

Influence of Wind Forces on the Seismic Vulnerability of Tall RC Buildings

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Abstract— The forces they encounter critically influence tall buildings' structural integrity, making their design a complex and challenging task. Designing tall RC buildings presents significant challenges due to the complex forces they endure. Both wind and seismic loads contribute to the nonlinear behaviour of these structures. This study explores the impact of wind loading on tall RC buildings' seismic performance by analysing wind speed variations. Three buildings, with heights of G+25, G+30, and G+35 stories, located in seismic Zone II, are evaluated under wind speeds of 33 m/s, 44 m/s, and 55 m/s. The analysis incorporates dynamic wind effects within a nonlinear static framework. Seismic fragility curves are developed for each case, and the vulnerability of the structures is assessed through the evaluation of the damage index. The G25WL55 model exhibits the highest collapse probability at the performance point, reaching 9.2%, with a seismic vulnerability index of 2.23.

Index Terms— Dynamic wind, Inter storey drift ratio, Pushover analysis, Fragility curve.

I. INTRODUCTION

In recent decades, the proliferation of tall buildings in urban areas has been driven by their economic viability and eco-friendly attributes. However, as these structures reach greater heights and become more slender, the impact of seismic and wind loads on their design and assessment has increased. A robust structural system for wind resistance is characterised by its solidity, weightiness, and strong connections, which effectively counteract wind forces acting on the building [20]. In contrast, seismic loading subjects the building to cyclic stresses, as its inertia synchronises with ground movements, requiring designs that can dissipate seismic energy through damping and yielding mechanisms. Conventional design codes often prioritise wind loads in regions with strong winds, but research indicates that actual seismic demands can surpass those estimates. To understand that, it is important to evaluate the seismic performance of buildings designed primarily for wind resistance [1, 2].

The performance-based design was implemented using pushover analysis to assess the building's performance under the specified loading conditions [17, 21]. Numerous studies have successfully evaluated various structures by applying performance-based design methodologies [16, 18]. The outcomes of the pushover analysis were employed to conduct a seismic assessment, explicitly determining the probability of exceedance for particular damage states when wind effects were included in the evaluation of seismic performance [20]. Subsequently, several methods were established to derive fragility curves [11, 13].

The present study examines the seismic performance of G+25, G+30, and G+35 storey tall buildings subjected to static wind, dynamic wind for 33 m/s, 44 m/s, and 55 m/s wind speeds, and static earthquake loading. All buildings' nonlinear behaviour is then obtained by performing a nonlinear static pushover analysis. The fragility assessment is conducted to evaluate the probability of exceedance of the damage state.

II. DETAILS OF THE BUILDING PROBLEM

The RC tall buildings of G+25, G+30 and G+35, including shear walls, are 3.5 m and 3 m of ground floor and typical floor heights, respectively, for the building plan are shown in Fig. 1. Buildings are loaded with 3.15 kN/m² dead load (considering 125 mm thickness) and 2 kN/m² as the live load of a slab [7]. The wall load on the beam are assumed to be 7 kN/m. Table I shows that the building's model IDs are assigned based on the wind loading applied to them. The RC buildings are assumed to be constructed on hard/rock soil of seismic zone-II (PGA= 0.36-g) with importance factor 1 and response reduction factor 5 as per BIS 1893 (Part-1), 2016 [6]. The fundamental time period of these frames is designed for a 5% damped response spectrum, and ductile detailing is incorporated using BIS 13920 (2016) [5].

