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Seismic Fragility Assessment of Residential RC Buildings with Roof Mounted Telecommunication Tower Structure

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Abstract

Installation of telecommunication tower at roof top of the building is being increasing rapidly. Cities have scarcity of free open spaces. So, we can observe these towers being mounted on roof top of residential or commercial buildings. In most of the cities, these towers are observed to be mounted on residential building after some years of construction which are either pre-engineered or basically designed structure whose design is limited to basic RC design only. The effect of these tower structure on seismic performance of building needs to be understood and from this understanding the owner of RC building can make a rational decision whether or not to allow the construction of tower structure in already designed and built residential RC structure. For this, the residential RC buildings were surveyed in Jhapa district with roof mounted communication tower structure. The residential RC building with symmetrical grid system were designed using Response Spectrum Method as per NBC 105:2020 (3 story, 4 story and 5 story) in ETABS V 21.0. First, the seismic response of these building were observed without positioning roof mounted tower. Next, tower structure were placed at center and corner of the symmetric building grid and seismic response were observed. Various damage states drift limits are taken from HAZUS 4.2 SP3. This research work presents the vulnerability assessment of the residential RC building with and without communication tower installed in the building. The result of the vulnerability assessment can be used as a reference by a residential house owner as a tool for decision making whether or not to allow installation of these tower in residential RC building. Also the effect of positioning and mass of tower with respect to seismic vulnerability can help house owner for informed decision-making in the design and placement of telecommunication towers. There is increase in vulnerability of the RC structure for corner placed tower structure than for centrally placed tower structure. The building having no telecommunication tower was found to be least vulnerable.Also the findings indicate that the structural dynamics and vulnerability of the building are highly responsive to changes in the mass of the tower, particularly when the tower is positioned at the corner of the structure.

Keywords

Residential Building, Telecommunication tower, Fragility Curve, Vulnerability, Bidirectional Earthquake

1. Introduction

1.1 Background

Wireless Network plays an important role in super fast transmission of data and communication based on information between users. To support these communication systems, there are different types of telecommunication structures installed at different places. Cities have scarcity of free open spaces. So, we can observe these towers being mounted on roof top of residential or commercial buildings. In most of the cities, these towers are observed to be mounted on residential building after some years of construction which are either pre-engineered or basically designed structure whose design is limited to basic RC design only.

In most of the cases, it is observed that communication tower structure are installed in already designed and constructed residential RC buildings. In this context, the effect of these tower structure on seismic performance of building needs to be understood and from this understanding the owner of RC building can make a rational decision whether or not to allow the construction of tower structure in already designed and built residential RC structure.

Seismic performance of building and vulnerability assessment has been the interest with the increase of the computational efficiency. Vulnerability of buildings can be evaluated by developing the fragility function which is expressed as fragility curve. With regard to a wide variety of ground motion intensities, fragility functions give the probability of exceeding beyond a specified threshold of damage. One rapidly spreading concept to handle the dynamic response of structures during earthquakes is performance-based earthquake engineering (PBEE). Among the several PBEE techniques, incremental dynamic analysis (IDA) is a technique for structural analysis that may be used to precisely extract seismic demand in order to examine the non-linear seismic behavior of structures. A series of nonlinear dynamic studies are conducted as part of IDA under a collection of ground motion records that have been multiplicatively scaled. When paired with fragility analysis, IDA also aids in doing probabilistic seismic hazard analysis to determine the mean yearly frequencies of limit-state exceedance [1]. From the fragility curve analysis, the assessment of vulnerability of tower building can be done and it can be used as a decision making tool whether or not to allow to construct these RC mounted communication tower structures. Also the effect of positioning and mass of tower with respect to seismic vulnerability can help house owner for informed decision-making in the design and placement of telecommunication towers .

1.2 Need of research

Addition of telecommunication tower at any time frame in the life span of RC residential building may result in increase in the vulnerability of the structural system. Building code of Nepal does not provide set of guidelines associated with the construction of RC buildings with roof mounted tower structures. Hence, it becomes necessary to analyze the increase in seismic vulnerability of the buildings mounted with telecommunication tower. Time history analysis provides a more accurate reaction from the structures since they respond to genuine ground motion data.A more accurate seismic evaluation will be possible using nonlinear time history analysis and probabilistic analysis. So, there is a need of research for evaluating the rise in vulnerability of buildings mounted with communication tower. Also, the effect of tower mass and positioning on seismic vulnerability needs to be ascertained.This understanding is crucial for informed decision-making in the design and placement of telecommunication towers in relation to residential structures.

1.3 Objectives

- To determine the seismic vulnerability of RC buildings with and without roof mounted telecommunication tower structure.
- To assess the effect of positioning and mass of telecommunication tower on seismic vulnerability of residential RC buildings.

