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Performance Assessment of Ductile Detailing Code-Based Reinforced Concrete Special Moment Resisting Frames

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ABSTRACT

Reinforced concrete (RC) buildings make up the majority of Indian building stocks. Structural elements of these buildings are often designed limited to non-ductile detailing. With a very low building replacement rate, many Indian buildings are vulnerable to earthquakes and pose a significant risk to lives, properties and economic activities. This paper examines the effectiveness of ductile-detailing in mitigating the seismic collapse risk by analyzing the behaviour of a four-storey RC Special Moment Resisting Frame (RC SMRF) using the latest codes of ductile detailing. It also aims to quantify the impact of lateral force resisting system detailing on the performance and cost of RC SMRF buildings and its benefits. The present study emphasizes the effect of ductile detailing on three fundamental aspects of the structure – safety, stability and economy. Two four-storeyed building models – one without ductile detailing and the other with ductile detailing are designed and then analyzed using non-linear static analysis. The results of this study represent the behaviour of ductile-detailed and non-ductile-detailed buildings in terms of pushover curves, and hinge behaviour and identify the mode of final failure. In extension to that, a cost-benefit analysis is done to study the benefits of ductile detailing with the increased cost. The marginal increase in initial cost associated with ductile detailing is significantly outweighed by the resulting savings in the repair and downtime costs during the service life of the building.

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1. INTRODUCTION

A severe earthquake is one of the most destructive phenomena of nature. It is impossible to predict an earthquake, as it causes a severe damage to the structure. The damage to a structure can be reduced by providing a proper design. In order to provide a proper design, it is required to estimate the actual loads (i.e., dead load, live load, wall load, floor load, floor finish load, seismic load, wind load etc.) hitting the structure accurately. Among all other loads, lateral dynamic loads due to wind and seismic forces generally exhibit the highest degree of uncertainty and causes more damage to the structure which is to be eliminated by a proper design. In seismic zones, structures when subjected to an earthquake, structure experiences more amount of the seismic energy in axial directions. In order to withstand and absorb the energy, structure should have to produce more plastic deformations which can be possible by adopting ductile materials. Previous works on performance evaluation of structure considering non-ductile detailing and ductile detailing, in terms of capacity, damage, response reduction factor and drift done using static non-linear analysis and fragility analysis for estimation of the post damage yielding behaviour of structure where studies have shown that the design will reduce the damage in the structure significantly and design code is recommending a higher response reduction factor value, due to which the member size decreases and lead the structure to have more damage compared to the ductile detailed structures, thus 'R' need to be defined [1]. IS code recommending a higher 'R'-value than the actual, which is potentially dangerous. The actual value of 'R' is expected to be even lower than IS recommendations, due to structural

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irregularity leading to minor to moderate torsional effects, lack of quality control during the construction, and not following the ductile detailing requirements exactly as per the guidelines [2]. Other studies explore the current ACI seismic design code for moderate seismic hazard and cost-benefits of various levels of ductile connection detailing requirements are reviewed for steel buildings in the United States resulting in increased rates for improved ductility, and thus lower member forces, in the response of the structure [3]. Modal pushover analysis provides accurate results for low rise structures and consecutive pushover analysis provides more efficient results for high-rise and mid-rise frames [4]. Pushover analysis is used to predict potential weak areas by tracking the sequence of damages of each member in the structure and determining the weak joints. Finally, concluded that the values obtained using both the codes are the same. It is observed for the same loading conditions using ACI code displacement along Y direction increases compared to IS code [5]. The performance of a structure depends on the loads acting on the structure**,** based on the loads acting, type of analysis is adopted. Generally, base shear for seismic design is two times higher than gravity load design [6]. Seismic evaluation of a structure can be done by using pushover analysis [7-9]. Effect of ductile detailing influences the stability and strength of the structure [10, 11]. Vulnerability of a high-rise structure under seismic load can be evaluated using fragility curves following performance-based approach [12]. Exact behaviour of beam-column joint with ductile detailed and non-ductile detailed can be evaluated by applying reverse cyclic quasi-static stress till failure [13]. The process of evaluation of a structure due to seismic loading can be performed by pushover analysis which is used in this study and when a structure subjected to imposed loading can be performed by modal pushover analysis [14-18].

