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Effect of staircase on seismic performance of RC frame building

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Abstract. Staircase is a vertical transportation element commonly used in every multistoried structure. Inclined flights of staircase are usually casted monolithically with RC frame. The structural configuration of stairs generally introduces discontinuities into the typical regular reinforced concrete frame composed of beams and columns. Inclined position of flight transfers both vertical as well as horizontal forces in the frame. Under lateral loading, staircase in a multistory RC frame building develops truss action creating a local stiffening effect. In case of seismic event the stiff area around staircase attracts larger force. Therefore, special attention is required while modeling and analyzing the building with staircase. However, in general design practice, designers usually ignore the staircase while modeling either due to ignorance or to avoid complexity. A numerical study has been conducted to examine the effect of ignoring staircase in modeling and design of RC frame buildings while they are really present in structure, may be at different locations. Linear dynamic analysis is performed on nine separate building models to evaluate influence of staircase on dynamic characteristics of building, followed by nonlinear static analysis on the same models to access their seismic performance. It is observed that effect of ignoring staircase in modeling is severe and leads to unsafe structure. Effect of location and orientation of staircase is also important in determining seismic performance of RC frame buildings.

Keywords: RC frame buildings; staircase; modeling; capacity curve; nonlinear static analysis

1. Introduction

In RC frame building, beams and columns are the primary load carrying elements, both for gravity as well as seismic loads. Other structural elements like infill wall, false roof, lintel, façade and even staircases are sometime considered as secondary elements by structural designers, therefore, the contribution in load resistance of these elements are generally ignored in modeling and analysis. Inaccurate modeling of structural elements has been identified as one of the major cause of failure in past earthquakes (EERI Special Earthquake Report 2001, Goel 2001, Agarwal *et al*. 2001, Arslan and Korkmazalso 2006). Observations on performance of RC buildings in Ahmedabad city which is more than 300 km away from epicenter of Bhuj earthquake (Humar *et al*.

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Murty *et al.* 2002, Singh and Kumar 2008), demonstrated that performance of RC buildings are worse than expected and extent of damage observed was considerably more than estimated in such moderate seismic zone. The extent of damages observed in various past earthquakes can rather be extended to improper modeling of structure. Out of the various modeling irregularities, the present paper deals with effect of staircase on performance of RC frame building.

Provision of lift core and staircase is a basic need in multistory buildings for vertical transportation. In RC frame building construction, the frame members and inclined flights of staircase are usually casted monolithically. Inclined position of flight transfers both vertical as well as horizontal forces in the frame, creating truss action (horizontal bracing effect) which excessively increases the stiffness in that localized area of the building. Moreover, due to the localized stiffening effect mode shapes of structure changes along with reduction in fundamental natural period. During earthquake, stiffer structure invites more seismic force and may result in severe damage if not designed for the same. Also the staircase connecting two buildings can suffer damage at joint regions of landing and flight due to truss action. After Turkey earthquake, Arslan and Korkmazalso (2006) pointed out failures caused in beams and columns supporting staircase. Further, the inclined flights are generally attached to the landing slab and beams at intermediate levels, which also creates discontinuities in the column-beam frames system. The intermediate discontinuity imparts short-column effect in supporting columns. The short column effect (Li *et al.* 2014) has been a major cause of damage to building in past earthquakes. Analysis of mathematical model of a building without incorporating staircase underestimates the seismic forces. Such designed structure fallouts as unsafe structure. Edoado *et al.* (2008), performed linear modal and nonlinear pushover analysis on a typical building frame with different models of staircase like, step constraint into inclined beams and steps simply supported by reinforced concrete slabs. They observed that staircase not only increases strength and stiffness of structure but also attracts more seismic force. Due to staircase shear failure becomes more predominant in the short columns supporting staircase. Xu and Li (2012) carried out response spectrum analysis of two six story RC frame buildings with and without modeling symmetrically placed staircase and concluded that the existence of staircase greatly influences the forces in beams and columns adjacent to staircase. Hongling *et al.* (2013), analyzed building models with and without incorporating staircase and observed that horizontal bracing effect develops due to staircase. It was reported that due to presence of staircase period of vibration as well as inter-story displacement decreases, whereas, base shear increases. Further, it was also indicated that the location of staircase induces torsion effect and changes the internal force distribution. Singh and Choudhury (2012) found that merely considering weight of staircase and neglecting its stiffness in computer modeling results in unsafe design.

In the present study, four aspects related to staircase viz. ignoring staircase in modeling, location of staircase, orientation of staircase and effect of symmetrical and asymmetrical placement of two staircase on behaviour of building have been considered. To keep primary focus on effect of staircase in building behavior, a regular and symmetrical building plan has been selected. Nine building models have been developed with same basic plan. In the first model staircase is ignored, whereas, in other six models location and orientation of staircase have been altered and further, on two models effect of symmetrical and asymmetrical placement of two staircase have been studied. Linear dynamic analysis has been performed to identify the effect on dynamic characteristics of building, followed by nonlinear static analysis on the same models to access their seismic performance.

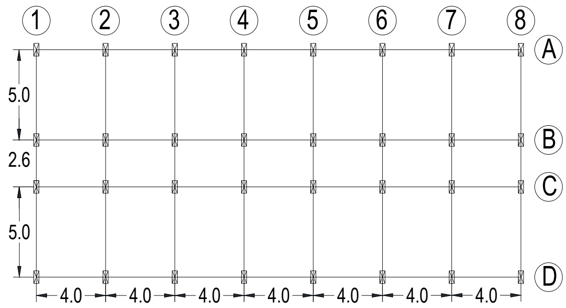


Fig. 1 Plan of a six story building (Model-S)

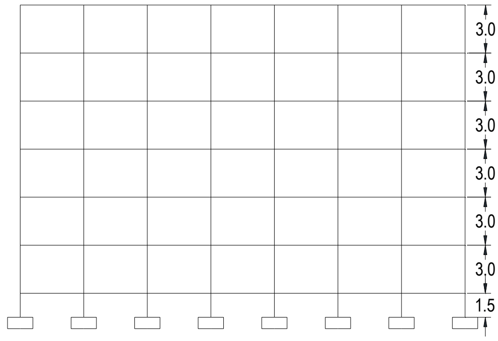


Fig. 2 Elevation of six story building

2. Specification of building

A regular and symmetric six storey building with plan shown in Fig. 1 has been selected for the study. The selected building plan is very similar to the plan of an office or a public building, having rooms on the both side of passage way. The building has seven equally spaced (at 4 m) bays in longitudinal direction. In transverse direction the building has three bays, the two exterior bays are of 5 m and the middle bay is of 3 m. The plan is symmetric in both longitudinal and transverse directions. Constant story height of 3 m is considered above plinth level and the foundation level is assumed at 1.5 m below the plinth level as shown in Fig. 2. Seismic force has been calculated as per Indian Standard IS 1893-2002. The building is assumed to be situated on medium soil strata (N value between 10 and 30) and located in the seismic zone V with peak ground acceleration (PGA) as 0.36 g under maximum considered earthquake. Special moment resisting frame (SMRF) is considered with response reduction factor (R) as 5. The reinforced concrete slab thickness is assumed as 150 mm and thickness of unreinforced masonry brick infill as 230 mm. Preliminary sizes of the frame members have been considered based on the deflection criteria given as per Indian standard IS 456-2000 and IS 13920-1993. The dead load and live load has been calculated as per Indian standard IS 875-1987 (Part 1 and Part 2).