2. Literature Review

The seismic responses of the triangular tower located at G+6 and G+10 story were found least for the model where the triangular tower was centrally positioned[2]. In a related study, it was observed that on a G+2 building with three ground motions for tower, building and tower on building, there was only a small difference in natural frequencies of both building and building with tower .The study indicated that all three possibilities of responses, i.e., the response can drastically increase or responses being similar to original structure or response of building can decrease after installation of communication tower[3].The Seismic amplification effects on rooftop telecommunication tower was observed in a study. It was found that small magnitude earthquake acceleration at ground can lead to large accelerations on the tower at roof[4]. For a typical G+5 story commercial building, it was observed that significant loads on RC structure were introduced by addition of rooftop tower and proper design check of the RCC structural member is needed before installation of tower structure on existing building. Also the results suggested that tower design cannot be based on analytical results obtained for similar configurations situated at ground level. Similar study suggested that inclusion of heavy antenna masses in the analysis showed conservative member forces being developed. However, modern digital transmission antenna being very small in size and lightweight, the effect can be negligible[5].A study of amplification factor recommended maximum rooftop acceleration amplification factor of 4 for low and medium rise buildings and 3 for flexible high rise buildings[6].Also, simply lumping the tower mass at roof level of the building underestimates the force and moment developed at member of building. It was found that installation of tower at rooftop makes the building more vulnerable to earthquake[7].The HAZUS manual purposed detail methodology for earthquake loss estimation using earthquake model. It Provides special procedures and guidelines for fragility curve development for Slight, Moderate, Extensive and Complete damage states[8].

3. Methodology

At initial phase of this study, number of residential buildings with roof top mounted telecommunication tower in Jhapa district are surveyed. These buildings are regular in plan dimensions as shown in Figure 3. This survey helped for the assumption of the tower parameters, sizes and dimensions and also beam column sizes for modeling . The sizes of beam, column, slab thickness is taken from the reference of the initial survey and also with reference to NBC 205: 1994 Ready To Use Guideline for Detailing Of Low Rise Reinforced Concrete Buildings Without Masonry Infill[9].The building modeling parameters is as shown in Table2.

In this study a symmetric RC frame is considered. The number of bays in X and Y directions are taken as symmetric. For this study G+2, G+3 and G+4 residential building models with and without roof mounted telecommunication tower structure are studied. Modeling is done using ETABS2020v21.Beams and Columns are modeled as frame elements and slabs as shell element.The connection of tower and rooftop is made rigid. The design of 3 story,4 story and 5 story residential building is done by response spectrum method as per NBC105:2020[10]. Then, roof mounted communication tower structure as defined in Table 3are located at two different positions, i.e., one at center and other at corner of symmetrical grid system. Linear static analysis and linear modal response spectrum analysis are done for design purpose, and nonlinear time history analysis is done to determine the maximum top floor displacements and maximum inter story displacements for accessing vulnerability of building.For non linear modeling, plastic hinges are assigned to beams and columns as per ASCE41-17[11] at a relative distance of 10% from each ends.

All real earthquake data are chosen for the study and no artificial data are generated. The earthquake data are downloaded from Pacific Earthquake Engineering Research (PEER) Center databases. Seven ground motions are selected as shown in Table 1 and both horizontal component of ground motion are considered during analysis and no vertical ground motion is considered. The ground motions are selected based on the principle that selected ground motions contain wide range of frequency content. These ground motions are downloaded without scaling, that they are as they are in the databases. Then they are matched scaled to the target spectrum of the selected site that is Damak city using Seismo match version 2023 . In this study,target response spectrum for soft soil(Type C), seismic Zone factor 0.3, Overstrength factor(ωu) 1.5 at 5% damping, provided as per NBC 105:2020 is used. The target spectrum is then scaled to various PGAs at interval of 0.2g from 0.2g to 1g, which are needed for carrying out the incremental dynamic analyses. Bidirectional earthquake load cases for fast non linear analysis is used for various levels of PGAs so that logarithmic interpolation can be done at 0.05g intervals of PGAs. The median values of displacement and beta values were taken form HAZUS 4.2 SP3[8] for moderate code seismic design level.The peak ground acceleration(PGA) value for Damak City is 0.3g, so comparisons of vulnerability through fragility curves are done at 0.3 g PGA value.The details of modeling parameters are as tabulated.

Table 1: Selected Ground Motions

Earthquake	Year	Magnitude	PGA	Mechanism
Northridge	1994	6.69	0.44g	Reverse
Chi-Chi	1999	7.62	0.25g	Rev. oblique
Chuetsu	2007	6.8	0.11g	Reverse
Darfield	2010	7.0	0.16g	Strike Slip
Italy	1980	6.9	0.07g	Normal
Landers	1992	7.28	0.28g	Strike Slip
San Fernando	1971	6.61	0.15g	Reverse

Table 2: Building Modeling Parameters

Bays in X dirn	3
Bays in Y dirn	3
Bay length	3m
No. of story	3,4,5
Story height	3.35m for Ground story 3.0 m for Other story
Beam Size	355mm*230mm for 3 story 400mm*230mm for 4 story 500mm*230mm for 3 story
Column Size	300mm*300mm for 3,4 story 330mm*330mm for 5 story
Concrete	M25
Steel	HYSD 415
Slab thickness	125mm
Response Reduction Factor	4
Seismic Zone Factor	0.3(Damak)
Soil Type	C
Importance Factor	1