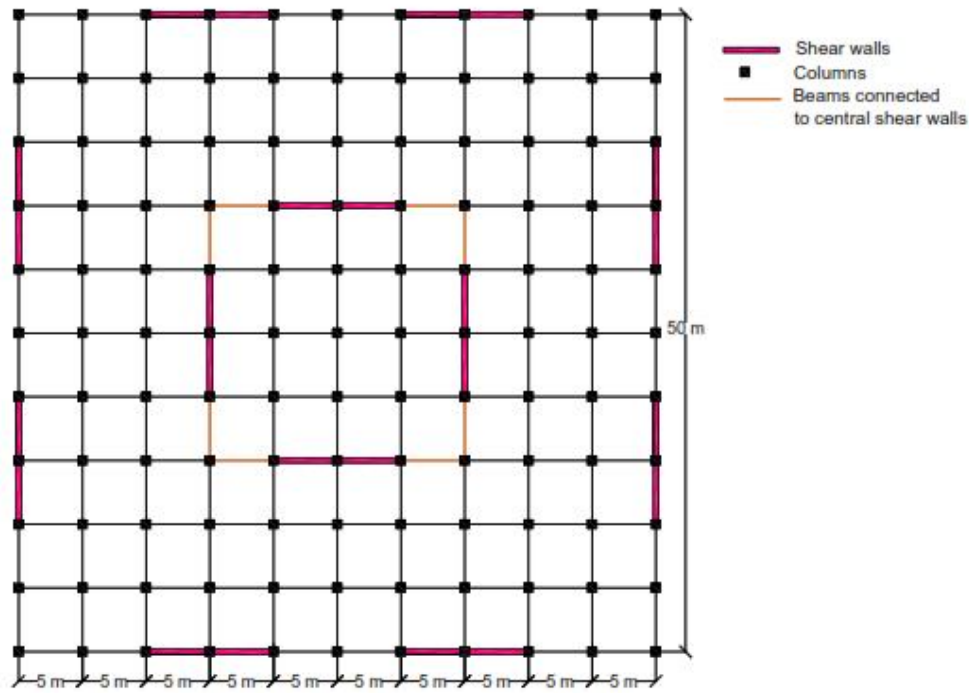


Figure 1. Plan of RC Buildings Considered in the Present Study

A. Dynamic Wind Loading

Tall buildings shall be designed for dynamic wind by multiplying the gust factor with the design hourly mean wind pressure [8]. All building structures in the present study are considered under the dynamic wind loading along and across wind direction for three types of wind speeds. The design along wind load and wind base bending moment at height z is obtained using equations (1) and (2), respectively.

$$F_{z, \text{along}} = C_{f,z} A_z \bar{P}_d G \quad (1)$$

$$M_{\text{along}} = \sum F_z Z \quad (2)$$

$C_{f,z}$ denotes the drag force coefficient of the building, A_z is the effective frontal area, $\bar{P}_d$ represents the design hourly mean wind pressure and G gust factor as per IS 875 part 3, 2015.

The design across wind base bending moment and wind load at height z is obtained using equations (3) and (4), respectively.

$$M_{\text{across}} = 0.5 g_h p_h b h^2 (1.06 - 0.06k) \sqrt{\left(\frac{\pi C_{fs}}{\beta}\right)} \quad (3)$$

$$F_{z, \text{across}} = \left(\frac{3M_{\text{across}}}{h^2}\right) \left(\frac{Z}{h}\right) \quad (4)$$

g_b denotes peak factor, b represents breath of the building normal to wind, h is the height of a building, k represents mode shape power exponent, C_{fs} is across wind force spectrum coefficient, and β is the damping coefficient of a building.

Table II shows the calculations to obtain the dynamic wind forces and the moment at each floor for the building model G25WL55. The reinforcement of the building structures, along with material and sectional details, are listed in Table III for all considered building models. Fig. 2 represents the inter-storey drift ratio observed at various floor levels due to earthquake and wind loading in various building models.

TABLE I. BUILDING MODEL IDS CONSIDERED IN THE PRESENT STUDY

Model ID	Floors	Building height (m)	Wind speed (m/s)
G25WL33	G+25	$3.5 + 3(25) = 78.5$	33
G25WL44		$3.5 + 3(25) = 78.5$	44
G25WL55		$3.5 + 3(25) = 78.5$	55
G30WL33	G+30	$3.5 + 3(30) = 93.5$	33
G30WL44		$3.5 + 3(30) = 93.5$	44
G30WL55		$3.5 + 3(30) = 93.5$	55
G35WL33	G+35	$3.5 + 3(35) = 108.5$	33
G35WL44		$3.5 + 3(35) = 108.5$	44
G35WL55		$3.5 + 3(35) = 108.5$	55

