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Effects of Member Sizes on Plastic Hinge Formation in RC Frames by Pushover Analysis

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Abstract—**In this study, the effects of member sizes on plastic hinge formation in RC frames are investigated by nonlinear pushover analysis. To achieve this objective, a 10-storied building was systematically simulated and analyzed utilizing SAP2000 software. The design of the 10-storied structure adheres to Eurocodes, with consideration of wind loads. Nonlinearity was introduced into the frame structure by implementing Moment (M) and interactive P-M hinges. The analysis process involved the incremental step-by-step displacement of the top node of the structure until reaching the limiting displacement, facilitating the generation of pushover curves. Concurrently, the sequence of plastic hinge formation and the performance points of beams and columns were recorded. This analysis was conducted across a range of member size configurations, providing comprehensive insights into the structural behavior. This study revealed that, when the total cross section area of members are increased by 10.24% 20.98% and 32.22% compared to initial structural model, the maximum base shear forces increased by 13.86%, 28.66%, 42.66% respectively.**

Keywords—Nonlinear pushover analysis, lateral displacement, plastic hinges, base shear

I. INTRODUCTION

Seismic waves and vibrations pose significant threats to building structures and human safety. While encounters with seismic waves are infrequent in Sri Lanka, it remains essential to design buildings that can withstand or mitigate the potential damage caused by these forces. Due to the random and unpredictable nature of seismic forces, a proper structural analysis should be conducted to ensure that buildings can endure the loads imposed by seismic events. Traditional linear elastic analysis methods are often inadequate for this purpose.

In response to this challenge, recent advancements in performance-based engineering have introduced the nonlinear static pushover analysis method, supplanting conventional linear elastic approaches. Pushover analysis can be executed through two primary methods: displacement controlled and force controlled. While the force-controlled method applies a monotonically increasing lateral load pattern to simulate inertial forces induced by seismic waves, the displacement-controlled method offers more accuracy, as it applies a predefined displacement to the structure and conducts the analysis until the target displacement is achieved, thereby establishing the pushover curve or capacity curve, which represents the nonlinear behavior of the structure [1].

A well-executed pushover analysis offers valuable insights into the structural factors influencing performance under seismic events. This type of analysis is likely to provide precise assessments of inelastic deformations, both at the global and local levels, for structures primarily exhibiting fundamental mode oscillations. [2]. Hinges are assigned to replicate the intricate nonlinear behavior inherent in structural components. Within the framework of pushover analysis, various types of hinges are utilized to symbolize distinct aspects of nonlinear behavior within structural elements. Some of the main hinge types are:

(1) Axial Hinge: This type of hinges represents the axial behavior of structural components, encompassing phenomena such as axial deformation and axial forces, primarily observed in columns and other vertical structural elements.

(2) Flexural Hinge: Flexural hinges represent flexural behavior of structural elements, encompassing aspects like bending deformations and bending moments, most prominently observed in beams and columns.

(3) Shear Hinge: Shear hinges represent the shear behavior demonstrated by structural elements, such as shear deformations and shear forces, in horizontal elements like beams and diaphragms.

Hinges account for both material and geometric nonlinearities. Material nonlinearities pertain to the plastic behavior exhibited by the structural material, while geometric nonlinearities consider the deformation characteristics as structures experience substantial displacements and rotations [3].

II. METHODOLOGY

In this study, a multistory building is designed and analyzed using pushover analysis to obtain the load-deformation behavior of the structure. The analysis process involve the incremental step-by-step displacement of the top node until reaching the limiting displacement representing the displacement experienced by the structure when subjected to seismic forces, facilitating the generation of pushover curve. Concurrently, the sequence of plastic hinge formation and the failure mechanisms of beams and columns are recorded. This analysis is conducted across 3 more variant building frame models and a comparative analysis will be conducted using the generated pushover curves of the building models.

A. Design of the Building Frame Structure

Medium rise 10-storey reinforced concrete framed building is considered in this study. The building is designed adhering to Eurocodes [4, 5, 6], with consideration of wind loads, dead loads and imposed loads from slabs, masonry walls, ceilings and service loads. These loads are applied to the beams of the building frame as distributed loads. The building category is considered as a Category A (residential and commercial) for the design. General details of the building, and material details are shown in the following tables.