1. 1. IS 13920-2016 Code Recommendations

Latest code for ductile detailing of structure is IS 13920-2016 recommends to adopt ductile detailing in medium and high seismic zones in the structure. Those recommendations are:

Seismic Zone -II can be made as ordinary moment resisting frame (OMRF). Ductile detailing can be adopted for seismic Zone-III with above five stories in height; for seismic Zone-IV and Zone-V, ductile detailing is mandatory. It recommends to use a minimum of M20 grade of concrete. It recommends to use M25 or more grade of concrete in the case of the structural height exceeds 15 meters in Zone – III, IV, V; use Fe415 or less grade of steel; use Fe500 or more if change in length of the member is more than 14.5%; recommends to adopt strong column-weak beam design concept.

The scope of the study is limited to a low to mid-rise RC frame structure. Two models (i) Structure without ductile detailing (Model-I); (ii) Structure with ductile detailing (Model-II) are modelled and analysed under seismic Zone IV condition. Seismic analysis is done using non-linear static analysis (i.e., pushover analysis) using ETABS software. Soil-structure interaction is not taken into consideration which means foundation design and analysis is neglected. Cost estimation is done using CSi Detail and MS Excel software tools. This study has significant importance in the current scenario of existing buildings in India. It deals with the importance of ductile detailing in RC buildings with the current design practice and presents a cost comparison with cost-benefit analysis. Main objectives to be carried out in this paper includes, the study on the behaviour of a ductile detailed structure over the non-ductile detailed structure using pushover analysis as per new code, assessment on the exact behaviour of the structure using pushover curves and finally, to perform cost-benefit analysis.

2. MODELING AND DESIGN OF RC FRAMES

In this study, two different models are considered, one is without ductile detailing and other is with ductile detailing and the comparative study is done to assess the performances of both the models (Figure 1). The modeling, analysis and the design are performed using software tools i.e., CSi ETABS and CSi Detail.

Assumed building parameters (Table 1), seismic parameters (Table 2) are provided below, and the building is assumed with a live load of 1.5 kN/m^2 on terrace and 3 kN/m^2 on typical floors, along with that wall loads are also taken as 4.9 kN/m^2 on terrace and 14.7 kN/m^2 on typical floors (values obtained based on the manual calculations done considering the material unit weight) respectively.

After analysing the structures using linear approach, both the RC frames are designed and its design section properties are as follows – (i) Structure without ductile detailing (Model-I) – Beam 350 mm X 400 mm, Column 400 mm X 450 mm, Slab 130 mm, (ii) Structure with

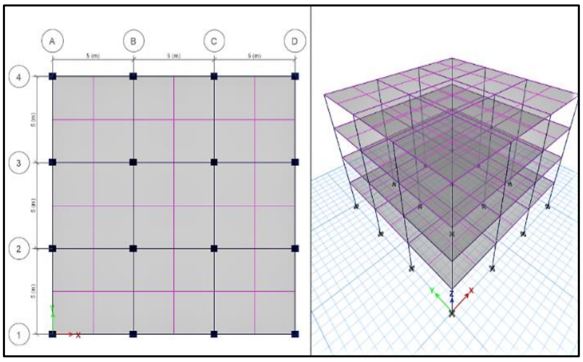


Figure 1. Plan and rendered view of model

ductile detailing (Model-II) – Beam 350 mm X 450 mm, Column-I 600 mm X 650 mm, Column-II 550 mm X 550 mm, Slab 130 mm.

After analyzing the frames based on the above assumed parameters, it is designed following three different code provisions in which for Model-I (Structure without ductile detailing) is designed using IS 456: 2000 + IS 1893: 2016 and Model-II Structure with ductile detailing) is designed using IS 456: 2000 + IS 1893: 2016 + IS 13920: 2016. The design output values of both the models which includes material properties (Tables 3 and 4).