In modern construction practice it is common to use high strength concrete. However, an improperly designed and detailed RC structure with high strength concrete could be more brittle in nature. In order to observe the effect of strength of concrete on seismic performance of building with and without staircase, three grades of concrete with nominal characteristic compressive strength of 20 MPa (M20) representing very low strength concrete, 30 MPa (M30) representing minimum code specified concrete and 60 MPa (M60) representing moderately high strength concrete, have been considered in the study. The reinforcing steel having yield strength of 415 MPa has been used in design. The seismic analysis has been performed as per IS 1893-2002 considering minimum base shear correction. Effective stiffness of frame members has been considered using equations proposed by Kumar and Singh (2010) for normal-strength concrete (20 MPa to 60 MPa).

3. Modeling and analysis

In multi-storey building construction practice it is common to provide one or more than one staircase. In the present study, nine different models of building have been considered for seismic performance assessment having same basic plan. First model represents building without staircase, which is a common practice in India and in many parts of the world and designated as ‘Model-S’ as shown in Fig. 1. There are various possibilities of locating staircase in the building plan. To recognize the effect of staircase location and orientation on performance of building, six different possible locations of single staircase have been identified and modelled. Nomenclatures of these six building models (Model 1-6) with description of location and orientation of staircase are presented in Table 1 with figures. In case when more than one staircase is present in the building, the staircases could purposely be arranged symmetrically with respect to floor plan in order to avoid torsion in the building. However, if addition staircase is provided to serve special purpose such as fire escape, they are located in exterior bay of the building. To recognize the effect of symmetrically placed multiple staircases; ‘Model-7’ has been developed in which two staircases are modelled and located symmetrically in the two exterior bays as shown in Table 1 with figure. To observe the effect of asymmetrically placed multiple staircases, ‘Model-8’ has been developed in which one staircase is located in the exterior bay and the other is located at central bay, however, oriented in parallel direction to the longer side of building as shown in Table 1 with figure.

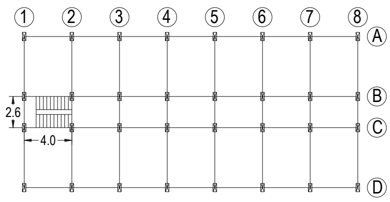
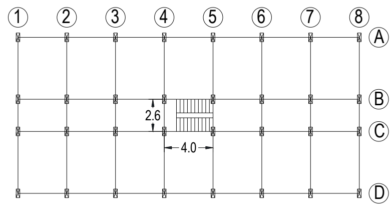
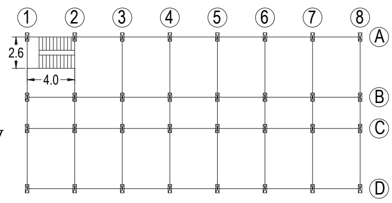
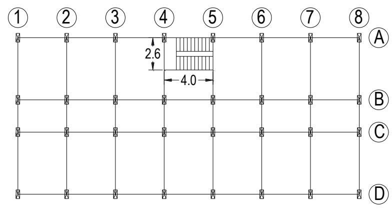
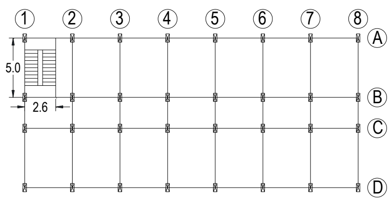
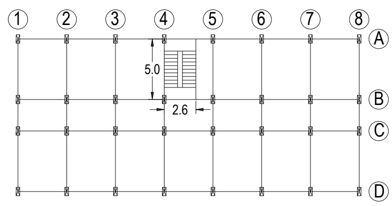
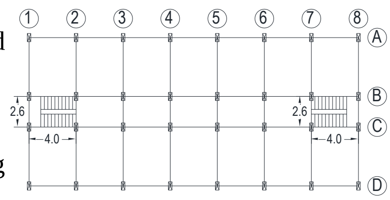
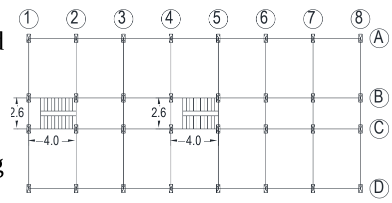
Structural modelling, analysis and design have been performed in SAP 2000 (V-14.2.4). Beams and columns have been modeled using 3D frame elements. The foundation has been considered as rigid and all the six degrees of freedoms at the base of the ground storey columns have been restrained. The in-plane rigidity of the slab has been modeled using diaphragm constraint. Response spectrum analysis is performed on the building ‘Model-S’ to compute seismic force. Three grades of concrete viz. M20, M30 and M60 have been used for ‘Model-S’ and ‘Model 1-6’. For ‘Model 7-8’ only M30 grade concrete has been used, since the purpose of these two models were to indicate the effect of symmetrical and asymmetrical placement of staircases on building performance. For comparison of models with different grades of concrete, the size of frame members have been kept same, however, the effect of grade of concrete has been reflected by reduction in quantity of reinforcing steel. The building is then designed and detailed for critical load combination as per Indian standard IS 1893-2002, IS 456-2000 and IS 13920-1993. Lumped plastic hinge model (FEMA 356/ASCE 41-06) has been used to simulate the nonlinear behavior of members. In case of beam members, uncoupled moment hinges (M3 hinge) and for column members, coupled axial force and biaxial bending moment hinges (P- M2-M3 hinge), have been assigned at both the ends. Nonlinear Static Procedure (NSP) has been used to study the nonlinear behavior of the buildings and to estimate the seismic performance. Parabolic lateral load deformation pattern based on storey mass and height as per FEMA 356 for obtaining capacity curve has been used.

The Displacement Modification Method (DMM) (ASCE 41; FEMA 440) has been used to obtain the performance point. To identify the effect of staircase on dynamic behavior and seismic performance of building, inclined waist slab of staircase has been modelled using thin shell element in the pre designed building ‘Model-S’ at specified location and orientation thus creating six different models i.e., ‘Model 1-6’ with single staircase (using three grades of concrete) and ‘Model 7-8’ with two staircases (using M30 grade concrete only). Therefore, a total of twenty three models have been analyzed including the ‘Model-S’. To assign nonlinear hinge property in the columns supporting staircase, special nodes in columns at mid landing level of staircase has been created and nonlinear hinge as per FEMA 356/ASCE 41-06 has been assigned.