Table 3: Tower Description

Tower Type	4 legged
Length at bottom	2m
Length at top	2m
Breadth at bottom	2m
Breadth at top	2m
Total no. of level	4
Height of each level	2.7m
Material	Steel(FE250)
Mass of tower	1126.63 kg
Horizontal member	ISA 45*45*4 mm
Vertical Diagonal member	ISA 75*75*5 mm
Tube(Vertical Member)	Ext.dia.90mm,thickness8 mm

Table 4: Loading

Live load in floors	2KN/m2
Live load in roof	1.5KN/m2
Floor finish	1.5KN/m2
Wall 9" load	14.7KN/m
Wall 4.5" load	7.35KN/m
Wall parapet load	2.2KN/m
Height of each level	2.7m

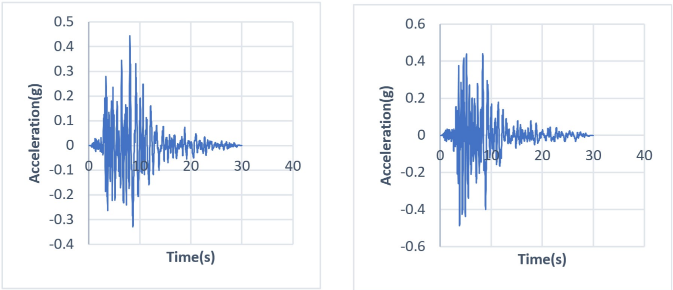


Figure 1: Earthquake GM of Northridge in X and Y

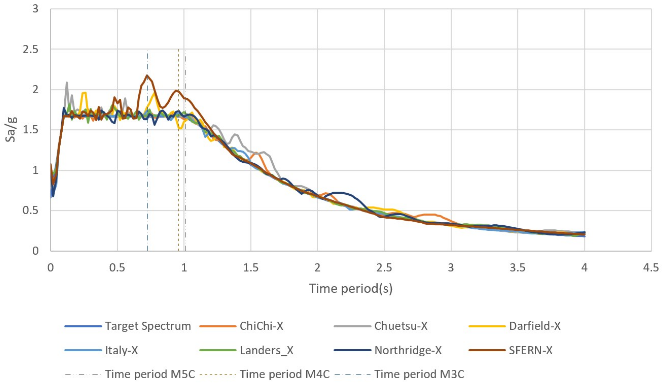


Figure 2: Matched Response spectrum in X

Table 5: Model details

Model	Description
M3	3 story without tower
M3C	3 story tower at center
M3COR	3 story tower at corner
M3C(x)	m3c model,mass of tower factored x times
M3COR(x)	m3cor model,mass of tower factored x times
M4	4 story without tower
M4C	4 story tower at center
M4COR	4 story tower at corner
M5	5 story without tower
M5C	5 story tower at center
M5COR	5 story tower at corner

Table 6: Damage States for Moderate Code Design Level for C1L building type[8]

Damage States	Displacement(mm)	Beta
Slight	22.86	0.89
Moderate	39.624	0.90
Extensive	106.68	0.90
Complete	274.32	0.88

Table 7: Damage States for Moderate Code Design Level for C1M building type[8]

Damage States	Displacement(mm)	Beta
Slight	38.1	0.69
Moderate	39.624	0.69
Extensive	106.68	0.69
Complete	274.32	0.90

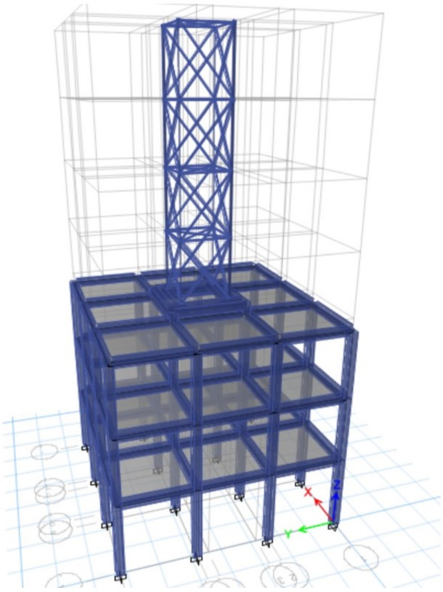


Figure 3: M3C Model 3D view

4. Results

In this study, maximum story displacement, maximum story drift, fundamental period of oscillation and story shear for linear static analysis are compared for with and without roof mounted telecommunication tower structure for residential RC buildings. From the non linear time history analysis(FNA), the maximum story drift ratios and maximum displacement of top story are the output parameters considered as these response data are used for the fragility curve development.