3. PERFORMANCE ASSESSMENT ON THE DESIGNED MODELS

To identify the maximum extent of failure of structures, new models have created with the designed properties obtained from linear approach and those new models are analyzed using pushover analysis with *displacement coefficient method*.

TABLE 1. Building parameters

Size of the plot	**15 m X 15 m**
Storey height	3 m
Total number of stories	G + 3

TABLE 2. Seismic parameters

Zone	**IV**
Zone value	0.24
Site soil type	II (medium)
Importance factor	1.5
Response reduction factor	5
Time period along X and Y	0.4835 sec

TABLE 3. Designed material properties of Model-I

Element	**Grade of concrete**	**Main reinforcement**	**Secondary reinforcement**	**Cover**
Beam	M25	Fe500	Fe415	25 mm
Column	M30	Fe500	Fe415	40 mm
Slab	M25	Fe500	Fe415	20 mm

TABLE 4. Designed material properties of Model-II

Element	**Grade of concrete**	**Main reinforcement**	**Secondary reinforcement**	**Cover**
Beam	M25	Fe500	Fe415	25 mm
Column	M30	Fe500	Fe415	40 mm
Slab	M25	Fe500	Fe415	20 mm

Pushover analysis is generally used to estimate forces and displacements of the structure; sequence of failure of an element and its effects over the stability of entire frame; it identifies the critical regions where inelastic deformations are expected to be high; performance of the structure can be assessed on studying the pushover curves which includes capacity-demand curve, hinge responses; condition of hinges explains the severity of the entire structure; hinges forms in three stages namely IO- immediate occupancy, LS- life safety, CP- collapse prevention (Figure 2).

In order to assess the performance of both the Models, new models are created in ETABS using the designed properties which were obtained first using linear approach are considered as inputs and created new models including reinforcement details using section designer in ETABS and analyzed using pushover analysis. The below mentioned figures (Figures 3 and 4) represents the cross-section details of beams and columns in both the models, which are used in creating new models.

The models are assigned with hinges in beams and columns near the either ends of the element. For beams assign hinges based on the code ASCE 41-17 under table 10-7 (concrete flexure beams) with M3 degree of freedom along Push X and Push Y. For columns assign hinges based on the code ASCE 41-13 under table 10-8(concrete columns) with P-M2-M3 interaction under flexure/shear failure condition along Push X and Push Y.