3.1 Modal analysis results

Presence of staircase increases stiffness of building, thereby altering the modal parameters. Consequently, modal analysis has been performed on all the considered building models. The effect of staircase on the modal characteristics and fundamental period of vibration of building have been determined and shown in Table 2. It can be observed from Table 2 that the 'Model-S' as

Table 1 Nomenclature of models

Model Description	Figure	Model Description	Figure
Model-1: Analysis model with staircase located at first bay along longer side and second bay along shorter side, parallel to longer side		**Model-2:** Analysis model with staircase located at fourth bay along longer side and second bay along shorter side, parallel to longer side	
Model-3: Analysis model with staircase located at first bay along longer side and third bay along shorter side, parallel to longer side		**Model-4:** Analysis model with staircase located at fourth bay along longer side and third bay along shorter side, parallel to longer side	
Model-5: Analysis model with staircase located at first bay along longer side and second bay along shorter side, parallel to shorter side		**Model-6:** Analysis model with staircase located at fourth bay along longer side and second bay along shorter side, parallel to shorter side	
Model-7: Analysis model with two staircases located at first bay and last bay along longer side and second bay along shorter side, parallel to longer side		**Model-8:** Analysis model with two staircases located at first bay and fourth bay along longer side and second bay along shorter side, parallel to longer side	

anticipated, is the most flexible with largest fundamental period of vibration observed in longitudinal direction (T_x) i.e., 1.77 s, 1.60 s and 1.34 s designed with M20, M30 and M60 grade of concrete, respectively. With insertion of staircase, a decrease in fundamental period is also evident from Table 2, which indicates an increase in stiffness. Interestingly, this decrease in fundamental period is not same for all the models even though the size of staircase is same, but highly dependent on location and orientation of staircase. Further, the effect of insertion of staircase is not limited to reduction in period of vibration but also alters the stiffness of building in such a way, that the second translational mode (T_y) of Model 2 and 6 changes to torsional mode (T_θ) for all the three grades of concrete considered in the study. First three natural periods of all the models is presented in Table 2. The effect on modal parameters for building with two staircases i.e., 'Modal 7-8' is more drastic. Since the two staircases are oriented parallel to longitudinal direction, the stiffness along longitudinal direction has increased significantly and thereby, the first

Table 2 Natural period(s) and modal mass participation ratio (%) of structures with different grades of concrete

Grade of concrete	Models	Vibration mode 1			Vibration mode 2			Vibration mode 3		
		Direction of Shift	Period (s)	Modal mass participation ratio (%)	Direction of Shift	Period (s)	Modal mass participation ratio (%)	Direction of Shift	Period (s)	Modal mass participation ratio (%)
M20	Model-S	T_x	1.776	76.3	T_y	1.391	73.0	T_θ	1.334	20.3
	Model-1	T_x	1.370	63.2	T_y	1.308	41.4	T_θ	1.124	0.026
	Model-2	T_x	1.348	76.5	T_θ	1.330	22.0	T_y	1.287	73.1
	Model-3	T_x	1.562	72.4	T_y	1.356	59.2	T_θ	1.145	3.39
	Model-4	T_x	1.560	69.6	T_y	1.310	71.2	T_θ	1.266	16.0
	Model-5	T_x	1.651	76.5	T_y	1.366	50.9	T_θ	0.99	0.015
	Model-6	T_x	1.651	76	T_θ	1.314	36.4	T_y	1.205	71.7
M30	Model-S	T_x	1.605	76.3	T_y	1.257	73	T_θ	1.205	20.9
	Model-1	T_x	1.267	77	T_y	1.238	51.8	T_θ	1.031	0
	Model-2	T_x	1.215	76.8	T_θ	1.199	22	T_y	1.132	72.2
	Model-3	T_x	1.574	72.8	T_y	1.357	57.9	T_θ	1.11	2.6
	Model-4	T_x	1.426	71.2	T_y	1.179	60.6	T_θ	1.146	3.96
	Model-5	T_x	1.511	76.7	T_y	1.235	52	T_θ	0.935	0.2
	Model-6	T_x	1.509	76.4	T_θ	1.191	39.3	T_y	1.111	69.9
	Model-7	T_y	1.084	75.5	T_x	1.081	78.98	T_θ	1	19.6
	Model-8	T_y	1.167	35.9	T_x	1.037	76.5	T_θ	0.981	3.48
M60	Model-S	T_x	1.349	76.3	T_y	1.057	73	T_θ	1.014	20.9
	Model-1	T_x	1.106	77.2	T_y	1.042	53.1	T_θ	0.888	0
	Model-2	T_x	1.09	77.3	T_θ	1.011	26.8	T_y	0.998	72.8
	Model-3	T_x	1.22	74.6	T_y	1.035	58.5	T_θ	0.868	2.5
	Model-4	T_x	1.214	72.9	T_y	0.998	60.8	T_θ	0.972	3.76
	Model-5	T_x	1.283	76.7	T_y	1.04	52.8	T_θ	0.817	0
	Model-6	T_x	1.287	76.6	T_θ	1.006	43.1	T_y	0.956	67

mode obtained has been in transverse direction. Due to asymmetrical placement of staircases in 'Model-8' the modal mass participation ratio in the first mode also drastically reduced.

Comparison of natural period of 'Model-S' with other models indicates considerable reduction in period of structure for first three modes due to staircase. When the single staircase is located at central portion of the structure (Model-2), a significant reduction in natural period of structure in the first mode of vibration has been observed i.e. 24% for building designed for M20 and M30 grade of concrete and 19% for the building designed for M60 grade of concrete. From the table it can be observed that reduction in period of structure of the six models i.e., 'Model 1-6' with single staircase is varying between 24% to 7% in first mode of vibration and 6% to 1.8% in second mode of vibration. In case of 'Model 7-8' with two staircase, the reduction in period is significant, i.e., 32% and 35% in transverse and 14% and 7% in longitudinal direction for 'Model-7' and 'Model-8' respectively. The reduction in natural period will lead to increased seismic force for which the building has actually not been designed. This can further lead to larger damage than anticipated.

Hongling *et al.* (2013) considered three models to check the effect of staircase. First model considered by them is similar to 'Model-S', second model is similar to 'Model-7' and the third model is similar to 'Model-3' of the present study. Even though the building plan considered by them is different form present study, similar conclusion of change in period of vibration due to staircase and effect of staircase in imparting the torsional effect in the structure have been drawn.

