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NONLINEAR SEISMIC ANALYSIS OF STEEL CONCRETE COMPOSITE STRUCTURES

[1]Hemant Chouhan, [2] Sumit Pahwa
[1]M.Tech Department of Civil Engineering Alpine Institute of Technology, Ujjain M.P.
[2] Associate Professor Department of Civil Engineering Alpine Institute of Technology, Ujjain M.P.

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Abstract: Reinforced concrete (R.C.) buildings are highly vulnerable to seismic failures due to soft story mechanisms and low ductility. Steel-concrete composite frames offer improved ductility, lateral load resistance, and energy absorption under seismic forces. This study investigates the seismic performance of steel-concrete composite buildings with and without masonry infill walls using a probabilistic fragility-based approach. A fifteen-story composite frame is analyzed in bare and infill configurations through non-linear static pushover analysis, and fragility curves are developed to assess damage probabilities at various performance levels.

The results demonstrate that composite infill frames significantly improve lateral stiffness, base shear capacity, and seismic resilience compared to bare frames. Incorporating masonry infill substantially reduces the probability of failure across all damage states. Additionally, seismic performance assessments of low-rise, mid-rise, and high-rise composite buildings using Incremental Dynamic Analysis (IDA) reveal that low-rise structures exhibit reduced dispersion and more predictable seismic responses.

This research highlights the effectiveness of masonry infill and composite construction in enhancing seismic safety and provides a valuable framework for performance-based seismic design in earthquake-prone regions.

Keywords*:* *Base Shear, Story Displacement, Story Drift, IS 800-2007, Response Spectrum Method*

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I.INTRODUCTION:

The soft story mechanism and low ductility are R.C. buildings' most frequent failure modes in high seismic zones. This results in localizing structures' seismic deformations and ruptures in one or two lower stories. The primary reason for such failure is the significant difference in column stiffness between the ground and the upper story. Many times, the collapse of buildings is observed after an earthquake. Such collapse behavior cannot be predicted at the design stage for many R.C. buildings. More precisely, some local brittle failure mechanisms occurred in the columns, generating complete collapse in most buildings, i.e., soft stories and low ductility caused 90% of failures in the earthquake. Hence, there is a need to resist lateral load efficiently and improve ductility for buildings situated in high seismic regions. This can be achieved by using steel concrete composite framed structures.

The current developments in the construction sector consist of steel, reinforced concrete, and steel-concrete composite structures collectively referred to as composite, mixed, or hybrid systems. These systems optimize the structural and economic benefits using each member type most efficiently. Composite structures have been widely used in skyscraper buildings and large-span facilities, particularly in the U.S., China, and Japan, over the last 20 years. The steel sections encased in concrete offer advantages like smaller sectional dimensions, higher load-carrying capacities, increased fire resistance, and superior seismic performance compared to reinforced concrete structures. The steel increases the ductility of composite construction, allowing it to absorb seismic energy applied to the system during earthquakes.

Because of the growing popularity and use of composite systems, frame analysis is required. On the other hand, system behavior still needs to be better understood. Hence, more research must be conducted to understand the non-linear seismic behavior of steel concrete composite frames. The non-linear analysis is an appropriate tool for better comprehending the system, particularly when the system is being excited by seismic activity. Unfortunately, many analysis software currently in use are best suited for simulating conventional steel or reinforced concrete structures; they must be applied to composite frames immediately. SAP 2000 and ETABS are used to analyze and design composite frames to understand non-linear behavior

II.OBJECTIVE

The objectives of the research work are as follows:

- To investigate the effect of infill walls on fragility curves and damage probability to improve lateral resistance and capacity of buildings.
- To investigate the effect of uncertainties in material strength and ground motion on structural behavior.
- To develop fragility curves and to predict the probability of different structural damage states.

