Journal of
Data Acquisition and Processing
ISSN: 1004-9037
https://sjcjycl.cn/
DOI: 10.5281/zenodo.777353

ANALYTICAL MODELLING OF STRUCTURAL RESPONSES OF RC FRAMES EXPOSED TO NEAR FAULT GROUND MOTIONS USING R-PROGRAMMING

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ABSTRACT

Purpose–Recent earthquake losses on contemporary structures have highlighted the critical need for research into evaluating various performance limit levels and seismic safety of code-compliant structures. So, the concepts of performance-based design and vulnerability assessment of structure have taken an alternative form in seismic analysis. This study is intended to meter the impact of the near field/fault ground motions on the response of G+10RC structures with varying geometry are exposed to the different magnitude of earthquake forces. Influence is measured directly by quantifying the potential of damage caused to the structure. Analytical paradigm was developed for relating specific structural response with various geometrical parameters and the type of ground motion applied.

Design/methodology/approach – In this study twenty-seven G+10 RC structural frames and 12 different near fault ground motions from minor, moderate and major earthquake categories are considered. For each ground motion response spectrum was developed by scaling it to target response spectrum. The nonlinear time history (NTHA) is carried out on each reinforced concrete frame by applying each ground motion. Responses of the structure were recorded in each THA. Recorded response were analysed and analytical models were developed relating the structural responses and characteristics of earthquake ground motion, geometry of the structure. Probabilities of damage of the structures are calculated based on Hazus-MH 2.1(***Hazus ®MH 2.1 Tech Manual***)[22]

Findings– The probability damage curves predicted the severity of damage of the structure for a given spectral displacement. The impact of the characteristics of near field ground motions and geometry of the structure on the response of the RC structure. And analytical model developed relating the structural responses and characteristics of near field ground motions and geometry of the structure.

Practical implications – Analytical models developed for structural responses of G+10 structure through NTHA of the structures can be used as an alternative for experimental modelling to study the impact of near field ground motions on structure. The curves developed for fragility are useful in gauging the extent of damage that occurs.

Originality/value – Most of the previous studies considered reinforced concrete structures subjected to one ground motion only. However, in the study presented in this paper, various seismic parameters for an RC structure subjected to various sets of ground motions were determined to assess influence of magnitude of ground motion and geometry of the structure

on structural response. This study is useful in assessing the seismic performance and vulnerability. Given the assessment, it will be useful in designing more efficient and economical structures.

INTRODUCTION

Seismic forces are inherently random and unpredictable. Hence structures have to be analysed under the influence of these forces. Seismic loads need to be properly devised to gauge the actual performance of structures with a comprehensive interpretation of the damage. In 1997 **Eggert V. and M. Nau, 1997[16]** adopted Linear Static examine the impact of mass & stiffness on structural response of regular and irregular structures. Linear static analysis presupposes that the building reacts in its fundamental mode and defined by a seismic design RSP. It is suitable to adopt for low rise structures which do not undergo significant ground vibration. Non-Linear Static Analysis (modal pushover analysis) is used by (Chopra and Goel, 2002)**[10]** to analyse a 9 storey steel structure and estimate seismic demands. Linear Dynamic Analysis **Krishnan and Muto, 2013[31]** concluded when higher mode effects are not important, static methods are appropriate. This is accurate for short, conventional structures. For high rise structures, structures which are torsional irregular, or non-conventional systems, a dynamic technique is required. In the linear dynamic process, the building is treated as a ‘multidegreefreedom (MDOF) system’ with a ‘linear elastic stiffness matrix’ and an ‘equivalent viscous damping matrix’ was developed. **Lestuzzi *et al.*, 2018[35]** attempted to assess the seismic efficiency of a non-primary structure of the Chancy-Pougny dam using NTHA and the displacement method (push-over analysis). It is concluded that the favourable results obtained by static pushover analysis are fully validated by the performed nonlinear time-history analyses. **Hamed Rajaei Lak*et al.*, 2023[21]** The study compared the impact of near field earthquakes on various RC frames tested using cutting-edge methodology. Far-fault ground motion recordings about 7 and 14near fault ground motion recordings with directivity and fling-step effects were chosen. Typical RC frames with shear walls and without shear walls have 4, 7, and 10 stories. They performed NTHA on RC frames using OpenSees software. Moreover, an ANN approach is used to predict the relation between structural response and intrinsic ground motion attributes, exhibiting how each characteristic affects structural response under various forms of ground motion data. It is concluded that near fault earthquakes considerably modify both frames' reactions in all situations with varying ground motion records, the average increase in the responses by 72%and 45%for frames with shear and without shear walls.

After reviewing the past literature, it is observed that there are limited few studies that are carried out quantifying the input (ground acceleration, velocity etc.) given and properties associated with the input (wave frequency, amplitude etc.) of far field and near field ground motions on different structures. However, the possibility of a structure being subjected to same ground motion for which it is designed for is rare. So, it is desirable to study the seismic efficiency of RC structures subjected to various ground motions and design it for the most critical response. Various seismic parameters for an RC structures were exposed to various sets of ground motions can be determined to assess influence of characteristics of ground motion and the geometry of the structure on structural response.

OBJECTIVES:

- Evaluate the seismic performance and vulnerability of the RC frames by calculating the damage probability of the structure.
- To develop an analytical model relating the structural responses and ground motion characteristics along with geometry of the structure.