3.2 Nonlinear analysis results

To access the performance of building, nonlinear static analysis has been performed. Pushover analysis is a nonlinear static procedure (NSP) in which the magnitude of the structural loading or displacement is incrementally increased in accordance with a certain predefined pattern. Pushover analysis estimates force and displacement capacity of structure along with sequential formation of hinges in the structure under nonlinear excursion. Result of pushover analysis is usually represented in the form of capacity curve which is the variation of base force (or base shear) with respect to roof displacement. However, there are some limitations of pushover analysis such as; the analysis should be performed on regular building plan, mode proportional pushover pattern can be selected for the building with pure translation mode along principle directions with high modal mass participation ratio and an accurate nonlinear behavior of buildings considering reversal of loads cannot be predicted by this method. In the present study, therefore, a regular symmetric building plan has been considered. Also, parabolic lateral load pattern as per FEMA 356 for pushover analysis has been preferred over the mode proportional pattern. It is due to the fact that, the insertion of staircase leads to local stiffening and thereby, for some models considered in the present study, pure translation mode along principle directions have not been achieved. It is also to be noted that the pushover curves depicts the nonlinearity in building under monotonic loading upto a point when majority of frame members reaches collapse. However, the present study is focused on effect of insertion of staircase on nonlinear behavior of building. The capacity curve is considered till the collapse level hinge formations occur in the frame members supporting staircase, and beyond collapse of the staircase, the multistoried building has been considered as unserviceable.

3.2.1 Behaviour of building with single staircase

Based on NSP, capacity curve of various models have been developed. Comparison of capacity curves for 'Model 1-6' with 'Model-S' (each model designed for three grades of concrete i.e., M20, M30 and M60) in longitudinal and transverse direction are shown in Figs. 3-16. Based on pushover curves the comparison of ductility, yield force, yield displacement, target displacement and over strength ratio for aforementioned models have been computed and are shown in Table 3, for longitudinal and transverse direction considering pushover in positive direction. Comparison of capacity curves of building 'Model-1' with 'Model-S' in longitudinal and transverse directions are shown in Figs. 3 and 4 respectively. It can be observed from Fig. 3, that in longitudinal direction, the initial stiffness of building 'Model-1 (M20)' is approximately 1.5 times higher than 'Model-S (M20)'. Moreover, for 'Model-1' with M30 and M60 grade concrete, the increase in initial stiffness is of the same order as observed with M20 grade concrete, but the plastic hinge in the column supporting staircase reached collapse level even before yielding of most of the frame members and therefore, nonlinearity in the building capacity curve has not been observed.

In transverse direction, the initial stiffness of 'Model-S' and 'Model-1' for the three grades of concrete is almost same since the truss action of staircase is not mobilized due to its orientation. It has also been observed that first hinge formation in 'Model-1' under longitudinal direction pushover occurred in short column created due to modeling of the staircase, whereas for 'Model-S' the first hinge developed in beam. In case of pushover in transverse direction first hinge formation

Table 3 Comparison of capacity curve results of models with single staircase along longitudinal and transverse direction for different grades of concrete (Pushover in positive direction)

Concrete Grade	Displacement direction	Longitudinal Direction							Transverse Direction						
	Model	S	1	2	3	4	5	6	S	1	2	3	4	5	6
M20	Ductility	3.33	1.945	1.04	1.4	1.98	1.913	2.56	3.25	2.58	2.3	1.522	3.78	3.883	2.25
	Yield force	6235	5580	8000	7000	6600	6100	5400	6220	6300	7200	5580	6700	4600	5200
	Yield displacement	0.235	0.164	0.2	0.2	0.202	0.23	0.22	0.192	0.19	0.16	0.164	0.164	0.12	0.16
	Target displacement	0.270	0.201	0.189	0.190	0.183	0.241	0.241	0.201	0.187	0.198	0.201	0.193	0.2	0.177
	Over strength ratio	2.256	2.019	2.895	2.345	2.388	2.207	1.954	2.251	2.28	2.605	2.019	2.424	1.664	1.882
M30	Ductility	3.636	1.000	1.417	1.000	3.688	2.727	2.778	2.667	2.727	2.375	2.143	2.400	3.900	1.833
	Yield force	6700	-	6000	-	7200	7200	7400	6800	5050	8000	5100	5600	5000	7200
	Yield displacement	0.220	-	0.120	-	0.160	0.220	0.180	0.150	0.110	0.160	0.140	0.100	0.100	0.120
	Target displacement	0.231	0.182	0.175	0.227	0.205	0.218	0.217	0.181	0.178	0.163	0.195	0.170	0.178	0.160
	Over strength ratio	2.424	-	2.171	-	2.605	2.605	2.678	2.461	1.827	2.895	1.845	2.026	1.809	2.605
M60	Ductility	2.778	1.000	2.077	1.000	1.375	2.778	2.632	2.917	1.500	3.200	2.667	2.400	3.222	2.000
	Yield force	7350	-	8200	-	8000	7400	7500	7700	7400	6800	6600	5600	5700	7700
	Yield displacement	0.180	-	0.130	-	0.160	0.180	0.130	0.120	0.100	0.100	0.090	0.100	0.090	0.100
	Target displacement	0.194	0.159	0.157	0.176	0.175	0.185	0.185	0.152	0.150	0.144	0.149	0.144	0.150	0.138
	Over strength ratio	2.660	-	2.967	-	2.895	2.678	2.714	2.786	2.678	2.461	2.388	2.026	2.063	2.786

occurred in beam for both 'Model-S' and 'Model-1' for all the three grades of concrete. From Table 3 it can be observed that by considering M20 grade of concrete there is 40% decrease in ductility in longitudinal direction for 'Model-1' as compared to 'Model-S', whereas, for higher grades of concrete failure of columns supporting staircase was very early and no ductility in the building has been observed. Also, it has been observed that even though the target displacement demand reduced for 'Model-1' the performance is poorer than 'Model-S'. At target displacement, performance of 'Model-S' was around life safety level but for 'Model-1' it crossed the collapse level. Due to modeling of staircase in the building, the building becomes unstable at very smaller displacement in longitudinal direction; on the other hand in transverse direction building perform alike to building without staircase which clearly indicates the effect of orientation of staircase. Furthermore, for the building models designed with higher grades of concrete in which the staircases inserted afterwards, the performance has been drastically reduced.

To identify the effect of change in the location of staircase keeping orientation same, the staircase at extreme left in the middle bay is shifted to the centre of the building and named as 'Model-2'. Comparison of capacity curves of building with centrally located staircase 'Model-2' and 'Model-S' are shown in Figs. 5 and 6. By comparing capacity curves of 'Model-2' and 'Model-S' (Figs. 5 and 6), the maximum increase in initial stiffness of building has been observed for M60 grade of concrete which is approximately 2 times and 1.1 times higher in longitudinal and transverse directions, respectively. For lower grade of concrete (M30 and M20) the increase in initial stiffness ranges from 1.2 to 1.6. Reduction in ductility is very significant in longitudinal direction, i.e., 'Model-2 (M20)' is almost showing brittle failure, whereas, for M30 and M60 grade of concrete little ductility has been observed in longitudinal direction. In 'Model-2' for all the considered grades of concrete, first immediate occupancy level hinge is formed in mid landing beam, moreover, the first collapse level hinge is formed in short column due to inclusion of staircase.