TABLE II. GUST FACTOR CALCULATION OF THE G25WL55 MODEL

Floor	Storey height (m)	G	$C_{f,z}$	P_z (N/m ²)	Along wind response		Across wind response	
					$F_{z,along}$ (kN)	M_{along} (kNm)	M_{across} (kNm)	$F_{z,across}$ (kN)
25	75	2.059	1.3	2.224	446.45	33484.09	381317.75	203.37
24	72	2.056	1.3	2.211	886.32	63814.90	349368.35	178.88
23	69	2.053	1.3	2.198	879.97	60717.81	318979.90	156.51
22	66	2.051	1.3	2.185	873.87	57675.68	290129.61	136.17
21	63	2.049	1.3	2.172	868.05	54687.28	262794.79	117.73
20	60	2.048	1.3	2.160	862.52	51751.30	236952.89	101.10
19	57	2.048	1.3	2.147	857.30	48866.34	212581.48	86.17
18	54	2.048	1.3	2.134	852.43	46030.95	189658.24	72.83
17	51	2.050	1.3	2.121	847.91	43243.56	168161.00	60.99
16	48	2.052	1.3	2.099	840.14	40326.80	147425.48	50.32
15	45	2.056	1.3	2.073	831.01	37395.34	127951.84	40.94
14	42	2.060	1.3	2.047	822.38	34540.16	110056.80	32.87
13	39	2.066	1.3	2.021	814.32	31758.42	93693.44	25.98
12	36	2.074	1.3	1.995	806.86	29047.12	78815.41	20.18
11	33	2.083	1.3	1.970	800.09	26403.07	65376.87	15.34
10	30	2.094	1.3	1.944	794.09	23822.79	53332.56	11.38
9	27	2.108	1.3	1.914	786.91	21246.64	42525.86	8.16
8	24	2.125	1.3	1.884	780.78	18738.68	33072.70	5.64
7	21	2.146	1.3	1.854	775.90	16293.98	24920.25	3.72
6	18	2.172	1.3	1.805	764.31	13757.52	17822.92	2.28
5	15	2.204	1.3	1.747	750.58	11258.72	11978.15	1.28
4	12	2.245	1.3	1.671	731.33	8775.92	7332.15	0.63
3	9	2.301	1.3	1.621	727.12	6544.06	4001.45	0.26
2	6	2.382	1.3	1.621	752.92	4517.53	1778.42	0.08
1	3	2.527	1.3	1.621	798.80	2396.40	444.61	0.01
0	0	2.059	1.3	2.224	446.45	33484.09	381317.75	203.37

B. Nonlinear Static Pushover Analysis

Unlike linear methods, which assume a constant relationship between loads and displacements, nonlinear pushover analysis accounts for the building's stiffness and strength changes as it deforms [9]. This allows for a more realistic assessment of a structure's performance under actual seismic events, capturing critical aspects such as materials yielding, forming plastic hinges, and overall structural behaviour beyond the elastic range.

The analysis is conducted using the MIDAS Gen, 2024 analytical tool [14], in which the plastic hinges for beam and column elements are generated using ASCE 41 (2017) and FEMA 356 (2000) [3, 10]. The plastic hinges for beam, column and shear wall elements are similar in every building structure [4, 17, 19].

Fig. 3 represents a capacity curve generated by performing nonlinear static pushover analysis, which plots the relationship between base shear and roof displacement.

TABLE III. ELEMENT DETAILS ADOPTED IN ALL STUDIED BUILDING MODELS

Elements	Grade	Size (mm)	Location	Reinforcement (%)
Beam	M25	300X800	Connected to a central shear wall in plan	1.5-2
		300X500	location other than the above	
Columns	M30	1200 x 1200	Ground floor-8	2-3
		1000 x 1000	9-15	
		800 x 800	16-21	
		600 x 600	22-top floor	
Shear wall	M30	300	Ground floor-8	0.5-1
		230	9-top floor	

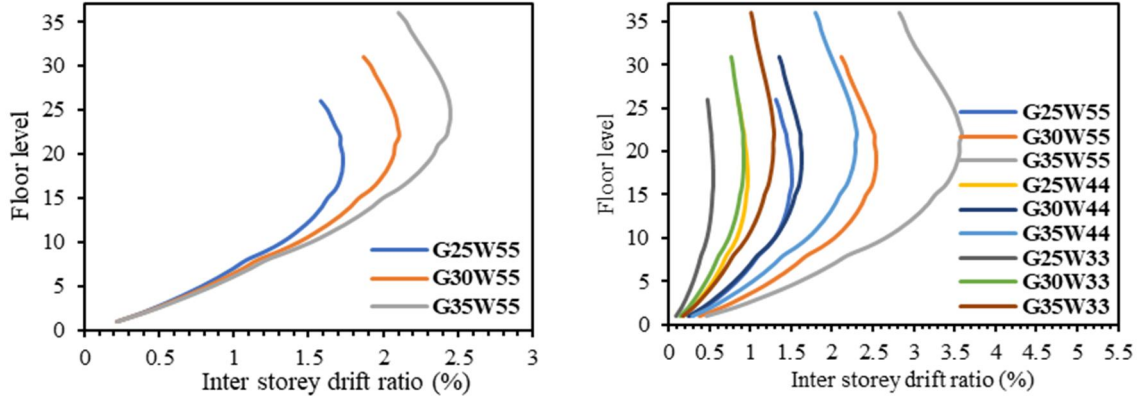


Figure 2. Inter Storey Drift Ratio at Various Floor Levels in a Studied Building Due to Static (A) Earthquake and (B) Wind Forces