4.1 Maximum displacement

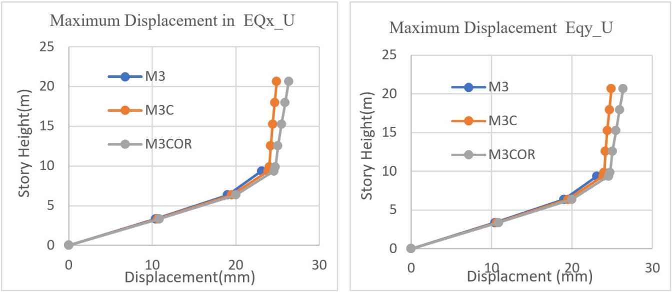


Figure 4: Maximum floor displacement for 3 story model

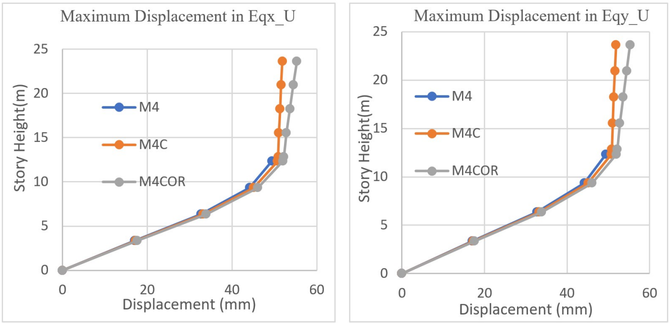


Figure 5: Maximum floor displacement for 4 story model

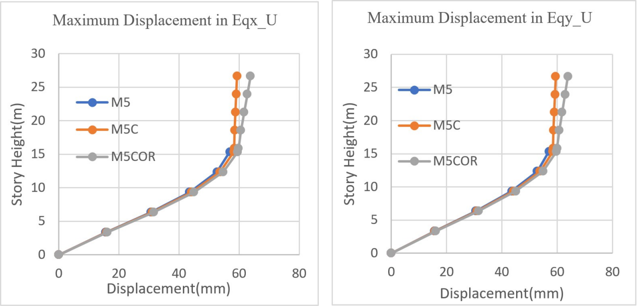


Figure 6: Maximum floor displacement for 5 story model

The maximum displacement in X and Y direction showed almost the same result as the model is symmetric. The maximum displacement along X direction is found to increase by 3.9% and 7.13% for M3C and M3COR model w.r.t. M3 model.The same is 2.66 % and 5.18 % for M4 model and 2.38% and 4.66% for M5 model. This indicates that eccentrically placed tower have highest maximum displacement.

4.2 Maximum story drift

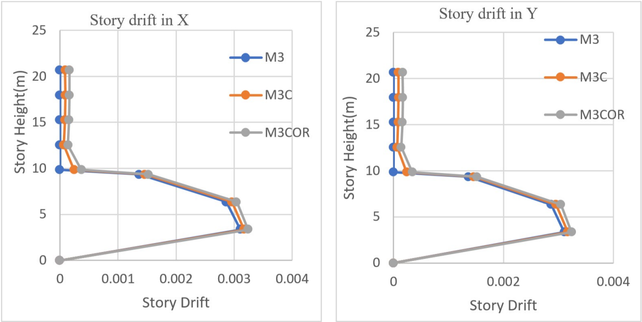


Figure 7: Maximum story drift for 3 story model

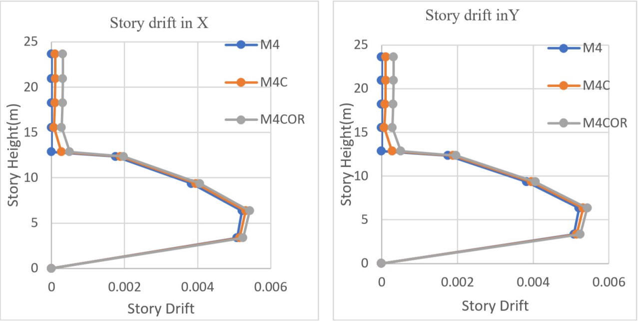


Figure 8: Maximum story drift for 4 story model

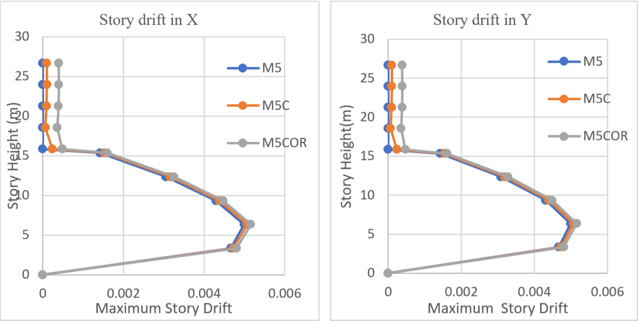


Figure 9: Maximum story drift for 5 story model

All the models are well under Ultimate limit state and serviceability limit state for story drift ratio as per NBC 105:2020. Maximum drift ratio is found for model with telecommunication tower at corner and minimum for model without telecommunication tower. For 3 story structure, maximum drift ratio occurred at story one and at story two for 4 and 5 story building.