METHODOLOGY

Typical RC framed structures with varying geometry are modelled and analysed using ETABS designing software according to **IS 456, 2000**[23] and**(IS 1893, 2016)**[26]. **(Boukhalkhal *et al.*, 2020)**[10] compared Non-linear dynamic analysis with static non-linear analysis **Dynamics of Structures by Anil K. Chopra.**[14]and concluded that the error in the structural responses are nominal but non-linear dynamic analysis provides the more accurate simulation of the dynamic forces compared to static non-linear analysis at it provides few characteristics of dynamic analysis. **(Yang *et al.*, 2021)**[35] adopted vertical mode decomposition RSP method and the THA method to assess the vertical seismic action and concluded THA is more precise. So THA is carried out for all the RC frames and structural responses are recorded. Here in this study fragility analysis is performed to obtain damage probabilities (Siva *et al.*, 2016)[03]performed seismic fragility analysis to assessed the performance of the systems resisting lateral load in the structures. Probabilities of damage are calculated as per **(Hazus- MH2.1)**[22]developed by FEMA. The methodology adopted is explained stepwise below

1. Twelve near fault ground motions are selected from major, moderate and minor categories.
2. The geometry of the control G+10 reinforced concrete building frame is fixed.
3. A control analytical model of G+10 reinforced concrete building frame is developed using ETABS.
4. Different reinforced concrete building frame models varying bay length in X-direction, Y-direction and storey height are developed.
5. Developing Analytical models for geometrical combination subjected to each ground motion at a time.
6. NTHA is carried out and the responses of the structure are calculated.
7. An analytical model is developed through regression model using R-Programming.

Calculation of Probability of damage of RC structure for given spectral displacements:

The damage probability can be estimated as per clause No. 6.4.3.1 of the Hazus manual[22] given by FEMA

$$"[P[\,dS/S_d] = \phi[(1/\beta\text{ds})\ \times \ln\,(S_d/S_{d,ds})]"$$

Where,

$S_{d,ds}$ – The median of spectral displacement when the structure is at the threshold of the damage state.

βds -The standard deviation of natural logarithm of spectral displacement for damage state

ϕ - The normal cumulative distribution function.

Many formulae are in wide use to calculate the median of spectral displacement. The following formulae in table-1 proposed by **(Barbat, Pujades and Lantada, 2008)**[07]using the capacity spectrum method in the evaluation of seismic damage of urban areas are considered, as the variables used are directly dependent on the criteria derived from the non-linear static pushover curve.

Table 1 Type of damage state and corresponding spectral displacement median value

Type of Damage	**Formula**
Slight	$[S_{d,ds} = 0.7\text{dy}]$
Moderate	$[S_{d,ds} = \text{dy}]$
Severe	$[S_{d,ds} = \text{dy} + 0.25(\text{du} - \text{dy})]$
Complete	$[S_{d,ds} = \text{du})]$

MODELLING:

Loads Considered

As per table-1 of (IS 875 : Part-1, 1987)[24]

Brick masonry's unit weight = 19 kN/m^{3y}

Reinforced cement concrete's unit weight = 24 kN/m^3

As per table-1 of (IS 875 : Part-2, 2008)[25]

Average floor live load = 2.5 kN/m^2

Roof live load = 2kN/m^2

Table 2 List of reinforced concrete building models considered for NTHA

Model Notation	Bay length in X direction (m)	Bay length in Y direction (m)	Storey Height (m)
M_{443}	4	4	3
M_{453}	4	5	3
M_{463}	4	6	3
$M_{443.3}$	4	4	3.3
$M_{453.3}$	4	5	3.3
$M_{463.3}$	4	6	3.3
$M_{443.6}$	4	4	3.6
$M_{453.6}$	4	5	3.6
$M_{463.6}$	4	6	3.6

M_{543}	5	4	3
M_{553}	5	5	3
M_{563}	5	6	3
$M_{543.3}$	5	4	3.3
$M_{553.3}$	5	5	3.3
$M_{563.3}$	5	6	3.3
$M_{543.6}$	5	4	3.6
$M_{553.6}$	5	5	3.6
$M_{563.6}$	5	6	3.6
M_{643}	6	4	3
M_{653}	6	5	3
M_{663}	6	6	3
$M_{653.3}$	6	4	3.3
$M_{643.3}$	6	5	3.3
$M_{663.3}$	6	6	3.3
$M_{643.6}$	6	4	3.6
$M_{653.6}$	6	5	3.6
$M_{663.6}$	6	6	3.6

Table 3 List of ground motions considered for the NTHA and given notations (Source: PEER ground motion database)

Type of Ground motion	Class	Name of GM	Magnitude	Notation given
Near Fault	Minor	Umbria-02, Italy	3.70	$(GM\text{-}1)_{NF}$
		Ridgemark_21309098	3.50	$(GM\text{-}2)_{NF}$
		Hamilton_51210970	3.20	$(GM\text{-}3)_{NF}$
		Santa Monica_ 9163314	3.08	$(GM\text{-}4)_{NF}$
	Moderate	El centro 07	5.01	$(GM\text{-}5)_{NF}$
		San Francisco	5.28	$(GM\text{-}6)_{NF}$

		Oroville-01	5.89	(GM-7)$_{NF}$
		Coyote Lake	5.74	(GM-8)$_{NF}$
	Major	Tabas, Iran	7.40	(GM-9)$_{NF}$
		Cape Mendocino	7.07	(GM-10)$_{NF}$
		Kocaeli, Turkey	7.51	(GM-11)$_{NF}$
		Denali, Alaska	7.90	(GM-12)$_{NF}$