TABLE I. GENERAL DETAILS OF THE BUILDING

Parameter	**Value**
Terrain Category	III
No of Stories	10
Story height	3.5 m
Total height	35 m
No. of bays in X- direction	5
Width of a bay in X- direction	8 m
No. of bays in Y-direction	3
Width of a bay in Y-direction	6 m
Total Width	18 m
Total Length	40 m

TABLE II. CONCRETE MATERIAL DETAILS

Parameter	**Value**
Concrete grade (fck)	35 MPa
Exposure class	XC1
Modulus of elasticity	34 GPa
Poisson ratio	0.2
Coefficient of thermal expansion	5.5E-06
Shear modulus	14 Gpa
Unit-weight	25 kN/m3

TABLE III. STEEL MATERIAL DETAILS

Parameter	**Value**
Steel strength	500 MPa
Density	78.5 kN/m3
Modulus of elasticity	200 GPa
Poisson ratio	0.3
Yield strength	500 MPa
Tensile strength	500 MPa

Initial member sizes of the building frame structure were determined adhering to Eurocode standards. SAP2000 [7] software was used to model the frame structure and to verify all members pass the design check for the Eurocode load combinations. The details of the building frame elements are shown in the Tab. 4.

TABLE IV. DETAILS OF THE BUILDING FRAME MEMBERS

Member type		**Dimensions(mm)**	
		Depth(D)	*Width(W)*
Beam	Edge-Long span	600	400
	Edge-Short span	500	300
	Int. - Long span	600	400
	Int. - Short span	500	300
Column	Corner(1-5)	500	500
	Corner(6-10)	500	500
	Interior(1-5)	650	650
	Interior(6-10)	500	500
	Long Edge(1-5)	600	600
	Long Edge(6-10)	500	500
	Short Edge(1-5)	600	400
	Short Edge(6-10)	500	400

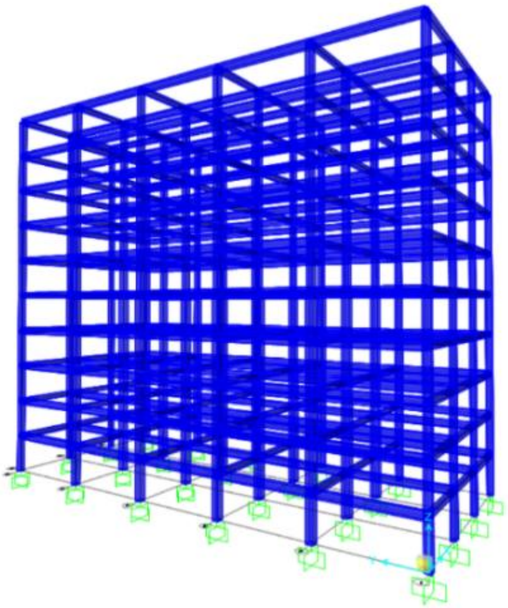


Fig. 1. SAP2000 building Frame model

B. Modelling of the Variant Models

The Initially designed building frame model is modified to obtain three variant building frame models by incrementing the beam and column dimensions of the original frame structure (Model 1). The dimension details of elements in each model are shown in the Table V. Where, LS-Long Span, SS-Short Span, LE- Long Edge, SE-Short Edge, Int.-Interior, Cor.-Corner, D-Depth (mm), W-Width (mm).

TABLE V. MEMBER DIMENSIONS OF THE MODELS

Member type		Model 1		Model 2		Model 3		Model 4	
		D	*W*	*D*	*W*	*D*	*W*	*D*	*W*
Beam	Edge-LS	600	400	625	425	650	450	675	475
	Edge-SS	500	300	525	325	550	350	575	375
	Int - LS	600	400	625	425	650	450	675	475
	Int - SS	500	300	525	325	550	350	575	375
Column	Cor.1-5	500	500	525	525	550	550	575	575
	Cor.6-10	500	500	525	525	550	550	575	575
	Int (1-5)	650	650	675	675	700	700	725	725
	Int(6-10)	500	500	525	525	550	550	575	575
	LE(1-5)	600	600	625	625	650	650	675	675
	LE(6-10)	500	500	525	525	550	550	575	575
	SE(1-5)	600	400	625	425	650	450	675	475
	SE(6-10)	500	400	525	425	550	450	575	475

The percentages of increase of the total cross sectional area of structural members of each model 2,3 and 4 compared to model 1 are as given below,

Model 2 – 10.24%

Model 3 – 20.98%

Model 4 – 32.22%

All the 3 variant building frame models were modelled using SAP2000 software and all the members are verified to pass the design check for the Eurocode load combinations.