4.3 Maximum story shear

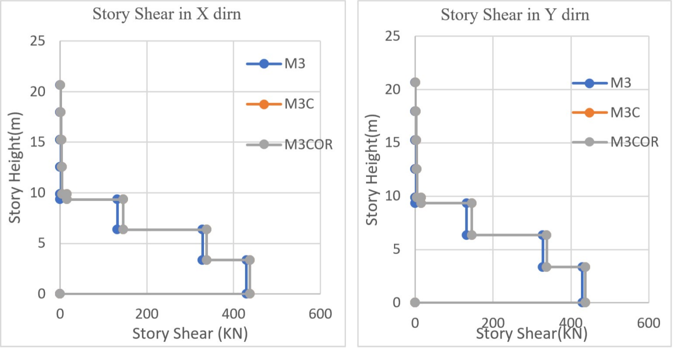


Figure 10: Maximum story shear for 3 story model

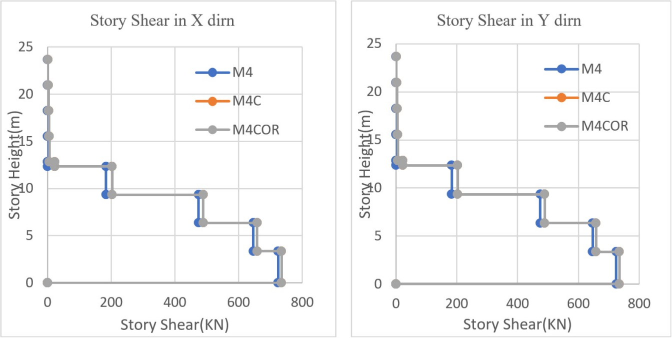


Figure 11: Maximum story shear for 4 story model

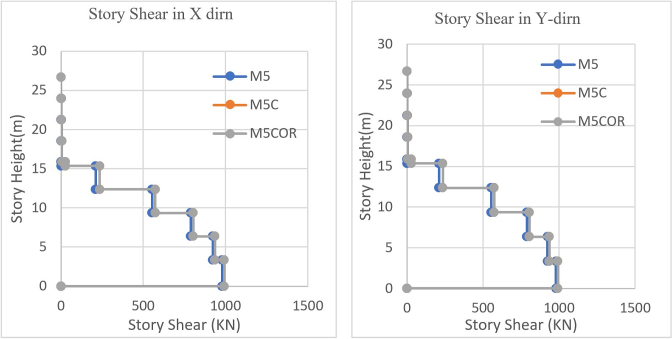


Figure 12: Maximum story shear for 5 story model

The story shear of telecommunication tower mounted structure is found slightly higher than that of bare frame structure. This is due to additional weight of the tower system that gets added upon the mass source that participates in the seismic event. No difference in base shear of the structure due to positioning of the telecommunication tower is observed as the seismic mass that participates in seismic event is same irrespective of its position.

4.4 Time Period

Fundamental time period of the building increases by 1.81% and 1.95% for M3C and M3COR model w.r.t.M3 model.The same increases by 1.26% and 1.47 % for M4C and M4COR model w.r.t M4 model and increases by 1.2% and 1.3 % for M5C and M5COR model w.r.t M5 model. Only Slight increase in fundamental period of vibration observed as the mass of tower is negligible w.r.t mass of building. However, model direction factor has significant redistribution for eccentrically placed tower structure indicating increase in eccentricity.

4.5 Fragility Analysis

The IDA curves showing the PGAs values in Y axis and drifts in X axis is shown for M3,M3C and M3COR model