III.FRAGILITY ANALYSIS FOR MASONRY INFILLED STEEL-CONCRETE COMPOSITE BUILDING

3.1Building Models

A 15-story composite frame structure with and without infill is considered for study. The floor height is 3.0m each, and the total height of the building is 45m; the plan and elevation of the structure are shown in Fig. 3.1. The roof and floor panels are assigned a thickness of 150mm. The concrete slabs are modeled as a shell element. The material properties are described in Table

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3.1. The live load intensity on all floors except the roof terrace is 3kN/m2. The live load intensity of 1.5kN/m2 on the terrace is considered. The intensity of floor finishes is taken as 1kN/m2. The roof water treatment is considered as 1.5kN/m2. The site is located in the Indian seismic zone V. The building rests on hard soil.

The non-linear structural analysis software ETABS V.18 designs composite columns. The SAP 2000 is used for non-linear modal pushover analysis. The detailed configuration of the models is shown in Table 3.2.

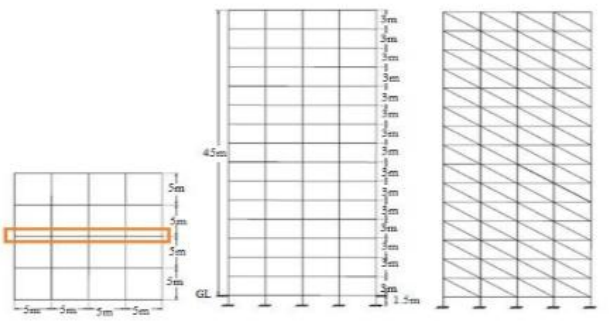

Fig. 3.1 Example building model a) Plan, b) Bare Frame, c) Infill frame

Table 3.1 Material properties

Sr. No.	Material	Grade	Yield Strength	Elastic Modulus
1.	Concrete	M30	$30N/mm^2$	$27386.13N/mm^2$
2.	Encased Steel	Fe 345	$345N/mm^2$	$2.1 \times 10^5 N/mm^2$
3.	Rebar	HYSD 415	$415N/mm^2$	$2.1\times 10^5 N/mm^2$

Table 3.2 Models configuration

Model No.	Model	Member Dimension (mm)	Location	Main steel	Ties	Encased section
1.	Composite Bare (CB)	C1 = 600×600	Up to 5th Floor	#12-16 ϕ	8ϕ @ 150c/c	ISMB150
		C2 = 500×500	6th to 10th floor	#12-16 ϕ		ISMB150
		C3 = 300×300	11th to 15th floor	#8-16 ϕ		ISLB100
		B = 300×400	All Floor	#8-16 ϕ		ISLB75
2.	Composite Infill (CI)	C1 = 600×600	Up to 5th Floor	Corner # 4-25 ϕ Face # 8-20 ϕ	8 ϕ @ 150 c/c	ISMB150
		C2 = 500×500	6th to 10th floor			ISMB150
		C3 = 300×300	11th to 15th floor	Corner #4-20 ϕ Face #4-16 ϕ		ISLB100
		B = 300×400	All Floor	#8-20 ϕ		ISLB75
		Strut = 690×300	All Diagonal	-	-	-

3.2Non-linear Static Analysis

The main aim of the pushover analysis is to develop the capacity curve in the form of a load-displacement curve, which is a plot of base shear versus lateral displacement. The hinge force-deformation requirements are defined using the model frame during the static non-linear modal pushover analysis. Four damage states are defined in terms of spectral displacement as slight, moderate, extensive and complete from the yield and ultimate displacements from the pushover idealized capacity curve. Non-linear static analysis is carried out on an example building, and Fig. 3.2 shows the relation between base shear and roof displacement in terms of modal pushover curve

Table 3.3 Yield and Ultimate Displacements

Model	Displacement (m)		Base Shear (kN)	
	D_y	D_u	V_y	V_u
1	0.21367	0.46831	1124.73	1282.56
2	0.27062	0.31418	2833.54	3539.42