Sample Scaled Ground Motions and Target Response Spectrum in X-Direction

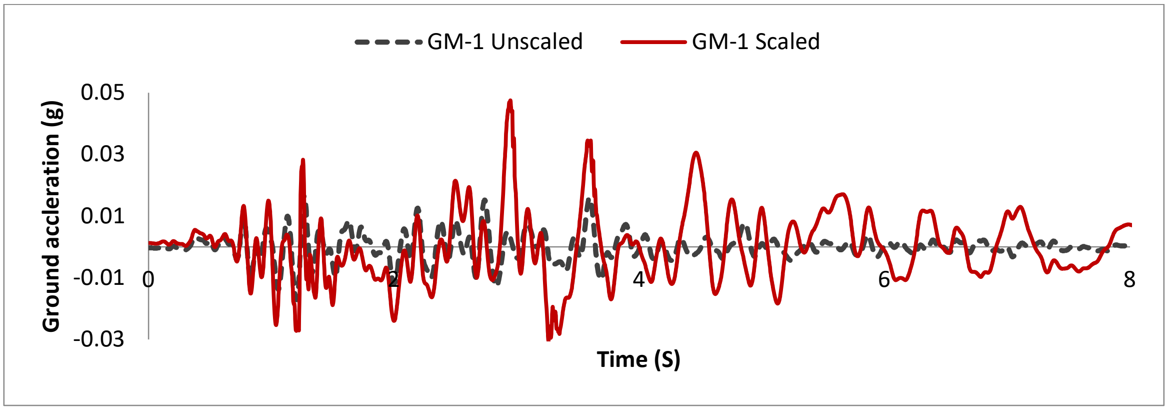

Figure 1 Scaled and UnscaledG.M-1 in X-Direction

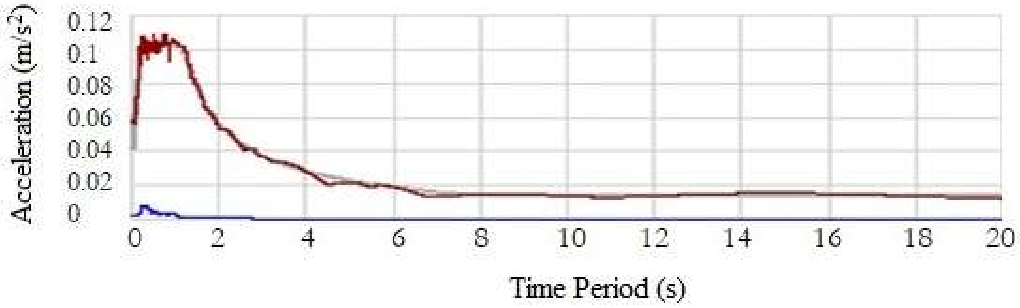

Figure 2 The target response spectrum of G.M-1 after scaling in X-Direction

RESULTSAND DISCUSSION

In the present study 27 RC frame models with different geometric combinations are analysed by applying 12 different ground motions. Out of all frame models $M_{663.6}$ is identified as most vulnerable frame. Structural responses of model $M_{663.6}$ are compared with that of control model M_{443} and presented below.

Average Maximum Storey Displacements:

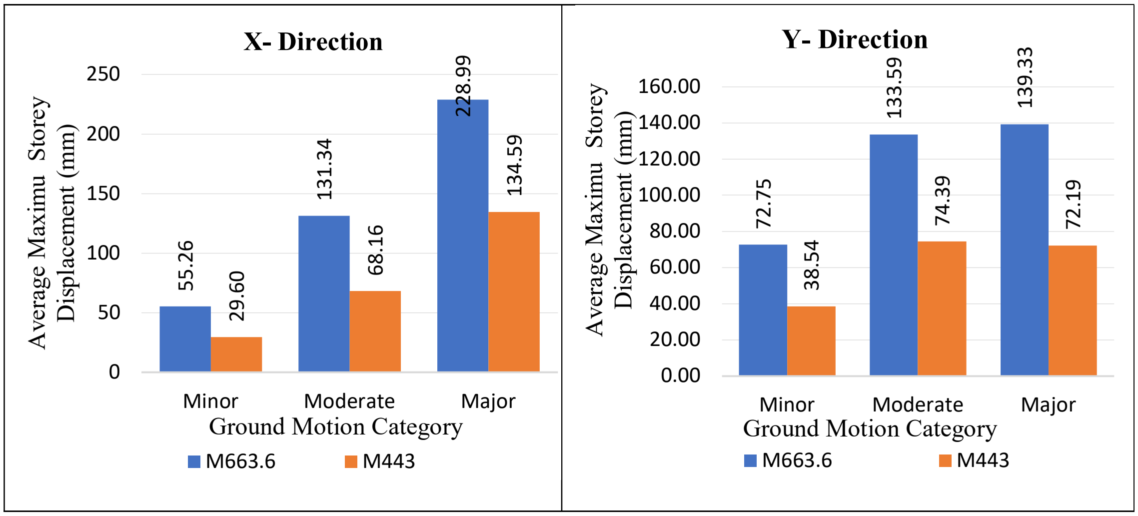

Figure 3 Avg. Maximum Storey Displacement of M_{443}& $M_{663.6}$ in X , Y Directions

From the above figure it is observed that $M_{663.6}$ is having highest average maximum storey displacement in X, Y directions when major, moderate, minor category ground motions are applied. $M_{663.6}$exhibited46.43%, 48.11%, 41.25% and 47.03%, 44.32%, 48.19% more maximum storey displacement in X and Y directions respectively compared to that of M_{443} when major, moderate and minor category ground motions are applied.

Average Maximum Storey Accelerations:

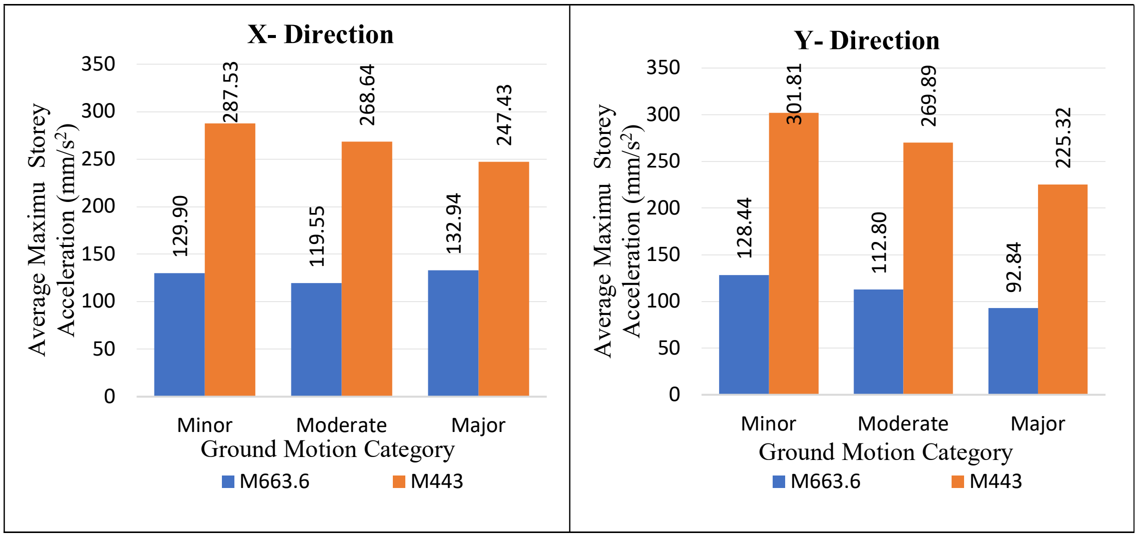

Figure 4 Avg. Maximum Storey Acceleration of M_{443}& $M_{663.6}$ in X and Y Directions

A significant decrement is observed in average maximum storey acceleration for model $M_{663.6}$ in X and Y directions when major, moderate, minor category ground motions are applied relative to those of M_{443}. $M_{663.6}$ exhibited 54.82%, 55.49%, 46.27% and 57.44%, 58.21%, 58.79% reduction maximum storey displacement in X and Y directions respectively in major, moderate and minor ground motion categories.

Average Maximum base shear:

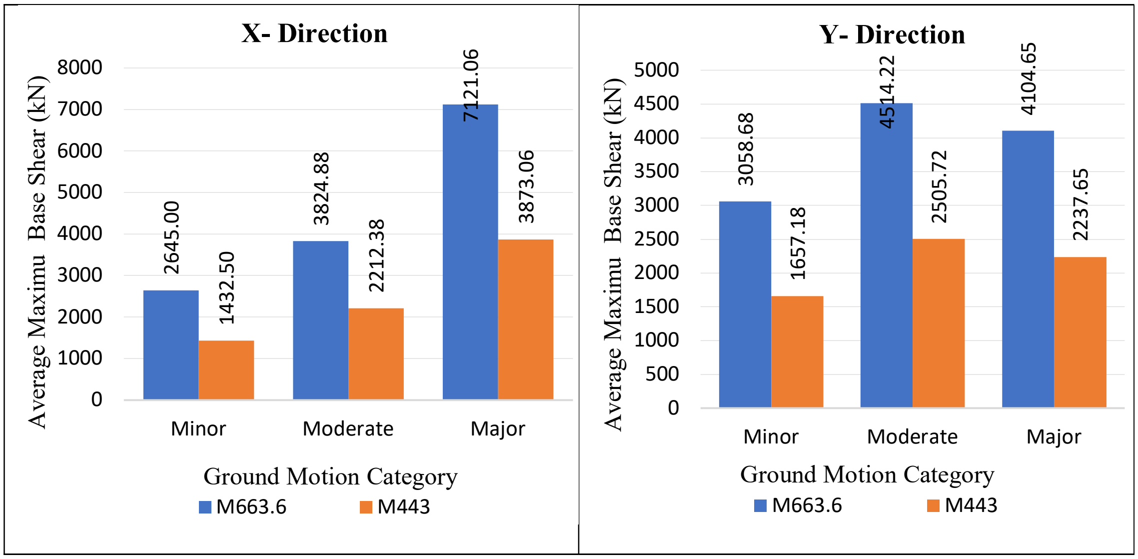

Figure 5 Avg. Maximum Base Shear of M_{443}& $M_{663.6}$ in X and Y Directions

It is conclusive that average maximum base shear for model$M_{663.6}$ is phenomenally high that that of model M_{443} in X and Y directions when major, moderate, minor category ground motions are applied. The difference is 45.84%, 42.16%, 45.61% and 45.82%, 44.93%, 45.49% in X, Y directions respectively.

Average Maximum IDR:

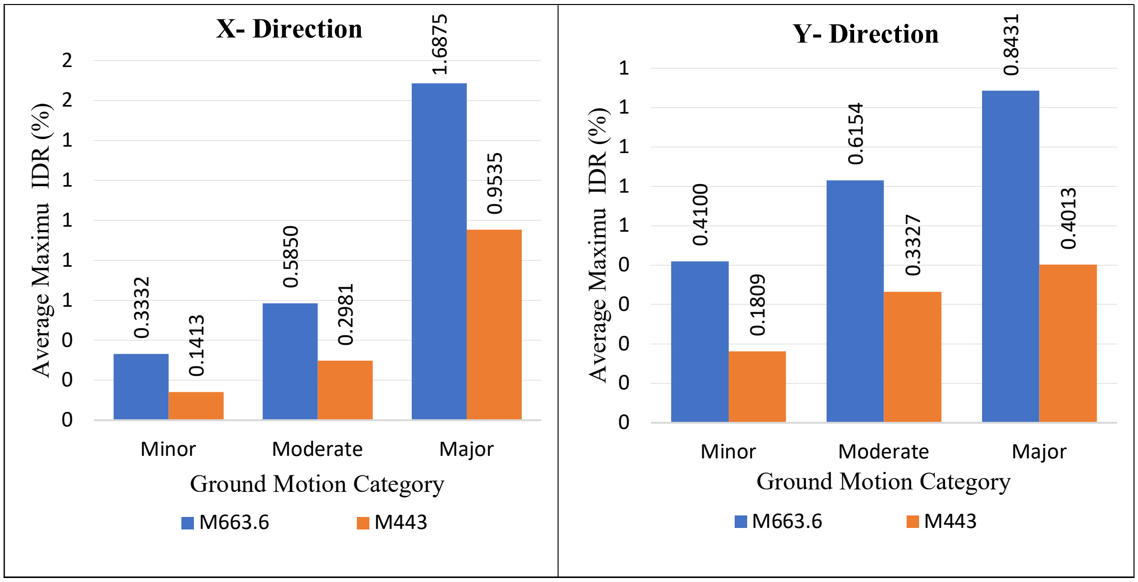

Figure 6 Avg. Maximum IDR of M_{443}& $M_{663.6}$ in X and Y Directions

About 57.59%, 49.04%, 43.49% and 55.87%, 45.93%, 52.39% of increase in average maximum IDR is observed in X and Y directions respectively in model $M_{663.6}$ relative to model M_{443} when major, moderate, minor category ground motions are applied.