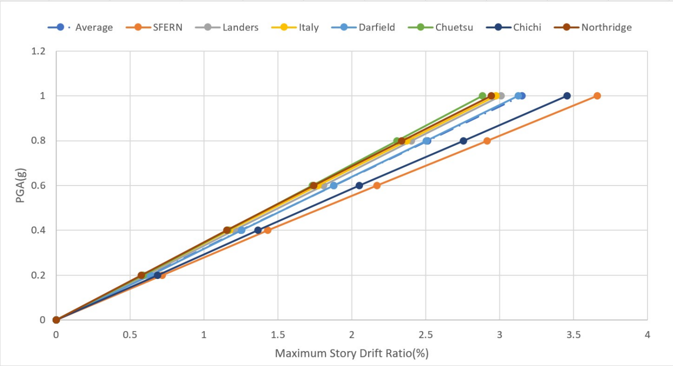


Figure 13: IDA curves for M3 model

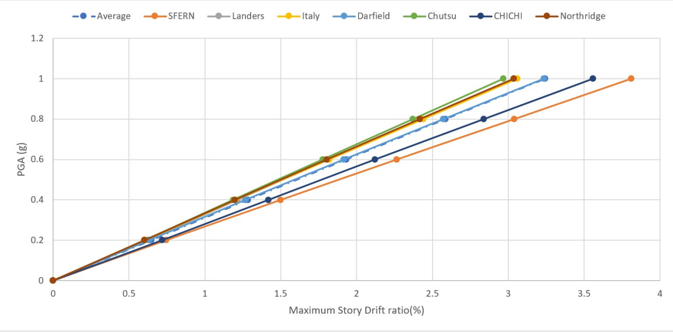


Figure 14: IDA curves for M3C model

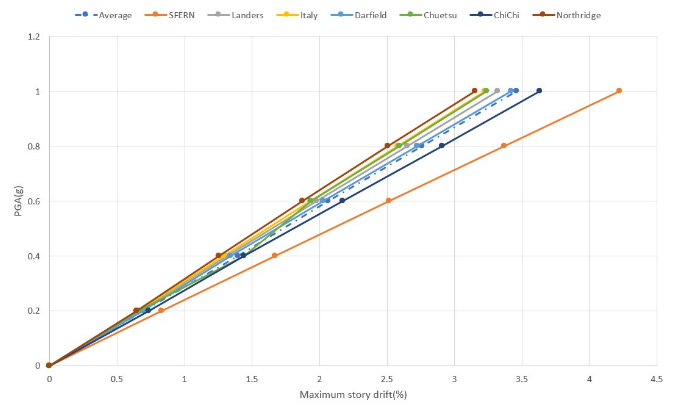


Figure 15: IDA curves for M3COR model

Table 8: PGA at 2.5% drift for Average GM

Model	PGA at 2.5% drift
M3	0.7956g
M3C	0.7729g
M3COR	0.7252g
M4	0.6176g
M4C	0.6096g
M4COR	0.5956g
M5	0.7184g
M5C	0.7082g
M5COR	0.6757g

The same value of drift ratio is attained at lower PGA values for eccentrically placed tower structure than that of tower placed at center of rooftop. The PGA value is highest for structure without telecommunication tower to attain 2.5% drift ratio.This indicates the increase in vulnerability of the as tower is introduced and being more vulnerable when its placed at corner of the rooftop.

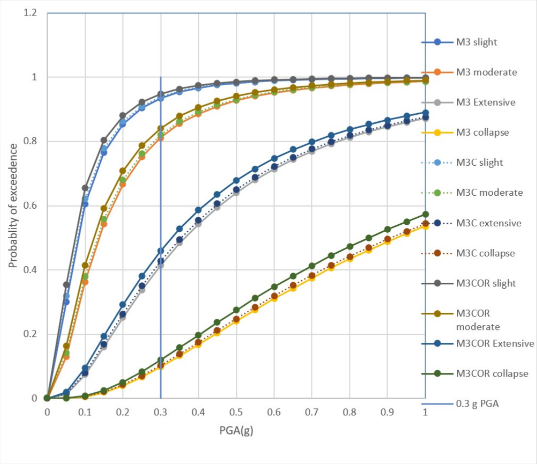
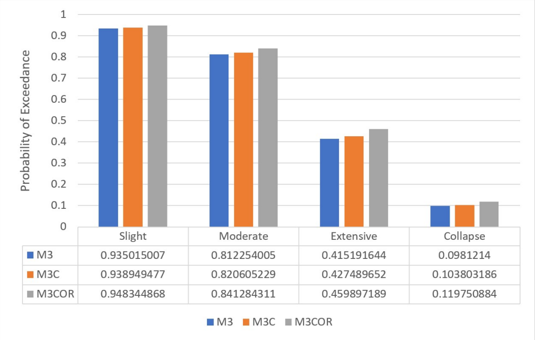


Figure 16: Fragility Curve comparison for 3 story model



	Slight	Moderate	Extensive	Collapse
■ M3	0.935015007	0.812254005	0.415191644	0.0981214
■ M3C	0.938949477	0.820605229	0.427489652	0.103803186
■ M3COR	0.948344868	0.841284311	0.459897189	0.119750884

Figure 17: Probability of exceedance for 0.3 PGA for 3 story Residential RC building

For 3 story RC building, at 0.3 g PGA, with reference to M3 model, the percentage increase in vulnerability are 0.41 % and 1.42 % for Slight damage state, 1.02 % and 3.57 % for moderate, 2.96 % and 10.766 % for extensive and 5.79% and 22% for complete damage state respectively for M3C and M3COR model.The increase in vulnerability is significantly more pronounced in situations involving extensive and complete collapse damage states.

