T.D Acceleration T.H Matching for G.M-04

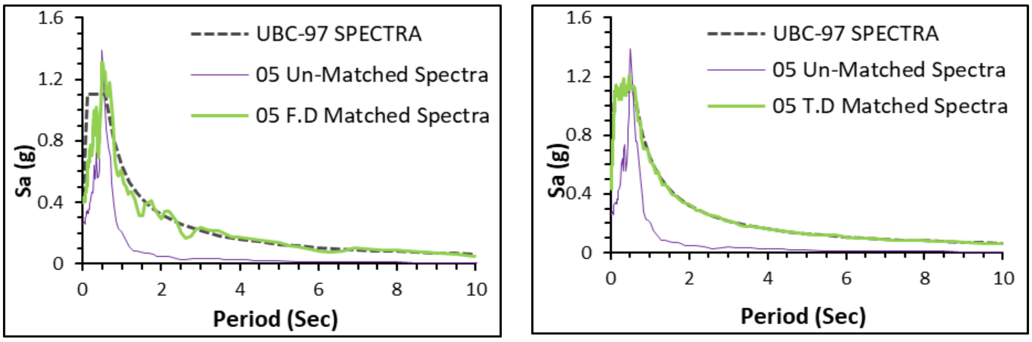


e) F.D Velocity T.H Matching for G.M-04 f) T.D Velocity T.H Matching for G.M-04

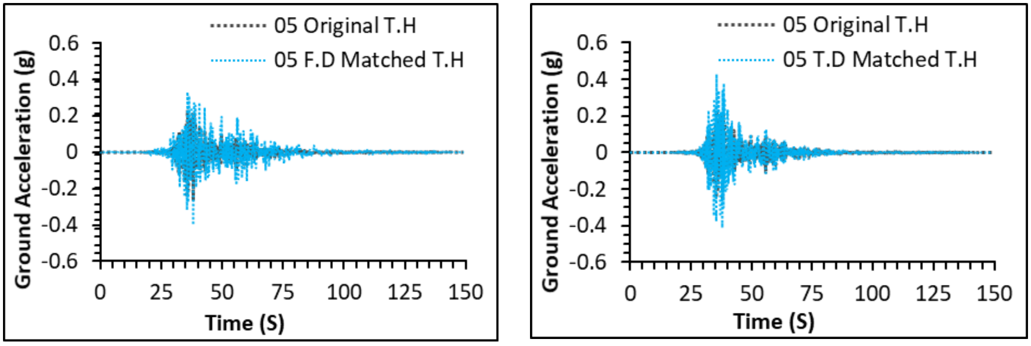


g) F.D Displacement T.H Matching for G.M-04 h) T.D Displacement T.H Matching for G.M-04

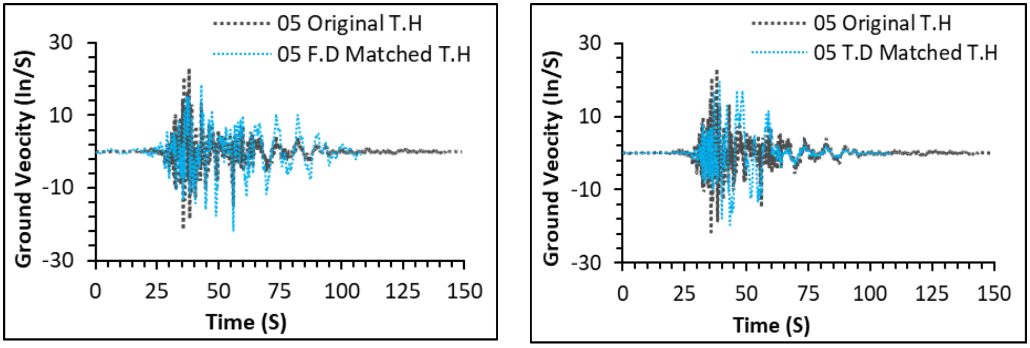
Figure B.4: Spectral matching plots on varied parameters for G.M-04



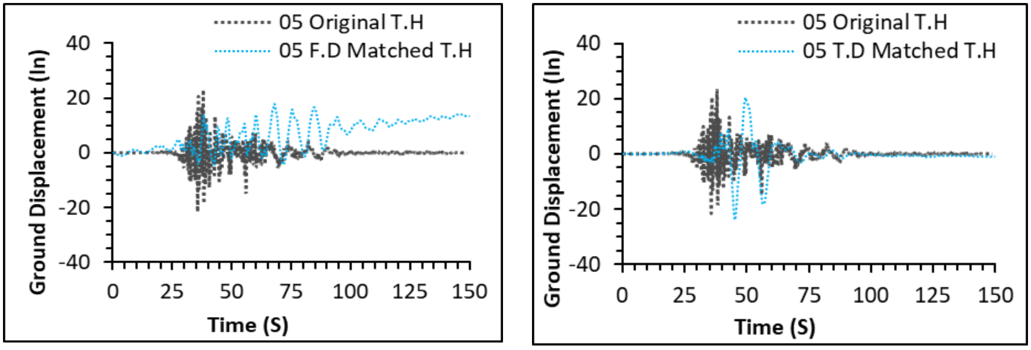
a) FDSM Aceleration Spectra for G.M-05 b) TDSM Aceleration Spectra for G.M-05



c) F.D Acceleration T.H Matching for G.M-05 d) T.D Acceleration T.H Matching for G.M-05

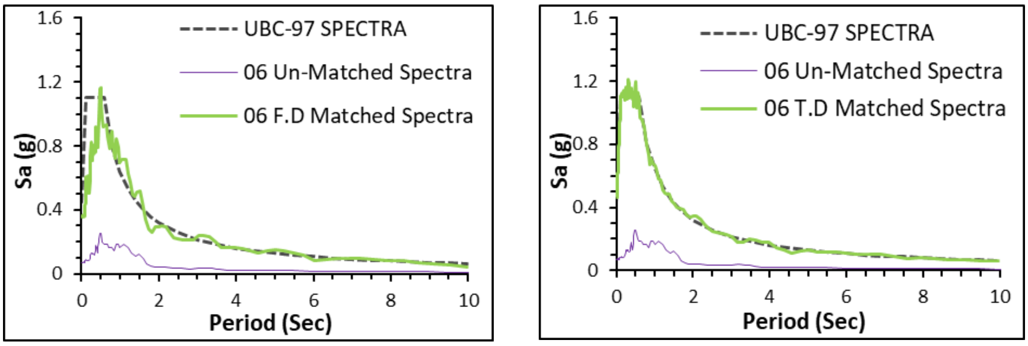


e) F.D Velocity T.H Matching for G.M-05 f) T.D Velocity T.H Matching for G.M-05

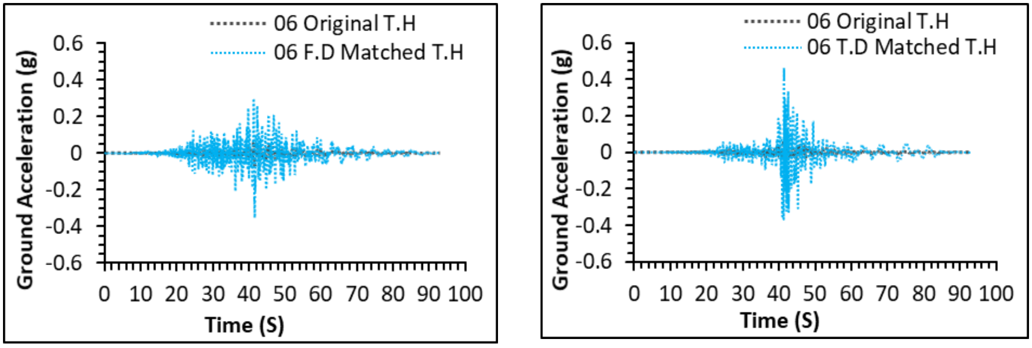


g) F.D Displacement T.H Matching for G.M-05 h) T.D Displacement T.H Matching for G.M-05

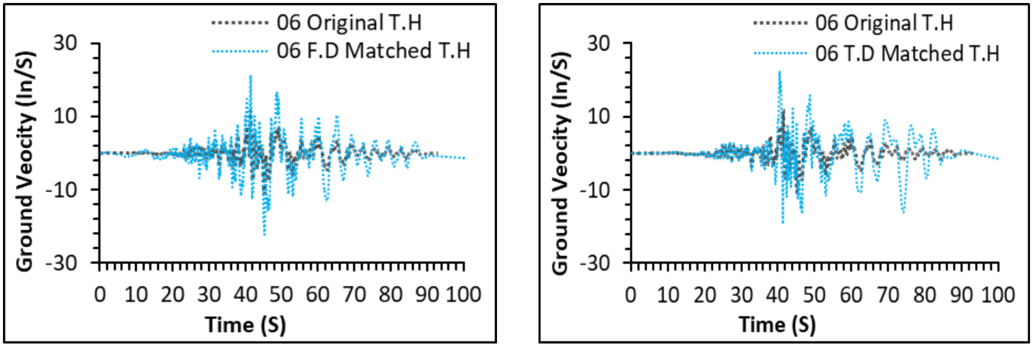
Figure B.5: Spectral matching plots on varied parameters for G.M-05



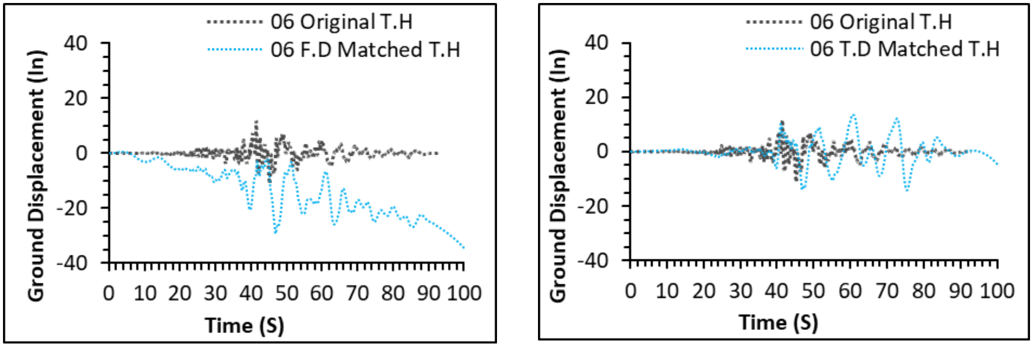
a) FDSM Aceleration Spectra for G.M-06 b) TDSM Aceleration Spectra for G.M-06



c) F.D Acceleration T.H Matching for G.M-06 d) T.D Acceleration T.H Matching for G.M-06

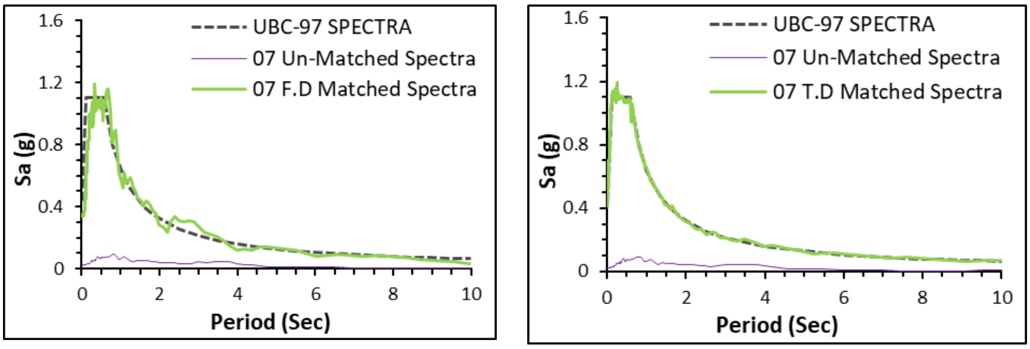


e) F.D Velocity T.H Matching for G.M-06 f) T.D Velocity T.H Matching for G.M-06

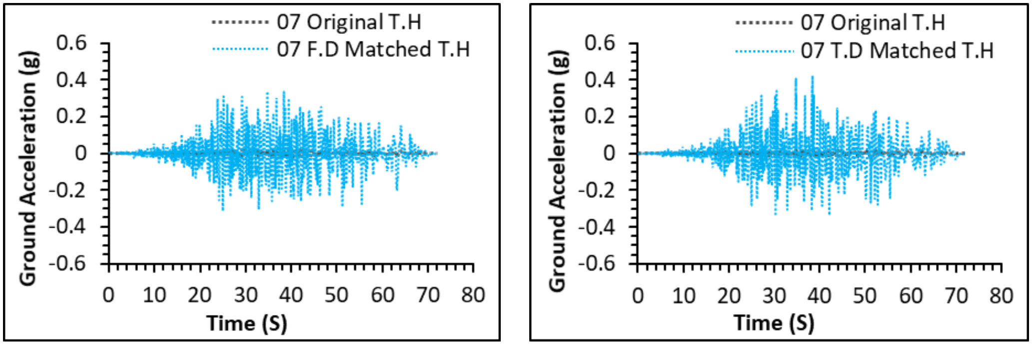


g) F.D Displacement T.H Matching for G.M-06 h) T.D Displacement T.H Matching for G.M-06