By observing Figs. 7-8, it can be understood that the effect of location of staircase on capacity curve is also quite considerable. It is interesting to note that even though the staircase is oriented in longitudinal direction, it has some effect in transverse direction also, which indicates the significance of location. Capacity curve of building with staircase located at extreme left corner of exterior bay 'Model-3' has been compared to 'Model-S'. From Figs. 9-10 and Tables 3-4, it can be seen that the ductility capacity in both directions of 'Model-3 (M20)' is 50 % lesser than 'Model-S'. For higher grades of concrete (M30 and M60), the building model shows brittle failure in longitudinal direction and considerable reduction of ductility in transverse direction. For the three grades of concrete considered in the study, it has been observed that the performance of 'Model-3' deteriorated as at target displacement it reaches collapse, which was under life safety level for 'Model-S'. The observed behavior of 'Model-3' is fairly similar to 'Model-1', however, it is to be noted that the formation of first hinge occurred in mid landing beam of staircase for 'Model-3' for all the grades considered in the study as compared to formation of first hinge in short columns for 'Model-1'. This may be attributed to the fact that, the 2.6 m wide staircase is resting on mid landing beam of the corner bay of 5 m in 'Model-3' whereas, in the 'Model-1' the width of bay was same as width of the staircase. However, with increase in roof displacement hinge formation in 'Model-3' occurred in short columns and collapse level reached earlier in longitudinal direction than 'Model-1'.

To realize the effect of location of staircase 'Model-4' has been developed which is similar to 'Model-3' with only difference that the location of staircase is shifted to the center of exterior bay in transverse direction. It has been observed that there is significant improvement in ductility

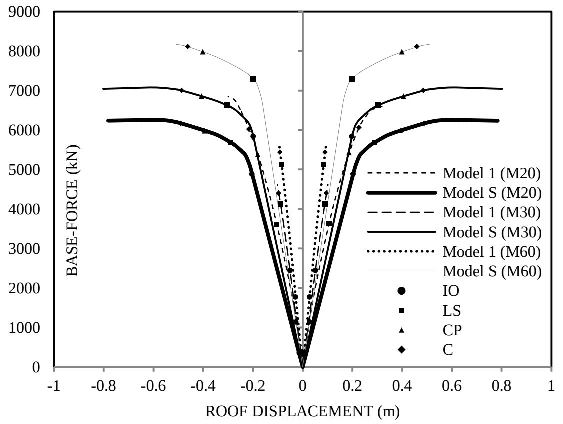


Fig. 3 Comparison of Capacity curves of Model-S and Model-1 in longitudinal direction

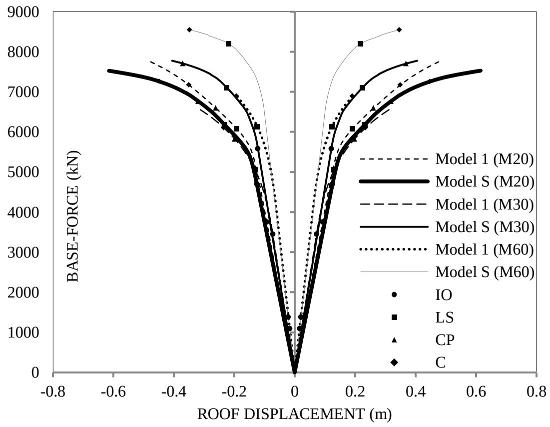


Fig. 4 Comparison of Capacity curves of Model-S and Model-1 in transverse direction

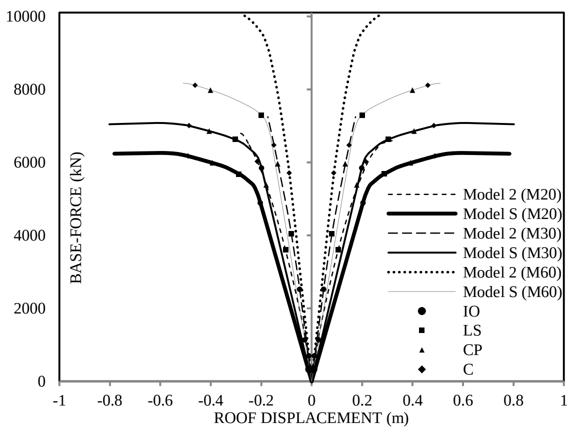


Fig. 5 Comparison of Capacity curves of Model-S and Model-2 in longitudinal direction

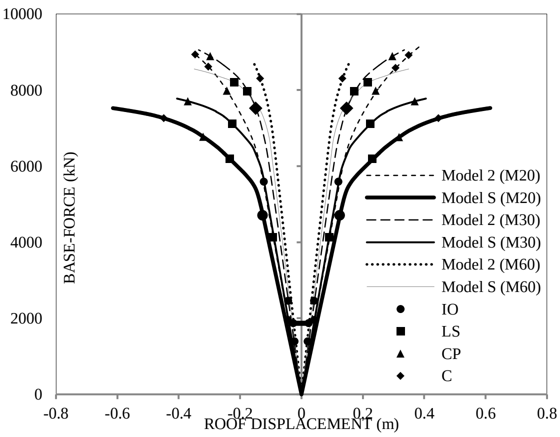


Fig. 6 Comparison of Capacity curves of Model-S and Model-2 in transverse direction

capacity of 'Model-4' as compared to other previous models except 'Model-S', which indicates the importance of location, however, the pattern of hinge formation is similar. Comparison of capacity curve in longitudinal and transverse direction of 'Model-4' with 'Model-S' (for three grades of concrete) are shown in Figs. 11-12. The increase in initial stiffness of 'Model-4' in comparison to 'Model-S' in both the directions can be observed from figures. Ductility capacity in longitudinal direction of 'Model-4' has reduced, but increased in transverse direction. In 'Model-5' staircase oriented along transverse direction, has been placed at extreme left corner of exterior bay. The orientation and location of staircase imparts high stiffness to this corner of the building due to which side opposite to staircase becomes flexible. In both longitudinal and transverse direction the formation of hinges starts at very low displacement as can be seen from Figs. 13-14.