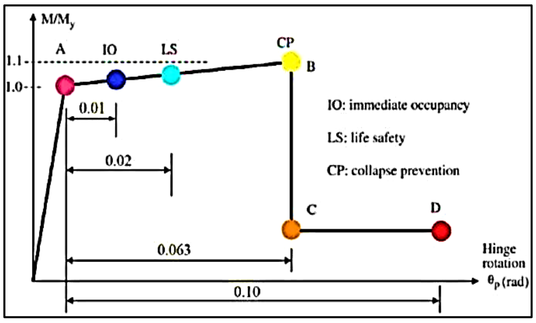


Figure 2. Behaviour of plastic hinge under pushover analysis

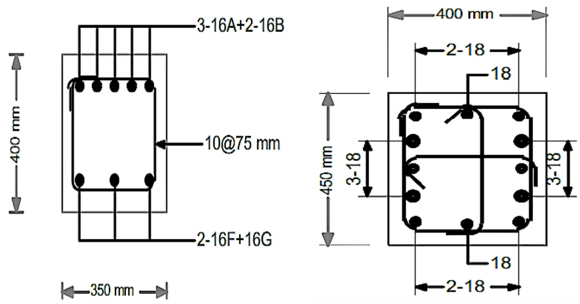


Figure 3. Designed section details of beams and columns in Model-I

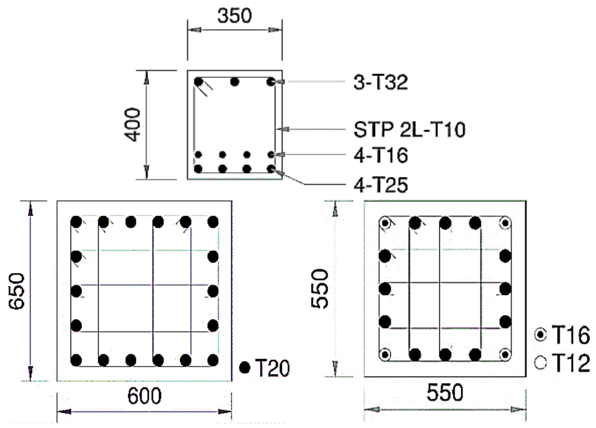


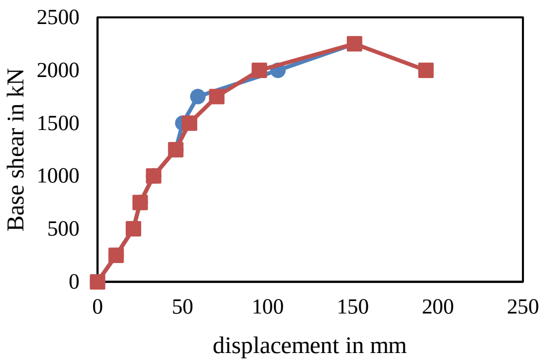
Figure 4. Designed section details of beams, columns in Model-II

3. 1. Hinge Formations in Model-I After pushover analysis on Model-I, the target displacement is observed to be 151 mm (Figure 5), the formation of hinges at this point are considered, which indicates that such amount of deformation occurs due to future earthquake (Figure 6).

3. 2. Hinge Formations in Model-II After pushover analysis on Model-II, the target displacement is observed to be 117 mm (Figure 7), the formations of hinges at this point are considered, which indicates that such amount of deformation occurs due to future earthquake (Figure 8).

4. COST-BENEFIT ANALYSIS OF RC FRAMES

A cost-benefit analysis is a process used to gauge the benefits of a decision or taking action minus the costs related to taking that action. Cost-benefit analysis is an economic analysis which gives you an outlook of changes in cost and the benefit which arises from it. The cost-benefit analysis may be applicable for both the new as well as old projects. It is based on an accepted social principle that is on individual preference. Based on the structural drawings obtained from the analysis and design configurations, the estimation and costing will be done to identify where actually the cost is getting fluctuated concerning each other and the major benefits of using ductile detailing are also pointed out. In depth analysis is carried out to find how and where the amount is getting increased compared to a conventional RC frame.



*Blue line indicates – Bilinear FD
*Red line indicates – Capacity curve
*Target displacement is noted to be 151 mm

Figure 5. Capacity-demand curve in Model-I

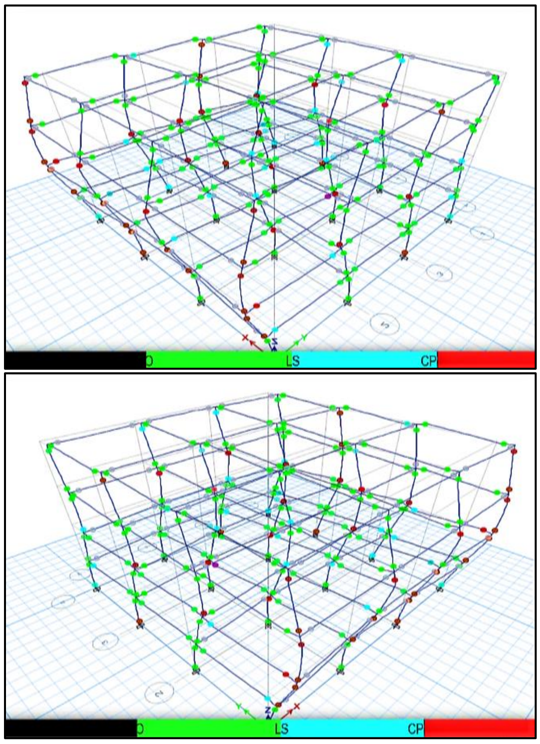
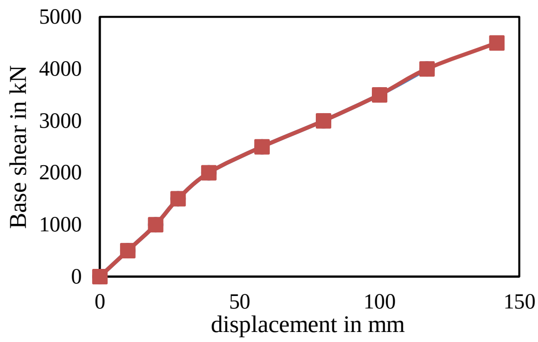