C. Hinge Application

Hinges are employed to replicate the intricate nonlinear behavior inherent in structural components. In this study, hinges are assigned to the beams and columns of the frame structures using default hinge properties of SAP2000. The P-M2-M3 hinges are assigned to columns and M3 Hinges are assigned to the beam members as described in FEMA-356 [8]. Concrete column failure condition is selected as flexure/shear condition.

For both column and beam members, hinge locations are assigned with a relative distance of 0.05m from the both ends of the member. For ground level column members, hinges are assigned only at the top end considering that a hinge will not develop at the bottom due to restrain at the bottom. Locations of assigned hinges for a frame section of the building is shown in Fig. 2.

FEMA 356 defines three primary performance levels: immediate occupancy (IO), life safety (LS), and collapse prevention (CP). Under the IO level, non-structural members may exhibit minor cracks, while structural members remain undamaged. The LS level permits limited damage while ensuring life safety, and it maintains the lateral stiffness and rigidity of structural elements. On the other hand, the CP level may involve the collapse of some walls and permanent structural displacements, but it effectively prevents total structural collapse.

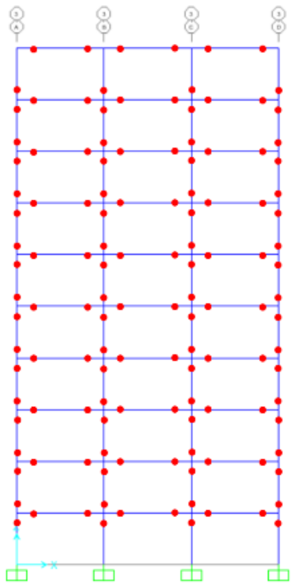


Fig. 2. Assigned hinges of the building frame structure

Fig. 3 illustrates the force-deformation relationship of plastic hinges used to define these performance levels and their associated damage scenarios.

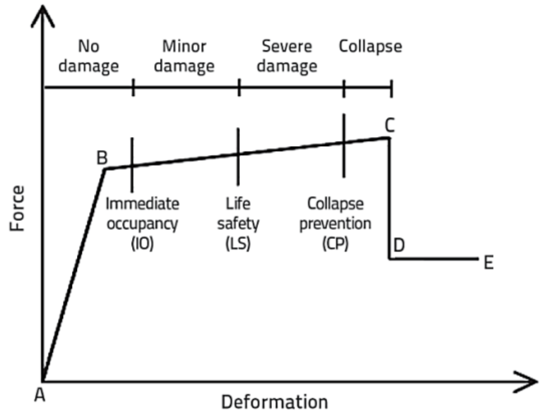


Fig. 3. FEMA-356 performance limits

D. Pushover Analysis

After designing, detailing, and assigning hinges to the reinforced concrete frame structures, a nonlinear pushover analysis is carried out for evaluating the structural seismic response. Pushover analysis is performed by displacement controlled method using SAP2000 software. According to the Eurocodes, it is suggested to push the structure to a top-displacement of 2%-3% h, where h is the height of the building. For this study, 800mm is selected as the monitored displacement magnitude which is 2.3% of the total height.

Control node is the location used to monitor displacements of the structure. Considering the center of gravity of the building frame structure, the assigned control nodes for the analysis are the top two nodes at the edge of the middle frames as shown in the Fig. 4.

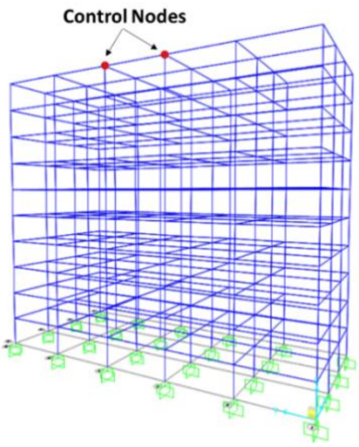


Fig.4. Control nodes of the structure

P-delta effect is considered in the analysis due to lateral deformation of the columns during the pushover. Number of pushover steps determines the accuracy and better capturing of the structural behavior. As the number of steps increases, the analysis can better capture the gradual development of plastic deformation and failure mechanisms in the structure. This is essential for understanding the building's actual response under lateral loads. In this study, Pushover analysis is performed for a minimum of 30 saved steps.

III. REESULTS AND DISCUSSIONS

A. Pushover Curves

The Pushover curves (capacity curves) obtained from the pushover analysis as displayed in the Fig. 5 illustrate similar characteristics for all four building models. Initially the structures behave linearly until a displacement of approximately 0.04m where it tend to show higher base shear increments with the displacement. Then the curves gradually deviate from linearity as the beams and columns experience inelastic behaviors, where it tend to show low rate of the base shear increment with the displacement.