It has been observed that particularly in transverse direction significant number of life safety and collapse level hinges formed in beams and columns of flexible side of building rather that in members around staircase. For 'Model-5' hinge formation pattern has not been affected by of

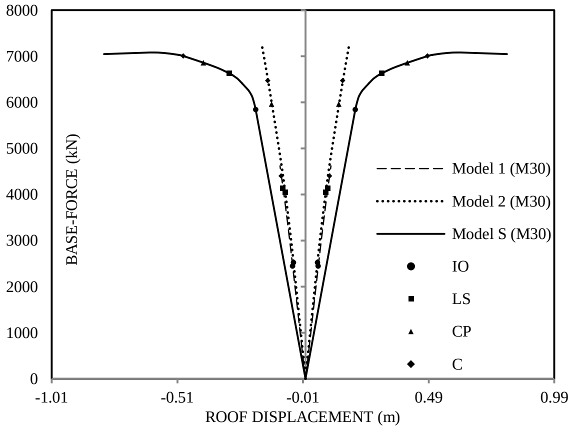


Fig. 7 Comparison of Capacity curves of Model-1 and Model-2 in longitudinal direction

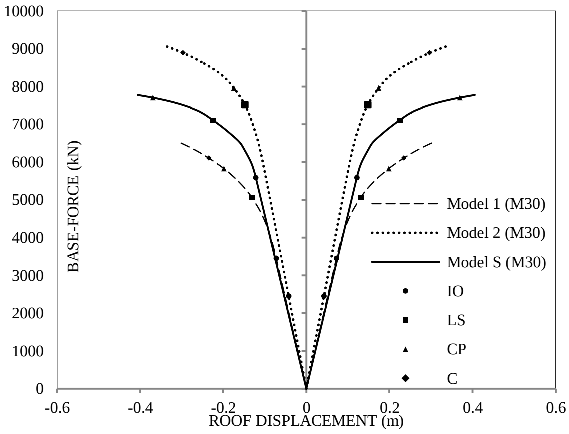


Fig. 8 Comparison of Capacity curves of Model-1 and Model-2 in transverse direction

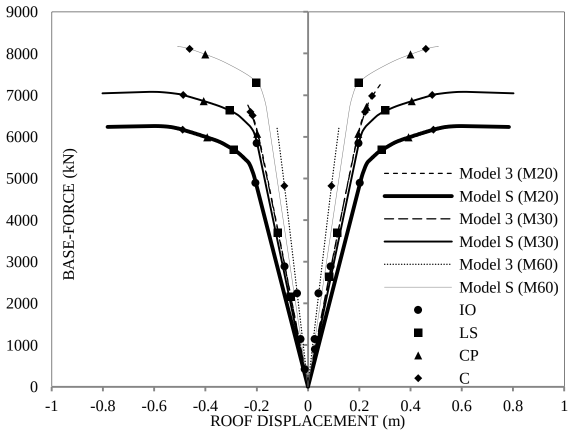


Fig. 9 Comparison of Pushover curves of Model-S and Model-3 in longitudinal direction

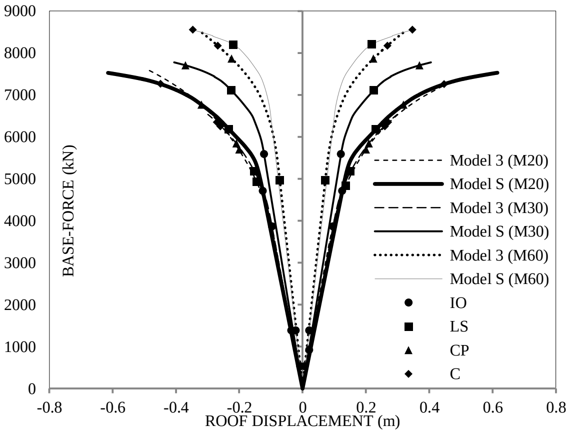


Fig. 10 Comparison of Pushover curves of Model-S and Model-3 in transverse direction

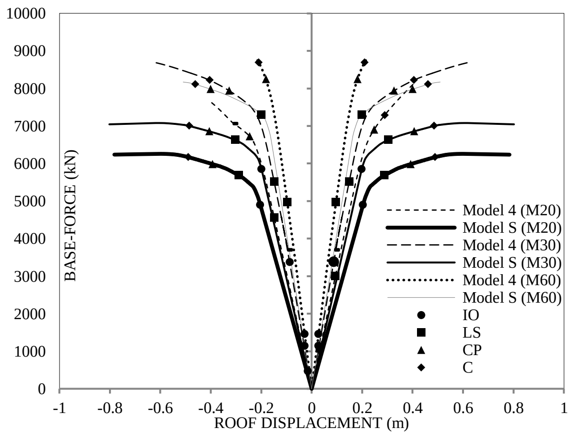


Fig. 11 Comparison of Capacity curves of Model-S and Model-4 in longitudinal direction

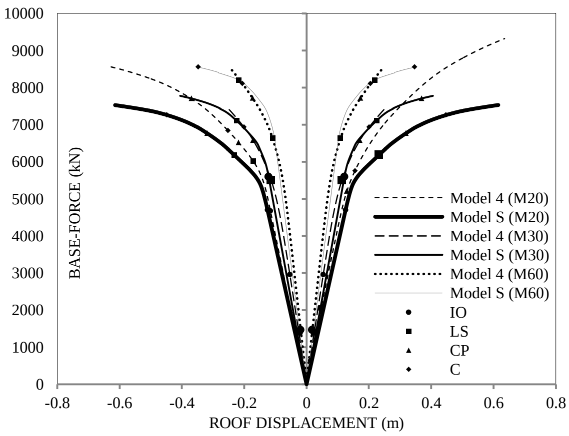


Fig.12 Comparison of Capacity curves of Model-S and model-4 in transverse direction

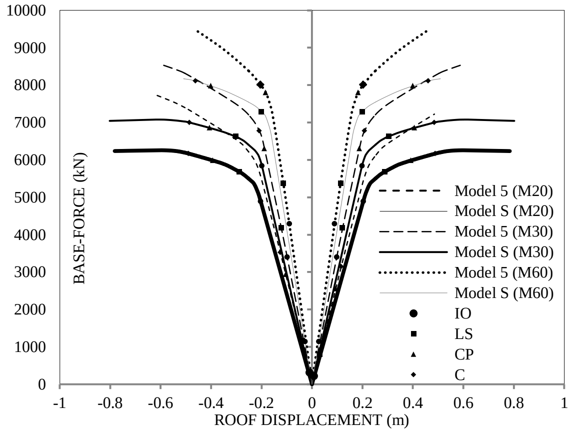


Fig. 13 Comparison of Capacity curves of Model-S and Model-5 in longitudinal direction