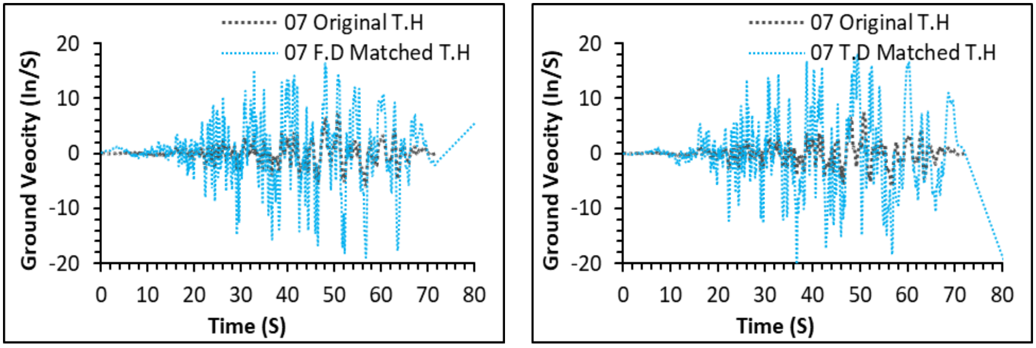
Figure B.6: Spectral matching plots on varied parameters for G.M-06



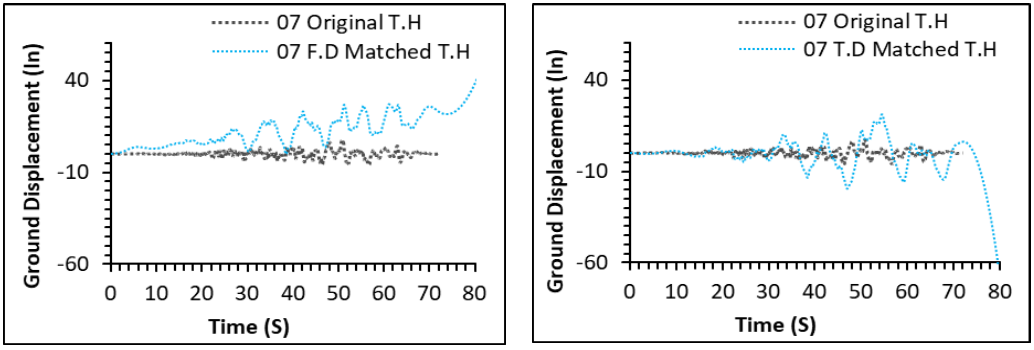
a) FDSM Aceleration Spectra for G.M-07 b) TDSM Aceleration Spectra for G.M-07



c) F.D Acceleration T.H Matching for G.M-07 d) T.D Acceleration T.H Matching for G.M-07

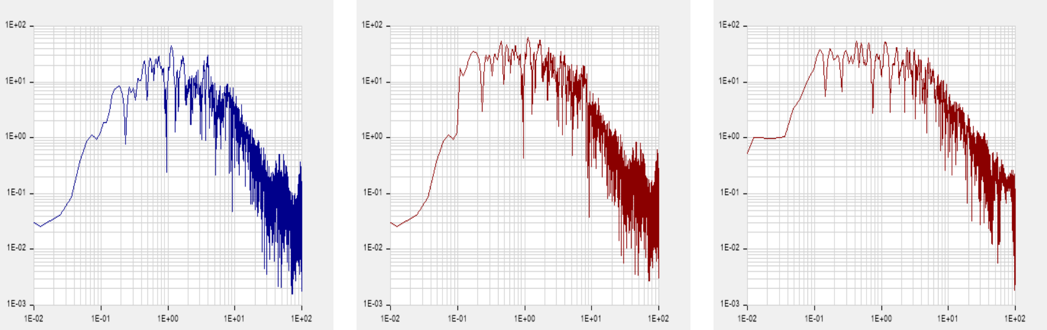


e) F.D Velocity T.H Matching for G.M-07 f) T.D Velocity T.H Matching for G.M-07

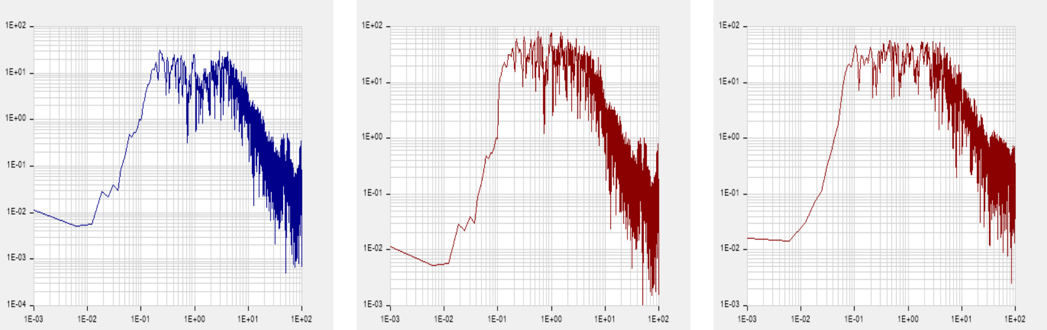


g) F.D Displacement T.H Matching for G.M-07 h) T.D Displacement T.H Matching for G.M-07

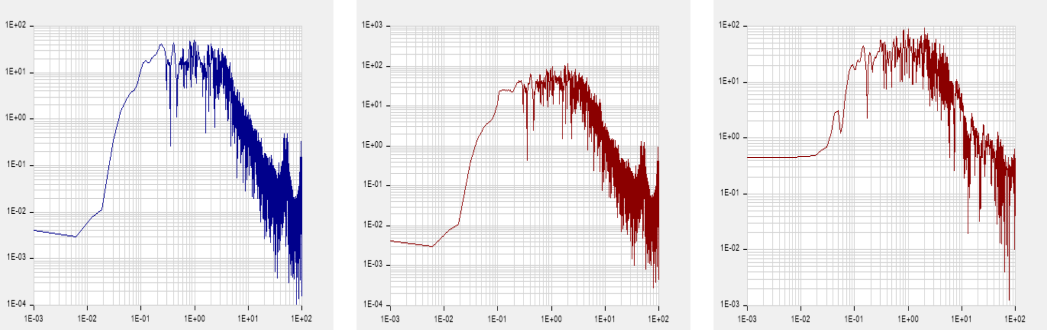
Figure B.7: Spectral matching plots on varied parameters for G.M-07



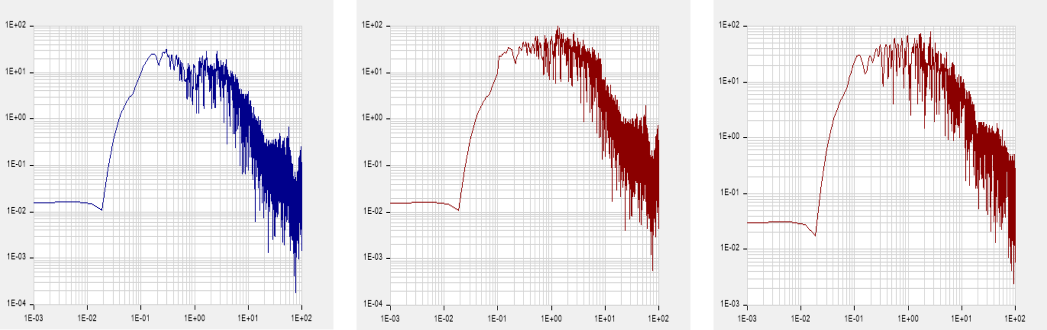
a) Original G.M-01 b) Matched F.D-01 c) Matched T.D-01



d) Original G.M-02 e) Matched F.D-02 f) Matched T.D-02

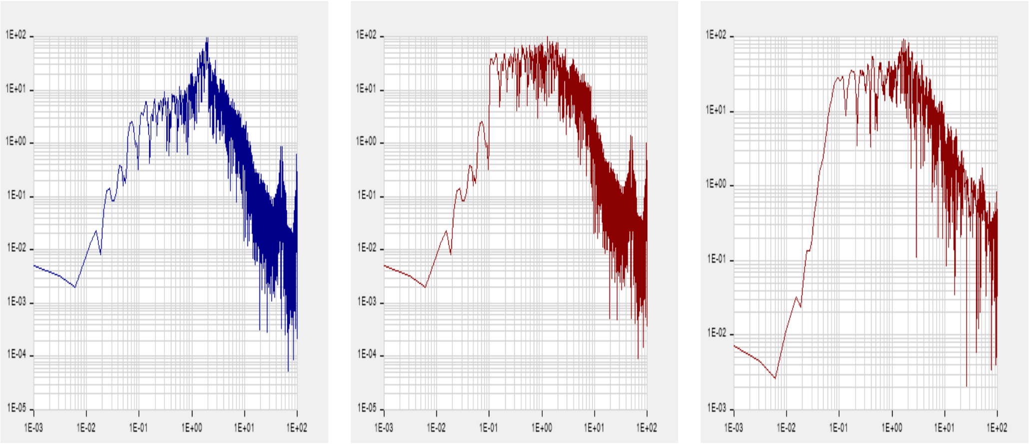


g) Original G.M-03 h) Matched F.D-03 i) Matched T.D-03

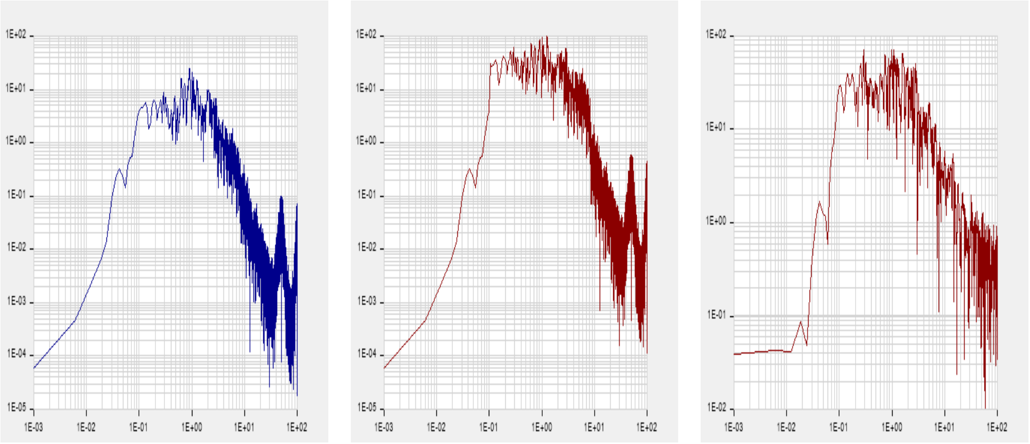


j) Original G.M-04 k) Matched F.D-04 l) Matched T.D-04

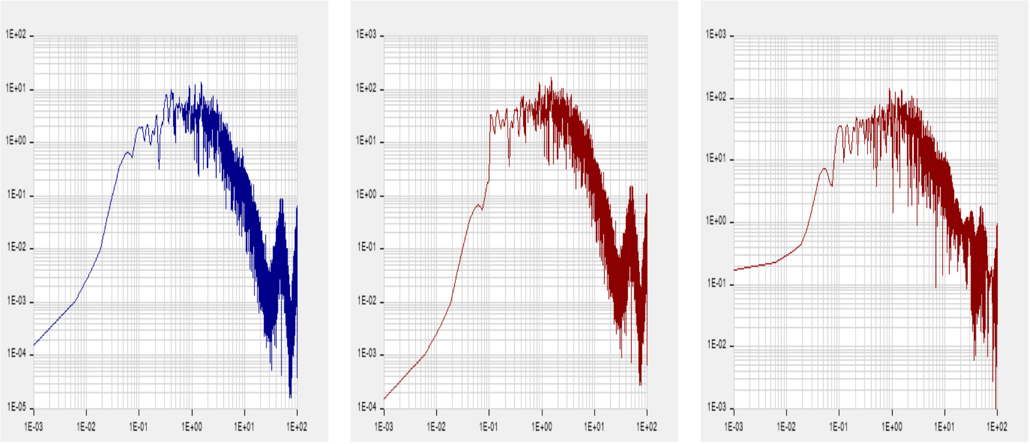
Figure B.8: Frequency content of original and spectrally matched records for G.M-1 to G,M-4 (Amplitude vs Frequency Content)