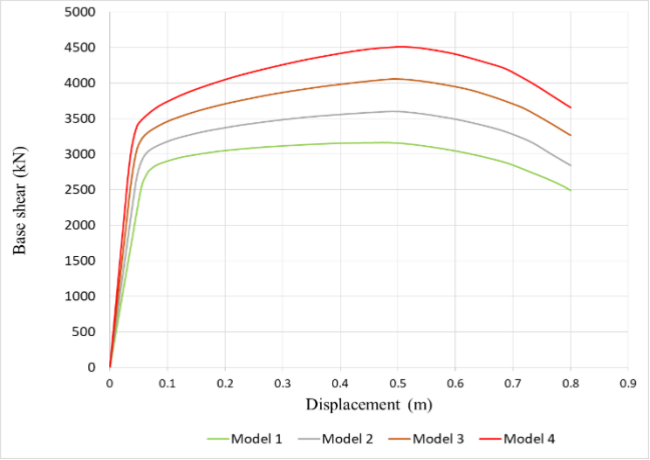


Fig. 5. Pushover curves of the building models

It is observed that the base shear force is increased from model 1 to model 4, which denotes that base shear force increases with the increase of the member sizes. The maximum base shear force recorded and increased percentage of base shear force compared to model 1 for the respective building models are shown in the Table VI. Furthermore, it is observed that the displacements corresponding to the maximum base shear force has increased from model 1 to 4 as shown in the Table VI.

TABLE VI. RECORDED MAXIMUM BASE SHEAR FORCES OF THE MODELS

Model No.	**Displacement (m)**	**Maximum Base shear force (kN)**	**Percentage of base shear force increment (%)**
Model 1	0.472	3161.9	-
Model 2	0.490	3600.3	13.86
Model 3	0.493	4057.9	28.33
Model 4	0.509	4510.5	42.65

B. Hinge Formation at Performance Levels

Hinge formation in frame elements of the 4 building frame models at the Performance levels; Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) as per FEMA-356 is shown in Fig. 6. As it progress from model 1 to model 4, base shear value has increased at formation of hinges for B-IO, IO-LS and C Performance levels.

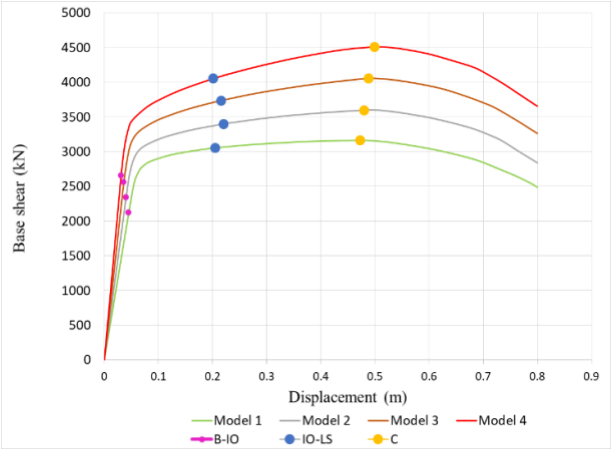


Fig. 6. Formation of hinges at performance levels as per FEMA-356

Observations reveal a slight decrease in hinge formation displacement within the B and Immediate Occupancy performance level as transition from model 1 to model 4 is considered. This suggests that B-IO hinges form at relatively smaller displacement values as member sizes increase.

Furthermore, it is evident that the displacement at the hinge formation between the IO -LS performance levels is approximately consistent in model 1 and model 4, with slightly higher displacement values observed in model 2 and model 3.

Moreover, as we consider the displacement at hinge formation beyond the critical Collapse (C) performance level, it becomes apparent that there is an increase from model 1 to model 4. This implies that hinges surpassing the Collapse performance level form at slightly higher displacement values as member sizes increase. Table VII includes the displacements and base shear forces associated with hinge formation at performance limits corresponding to the building frame models.