Variation of average maximum storey displacements

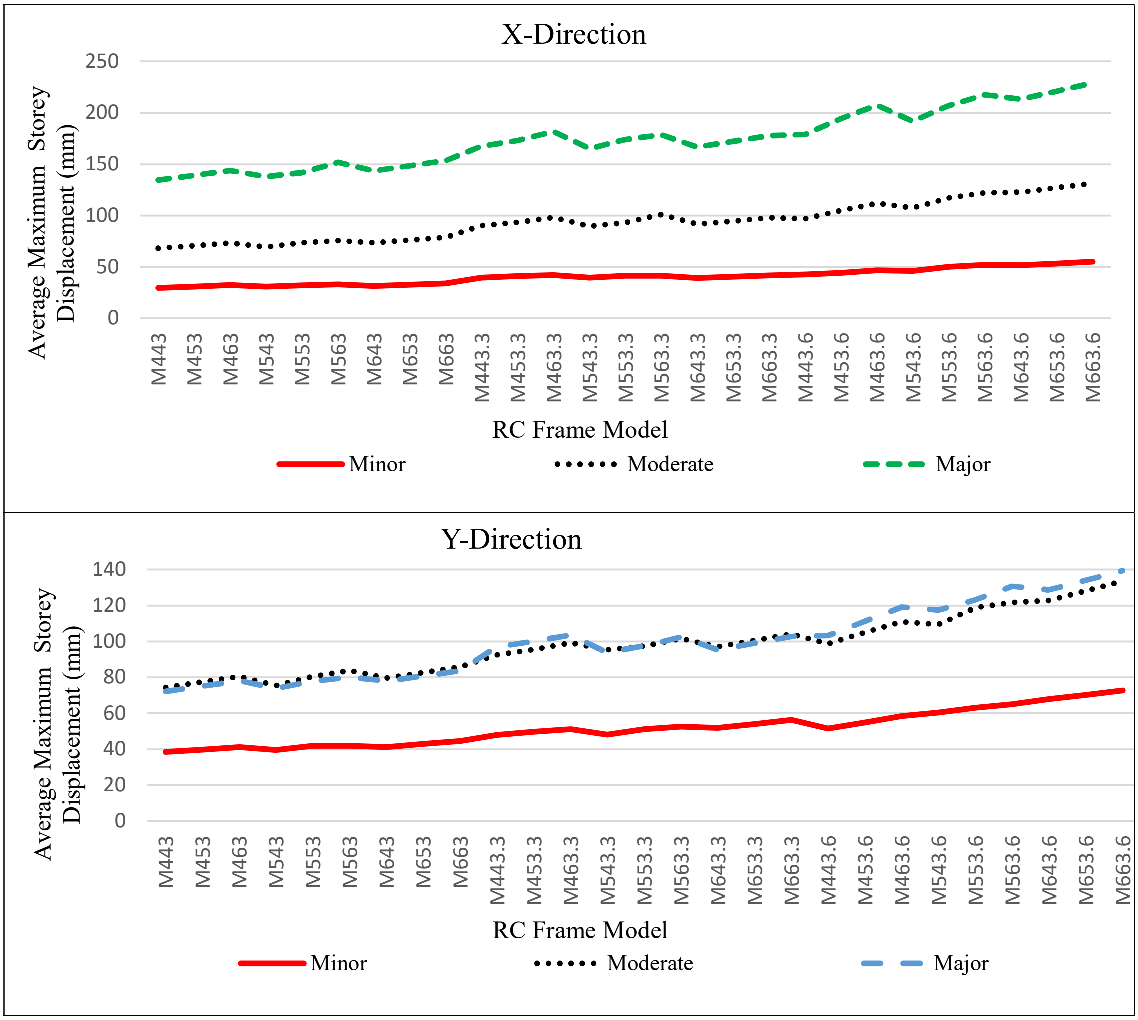

Figure 7 Average Maximum Storey Displacement (mm)of all RC models in X and Y Directions

It is observed from the above figures that average maximum storey displacement in X and Y directions are incremental in nature with increase in dimensions of the structure irrespective of category of ground motion put in. In X direction higher displacements are observed when major ground motions are put in. But in Y direction displacement in all RC frames are nearly equal when major and moderate ground motions are applied. This may be due to due to predominant ground acceleration in Y direction. A sudden increase is observed in displacements when the storey height is increased, and the increment is nominal with change in the bay lengths in either direction.