m) Original G.M-05 n) Matched F.D-05 o) Matched T.D-05



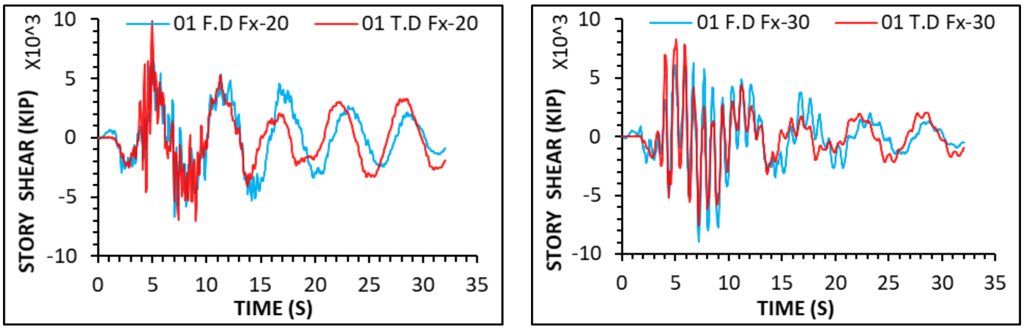
p) Original G.M-06 q) Matched F.D-06 r) Matched T.D-06



s) Original G.M-07 t) Matched F.D-07 u) Matched T.D-07

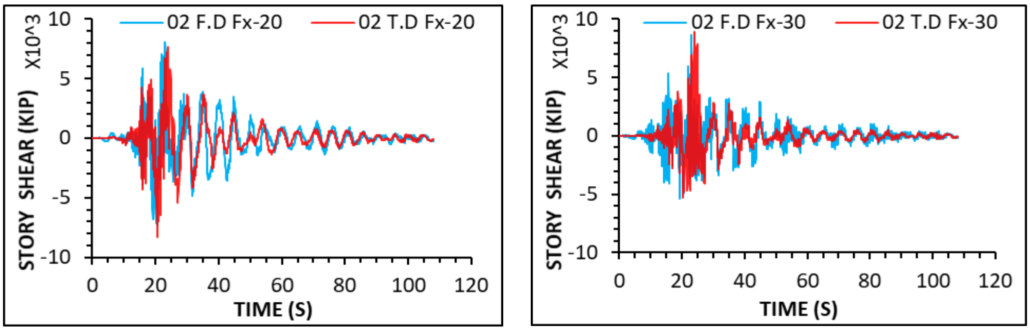
Figure B.9: Frequency content of original and spectrally matched records for G.M-5 to G,M-7 (Amplitude vs Frequency Content)

Annexure C



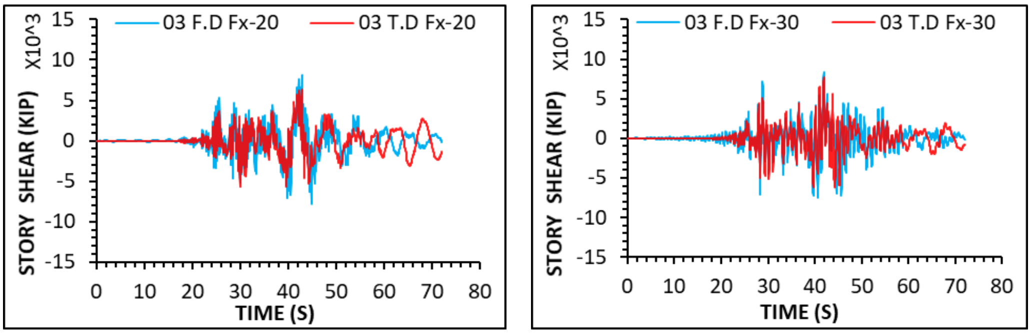
a) Story Shear vs T.H at Story-20 for G.M-01

b) Story Shear vs T.H at Story-30 for G.M-01



c) Story Shear vs T.H at Story-20 for G.M-02

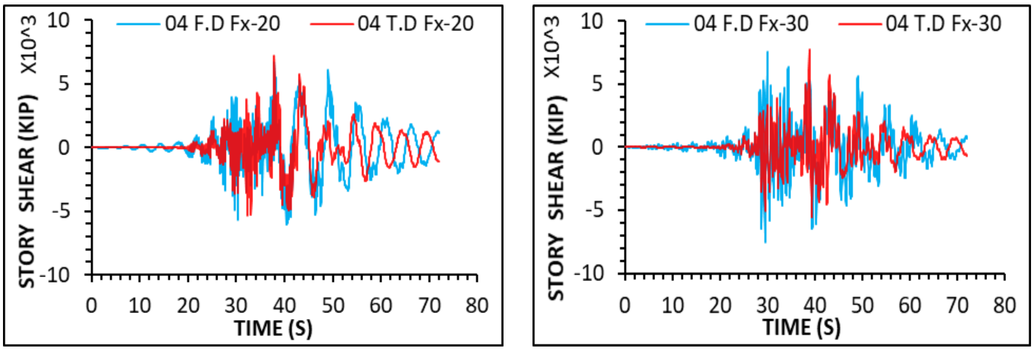
d) Story Shear vs T.H at Story-30 for G.M-02



e) Story Shear vs T.H at Story-20 for G.M-03

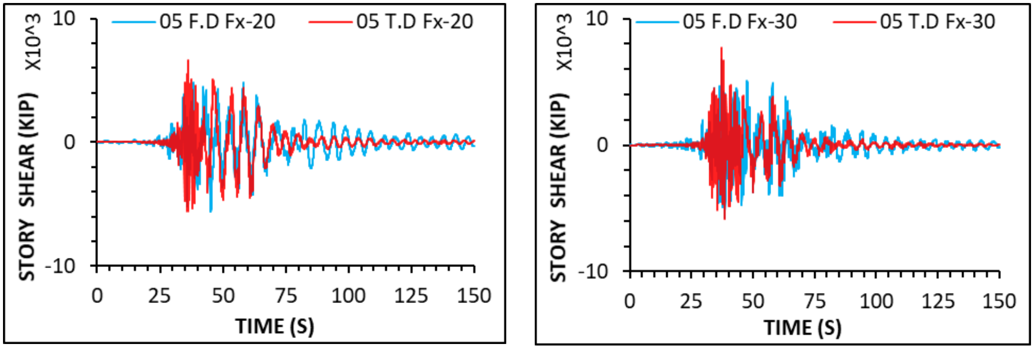
f) Story Shear vs T.H at Story-30 for G.M-03

Figure C.1: Story Shear plots against time history for Level-20 Level-30



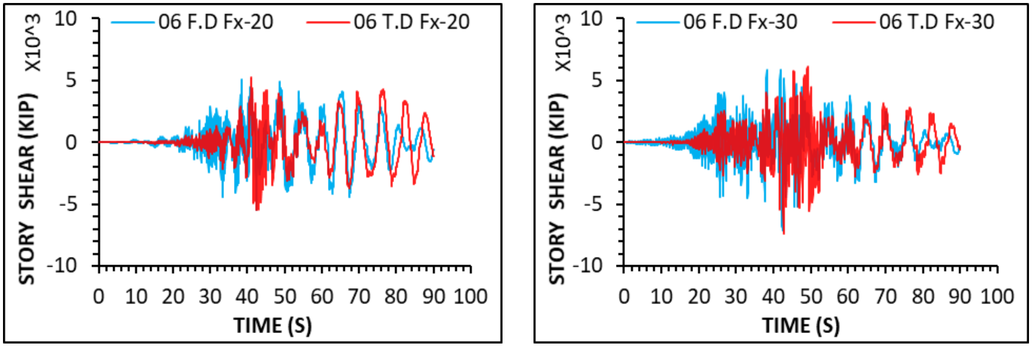
g) Story Shear vs T.H at Story-00 for G.M-04

h) Story Shear vs T.H at Story-10



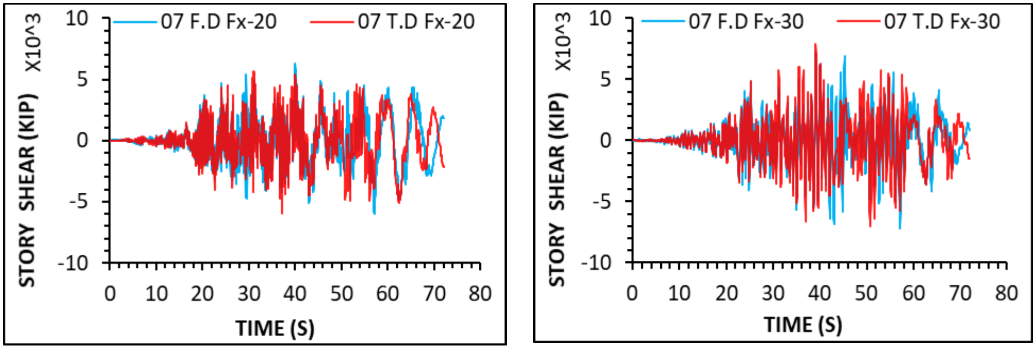
i) Story Shear vs T.H at Story-20 for G.M-05

j) Story Shear vs T.H at Story-30 for G.M-05



k) Story Shear vs T.H at Story-20 for G.M-06

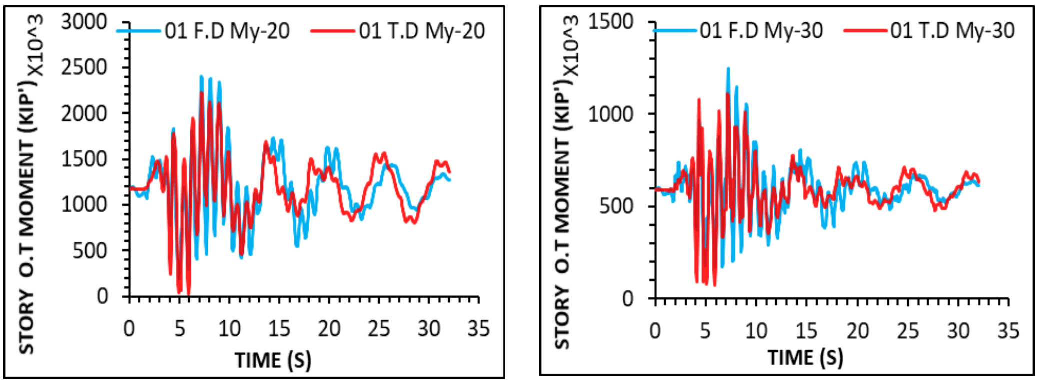
l) Story Shear vs T.H at Story-30 for G.M-06