C. Seismic Performance Assessment

The derived fragility curves for different levels of damage and utilised this translated spectral displacement. These curves represent the probability of achieving or surpassing a specific damage state based on a parameter that reflects the seismic activity impacting the building. As demonstrated in equation (5), the lognormal probability distribution is commonly applied to model these fragility curves accurately [15].

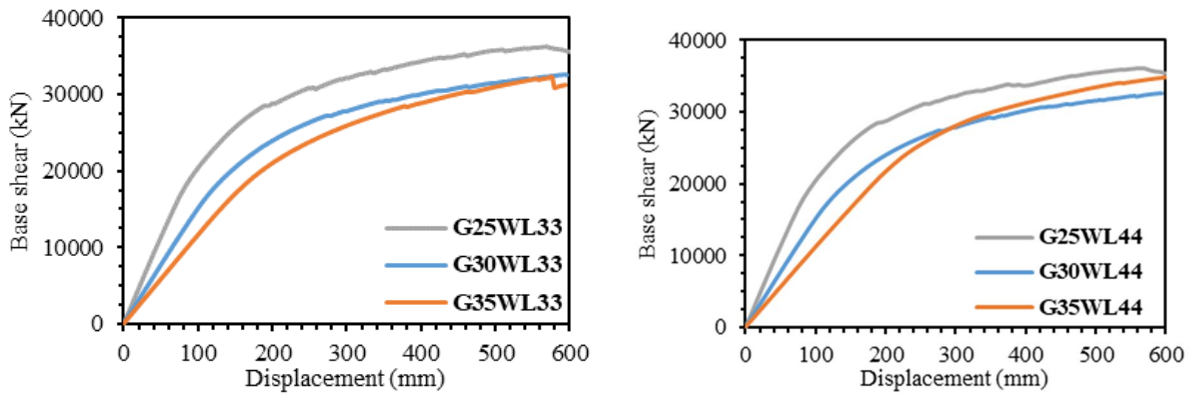
$$P_K(S_D) = \Phi \left[\frac{1}{\beta_K} \ln \left(\frac{S_D}{S_{D,m}} \right) \right] \quad (5)$$

S_D denotes the spectral displacement, while $S_{D,m}$ signifies the mean spectral displacement. β_K represents the standard deviation of the natural logarithm of spectral displacement for different damage levels, and Φ corresponds to the standard normal cumulative distribution function. The threshold values for the various damage states are provided in Table IV.

Damage likelihood matrices are defined as the weighted average damage index (DS_x) for the maximum likelihood of the RC frame building damage state i.e., seismic vulnerability, which can be derived from equation (6) [12].

$$DS_x = \sum_{i=1}^4 K P_K[N, d] \quad (6)$$

In this study, the value of k ranges from 1 to 4 for the damage grades analysed, with $P_K[N, d]$ indicating the corresponding probability of occurrence.



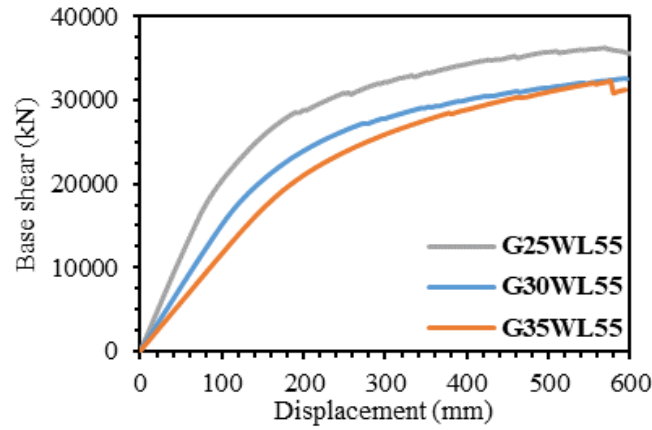


Figure 3. Pushover Curves of Various Rc Building Models

TABLE IV. THRESHOLD VALUES TO ESTIMATE DAMAGE FROM MEAN DAMAGE INDEX INTERVALS

More likely damage state	Damage state threshold	Mean damage index intervals
No-damage (S_{D0})	-	0.0-0.5
Slight (S_{D1})	$0.7*(S_{DY})$	0.5-1.5
Moderate (S_{D2})	S_{DY}	1.5-2.5
Severe (S_{D3})	$S_{DY} + 0.25 * (S_{DU} - S_{DY})$	2.5-3.5
Complete (S_{D4})	S_{DU}	3.5-4.0