Figure 6. Maximum target displacement and hinge response at that point



*Blue line indicates – Bilinear FD
*Red line indicates – Capacity curve
*Target displacement is noted to be 117 mm

Figure 7. Capacity-demand curve in Model-II

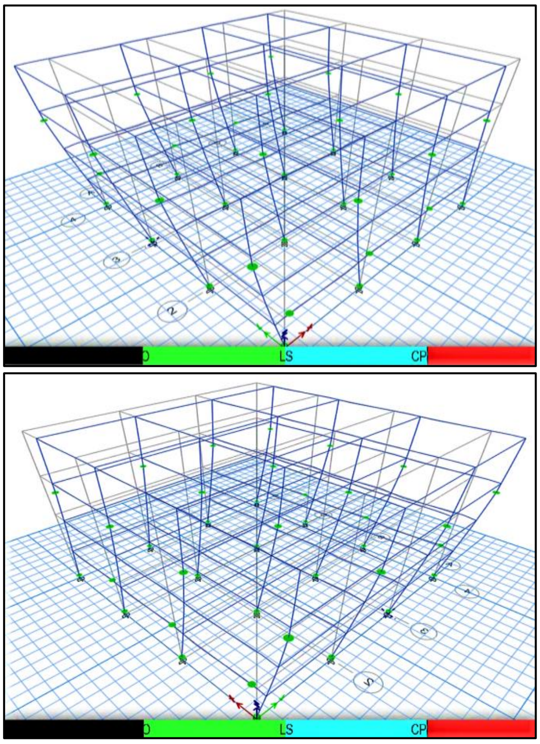


Figure 8. Maximum target displacement and hinge response at that point

The main objective of cost-benefit analysis is to identify and compare the cost increase in ductile detailed building to non-ductile detailed building. In this study, the cost difference is investigated for structural components specifically. The quantity and cost estimation are limited to beams, columns and slabs only. Indirect costs such as electrification charges, sanitary charges are not included because those remain almost the same for both buildings. Labour charges and their wages are also considered and computed accordingly. The cost for 1kg of steel is taken as 56/- INR, cost for 1 m^3 of concrete is taken as 3800/- INR and is taken based on 'Standard Schedule of Rates' given by Telangana state I&CAD department, India, 2021.

The complete quantity and cost comparison is given in Tables 5 and 6. Benefits of using ductile detailing can be stated after estimating the whole cost of construction of both the models.

Labour wages are estimated and computed based on the quantity of materials such as concrete and steel occurred in different RCC works such as column, beams, slab work (Table 5).