Variation of average maximum base shear

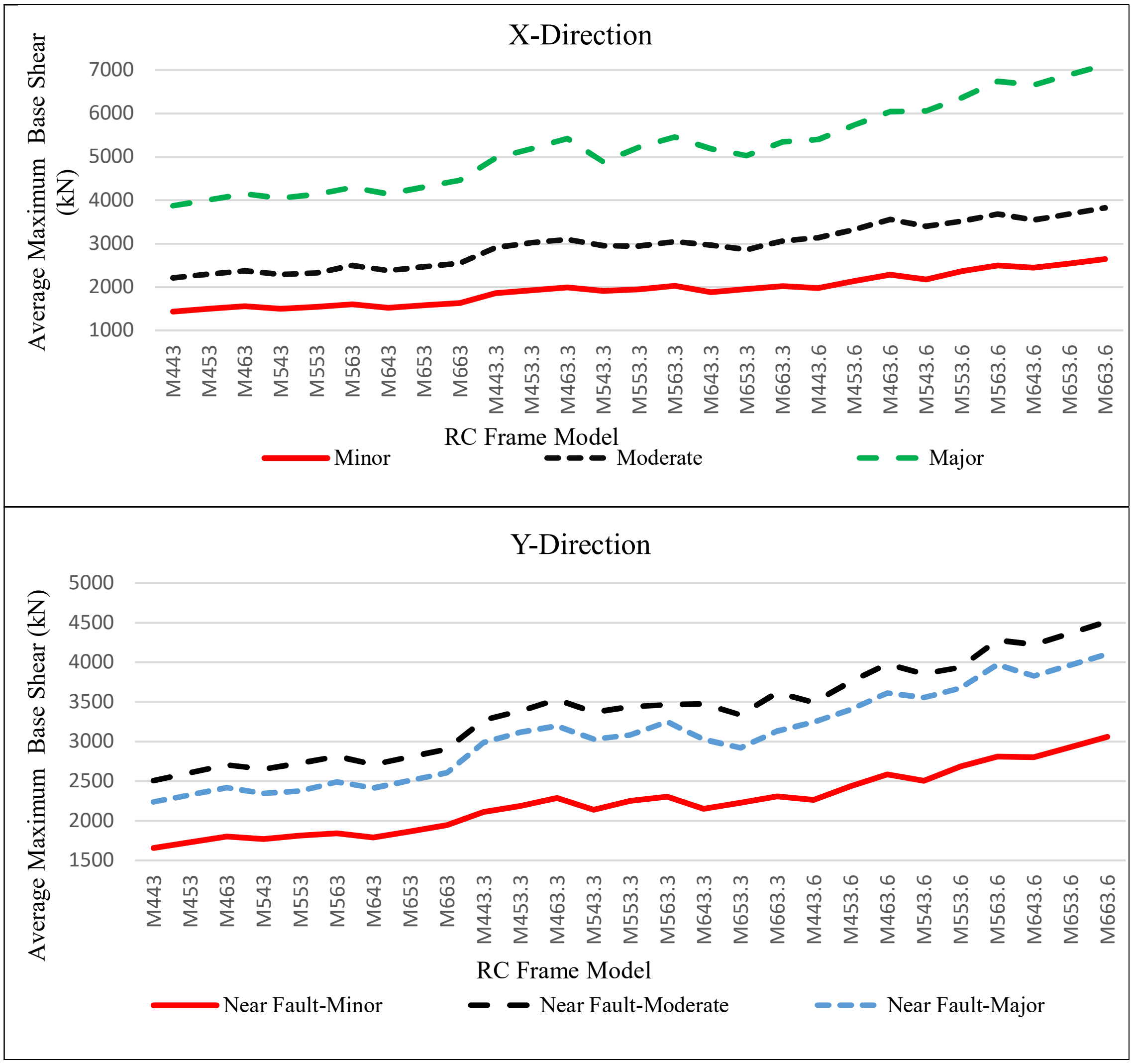

Figure 8 Avg. Maximum Base shear of all RC models in X and Y Directions

It is observed from the above figures that average maximum base shear in X and Y directions is increasing with increase in dimensions of the frame for all categories of ground motion applied. Similar to the maximum storey displacement, maximum base shear in X direction are when major ground motions are applied. And in Y direction maximum base shear is higher when moderate ground motions are applied. This is due to higher ground accelerations in Y direction for moderate ground motions.