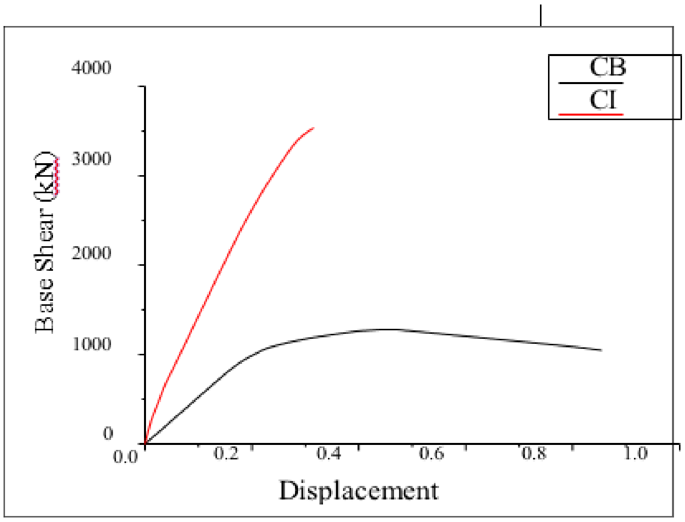

Fig. 3.2 Capacity Curve

1. The maximum yield displacement developed is 0.2706m in the composite infill frame, which is 21.04% more than the composite bare frame.
2. The ultimate displacement developed, i.e., 0.3142m in the composite infill frame, is 22.56% less than the composite bare frame.
3. The pushover curve for the composite bare frame and composite infill frame shows the effect of infill action. The maximum base shear developed, i.e., 1282.56kN in the composite bare structure, is 63.76% less than the composite infill frame.
4. The mximum yield base shear developed, i.e., 1124.73kN in the composite bare frame, is 60.30% less than the composite infill frame.

3.3Fragility Analysis

There are many uncertainties involved in seismic fragility analysis, including material properties, geometric sizes, boundary conditions, seismic action, and analysis models. These uncertainties will inevitably result in the randomness of structural dynamic response. The pushover method is employed to determine the seismic fragility analysis's seismic performance level based on performance.

Fragility curves show the probability of a structure exceeding a specific level of damage. The thresholds for damage states are listed in Table 3.4.

Table 3.4 Damage state threshold

Sr. No.	Displacements	Median Spectral Displacement (S_d)	Damage state threshold
1	$0.7 D_y$	S_{d1}	Slight
2	D_y	S_{d2}	Moderate
3	$D_y + 0.25(D_u\text{-}D_y)$	S_{d3}	Extensive
4	D_u	S_{d4}	Collapse

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Table 3.5 Fragility curve estimated parameters

Model	Damage States			
	Slight ($Sd1$) (m)	Moderate ($Sd2$) (m)	Extensive ($Sd3$) (m)	Complete ($Sd4$) (m)
CB	0.14957	0.2137	0.2773	0.4683
CI	0.1403	0.2004	0.2288	0.3142

Fragility curves are developed for the current study using capacity spectra obtained from pushover analysis. The yield displacement (Dy) and ultimate displacement (Du) are calculated based on these capacity spectra. The fragility curve estimated parameters are shown in Table 3.5.