Wages of labour are differentiated based on labour category, such as skilled labour and unskilled labour. Mason and blacksmith come under skilled labours whereas Mazdoor, Beldar, Mistri, Bisti comes under unskilled labours. Based on Indian conditions expected

TABLE 5. Quantity estimation comparison between the Models

S. No	Quantity	Structural element	Quantity in Model-I	Quantity in Model-II
1.	Concrete (in m^3)	Slab	117.00	179.84
		Beam	100.80	25.62
		Column	60.48	98.47
2.	Steel Rebar (in kg)	Slab	8,549.00	11,231.36
		Beam	14,050.00	10,436.53
		Column	10,426.00	23,288.51

TABLE 6. Cost comparison between the models

S. No	Material Type	Cost for Model-I	Cost for Model-II	Remarks
1	Concrete	10,69,560/-	14,70,135/-	**37.45%**
2	Steel Rebar	18,49,456/-	25,54,310/-	**38.11%**
3	Total Cost	29,19,016/-	39,87,695/-	**36.60%**

Note: The costs of the materials for both the Models are estimated in INR (Indian Rupee).

out-turn of a labour per day (8 hours of work), for RCC work is 3.00 cum per mason. Labour requirement for different works in Indian condition is shown below in Table 7.

Expected wages of labour are taken from "Building material prices and wages of labour a statistical compendium 2014 – National buildings organisation, Government of India" based on it, labour wages for (i) Mason – 500 INR, (ii) Unskilled labour Male – 350 INR, (iii) Unskilled labour Female – 300 INR. The above-mentioned wages are computed with reference to a city lies in seismic Zone-IV. With reference to the above-mentioned labour charges, total cost incurred in ductile detailed and non-ductile detailed are computed as follows:

Benefit-cost ratio is evaluated to verify whether benefits over weighs cost or not (Figure 9).

TABLE 7. Labour requirement for out-turn

Type of work	Labour type	Labour per day
RCC work (for 2.83 cum)	Beldar	2
	Mazdoor	3
	Bhisti	1.5
	Mason	0.5
Reinforcement work (for 1 quintal)	Blacksmith	1
	Beldar	1

TABLE 8. Total labour wages during construction

Type of work	Labour type	Total labour wages in Model-I (in INR)	Total labour wages in Model-II (in INR)
Column	Mason	20,000	32,500
	Unskilled labour (Male)	28,000	45,400
	Unskilled labour (Female)	24,000	39,000
Beam	Mason	33,000	9,000
	Unskilled labour (Male)	46,200	12,600
	Unskilled labour (Female)	39,600	10,800
Slab	Mason	39,000	60,000
	Unskilled labour (Male)	54,600	84,000
	Unskilled labour (Female)	46,800	72,000
TOTAL COST		**3,31,200**	**3,65,300**

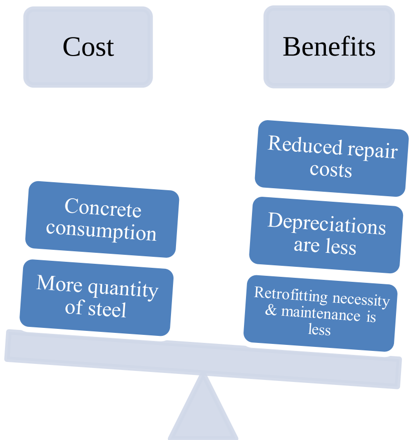


Figure 9. Chart representing benefit-cost ratio of Model-II

5. RESULTS AND DISCUSSION

5. 1. Pushover Analysis Results Comparison

5. 1. Capacity-demand Curves Model-I exhibits a maximum target displacement of 155.63 mm at 2289.89 KN base shear (Figure 10), but has a capability to exhibit non-linearity up to 220.45 mm at2068.35 KN base force. Model-II exhibits a maximum target displacement of 117 mm at 4307.82 KN base shear but has a capability to exhibit non-linearity up to 162.54 mm at 3769.53 KN base force.

5. 2. Base Shear vs Displacement Curves It is noted that a maximum inelastic displacement of 275.14 mm at 2512.56 kN base shear in Model-I and a maximum inelastic displacement of 329.14 mm at 6612.51 kN base shear. This result says that the capacity of Model-II (Figure 11) is more as it experiences more inelastic deformations by absorbing more amount of base shear compared to Model-I.