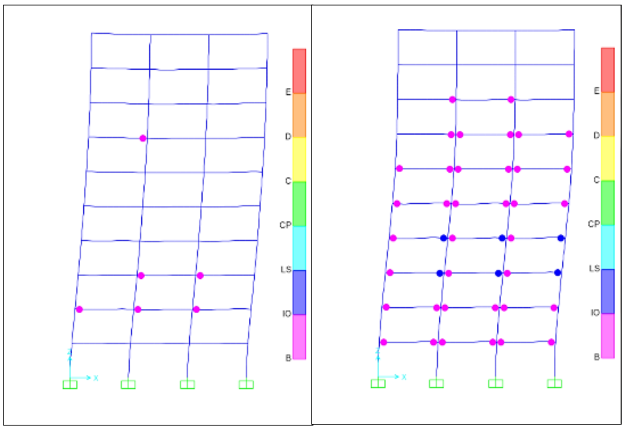
TABLE VII. DISPLACEMENT AND BASE SHEAR FORCES ASSOCIATED WITH HINGE FORMATION AT PERFORMANCE LIMITS

	B-IO		**IO -LS**		**C-D**	
	Displacement (mm)	*Base Force (kN)*	*Displacement (mm)*	*Base Force (kN)*	*Displacement (mm)*	*Base Force (kN)*
Model 1	45	2121.8	204	3054.0	472	3161.9
Model 2	40	2342.1	220	3399.1	480	3598.3
Model 3	36	2562.5	215	3736.7	488	4056.9
Model 4	31	2654.6	201	4052.4	498	4509.4

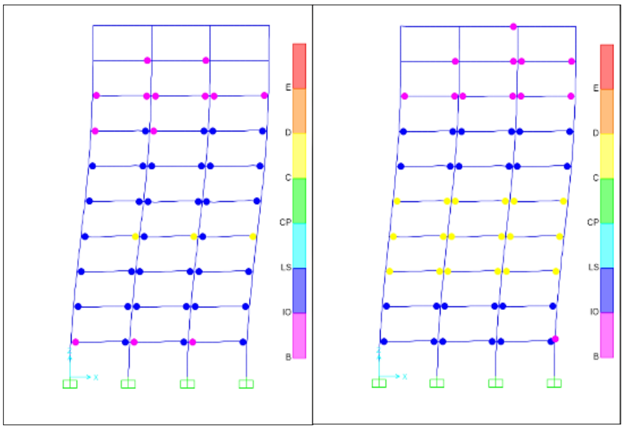
C. Hinge Formation Pattern and Sequence

Hinge formation sequence in the interior frame of model 1 is shown in Fig. 6. Where δ denotes control node displacement and 'BSF' denotes the base shear force. Hinge formation pattern in the columns and beams of every model is generally similar with slight deviations. While performing the pushover analysis, plastic hinges start to form at beam ends of the bottom most stories of the building frame structure around a displacement, δ, of around 0.05m, as shown in Fig. 6(a), then eventually plastic hinges of beams starts forming ascending the story levels as shown in Fig. 6(b). Initial formation of plastic hinges in beams passing IO limit is observed at story level 3, 4 at around a displacement of 0.2m as shown in the Fig. 6(b), eventually forming up to the 7,8 story levels as shown in Fig. 6(c). Plastic hinges initiate to pass the collapse limit at beam ends of story level 5 around a displacement of 0.5m as shown in Fig. 6(c) and eventually transforming every beam hinge at 2nd story to 6th story level to pass the collapse limit shown in the Fig. 6(e).

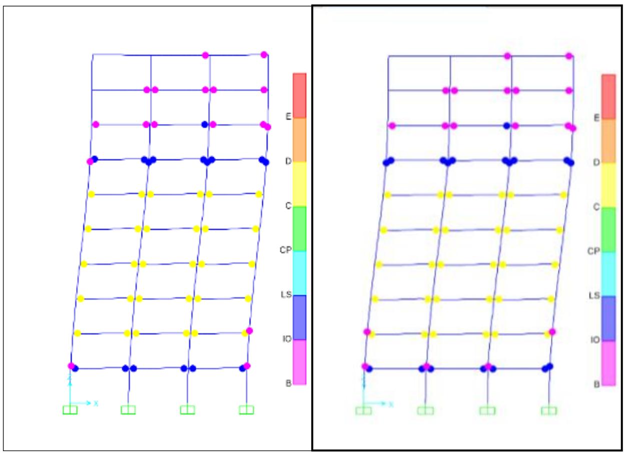
When comparing the column hinge formation of each model, it is observed that column hinges initiate to form after beam hinges pass the collapse limit for the model 1, 2 and 3 as shown in Fig. 7(a), Fig. 7(b) and Fig. 7(c). But in model 4, column hinges initiate to form before beam hinges reaching collapse limit as shown in Fig. 7(d). Thereby, it is evident that as the member sizes of the frame increases, tendency to form column hinges is less while the beam hinges are passing collapse limit.