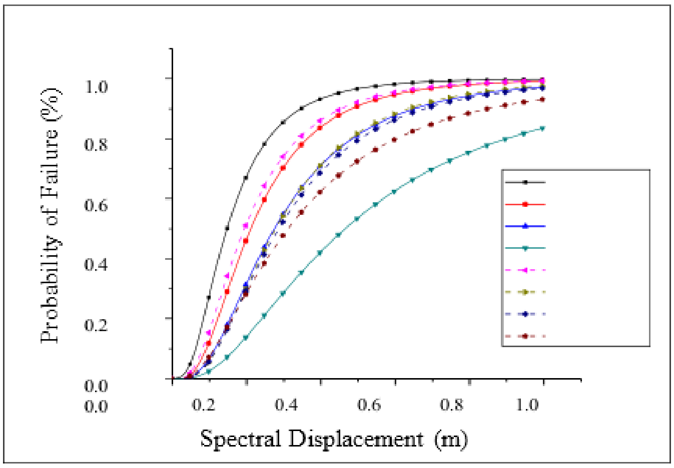

Fig. 3.3 Fragility Curve

IV.SEISMIC FRAGILITY ANALYSIS OF COMPOSITE BUILDINGS

4.1General

The seismic analysis is performed on the three building models: dynamic modal analysis, Incremental Dynamic Analysis (IDA), and fragility assessment. The modal analysis determines the buildings' fundamental periods, an essential step in selecting and scaling ground motion input for the time history analysis in the IDA. The IDA method is selected to determine building responses and visualize these responses from elastic to inelastic behavior by considering material and geometric nonlinearity. To perform IDA, a number of ground motions are selected as per FEMA p695 criteria. Each selected ground motion is scaled to perform IDA until complete failure is obtained. Since the buildings are designed to resist future earthquakes, probabilistic analysis is essential to expect future damage due to earthquakes. To show the probability of damage or exceeding any limit state, a fragility assessment is performed by creating the fragility curves.

4.1.1 Details of the plan, elevation, and 3D View

The details of plan, elevation, and 3D view of model 1, model 2, and model 3 are presented in Fig. 4.1 (a)

The cross-sectional properties, reinforcement arrangement, and details of the encased section are shown in Table 4.1 and Fig. 4.1(b).

Table 4.1 Model and Sectional Properties

Model No.	Model	Member Dimension (mm)	Location	Main steel (HYSD	Ties (HYSD 500)	Encased
1	G+14 Story (High Rise)	C1 = 900×900	Up to 5th Floor	#18-25 ϕ	10 ϕ @ 150 c/c	ISHB250
		C2 =600×600	6th to 10th floor	#18-25 ϕ		ISHB250
		C3 =500×500	11th to 15th floor	#14-25 ϕ		ISHB250
		Beam = 960×500	All Floor	#14-25 ϕ		-
2	G+6 Story (Mid	C1 = 800×800	Up to 4th Floor	#18-25 ϕ	10 ϕ @ 150 c/c	ISHB250
		C2 =600×600	5th to 7th floor	#18-25 ϕ		ISHB250
		Beam =	All Floor	#14-25 ϕ		-
3	G+3 Story (Low	C1 = 600×600	Up to 2nd Floor	#18-25 ϕ	10 ϕ @ 150 c/c	ISHB250
		C2 =500×500	3th to 4th floor	#18-25 ϕ		ISHB250
		Beam =	All Floor	#14-25 ϕ		-