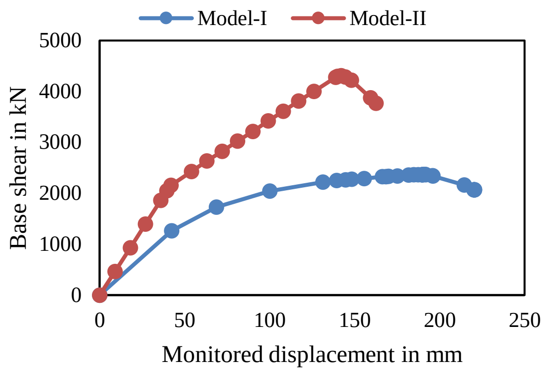


Figure 10. Capacity-demand curve

5. 3. Storey Displacement Model-I exhibits a maximum displacement of 42.448 mm at 12 m height, it is clear that storey drift increases from base of the structure at an average increasing rate of 43.446 %.

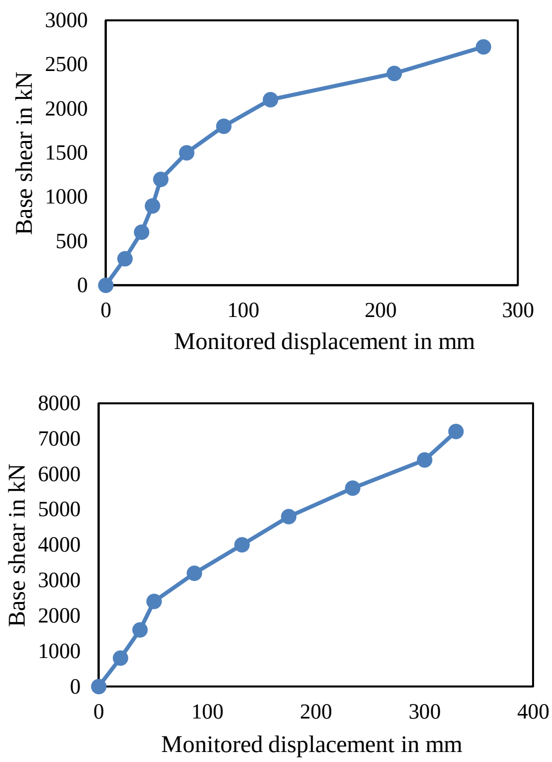


Figure 11. Base shear vs monitored displacement curves in Model-I and Model-II

Model-II exhibits a maximum displacement of 9.024 mm at 12 m height, it is clear that storey drift increases from base of the structure at an average increasing rate of 56.968 %. As Model-II has ductile detailing and confinement of steel is more, so it exhibited less storey displacement (Figure 12).