(a) δ= 0.05 m, BSF=2554.0 kN (b) δ=0.20 m, BSF=3054.0 kN



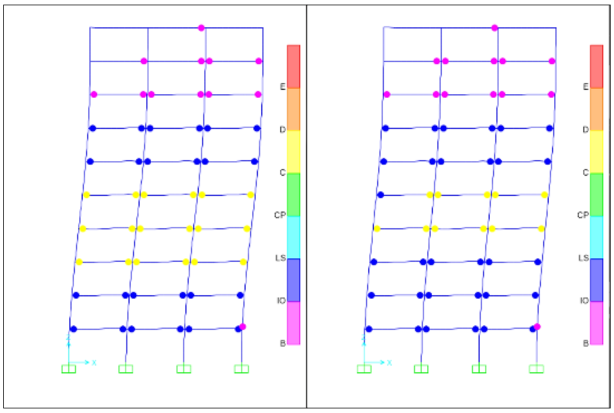
(c) δ= 0.47 m, BSF= 3161.9 kN (d) δ=0.56m, BSF=3088.0 kN



(e) δ= 0.75m, BSF= 2651.9 kN (f) δ=0.80m, BSF= 2487.1kN

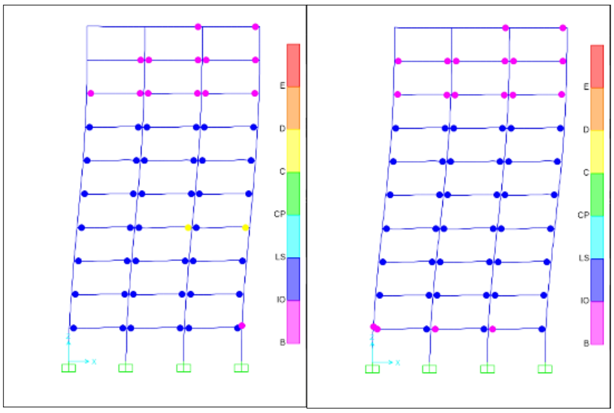
Fig. 6. Plastic hinge formation (Model 1)

Furthermore, at the first column hinge formation, it is observed that the top node displacement is decreased and base shear force get increased when transition from model 1 to model 4.



(a) Model 1
δ= 0.56 m, BSF= 3088.0 kN

(b) Model 2
(b). δ=0.51 m, BSF- 3595.2 kN



(c) Model 3
δ= 0.48m, BSF= 4056.9 kN

(d) Model 4
δ=0.46m, BSF=4489.6 kN

Fig. 7. Initiation of plastic hinge formation at columns

IV. CONCLUSION

Pushover analysis, as demonstrated in this study, is a valuable and straightforward method for accurately capturing the nonlinear responses exhibited by structures, particularly when they undergo inelastic deformations in response to significant lateral displacements. The step-by-step analysis of plastic hinge formation offers a distinctive insight into the hinge formation locations, critical hinges, and hinge formation patterns of these crucial structural elements. The following conclusions can be drawn based on this study.

- When the total cross section area of members are increased by 10.24% 20.98% and 32.22% compared to initial structural model, the corresponding maximum base shear forces increased by 13.86%, 28.66% and 42.66%.
- The displacements corresponding to the maximum base shear force were increased by 3.81%, 4.45% and 7.84% compared to initial structural model as the member sizes were increased.
- When member sizes increased, the number of beam hinges formed surpassing the collapse limit were decreased by the time of initiation of plastic hinge formation in columns.
- The displacement corresponding to the hinges formed at collapse performance level was increased as the member sizes were increased.
- When member sizes were increased, a decrease in the recorded displacement at the initiation of plastic hinge formation in columns was observed and concurrently, there was an increase in the base shear values as member sizes were increased.
- As member sizes increased, there was a notable reduction in the number of beam hinges formed beyond the collapse limit at the beginning of plastic hinge formation in columns.
- As expected, the initiation of plastic hinge formation was occurred in lower-level column members. This emphasizes the importance of prioritizing the adequate strengthening of these columns to enhance their resilience against seismic events.

In future continuation of this study, additional models can be generated by systematically increasing member sizes, thereby producing a broader range of pushover curves. This approach would facilitate the collection of more comprehensive base shear and corresponding displacement data. Subsequently, the gathered data could be used to develop a statistical equation, enabling the estimation of base shear values for given displacements without necessitating a pushover analysis.

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