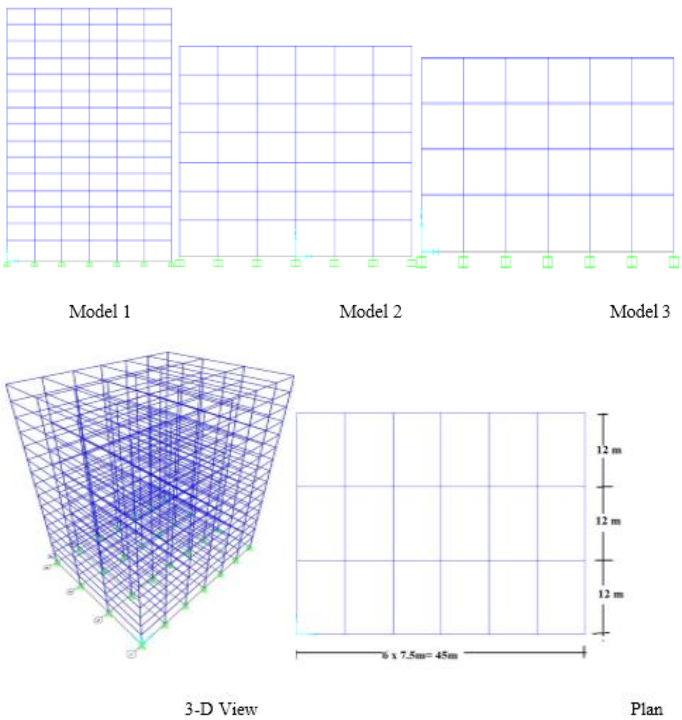

Fig. 4.1 (a) 3-D View, Plan, and Elevation of Composite Structure

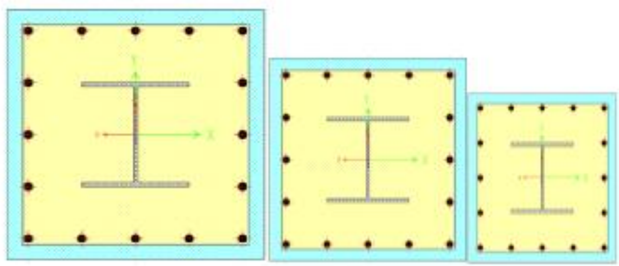

Fig. 4.1 (b) Cross Section of column

4.2Modal Analysis

Modal analysis is an elastic structural dynamic analysis that assumes that the structure's material properties remain within the elastic range throughout the calculations. This is a common assumption in linear analysis methods. Performing modal analysis is not only essential for determining dynamic characteristics but

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also for ensuring the numerical stability of the structural model. It helps to verify the accuracy and reliability of the numerical model. ETABS is a widely used structural analysis and design software, particularly in building structures. The fundamental period for Model 1, Model 2, and Model 3 along X and Y directions are shown in Table 4.2.

Table 4.2 Fundamental time periods for considered models.

Mode	Fundamental time period in X direction in sec			Fundamental time period in Y direction in sec		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
1	4.134	1.67	0.950	4.782	1.992	1.118
2	1.476	0.60	0.293	1.692	0.686	0.333
3	0.612	0.23	0.109	0.837	0.438	0.192

4.3Discussion on Modal Analysis

1.The fundamental period for the model 3 composite frame is reduced by 43.11% and 77.02% compared to model 2 and model 1 in the X direction. Hence, stiffness is highest for 4-story composite structures compared to 7-story and 15-story structures along the X direction.

2.The fundamental period for the model 3 composite frame is reduced by 43.87% and 76.62% compared to model 2 and model 1in the Y direction. Hence, stiffness is highest for 4-story composite structures compared to 7-story and 15-story structures along the Y direction

4.4 Methodology

4.4.1Incremental Dynamic Analysis (IDA)

This study adopted a direct integration time history method for each selected incremental ground motion. Incremental Dynamic Analysis is a powerful tool allowing engineers to systematically evaluate and understand structures' seismic performance. The resulting IDA curves offer valuable information for making informed decisions about the design, retrofitting, and risk mitigation strategies for buildings in earthquake-prone regions.

4.4.2 Scaling of Ground Motion

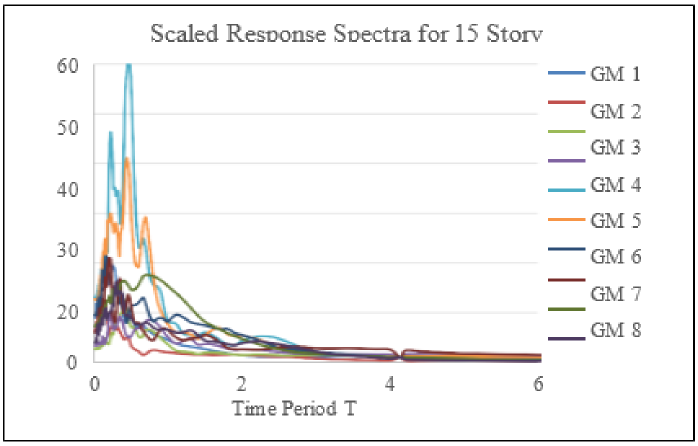
In seismic design and engineering, it's common to use ground motion records from actual earthquakes to assess the performance of structures. The ground motions are either scaled up or down depending on the structure's capacity to the intensity level, which causes dynamic instability. This scaling process is crucial for designing systems that can withstand various seismic events, ensuring they are both safe and economically viable. Engineers use tools like response spectrum analysis or time history analysis to evaluate how structures will respond to different ground motions and to ensure that they can withstand the forces generated by earthquakes.