Variation of average maximum storey displacements

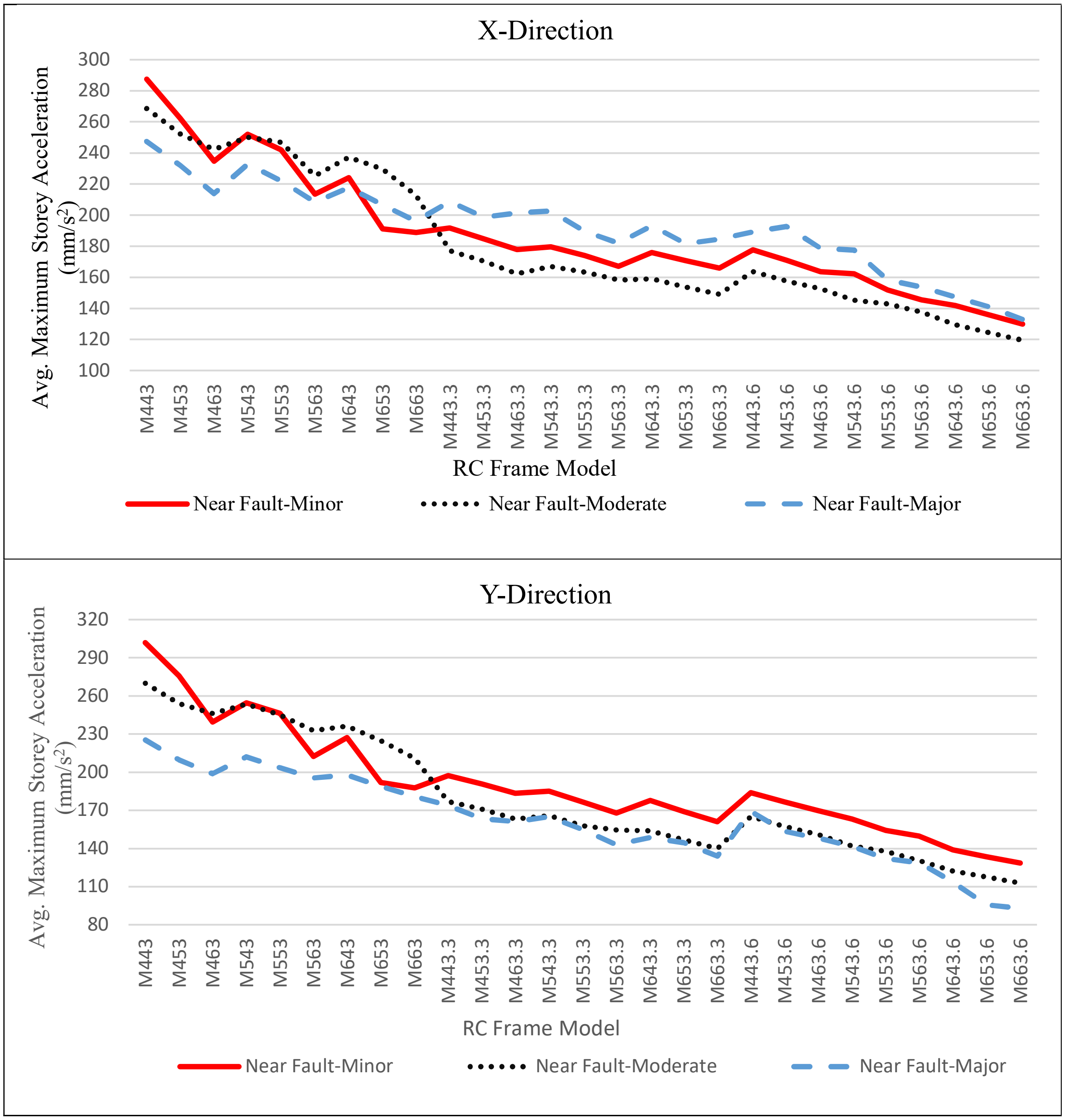

Figure 9 Avg. Maximum Storey Acceleration all RC models in X and Y Directions

The maximum storey acceleration is found to be highest for the control model M_{443} irrespective of the ground motion applied. And maximum storey acceleration is decreased with increase in the dimension of the structure. But there is a steep decrement is observed with increase in storey height when the moderate category ground motions are applied. The increase in the storey height might have induced higher amplitudes and time periods subsequently reduction in the storey accelerations.

Fragility curves:

Following are the curves for fragility developed and utilized to evaluate the probability of damage of the structural.

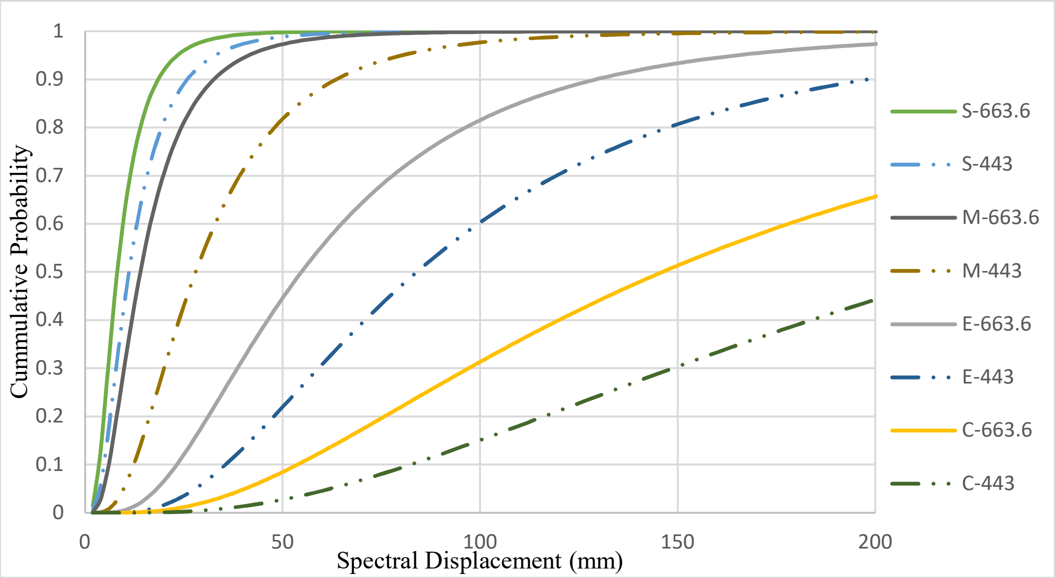

Figure 10 Fragility curve of models M_{443}& $M_{663.6}$

From the above graph it is evident that $M_{663.6}$ is prone to more damage compared to that of M_{443}. Model $M_{663.6}$ is having collapse damage probability about 0.5 at 146mm storey displacement and model $M_{443}$is having 0.298 damage probability for the same storey displacement. Similarly for extensive damage state model $M_{663.6}$ is having 0.5 damage probability at 54mm storey displacement and model M_{443} is having 0.255 damage probability at same storey displacement. In moderate damage state models M_{443}& $M_{663.6}$ are achieving damage probability about 1.00 at 68mm, 120mm respectively. But models $M_{643.6}$, M_{443} are achieving a damage probability about 1.00 in slight damage state at 46mm and 64 mm displacement.

MATHEMATICAL MODELLING USING REGRESSION

In present study bay lengths in X & Y directions, storey height, distance between ground motion record and place of origin of earthquake, ground motions shear wave velocity are considered as the independents and maximum storey displacement, maximum base shear, maximum storey acceleration and 'maximum IDR' are appraised as dependents. Number of models were run to establish the appropriate relationship between the dependents and the independents.