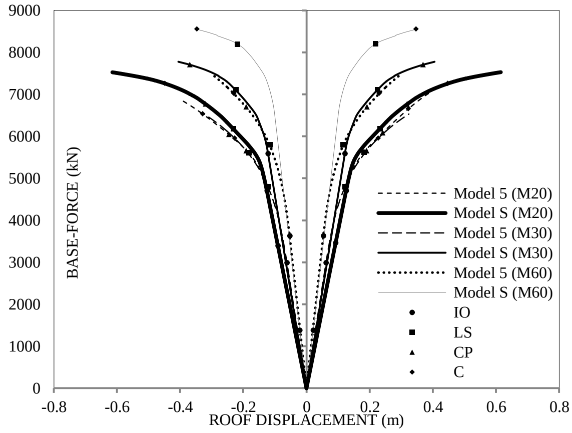


Fig. 14 Comparison of Capacity curves of Model-S and Model-5 in transverse direction

grade of concrete. Comparison of ‘Model-3’ and ‘Model-5’ clearly indicates the effect of orientation of staircase. Since, in ‘Model-3’ the orientation of staircase was parallel to longitudinal side, building was showing almost brittle failure, however, in ‘Model-5’ the staircase has been placed at same location but oriented along transverse and therefore, the building shows ductile behaviour in longitudinal direction. But overall in comparison to ‘Model-S’ a reduction in performance of ‘Model-5’ has been observed i.e., at target displacement the building ‘Model-5’ reaches collapse condition. In a similar condition when staircase is also oriented along transverse direction but located at middle bay i.e., ‘Model-6’, the performance of building for all the three grades of concrete have been improved. It can be observed from Figs. 15-16 that the hinge formation is similar to ‘Model-S’. In comparison to ‘Model-S’ the overall ductility capacity of ‘Model-6’reduced by 30% and 45% in longitudinal and transverse directions, respectively. From nonlinear analysis on a similar model conducted by Singh and Choudhury (2012) it has been

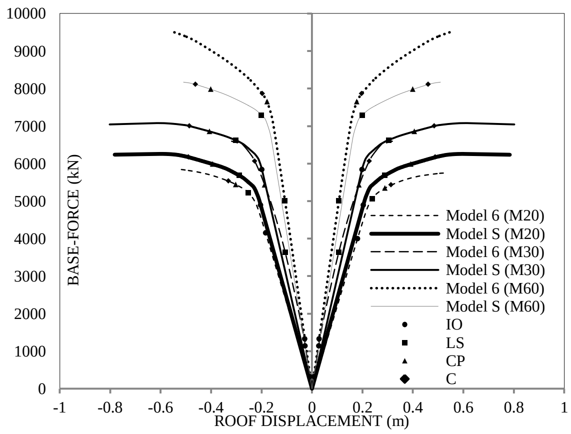


Fig. 15 Comparison of Capacity curves of Model-S and Model-6 in longitudinal direction

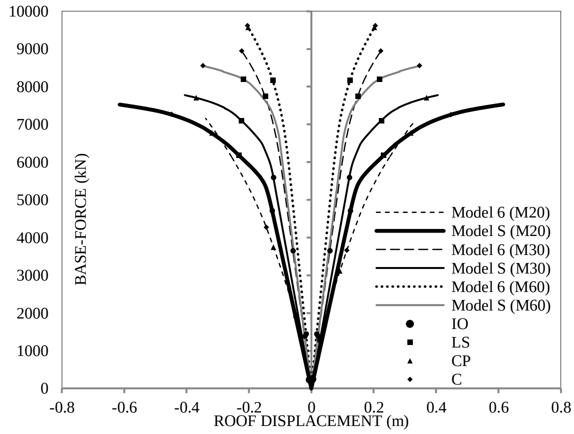


Fig. 16 Comparison of Capacity curves of Model-S and Model-6 in transverse direction

reported that in transverse direction (the direction in which staircase is oriented) the ultimate base shear increased significantly, but ultimate displacement reduced to two third, similar results has been found for ‘Model-6’ in which base shear increased by 15% and ultimate displacement reduced to two third. They have also shown that the effect of staircase in not significant in longitudinal direction as observed in present study with ‘Model-6’.

3.2.2 Behaviour of building with two staircases

Model 7-8, have been developed to evaluate the performance of buildings with two staircases. In both the models the staircases are oriented in longitudinal direction and therefore, from Figs. 17-18 it can be observed that increase in initial stiffness is significant in the longitudinal direction. In transverse direction (Fig. 18) the initial stiffness is almost same. In ‘Model-7’ with symmetrical placement of staircase, it has been observed that for pushover along longitudinal direction the hinge formation is concentrated around staircase region. Most of hinges formed in the short columns supporting the staircase and reached collapse level much before the target displacement. In transverse direction the effect of bracing action is small and therefore, uniform hinge formation in beams has been observed. Since, ‘Model-7’ is symmetrical with respect to plan as well as placement of staircase, formation of hinges are also symmetrical.

In case of ‘Model-8’ with asymmetrical placement of staircase, the pushover curves in longitudinal directions for positive and negative push are different. This can be attributed to asymmetric placement of staircase. Due to pushover along positive longitudinal direction, the left portion of building having two staircase experiences tension and thereby, the early hinge formation starts in column supporting staircase and reaches collapse level, whereas, due to pushover in negative longitudinal direction the columns supporting staircase experiences compression and therefore, the overall capacity increases. However, it is to be noted that in both the cases the columns supporting staircase reaches collapse level. The effect of asymmetrical placement of staircases has also been observed in transverse direction. In transverse direction it has been observed that hinge formation is concentrated in the beams of right portion of the building i.e., on the opposite side of the staircase, which reaches collapse level before the left side beam.

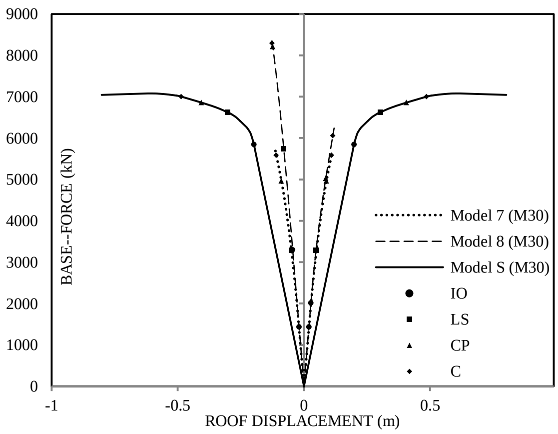


Fig. 17 Comparison of Capacity curves of Model S and Model 7-8 in longitudinal direction

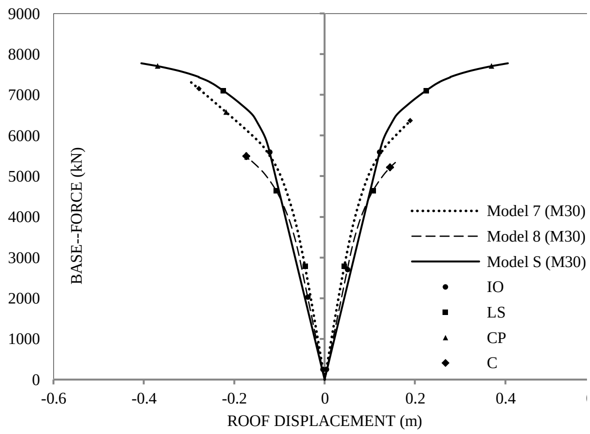


Fig. 18 Comparison of Capacity curves of Model S and Model 7-8 in transverse direction