S_{DY} = yield spectral displacement, S_{DU} = ultimate spectral displacement

III. RESULTS AND DISCUSSIONS

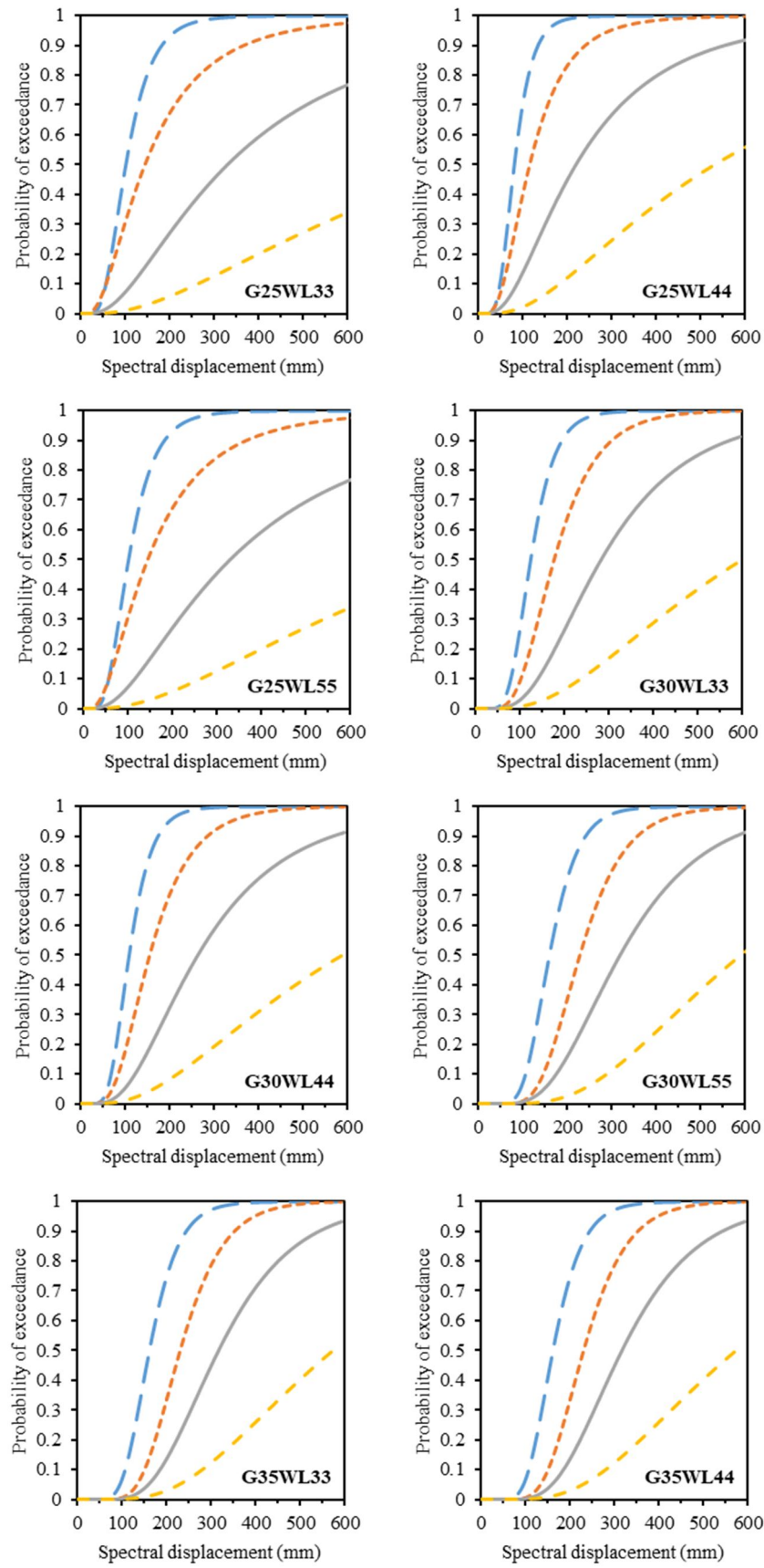
The current study investigates the impact of wind loading on the seismic damage of tall building structures. Specifically, buildings with heights corresponding to G+25, G+30, and G+35 stories are analysed under three different wind speeds. To enhance accuracy, the analysis incorporated both dynamic and static wind effects. In addition to wind loading, seismic loading is applied to all buildings, and their inter-storey drift ratios are determined. Subsequently, a nonlinear static pushover analysis is performed to assess the nonlinear behaviour of the buildings, which is then utilised to evaluate the probability of damage exceedance.