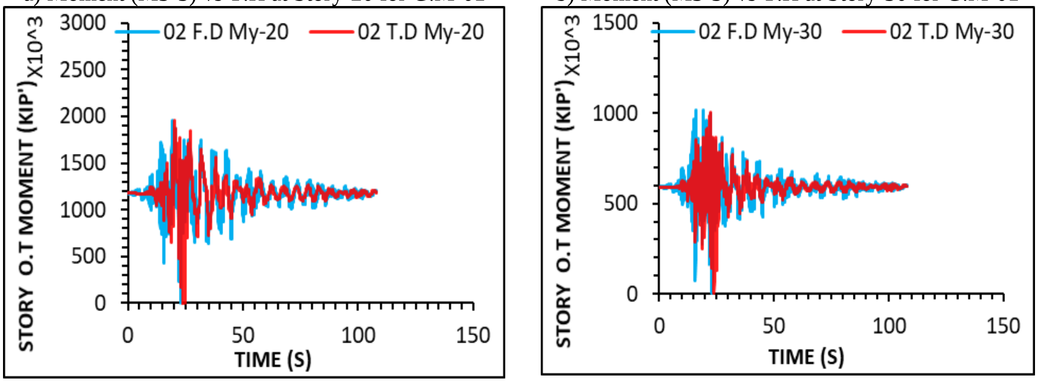
m) Story Shear vs T.H at Story-20 for G.M-07

n) Story Shear vs T.H at Story-30 for G.M-07

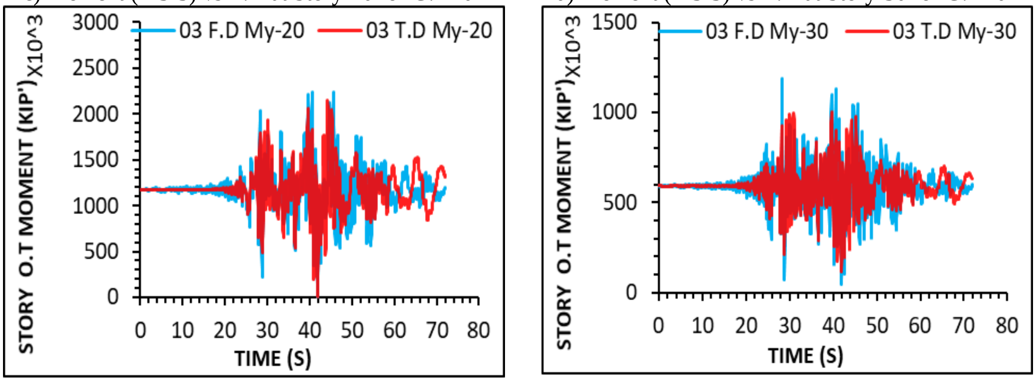
FIGURE C.2: Story Shear plots against time history for Level-20 Level-30



a) Moment (M3-3) vs T.H at Story-20 for G.M-01 b) Moment (M3-3) vs T.H at Story-30 for G.M-01

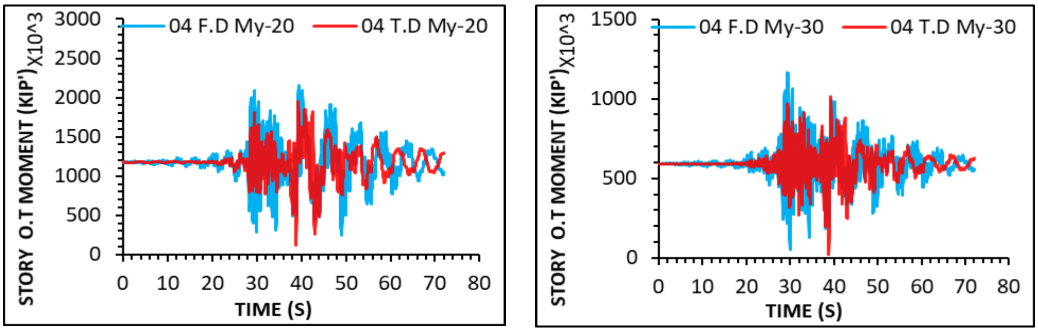


c) Moment (M3-3) vs T.H at Story-20 for G.M-02 d) Moment (M3-3) vs T.H at Story-30 for G.M-02

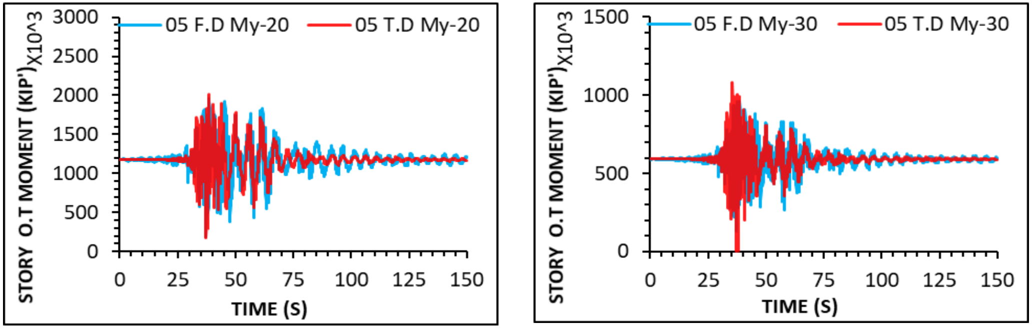


e) Moment (M3-3) vs T.H at Story-20 for G.M-03 f) Moment (M3-3) vs T.H at Story-30 for G.M-03

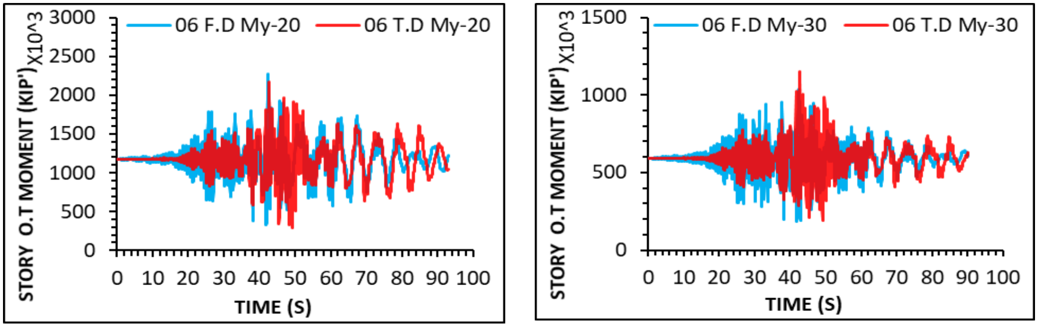
FIGURE C.3: Moment (M3-3) plots against T.H for Level-20 Level-30



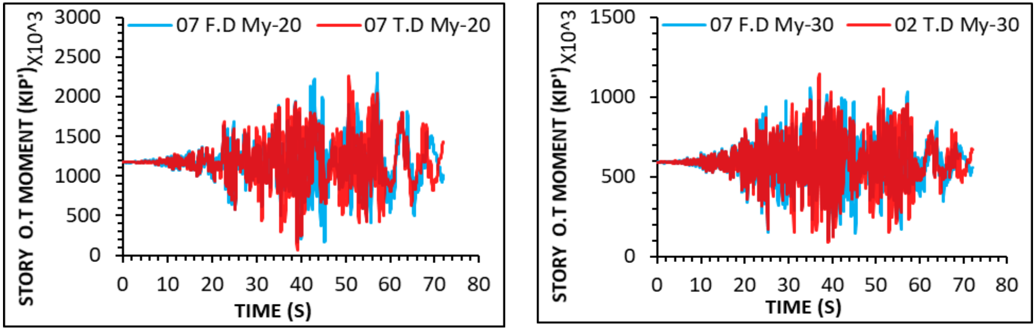
g) Moment (M3-3) vs T.H at Story-00 for G.M-04 h) Moment (M3-3) vs T.H at Story-10 for G.M-04



i) Moment (M3-3) vs T.H at Story-20 for G.M-05 j) Moment (M3-3) vs T.H at Story-30 for G.M-05

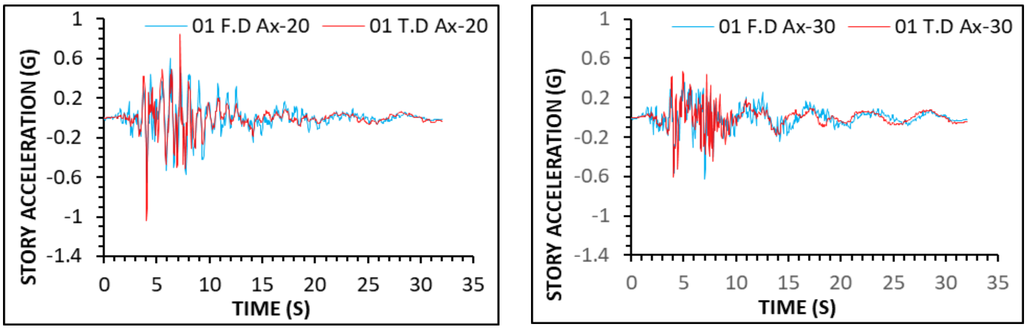


k) Moment (M3-3) vs T.H at Story-20 for G.M-06 l) Moment (M3-3) vs T.H at Story-30 for G.M-06

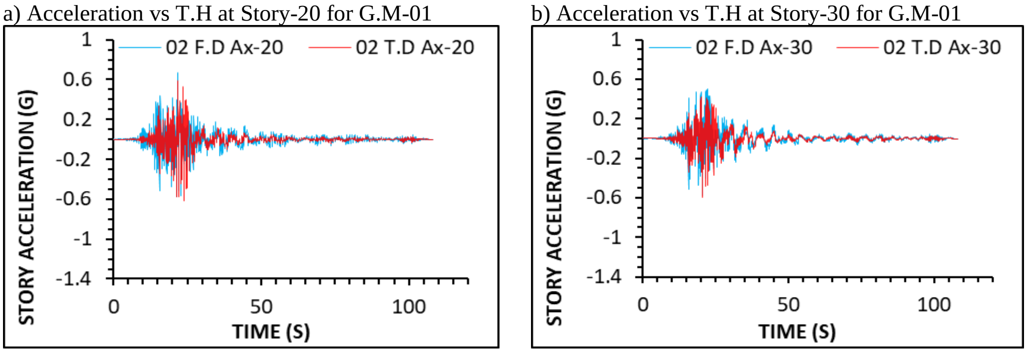


m) Moment (M3-3) vs T.H at Story-20 for G.M-07 n) Moment (M3-3) vs T.H at Story-30 for G.M-07

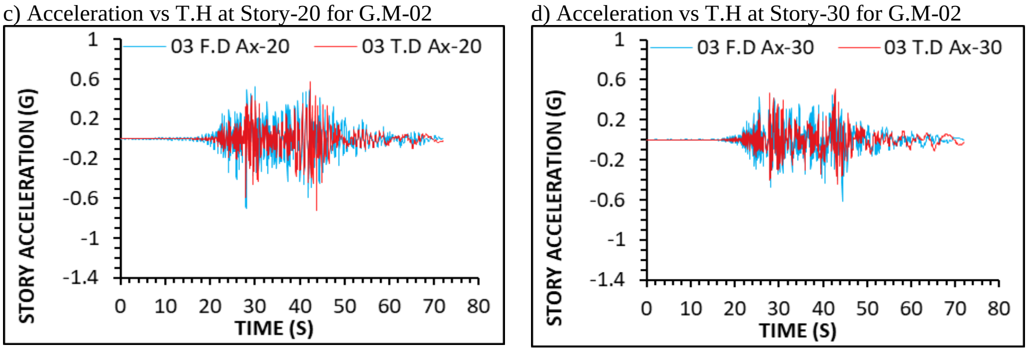
Figure C.4: Moment (M3-3) plots against T.H for Level-20 Level-30