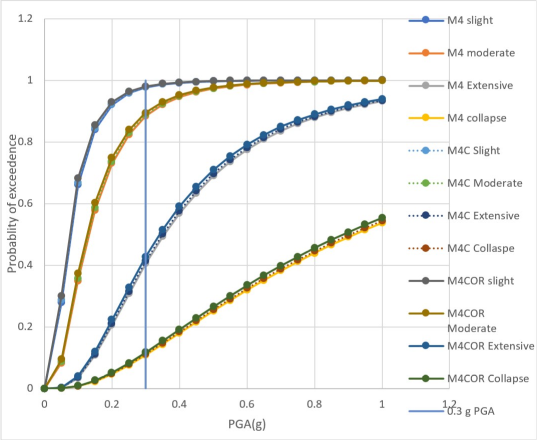
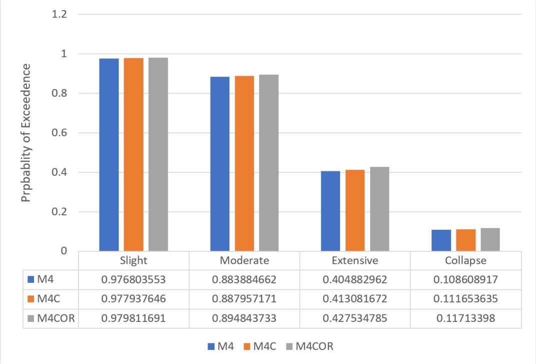


Figure 18: Fragility Curve comparison for 4 story model



	Slight	Moderate	Extensive	Collapse
■ M4	0.976803553	0.883884662	0.404882962	0.108608917
■ M4C	0.977937646	0.887957171	0.413081672	0.111653635
■ M4COR	0.979811691	0.894843733	0.427534785	0.11713398

Figure 19: Probability of exceedance for 0.3 PGA for 4 story Residential RC building

For 4 story RC building, at 0.3 g PGA, with reference to M4 model, the percentage increase in vulnerability are 0.12 % and 0.30 % for Slight damage state, 0.46 % and 1.24 % for moderate, 2.02 % and 5.59 % for extensive and 2.80% and 7.84% for collapse damage state respectively for M4C and M4COR model.

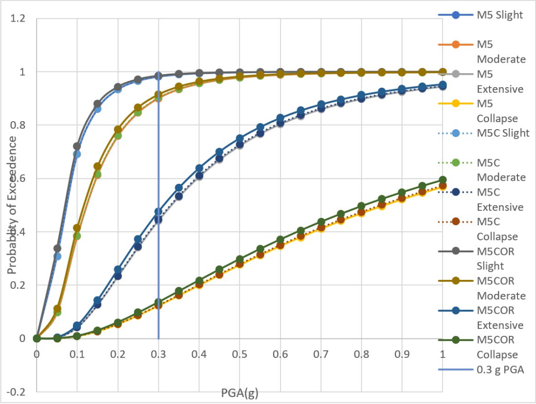


Figure 20: Fragility Curve comparison for 5 story model

For 5 story RC building, at 0.3 g PGA, with reference to M5 model, the percentage increase in vulnerability are 0.052% and 0.36 % for Slight damage state 0.221% and 1.58% for moderate, 1.03% and 7.77% for extensive and 1.47% and 11.42% for collapse damage state respectively for M5C and M5COR model.

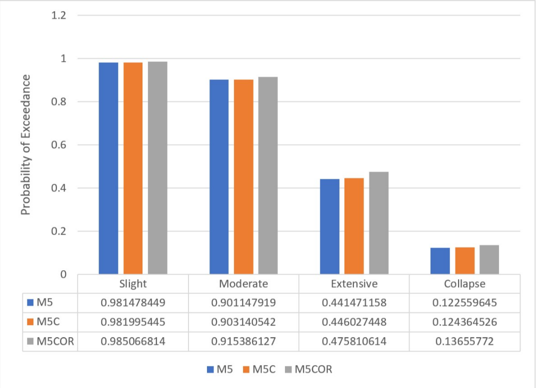


Figure 21: Probability of exceedance for 0.3 PGA for 5 story Residential RC building

4.6 Effect of mass of tower on vulnerability of 3 story building

Mass of tower for three story building is increased by two, four, six, eight and ten times respectively for central and corner positioning and for each increment of mass of tower, FNA is done considering all earthquakes at 0.2 g, 0.4g, 0.6g, 0.8g, and 1g PGA.

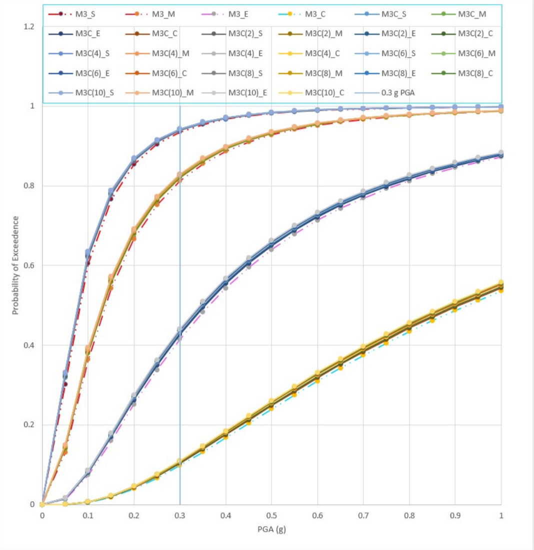


Figure 22: Fragility curve comparison for 3 story(tower at center) with factored mass of tower

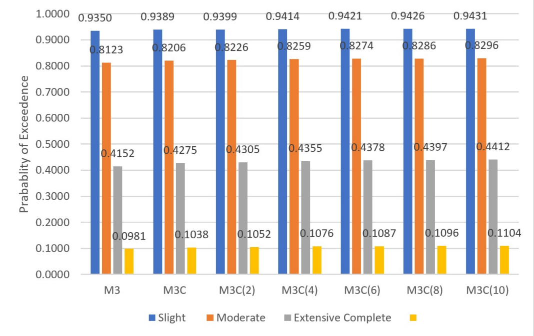


Figure 23: Probability of exceedance for 0.3 g PGA for 3 story building with factored tower mass mounted at center.