Table 4.4 Scale Factors for IDA in X Direction

G.M.	Model 1		Model 2		Model 3	
	Sa(T1,5%) g	S.F.	Sa(T1,5%) g	S.F.	Sa(T1,5%) g	S.F.
1	0.201	48.89	0.204	48.16	0.215	45.54
2	0.083	118.00	0.094	104.39	0.235	41.76
3	0.237	41.45	0.239	41.09	0.228	43.07
4	0.250	39.31	0.249	39.35	0.383	25.62
5	0.104	94.39	0.116	84.75	0.302	32.48
6	0.057	170.64	0.067	146.84	0.152	64.61
7	0.046	211.50	0.049	200.92	0.067	146.89
8	0.035	278.01	0.040	247.17	0.105	93.68
9	0.154	63.74	0.165	59.31	0.502	19.55
10	0.150	65.44	0.176	55.89	0.481	20.38

Table 4.5 Scale Factors for IDA in Y Direction

Ground Motions	Model 1		Model 2		Model 3	
	Sa(T1,5%)g	S.F.	Sa(T1,5%) g	S.F.	Sa(T1,5%) g	S.F.
1	0.167	58.72	0.184	53.39	0.194	50.65
2	0.057	172.38	0.067	146.41	0.216	45.33
3	0.151	65.13	0.189	51.80	0.235	41.75
4	0.239	40.97	0.245	40.10	0.364	26.98
5	0.037	263.80	0.041	239.18	0.191	51.23
6	0.042	231.39	0.039	252.27	0.163	60.21
7	0.054	180.75	0.064	153.49	0.227	43.25
8	0.135	72.92	0.144	68.07	0.141	69.73
9	0.120	81.59	0.056	174.93	0.417	23.54
10	0.084	116.69	0.137	71.70	0.492	19.94



The unscaled and scaled response spectra for a selected set of ground motions are shown in below Fig.