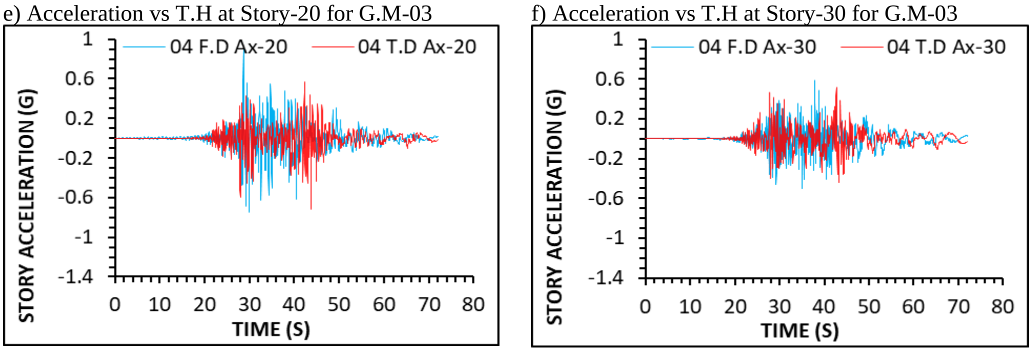
a) Acceleration vs T.H at Story-20 for G.M-01 b) Acceleration vs T.H at Story-30 for G.M-01



c) Acceleration vs T.H at Story-20 for G.M-02 d) Acceleration vs T.H at Story-30 for G.M-02

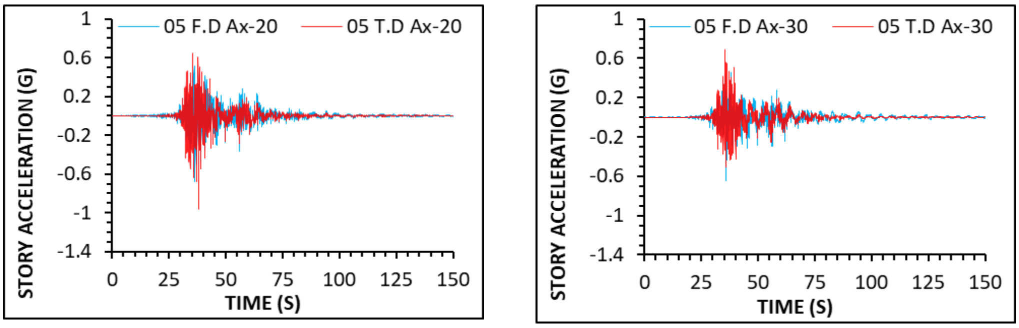


e) Acceleration vs T.H at Story-20 for G.M-03 f) Acceleration vs T.H at Story-30 for G.M-03

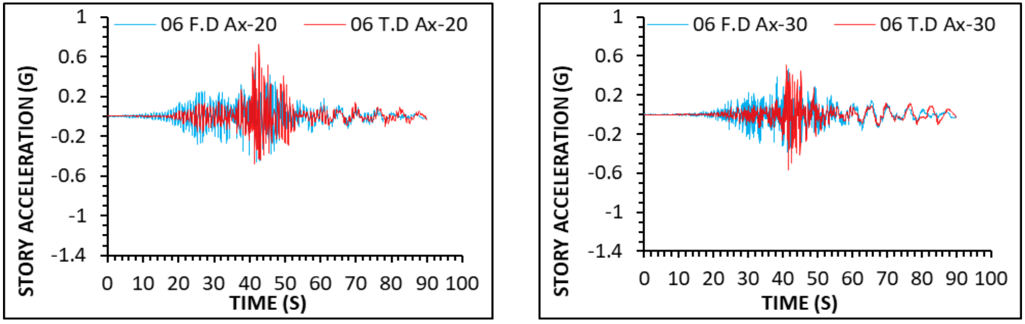


g) Acceleration vs T.H at Story-00 for G.M-04 h) Acceleration vs T.H at Story-10 for G.M-04

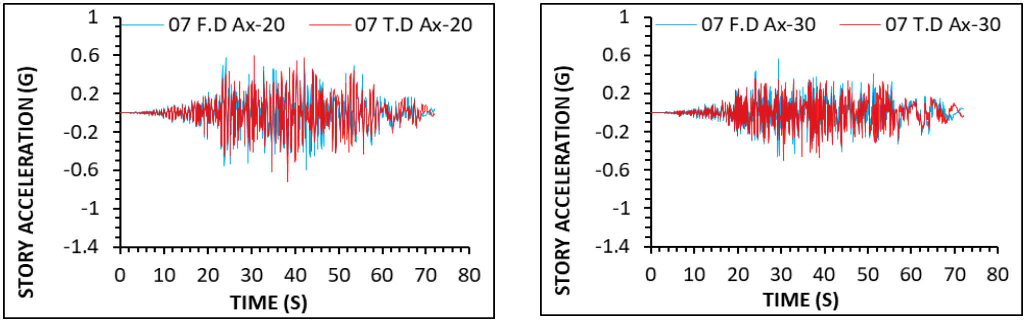
Figure C.5: Acceleration vs time history plots for Level-20, Level-30 Level-40



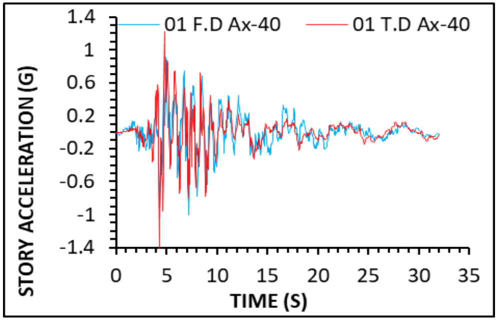
i) Acceleration vs T.H at Story-20 for G.M-05 j) Acceleration vs T.H at Story-30 for G.M-05



k) Acceleration vs T.H at Story-20 for G.M-06 l) Acceleration vs T.H at Story-30 for G.M-06

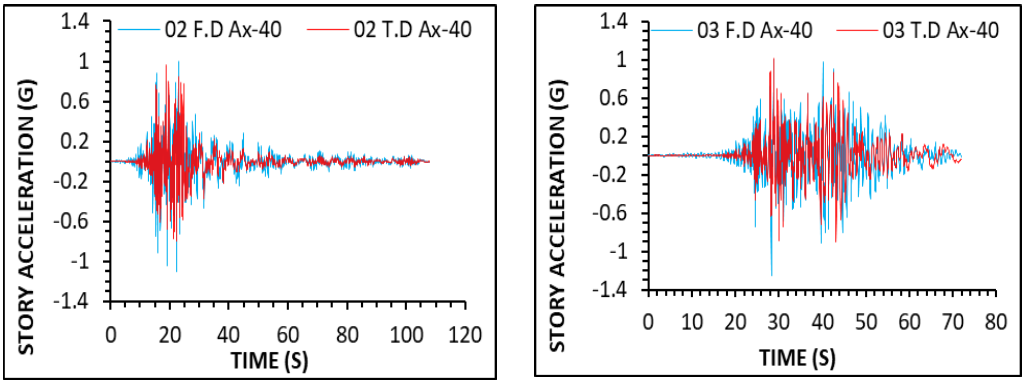


m) Acceleration vs T.H at Story-20 for G.M-07 n) Acceleration vs T.H at Story-30 for G.M-07

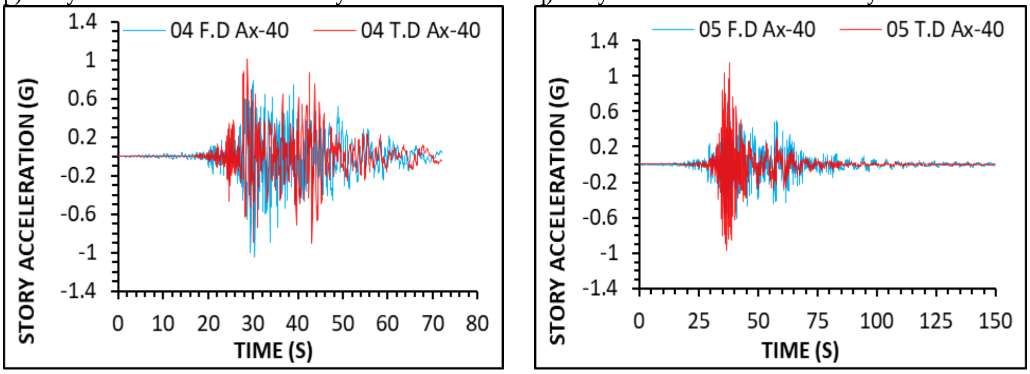


o) Story Acceleration vs T.H at Story-40 for G.M-01

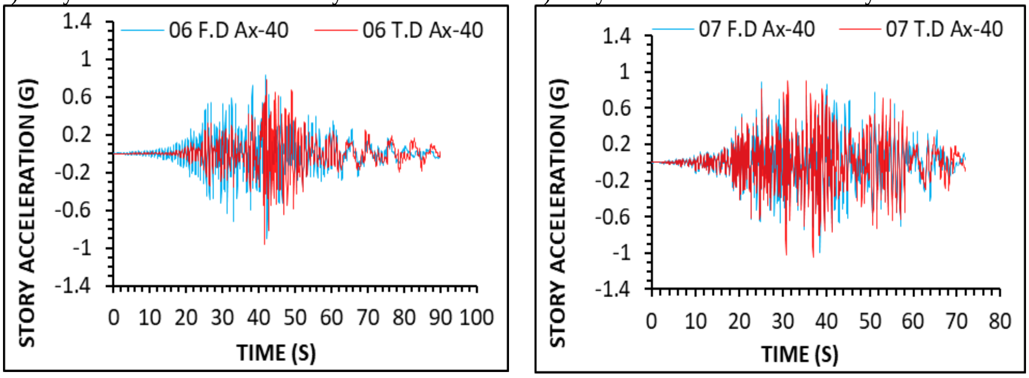
FIGURE C.6: Acceleration vs time history plots for Level-20, Level-30 Level-40



p) Story Acceleration vs T.H at Story-40 for G.M-02 q) Story Acceleration vs T.H at Story-40 for G.M-03

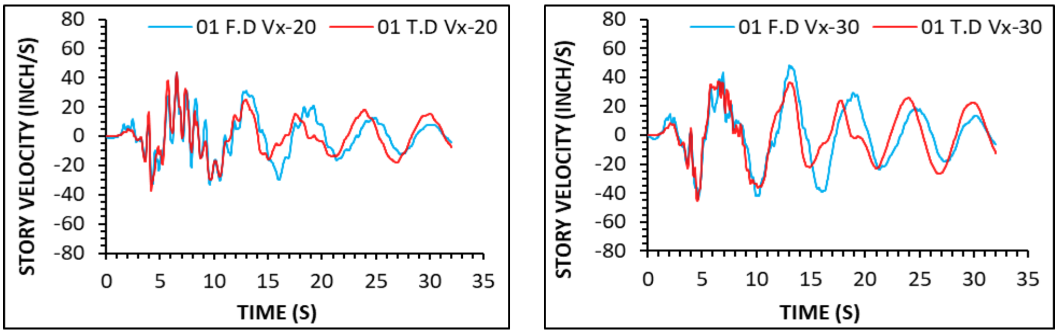


r) Story Acceleration vs T.H at Story-40 for G.M-04 s) Story Acceleration vs T.H at Story-40 for G.M-05