The probability of exceedance of slight and moderate damage states for 3 story building with tower mounted at center showed very slight effect w.r.t increase in mass of the tower.The same is quiet more significant for extensive and complete collapse damage states.

Table 9: % increase in vulnerability w.r.t. M3C model

Model	slight	Moderate	Extensive	Collapse
M3C(2)	0.11%	0.24%	0.7%	1.34%
M3C(4)	0.27%	0.65%	1.87%	3.66%
M3C(6)	0.34%	0.83%	2.41%	4.72%
M3C(8)	0.39%	0.97%	2.85%	5.59%
M3C(10)	0.45%	1.1%	3.21%	6.36%

Mass of tower is increased by increasing the mass density of the tower material.Finally,fragility curve is generated for each case and compared.

The probability of exceedance of all the damage states for 3 story building with tower mounted at corner showed significant effect w.r.t increase in mass of the tower.

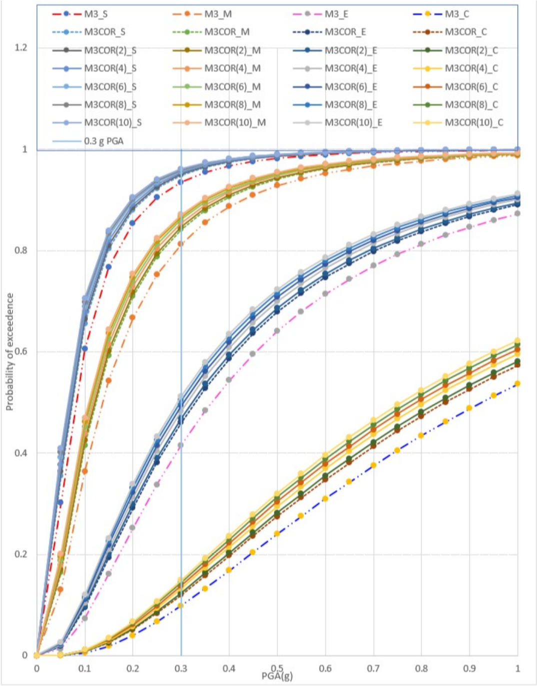


Figure 24: Fragility curve comparison for 3 story(tower at corner) with factored mass of tower

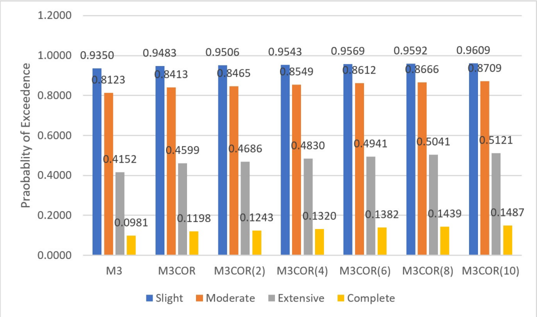


Figure 25: Probability of exceedance for 0.3 g PGA for 3 story building with factored tower mass mounted at corner

Table 10: % increase in vulnerability w.r.t. M3COR model

Model	slight	Moderate	Extensive	Collapse
M3COR(2)	0.24%	0.62%	1.89%	3.75%
M3COR(4)	0.63%	1.62%	5.02%	10.18%
M3COR(6)	0.91%	2.37%	7.44%	15.35%
M3COR(8)	1.15%	3.00%	9.61%	20.12%
M3COR(10)	1.32%	3.52%	11.35%	24.12%

5. Conclusion

Fragility curve indicates the increase in vulnerability of the RC structure for corner placed tower structure than for centrally placed tower structure. The model having no telecommunication tower is found to be least vulnerable in seismic event. The percentage increase in vulnerability was found higher for 3 story building. This is because of the inherent stiffness of the building as lower section sized structural members were used for 3 story building. This indicates poorly designed building are more vulnerable because of the introduction of the tower structures. The same value of drift ratio is attained at lower PGA values for eccentrically placed tower structure than that of tower placed at center of rooftop. The structural dynamics and vulnerability of the building are highly responsive to changes in the mass of the tower, particularly when the tower is positioned at the corner of the structure. Essentially, the location of the tower introduces a heightened sensitivity to variations in mass, amplifying the structural effects. Also, the influence of an increased tower mass becomes significantly more pronounced in situations involving extensive and complete collapse damage states. For 3 story residential RC building, corner placed tower structure is more vulnerable than centrally placed tower structure with mass of tower factored ten times.

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