Sample regression model developed for different structural responses in R-Programming

```
> setwd()
[1] "C:/Users/Admin/Desktop/Bhanu Docs/Literature Review/Documentation/R-P
rogramming"
>reg= read.csv("regressionnf.csv")
> modeldisp= lm(dispx~l+b+h+mag+rjb+v30,data=data)
> modelbs= lm(bsx~l+b+h+mag+rjb+v30,data=data)
> modesa= lm(bsx~l+b+h+mag+rjb+v30,data=data)
> modelsa= lm(bsx~l+b+h+mag+rjb+v30,data=data)
> modelidr= lm(bsx~l+b+h+mag+rjb+v30,data=data)
> summary(modeldisp)
```

```
Call:
lm(formula = dispx ~ l + b + h + mag + rjb + v30, data = reg)

Residual:
    Mini    1Q  Medians     3Q     Maxi
-69.074 -15.620   2.844  19.759  67.308

Coefficient:
              Estimate Stand. Error t value Pr(>|t|)
(Intercept) -3.776e+02  2.400e+01 -15.732   <2e-16 ***
l            4.113e+00  1.803e+00   2.281   0.0232 **
b            3.589e+00  1.882e+00   1.907   0.0574 *
h            6.553e+01  6.169e+00  10.623   <2e-16 ***
mag          3.475e+01  1.082e+00  32.128   <2e-16 ***
rjb         -7.073e-01  4.523e-01  -1.564   0.1189 **
v30          7.802e-02  8.724e-03   8.944   <2e-16***
---
Sign. codes:  0 “***” 0.001 “**” 0.01 “*” 0.05 “.” 0.1 ‘ ’ 1

Residual standard error: 26.49 on 317 degrees of freedom
Multiple R-squared:  0.8387,  Adjusted R-squared:  0.8357
F-statistic: 274.7 on 6 and 317 DF,  p-value: < 2.2e-16
```

Table 4 sample Input data for regression analysis

L	B	H	Magnitude	R_{jb}	V_{30}	Displacement	Inter Storey Drift Ratio	Base Shear	Spectral Acceleration
4	4	3	3.70	4.11	670.00	57.02	0.00197	2409.90	132.50
4	4	3	3.50	13.26	643.80	28.10	0.00163	1404.50	85.79
4	4	3	3.20	6.31	471.00	25.42	0.00140	1162.50	97.02
4	4	3	3.08	4.87	377.62	7.86	0.00064	753.10	114.83
4	4	3	5.89	7.32	210.51	43.36	0.00186	1894.61	116.21
4	4	3	5.74	9.74	874.72	84.98	0.00375	2755.40	90.11
4	4	3	5.28	7.79	680.37	105.23	0.00401	2908.90	83.51
4	4	3	5.01	0.47	663.31	39.08	0.00190	1290.60	104.74
4	4	3	7.40	0.00	471.53	130.16	0.00915	3721.04	155.34
4	4	3	7.07	0.00	422.17	121.02	0.00872	3457.70	153.52
4	4	3	7.51	1.38	297.00	138.08	0.00945	4261.70	129.07

4	4	3	3.70	4.11	670.00	57.02	0.00197	2409.90	132.50

Table5 of coefficients, R^2 and Significance level for Maximum Storey Displacement

Independents	**Coefficients**	$\mathbf{R^2}$	**Significance level**
Storey Height (H)	65.53	0.8357	High
Bay Length in X-Direction (L)	4.113	0.8357	Moderate
Bay Length in Y-Direction (B)	3.589	0.8357	Low
Magnitude of the ground Motion (mag)	34.75	0.8357	High
Distance to the recording station from epicentre (R_{jb})	-0.707	0.8357	Moderate
Shear Wave Velocity (V_{30})	0.078	0.8357	High
Intercept	-377.6	0.8357	High

Table6 of coefficients, R^2 and Significance level for Maximum Base Shear

Independents	**Coefficients**	$\mathbf{R^2}$	**Significance level**
Storey Height (H)	2212	0.7854	High
Bay Length in X-Direction (L)	136.0	0.7854	Low
Bay Length in Y-Direction (B)	102.9	0.7854	-
Magnitude of the ground Motion (mag)	869.2	0.7854	High
Distance to the recording station from epicentre (R_{jb})	-1.265	0.7854	Moderate
Shear Wave Velocity (V_{30})	0.078	0.7854	High
Intercept	-10493.1	0.7854	High

Table 7of coefficients, R^2 and Significance level for Maximum Storey Acceleration

Independents	Coefficients	R^2	Significance level
Storey Height (H)	-56.79	0.8134	High

Bay Length in X-Direction (L)	-2.234	0.8134	-
Bay Length in Y-Direction (B)	4.892	0.8134	-
Magnitude of the ground Motion (mag)	4.264	0.8134	Moderate
Distance to the recording station from epicentre (R_{jb})	-6.148	0.8134	High
Shear Wave Velocity (V_{30})	-0.043	0.8134	High
Intercept	386.46	0.8134	High

Table8 of coefficients, R^2 and Significance level for Maximum Storey Acceleration

Independents	**Coefficients**	**R^2**	**Significance level**
Storey Height (H)	-0.00385	0.8334	High
Bay Length in X-Direction (L)	0.000263	0.8334	-
Bay Length in Y-Direction (B)	0.000234	0.8334	-
Magnitude of the ground Motion (mag)	0.002299	0.8334	High
Distance to the recording station from epicentre (R_{jb})	-0.000168	0.8334	High
Shear Wave Velocity (V_{30})	-9.11×10^{-7}	0.8334	High
Intercept	-0.02130	0.8334	High

CONCLUSIONS

It is conclusive that Near fault ground motions induced strong impulse due to high directivity effect compared to that of conventional ground motions. Near fault ground motions caused higher maximum sotrey displacement, maximum base shear in X direction in major, moderate and minor ground motion categories, relative to that of conventional ground motions. But in Y direction near fault ground motions induced less maximum sotrey displacement, maximum base shear in major ground motion category due to predominant ground acceleration in Y-direction than that of in X-direction. A significant increment was found in maximum base shear with increase in storey height but the increase in bay length in X, Y directions produced moderate increment in maximum base shear. Maximum storey accelerations decremental with increase in storey height but very marginal increment was found with increase in bay lengths in X, Y directions. Probability of damage of the reinforced concrete framed structures is drastically increasing in collapse and extensive damage states with increase in storey height. In slight and moderate damage states damage probability is increasing with a negligible the rate of increase. The nonlinear regression models developed for maximum storey displacement, maximum base shear, maximum storey acceleration and maximum IDR using R-Programming achieved 88.57%, 78.54% , 81.34% and 83.34% confidence levels respectively.

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