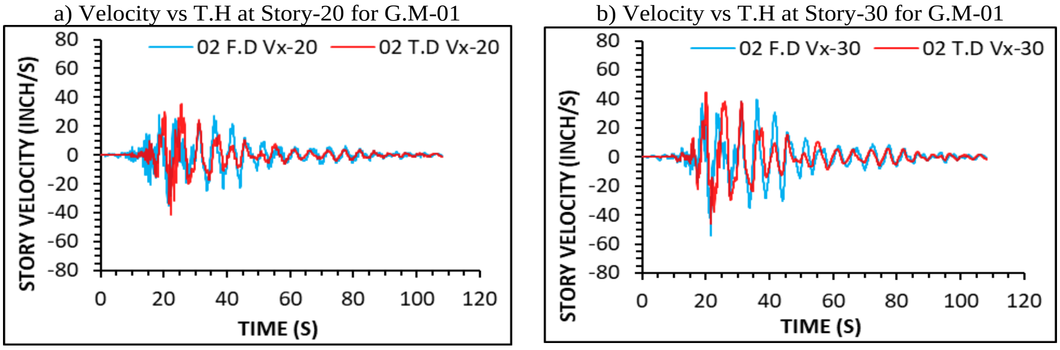


t) Story Acceleration vs T.H at Story-40 for G.M-06 u) Story Acceleration vs T.H at Story-40 for G.M-07

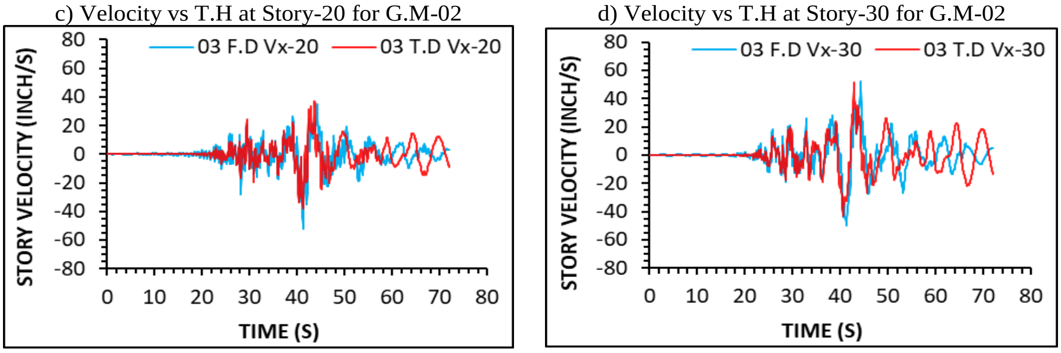
Figure C.7: Acceleration vs time history plots for Level-20, Level-30 Level-40



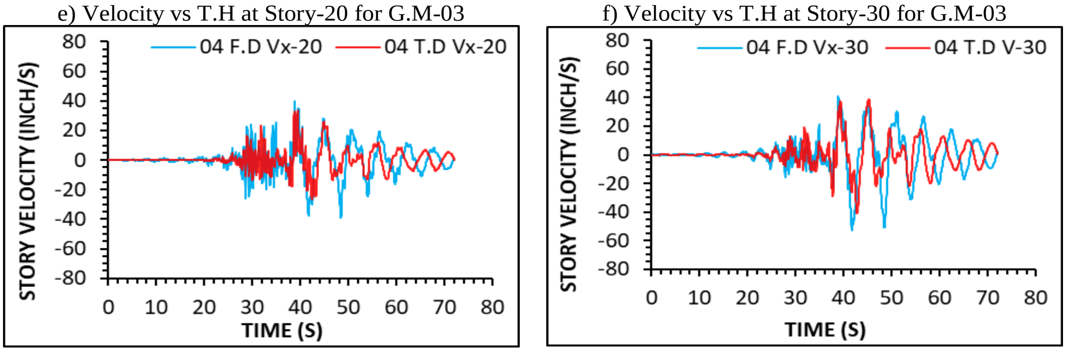
a) Velocity vs T.H at Story-20 for G.M-01 b) Velocity vs T.H at Story-30 for G.M-01



c) Velocity vs T.H at Story-20 for G.M-02 d) Velocity vs T.H at Story-30 for G.M-02

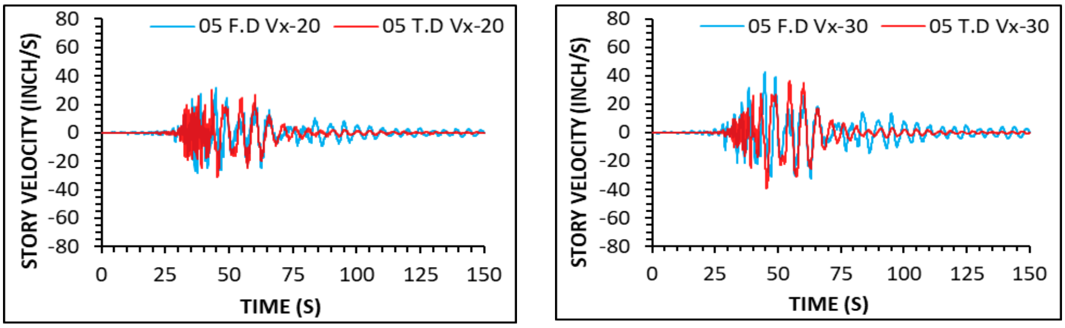


e) Velocity vs T.H at Story-20 for G.M-03 f) Velocity vs T.H at Story-30 for G.M-03

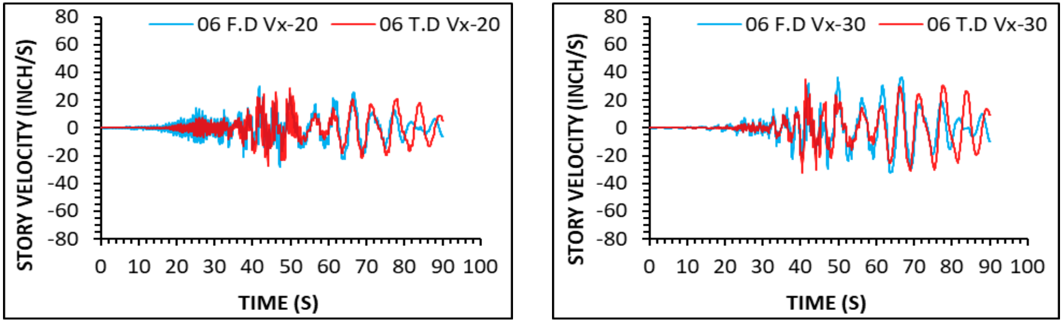


g) Velocity vs T.H at Story-00 for G.M-04 h) Velocity vs T.H at Story-10 for G.M-04

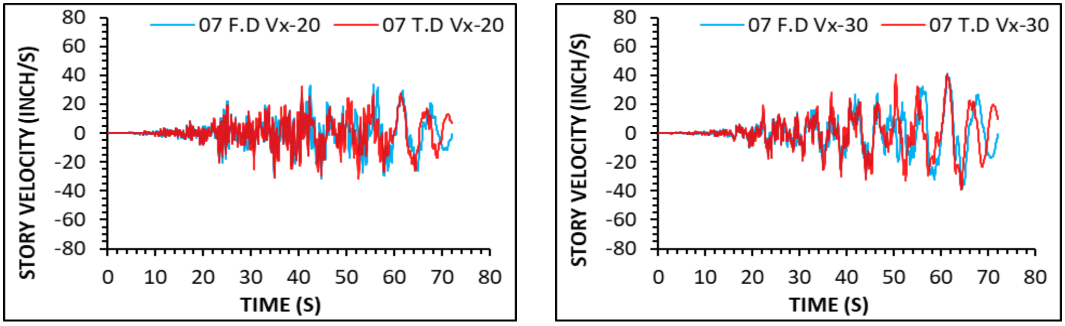
Figure C.8: Velocity plots against time history for Level-20, Level-30 Level-40



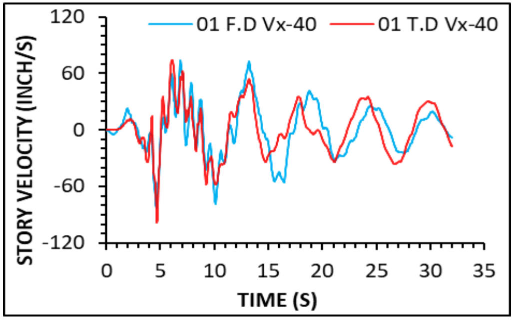
i) Velocity vs T.H at Story-20 for G.M-05 j) Velocity vs T.H at Story-30 for G.M-05



k) Velocity vs T.H at Story-20 for G.M-06 l) Velocity vs T.H at Story-30 for G.M-06

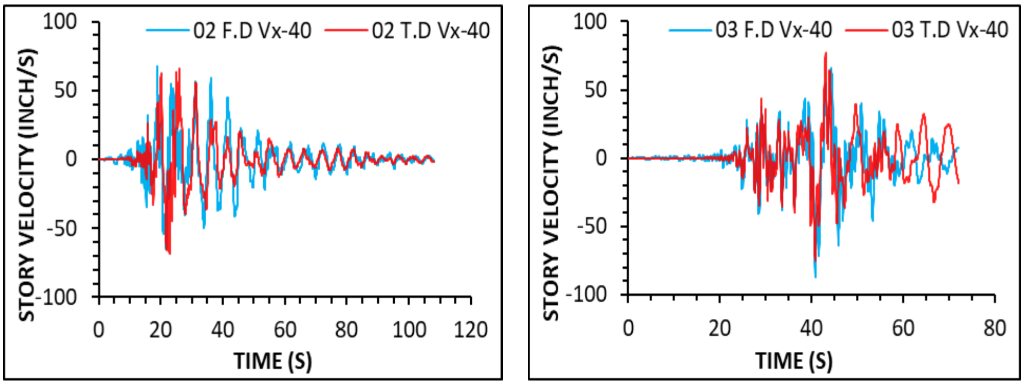


m) Velocity vs T.H at Story-20 for G.M-07 n) Velocity vs T.H at Story-30 for G.M-07

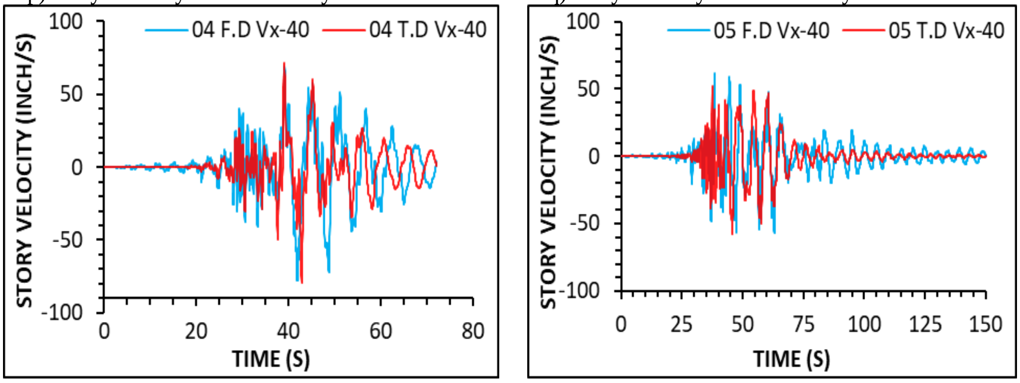


o) Story Velocity vs T.H at Story-40 for G.M-01

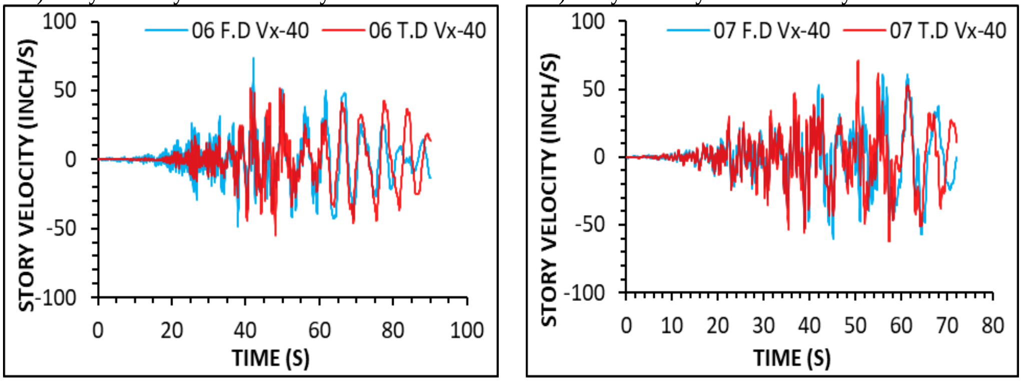
FIGURE C.9: Velocity plots against time history for Level-20, Level-30 Level-40



p) Story Velocity vs T.H at Story-40 for G.M-02 q) Story Velocity vs T.H at Story-40 for G.M-03