4. Conclusions

The present study outlines the effect of grade of concrete, modeling, orientation and location of staircase in seismic behavior and performance of RC frame building using single and multiple staircases. A six storey building with plan representing a typical office or public building has been modeled and designed for three grades of concrete (with nominal characteristic strength of 20 MPa, 30 MPa and 60 MPa) without considering staircase. Further six building model plans (each considering three grades of concrete) by inserting single staircase at different location and orientation, in the model without staircase has been developed. To study the effect of multiple staircase, two models have been considered (for 30 MPa concrete only) with two staircases symmetrically and asymmetrically placed. It has been observed from modal analysis that insertion of staircase not only affect the fundamental period of vibration significantly, but also the appearance of mode changes i.e., in some cases second translational mode changes to torsional mode. Moreover, the effect of same staircase placed at different locations and in different orientations, significantly affects modal characteristics i.e., the variation of fundamental period of vibration for single staircase ranges from 7 to 22% and for two staircase model it reduces upto 35% for different models. In order to estimate seismic performance of aforementioned models capacity curves have been developed using NSP as per FEMA 356/ASCE 41-06 guidelines. Superior performance of building model without staircase has been drastically reduced due to inclusion of staircase. Some building models with higher grade of concrete exhibited brittle failure due to collapse of columns supporting inserted staircases. Even for the building model with low strength concrete (20 MPa) upto 70% reduction in ductility capacity due to inclusion of staircase has been observed. Moreover, in most of the cases early development of plastic hinge in short column which is created due to inclusion of staircase lead to pushing the building to collapse level. It has also been observed that location and orientation of staircase plays an important role in deciding the performance of building. From the study it can be concluded that for the considered building, ignoring the contribution of staircase in structural modeling and design can lead to excessive damage and even collapse under seismic event.

References

Agarwal, P., Thakkar, S.K. and Dubey, R.N. (2002), "Seismic performance of reinforced concrete buildings during Bhuj earthquake of January 26, 2001", *ISET J. Earthq. Technol.*, **39**(3), 195-217.

Arslan, M.H. and Korkmazalso, H.H. (2006), "What is to be learned from damage and failure of reinforced concrete structures during recent earthquakes in Turkey?", *J. Eng. Fail. Anal.*, **14**(1), 1-22.

ASCE 41 (2007), *Seismic Rehabilitation of Existing Buildings (ASCE)*, American society of Civil Engineers, Reston, VA.

Cengiz, O.Z. and Ali, Hsan (2007), "Commonly encountered seismic design faults due to the architectural design of residential buildings in Turkey", *J. Build. Envir.*, **42**(3), 1406-1416.

Edoado, C., Gerardo, M.V. and Alessandra, Z. (2008), "Seismic performance of stairs in the existing reinforced concrete building", *Proceeding of 14th World Conference of Earthquake Engineering*, Beijing, China.

EERI Special Earthquake Report (2001), "Learning from Earthquakes: Preliminary observations on the origin and effects of the January 26, 2001 Bhuj (Gujarat, India) Earthquake", *EERI Newsletter*, **35**(4).

FEMA 356 (2000), *Pre-standard and commentary for the seismic rehabilitation of buildings*, Federal Emergency Management Agency, Washington, DC.

FEMA 440 (2005), *Improvement of Nonlinear Static Seismic Analysis Procedures*, Federal Emergency Management Agency, Washington, DC.
Goel, R.K. (2001), "Performance of buildings during the January 26, 2001 Bhuj earthquake", *Earthq. Eng. Res. Inst.*, Oakland, CA.
Hongling, S., Aiping, Z. and Jiangtao, C. (2013), "Earthquake response analysis for stairs about frame structure", *J. Eng. Fail. Anal.*, **33**, 490-496.
Humar, J., Lau, D. and Pierre, J.R. (2001), "Performance of buildings during the 2001 Bhuj earthquake", *Can. J. Civ. Eng*., **28**(6), 979-991.
IS 1893 (Part 1) (2002), *Criteria for Earthquake Resistant Design of Structures*: *Part 1 General Provision and Buildings* (fifth revision), BIS, New Delhi, India.
IS 456 (2000), *Plain and Reinforced Concrete - Code of Practice* (fourth revision), BIS, New Delhi, India.
IS 13920 (1993), *Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces - Code of Practice*, BIS, New Delhi, India.
IS 875 (Part 1) (1987), *Code of Practice for Design Loads (other than Earthquake) for Buildings and Structures: Part 1-Dead Loads* (second revision), BIS, New Delhi, India.
IS 875(Part 2) (1987), *Code of Practice for Design Loads (other than Earthquake) for Buildings and Structures: Part 2- Imposed Loads* (second revision), BIS, New Delhi, India.
Kumar, R. and Singh, Y. (2010), "Stiffness of reinforced concrete frame members for seismic analysis", *ACI Struct. J.*, **107**(5), 607-615.
Li, Y.A., Huang, Y.T. and Hwang, S.J. (2014), "Seismic response of reinforced concrete short columns failed in shear", *ACI Struct. J.*, **111**(4), 945-954.
Murty, C.V.R., Goel, R.K., Goyal, A., Jain, S.K., Sinha, R., Rai, D.C., Arlekar, J.N. and Metzger, R. (2002), "Reinforced concrete structures", *Earthq. Spectra*, **18**(S1), 149-185.
SAP2000 Tutorial Manual, *SAP2000 Integrated Finite Elements Analysis and Design of Structures tutorial Manual*, Computers and Structures, Inc., Berkeley, California, USA.
Singh, S.N. and Choudhury, S. (2012), "Effects of staircase on the seismic performance of RCC frame building", *ISJEST*, **4**(4), 1336-1350.
Singh, Y. and Kumar, R. (2008), "Performance of structures during past earthquakes: Lessons for construction industry", *International Conference on Construction Managing Earthquake Risk*, India Habitat Centre New Delhi, India.
Xu, C. and Li, T. (2012), "The impact of the stairs to the earthquake resistance of reinforced concrete frame structure", *Proceedings of 2nd International Conference on Electronics and Mechanical Engineering and Information Technology*, Paris, France.

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List of Notations

R	Response reduction factor
M20	Characteristic compressive strength of concrete as 20MPa
M30	Characteristic compressive strength of concrete as 30MPa
M60	Characteristic compressive strength of concrete as 60MPa
P-M2-M3	Coupled axial force and biaxial bending moment hinge
M3	Uncoupled moment hinge
T_x	Period of vibration along longitudinal direction
T_y	Period of vibration along transverse direction

T_θ	Period of vibration in torsion
IO	Immediate occupancy performance level
LS	Life safety performance level
CP	Collapse prevention performance level
C	Collapse level