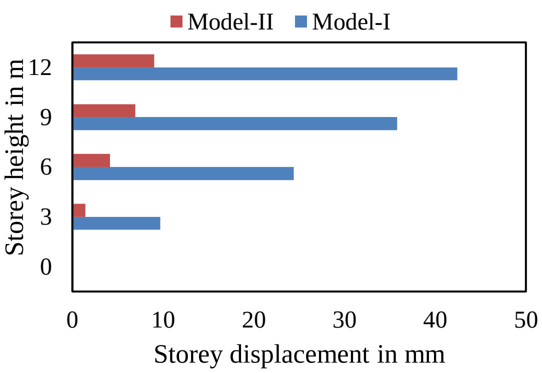


Figure 12. Maximum storey displacement

6. SUMMARY AND CONCLUSIONS

From the hinge responses obtained from pushover curves, in non-ductile detailed structure, the performance of this model says that it has less capacity and resistance against seismic load and its target displacement is 151 mm which means that the structure experiences such displacement under future earthquake. Whereas, in ductile detailed structure, target displacement is 117 mm and less hinges are formed which are in the limits (none exceeded collapse prevention stage), and hinge response says that the structure can safely carry the future seismic load. Maximum inelastic displacement of 329.14 mm at 6612.51 kN base shear is recorded in ductile detailed structure, where non-ductile detailed has experienced 275.14 mm at 2512.56 kN base shear which says that ductile detailed structure has high ability to take absorb forces acting due to seismic excitation. Since lateral ties, stirrups are used more near the supports in Model-II to enhance the stiffness of the structure in column and beams resulting in strong-column weak-beam mechanism and usage of low-grade of steel in ductile detailed structure has increased the ductile nature of the structure resulting in more plastic deformations, which is a desirable property.Further, a maximum storey displacement of 42.44 mm is observed in non-ductile detailed structure, whereas a maximum of 9.02 mm is observed in ductile detailed structure. Ductile detailed structure has 78.74% less displacement compared to non-ductile detailed structure. Ductile detailed structure is more flexible than structure without ductile detailing. It is possible to create “no sudden collapse (brittle failure)” using ductile detailing. Occupants will have sufficient warning before its final failure. Plastic deformations will be more and energy will get dissipated uniformly reducing the impact of seismic effect on the structure.

Further, it was also observed that the structure with ductile detailing has increased its cost by 36.60% compared to structure with non-ductile detailing, due to a greater number of steel bars in ductile detailed structure. Rebar count is more in Model-II with an increased value of 38.11% and it is mainly due to confinement of reinforcement in beams. As the grade of steel in Model-II is restricted to Fe415, a greater number of bars are used to enhance the lateral stability of the structure, due to which geometry is required more, which reflected in more quantity of concrete consumption in Model-II with an increased rate of 37.4%. As lateral ties, stirrups are more used more near the supports in ductile detailed structure to enhance the stiffness of the structure. Labour wages estimation between both the Models have shown minimal difference in its cost, therefore labour wages difference is not much effective. Benefit-cost ratio is high in ductile detailed structure and benefits exceeds over cost, and it was found that the marginal initial cost increase associated with ductile detailing is considerably outweighed by the resulting savings in the repair and downtime costs and concludes that it is economical.

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Persian Abstract

چکیده

ساختمان های بتن آرمه (RC)اکثریت ساختمان های هند را تشکیل می دهند. عناصر سازه ای این ساختمان ها اغلب محدود به جزئیات غیر شکل پذیر طراحی می شوند. با نرخ بسیار پایین تعویض ساختمان، بسیاری از ساختمان های هندی در برابر زلزله آسیب پذیر هستند و خطرات قابل توجهی برای جان، اموال و فعالیت های اقتصادی به همراه دارند. این مقاله اثربخشی جزئیات شکل پذیر را در کاهش خطر فروپاشی لرزه ای با تجزیه و تحلیل رفتار یک قاب چهار طبقه مقاوم در برابر ممان ویژه RC (RC SMRF) با استفاده از آخرین کدهای جزئیات انعطاف پذیر بررسی می کند. همچنین هدف آن تعیین کمیت تأثیر سیستم مقاوم در برابر نیروی جانبی بر روی عملکرد و هزینه ساختمان‌های RC SMRF و مزایای آن است. مطالعه حاضر بر تأثیر جزئیات شکل پذیر بر سه جنبه اساسی سازه – ایمنی، پایداری و اقتصاد تأکید دارد. دو مدل ساختمان چهار طبقه – یکی بدون جزئیات شکل پذیر و دیگری با جزئیات شکل پذیر طراحی شده و سپس با استفاده از تحلیل استاتیکی غیر خطی مورد تجزیه و تحلیل قرار می گیرند. نتایج این مطالعه نشان دهنده رفتار ساختمان‌های با جزئیات شکل‌پذیر و غیر شکل‌پذیر از نظر منحنی‌های فشار آور و رفتار لولا و شناسایی حالت شکست نهایی است. در بسط آن، یک تحلیل هزینه–فایده برای مطالعه مزایای جزئیات شکل پذیر با افزایش هزینه انجام می شود. افزایش حاشیه ای در هزینه اولیه مرتبط با جزئیات شکل پذیر به طور قابل توجهی با صرفه جویی در هزینه های تعمیر و خرابی در طول عمر ساختمان جبران می شود.