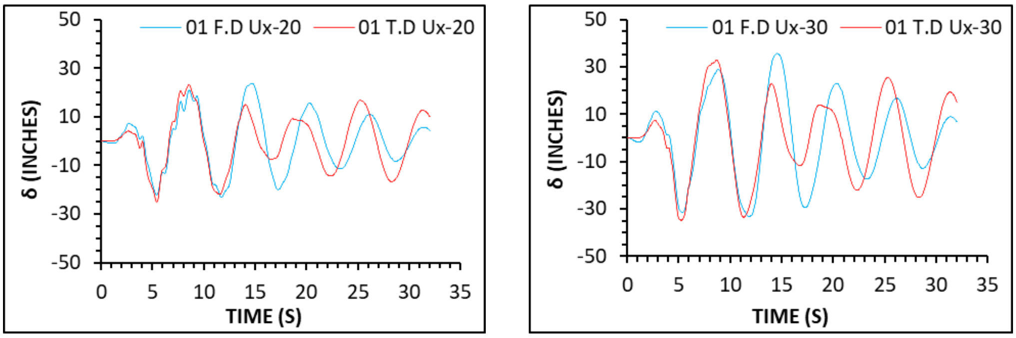


r) Story Velocity vs T.H at Story-40 for G.M-04 s) Story Velocity vs T.H at Story-40 for G.M-05

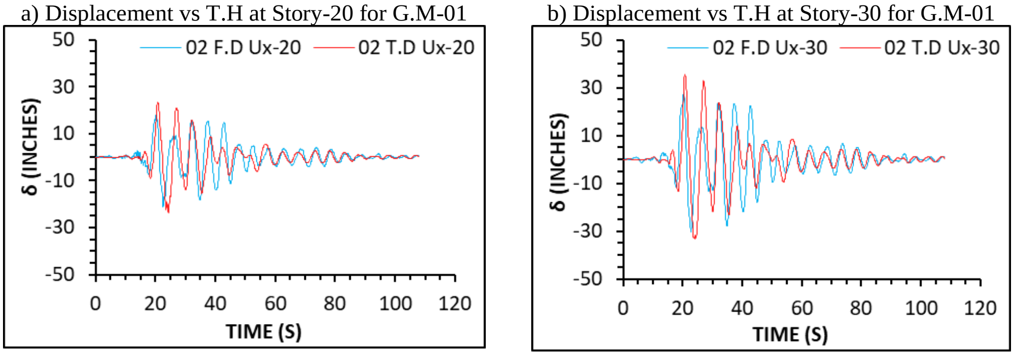


t) Story Velocity vs T.H at Story-40 for G.M-06 u) Story Velocity vs T.H at Story-40 for G.M-07

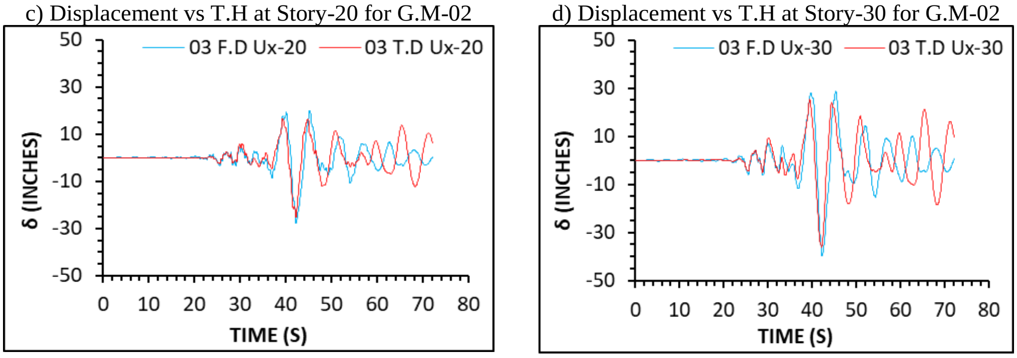
FIGURE C.10: Velocity plots against time history for Level-20, Level-30 Level-40



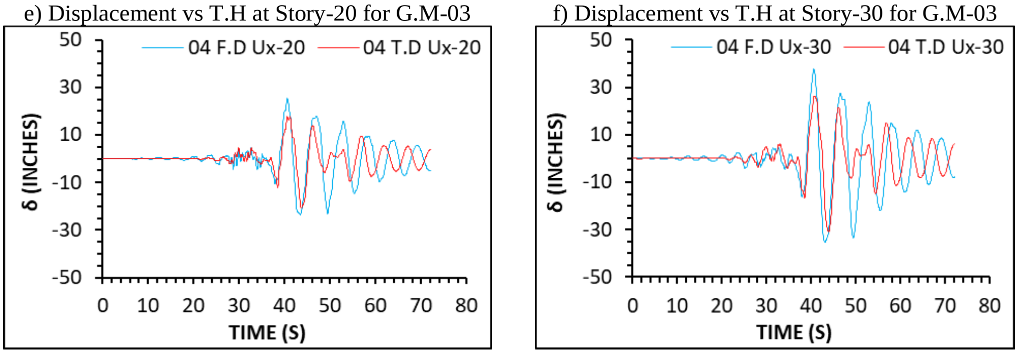
a) Displacement vs T.H at Story-20 for G.M-01 b) Displacement vs T.H at Story-30 for G.M-01



c) Displacement vs T.H at Story-20 for G.M-02 d) Displacement vs T.H at Story-30 for G.M-02

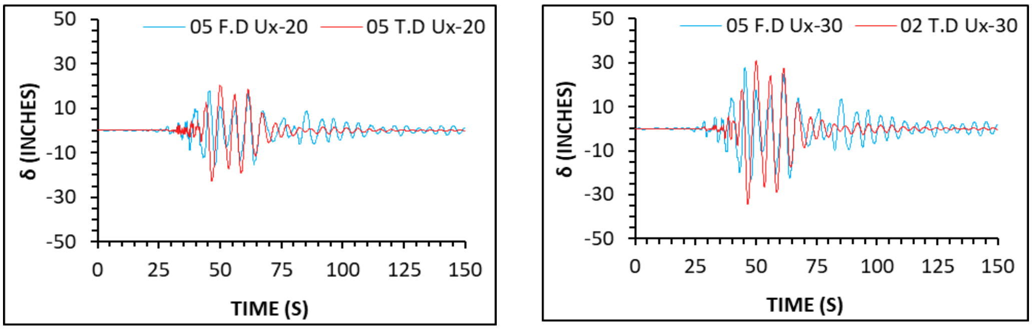


e) Displacement vs T.H at Story-20 for G.M-03 f) Displacement vs T.H at Story-30 for G.M-03

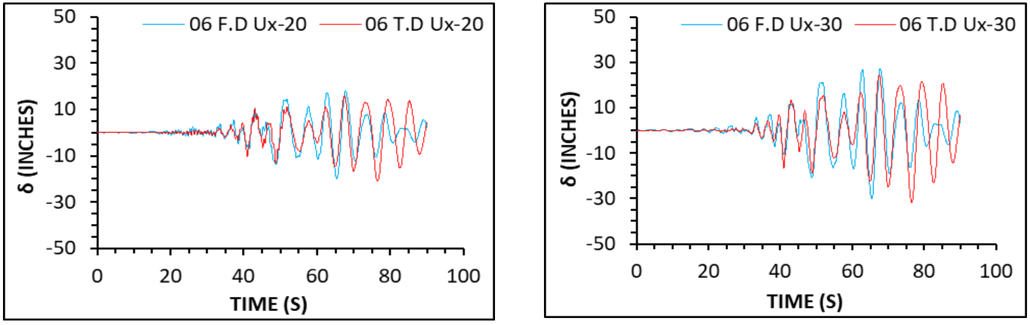


g) Displacement vs T.H at Story-00 for G.M-04 h) Displacement vs T.H at Story-10 for G.M-04

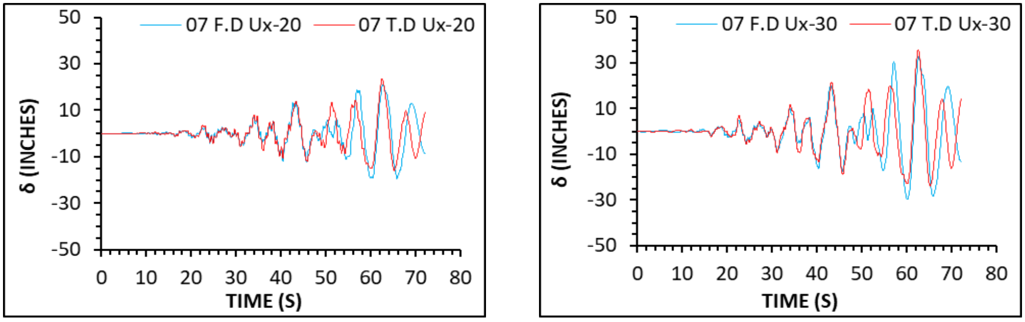
FIGURE C.11: Displacement time history plots for Level-20, Level-30 Level-40



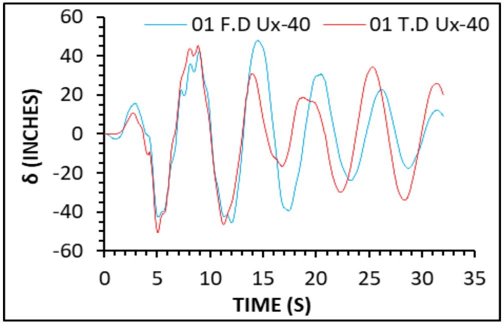
i) Displacement vs T.H at Story-20 for G.M-05 j) Displacement vs T.H at Story-30 for G.M-05



k) Displacement vs T.H at Story-20 for G.M-06 l) Displacement vs T.H at Story-30 for G.M-06

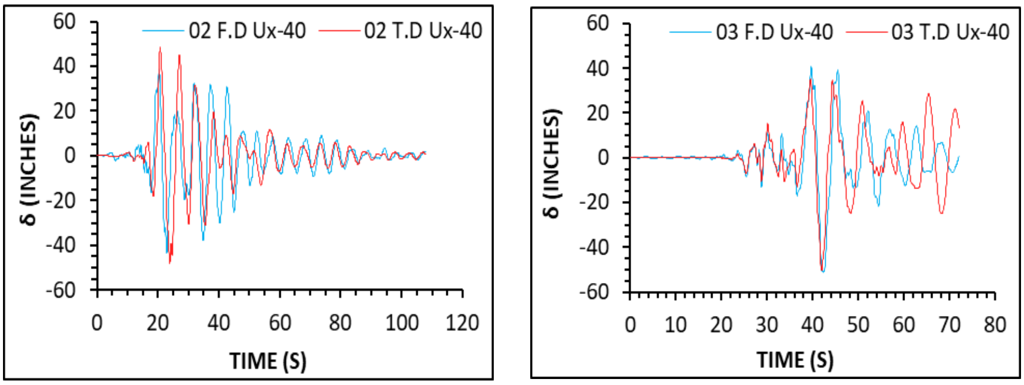


m) Displacement vs T.H at Story-20 for G.M-07 n) Displacement vs T.H at Story-30 for G.M-07