Fig. 4 illustrates the probability of exceeding different damage states for each building model. It is observed that this probability increases across all damage states as the building height increases. Furthermore, as wind speed intensifies, the probability of exceedance at the performance point also rises. Notably, the G25WL55 model exhibits the highest collapse probability at the performance point, reaching 9.2%. This finding suggests that lower-height buildings are more susceptible to collapse under higher wind speeds compared to buildings with higher heights.

The damage states reflect the mean damage index for each RC frame building, representing the most probable damage condition shown in Table V. All the building models observed moderate damage state. However, the G+25 building with 55 m/s wind speed observed a damage index of more than 2.

TABLE V. DAMAGE INDEX (DSx) AND DAMAGE STATE OF CONSIDERED BUILDING MODELS

Model ID	Spectral displacement (mm)					Uncertainty (β)				Damage Index (DSx)	Damage state
	S_{DP}	S_{D1}	S_{D2}	S_{D3}	S_{D4}	β_1	β_2	β_3	β_4		
G25WL33	201	100	144	330	888	0.45	0.73	0.82	0.95	1.96	Moderate
G25WL44	150	80	115	219	532	0.39	0.57	0.72	0.83	2.00	Moderate
G25WL55	252	100	144	330	888	0.45	0.73	0.82	0.94	2.23	Moderate
G30WL33	189	123	177	282	600	0.35	0.43	0.54	0.72	1.76	Moderate
G30WL44	183	108	155	263	590	0.36	0.47	0.60	0.77	1.92	Moderate
G30WL55	258	159	228	318	591	0.32	0.34	0.46	0.55	1.98	Moderate
G35WL33	222	161	231	317	576	0.32	0.33	0.41	0.56	1.57	Moderate
G35WL44	225	159	230	315	570	0.30	0.31	0.39	0.55	1.61	Moderate
G35WL55	279	161	230	285	453	0.30	0.27	0.33	0.40	1.77	Moderate



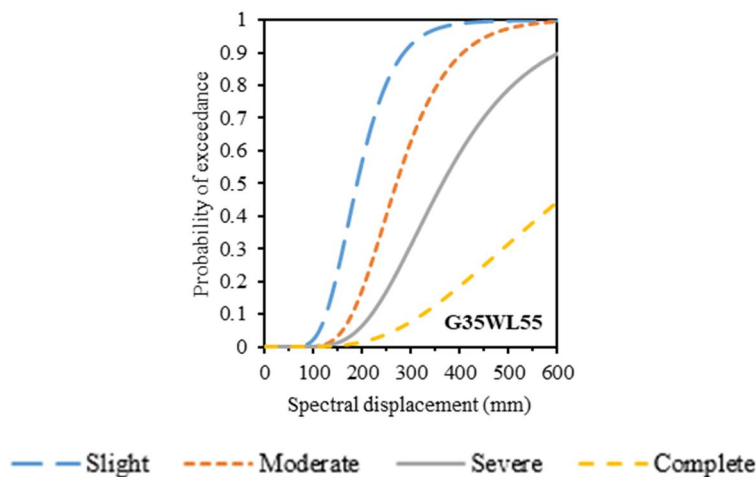


Figure 4. Seismic Fragility Curves Generated for Various Damage States

IV. CONCLUSIONS

In this study, nine building structures are analysed to assess the impact of wind loading on the seismic performance of tall buildings. Wind speeds of 33 m/s, 44 m/s, and 55 m/s were applied to G+25, G+30, and G+35 structures. The analysis of the nonlinear behaviour of these buildings facilitated the seismic fragility assessment. The fragility assessment indicated that all structures are in a moderate damage state. However, the G+25 building, with a wind speed of 55 m/s, exhibited the highest probability of collapse. The damage index in this case exceeded 2, indicating that tall buildings with more height are more susceptible to wind and earthquakes due to their greater flexibility.

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