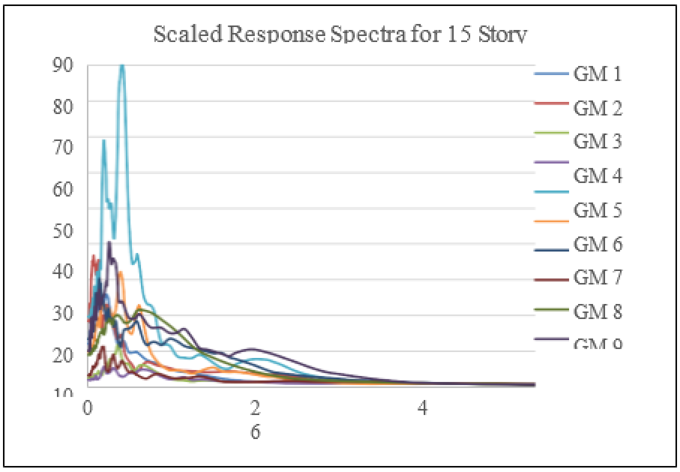


Fig. 4.2. Response Spectra a) Model 1 RS X Direction b) Model 1 R.S. Y Direction

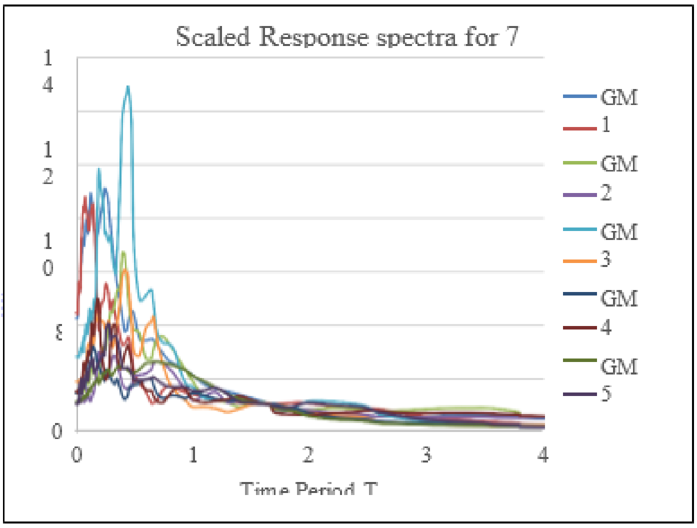


Fig. 4.3 Model 2 Scaled Response Spectra

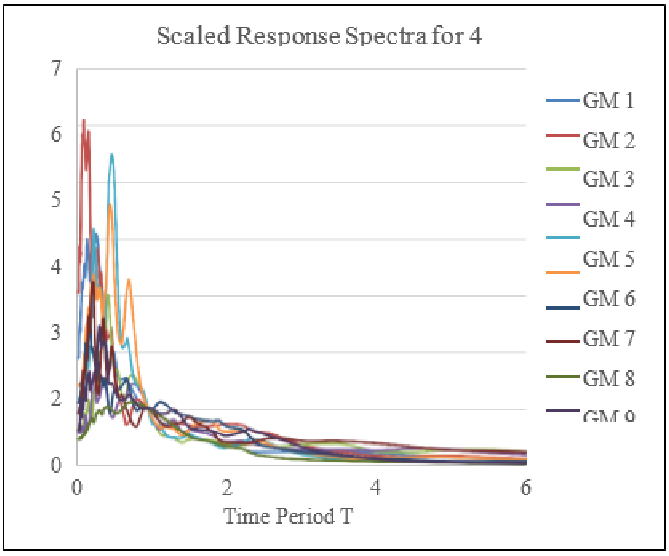


Fig. 4.4 Model 3 Scaled Response Spectra

V.CONCLUSION

5.1Conclusions

This study presents a detailed seismic fragility assessment of steel-concrete composite buildings, focusing on the influence of masonry infill and comparing seismic responses across various building heights. Key findings from the research are summarized as follows:

1. The inclusion of masonry infill walls significantly enhances the stiffness and seismic resistance of steel-concrete composite frames. The composite infill frame demonstrated a reduction in the fundamental period by 1.62% compared to the bare frame, indicating improved lateral stiffness.

2. Non-linear static pushover analysis revealed that the composite infill frame achieved a 21.04% higher yield displacement and a 63.76% increase in base shear capacity compared to the composite bare frame. This clearly highlights the beneficial role of masonry infill in increasing both strength and ductility.

3. The performance point analysis showed that the composite infill frame remained within the elastic range, while the composite bare frame transitioned into the inelastic range. This indicates a superior seismic performance of the infill frame under design-level earthquakes.

4. The fragility curves developed from the analysis confirmed that the probability of exceeding damage states is significantly lower in composite infill frames than in bare frames across all seismic intensities.

5. The seismic analysis of low-rise, mid-rise, and high-rise composite buildings using Incremental Dynamic Analysis (IDA) demonstrated that low-rise structures exhibit the least dispersion and the most robust, predictable seismic behavior.

6. Comparison of the lateral force method and response spectrum method indicated that displacements and storey shear forces obtained by the dynamic response spectrum method are consistently lower than those predicted by the lateral force method, providing a more reliable assessment of actual seismic performance

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