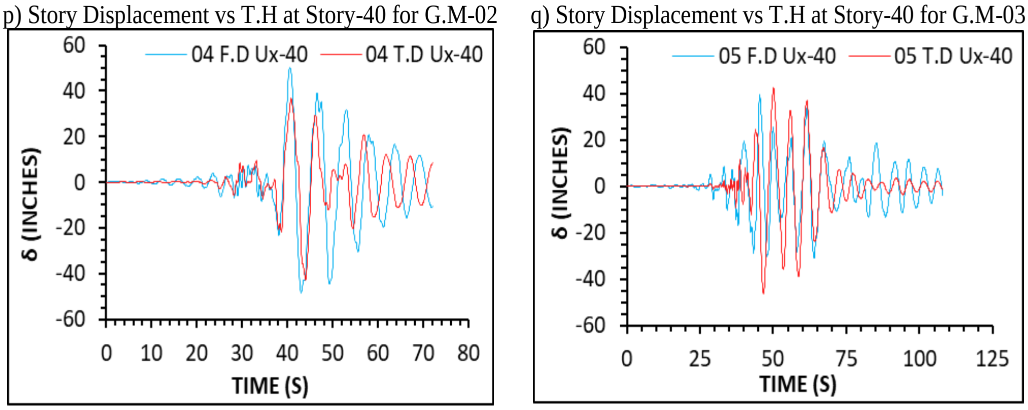


o) Story Displacement vs T.H at Story-40 for G.M-01

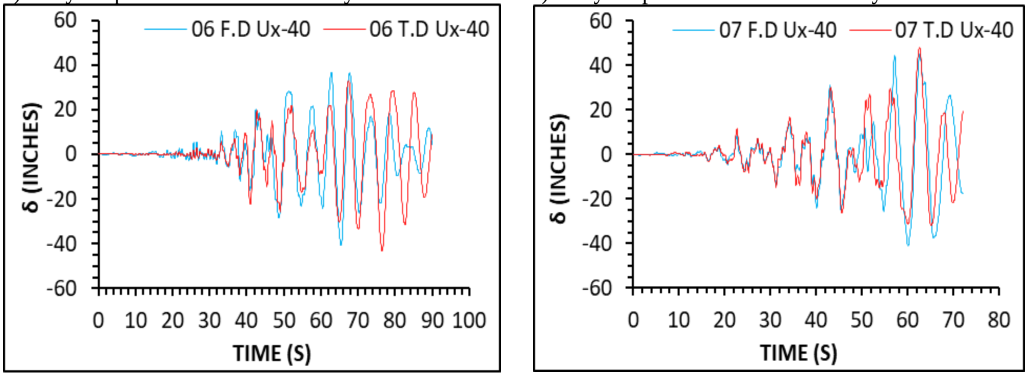
Figure C.12: Displacement time history plots for Level-20, Level-30 Level-40



p) Story Displacement vs T.H at Story-40 for G.M-02 q) Story Displacement vs T.H at Story-40 for G.M-03



r) Story Displacement vs T.H at Story-40 for G.M-04 s) Story Displacement vs T.H at Story-40 for G.M-05



t) Story Displacement vs T.H at Story-40 for G.M-06 u) Story Displacement vs T.H at Story-40 for G.M-07

Figure C.13: Displacement time history plots for Level-20, Level-30 Level-40

Annexure D

STATIC LOAD COMBINATIONS

Combo	Type	Case	Factor
F1	ADD	DEAD	1.4
F2	ADD	DEAD	1.2
F2		LIVE	1.6
F2		ROOFl	0.5
F3	ADD	DEAD	1.2
F3		LIVE	0.5
F3		ROOFl	1.6

Ca 0.44
I 1
Υ 1.1

Υ * 0.5 Ca I D	**0.242**	**D**	**Υ * 0.5 Ca I D**	**0.242**	**D**
Υ * 0.9D	**0.99**	**D**	**Υ * 1.2 D**	**1.32**	**D**
Total	**0.7480**	**D**	**Total**	**1.562**	**D**

SEISMIC LOAD COMBINATIONS (For seismic zone = 4, Soil Profile Type = S_d and Importance Factor = 1)

Considering:

EQX = X Dir + Y Eccentricity
EQY = Y Dir + X Eccentricity

Combo	Type	Case	Factor
F4	ADD	DEAD	1.562
F4		LIVE	0.550
F4		EQX	1.100
F4		EQY	0.330
F5	ADD	DEAD	1.562
F5		LIVE	0.550
F5		EQX	1.100
F5		EQY	-0.330
F6	ADD	DEAD	1.562
F6		LIVE	0.550
F6		EQX	-1.100
F6		EQY	0.330
F7	ADD	DEAD	1.562
F7		LIVE	0.550
F7		EQX	-1.100
F7		EQY	-0.330
F8	ADD	DEAD	1.562
F8		LIVE	0.550
F8		EQX	0.330
F8		EQY	1.100
F9	ADD	DEAD	1.562
F9		LIVE	0.550
F9		EQX	-0.330
F9		EQY	1.100
F10	ADD	DEAD	1.562
F10		LIVE	0.550
F10		EQX	0.330
F10		EQY	-1.100
F11	ADD	DEAD	1.562
F11		LIVE	0.550
F11		EQX	-0.330
F11		EQY	-1.100
F12	ADD	DEAD	0.748
F12		EQX	1.100
F12		EQY	0.330
F13	ADD	DEAD	0.748
F13		EQX	1.100
F13		EQY	-0.330
F14	ADD	DEAD	0.748
F14		EQX	-1.100
F14		EQY	0.330
F15	ADD	DEAD	0.748
F15		EQX	-1.100
F15		EQY	-0.330
F16	ADD	DEAD	0.748
F16		EQX	0.330
F16		EQY	1.100
F17	ADD	DEAD	0.748
F17		EQX	-0.330
F17		EQY	1.100
F18	ADD	DEAD	0.748
F18		EQX	0.330
F18		EQY	-1.100
F19	ADD	DEAD	0.748
F19		EQX	-0.330
F19		EQY	-1.100

Considering:

EQXA = X Dir - Y Eccentricity
EQYA = Y Dir - X Eccentricity

Combo	Type	Case	Factor
F4A	ADD	DEAD	1.562
F4A		LIVE	0.550
F4A		EQXA	1.100
F4A		EQYA	0.330
F5A	ADD	DEAD	1.562
F5A		LIVE	0.550
F5A		EQXA	1.100
F5A		EQYA	-0.330
F6A	ADD	DEAD	1.562
F6A		LIVE	0.550
F6A		EQXA	-1.100
F6A		EQYA	0.330
F7A	ADD	DEAD	1.562
F7A		LIVE	0.550
F7A		EQXA	-1.100
F7A		EQYA	-0.330
F8A	ADD	DEAD	1.562
F8A		LIVE	0.550
F8A		EQXA	0.330
F8A		EQYA	1.100
F9A	ADD	DEAD	1.562
F9A		LIVE	0.550
F9A		EQXA	-0.330
F9A		EQYA	1.100
F10A	ADD	DEAD	1.562
F10A		LIVE	0.550
F10A		EQXA	0.330
F10A		EQYA	-1.100
F11A	ADD	DEAD	1.562
F11A		LIVE	0.550
F11A		EQXA	-0.330
F11A		EQYA	-1.100
F12A	ADD	DEAD	0.748
F12A		EQXA	1.100
F12A		EQYA	0.330
F13A	ADD	DEAD	0.748
F13A		EQXA	1.100
F13A		EQYA	-0.330
F14A	ADD	DEAD	0.748
F14A		EQXA	-1.100
F14A		EQYA	0.330
F15A	ADD	DEAD	0.748
F15A		EQXA	-1.100
F15A		EQYA	-0.330
F16A	ADD	DEAD	0.748
F16A		EQXA	0.330
F16A		EQYA	1.100
F17A	ADD	DEAD	0.748
F17A		EQXA	-0.330
F17A		EQYA	1.100
F18A	ADD	DEAD	0.748
F18A		EQXA	0.330
F18A		EQYA	-1.100
F19A	ADD	DEAD	0.748
F19A		EQXA	-0.330
F19A		EQYA	-1.100

Considering:

EQX = X Dir + Y Eccentricity
EQYA = Y Dir - X Eccentricity

Combo	Type	Case	Factor
F4B	ADD	DEAD	1.562
F4B		LIVE	0.550
F4B		EQX	1.100
F4B		EQYA	0.330
F5B	ADD	DEAD	1.562
F5B		LIVE	0.550
F5B		EQX	1.100
F5B		EQYA	-0.330
F6B	ADD	DEAD	1.562
F6B		LIVE	0.550
F6B		EQX	-1.100
F6B		EQYA	0.330
F7B	ADD	DEAD	1.562
F7B		LIVE	0.550
F7B		EQX	-1.100
F7B		EQYA	-0.330
F8B	ADD	DEAD	1.562
F8B		LIVE	0.550
F8B		EQX	0.330
F8B		EQYA	1.100
F9B	ADD	DEAD	1.562
F9B		LIVE	0.550
F9B		EQX	-0.330
F9B		EQYA	1.100
F10B	ADD	DEAD	1.562
F10B		LIVE	0.550
F10B		EQX	0.330
F10B		EQYA	-1.100
F11B	ADD	DEAD	1.562
F11B		LIVE	0.550
F11B		EQX	-0.330
F11B		EQYA	-1.100
F12B	ADD	DEAD	0.748
F12B		EQX	1.100
F12B		EQYA	0.330
F13B	ADD	DEAD	0.748
F13B		EQX	1.100
F13B		EQYA	-0.330
F14B	ADD	DEAD	0.748
F14B		EQX	-1.100
F14B		EQYA	0.330
F15B	ADD	DEAD	0.748
F15B		EQX	-1.100
F15B		EQYA	-0.330
F16B	ADD	DEAD	0.748
F16B		EQX	0.330
F16B		EQYA	1.100
F17B	ADD	DEAD	0.748
F17B		EQX	-0.330
F17B		EQYA	1.100
F18B	ADD	DEAD	0.748
F18B		EQX	0.330
F18B		EQYA	-1.100
F19B	ADD	DEAD	0.748
F19B		EQX	-0.330
F19B		EQYA	-1.100

Considering:

EQXA = X Dir - Y Eccentricity
EQY = Y Dir + X Eccentricity

Combo	Type	Case	Factor
F4C	ADD	DEAD	1.562
F4C		LIVE	0.550
F4C		EQXA	1.100
F4C		EQY	0.330
F5C	ADD	DEAD	1.562
F5C		LIVE	0.550
F5C		EQXA	1.100
F5C		EQY	-0.330
F6C	ADD	DEAD	1.562
F6C		LIVE	0.550
F6C		EQXA	-1.100
F6C		EQY	0.330
F7C	ADD	DEAD	1.562
F7C		LIVE	0.550
F7C		EQXA	-1.100
F7C		EQY	-0.330
F8C	ADD	DEAD	1.562
F8C		LIVE	0.550
F8C		EQXA	0.330
F8C		EQY	1.100
F9C	ADD	DEAD	1.562
F9C		LIVE	0.550
F9C		EQXA	-0.330
F9C		EQY	1.100
F10C	ADD	DEAD	1.562
F10C		LIVE	0.550
F10C		EQXA	0.330
F10C		EQY	-1.100
F11C	ADD	DEAD	1.562
F11C		LIVE	0.550
F11C		EQXA	-0.330
F11C		EQY	-1.100
F12C	ADD	DEAD	0.748
F12C		EQXA	1.100
F12C		EQY	0.330
F13C	ADD	DEAD	0.748
F13C		EQXA	1.100
F13C		EQY	-0.330
F14C	ADD	DEAD	0.748
F14C		EQXA	-1.100
F14C		EQY	0.330
F15C	ADD	DEAD	0.748
F15C		EQXA	-1.100
F15C		EQY	-0.330
F16C	ADD	DEAD	0.748
F16C		EQXA	0.330
F16C		EQY	1.100
F17C	ADD	DEAD	0.748
F17C		EQXA	-0.330
F17C		EQY	1.100
F18C	ADD	DEAD	0.748
F18C		EQXA	0.330
F18C		EQY	-1.100
F19C	ADD	DEAD	0.748
F19C		EQXA	-0.330
F19C		EQY	-1.100

FIGURE D.1: Static Load Combinations for Equivalent Static and RS Analysis