بررسی تأثیر بتن ضعیف بر فروریزش لرزه‌ای ساختمان‌های بتن مسلح با و بدون دیوار برشی

مژده رضانیا[1]، نعمت حسنی*[2]، حمید بایسته[3]

۱- دانشجوی دکتری، دانشکده عمران، آب و محیط‌زیست ، دانشگاه شهید بهشتی ، تهران، ایران

۲- دانشیار، دانشکده عمران، آب و محیط‌زیست ، دانشگاه شهید بهشتی ، تهران، ایران

۳-استادیار، دانشکده عمران، آب و محیط‌زیست ، دانشگاه شهید بهشتی ، تهران، ایران

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پست الکترونیکی نویسنده مسئول: *n_hassani@sbu.ac.ir

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چکیده:

فروریزش لرزه ای یکی از مهم‌ترین حالات گسیختگی در ساختمان‌های بتن مسلح با قاب خمشی (RC-MRF) بویژه در ساختمانهای با کیفیت ساخت پایین و ضعف مقاومت فشاری بتن است. در این پژوهش، تأثیر افزودن حداقل دیوارهای برشی با هدف افزایش سختی جانبی و جلوگیری از فروریزش لرزه ای مورد بررسی قرار گرفته است. بدین منظور، یک مدل مرجع با چهار سطح کاهش مقاومت فشاری بتن، از بسیار جزئی تا شدید، تعریف شد. تحلیل‌های عددی غیرخطی دینامیکی بر روی ساختمان‌های بتن‌آرمه ۳، ۶ و ۸ طبقه با سیستم قاب خمشی، در دو حالت با و بدون دیوار برشی، انجام گرفت. شاخص‌های اصلی شامل دریفت طبقات، نحوه شکل‌گیری مفاصل پلاستیک و شاخص تاب‌آوری سازه ارزیابی شدند. نتایج نشان داد کاهش مقاومت فشاری بتن موجب افزایش قابل‌توجه دریفت طبقات، به‌ویژه در طبقه اول مدل‌های بدون دیوار برشی، و در پی آن افزایش تشکیل مفاصل پلاستیک و خطر فروریزش می‌شود. در مقابل، مدلهای با دیوارهای برشی حتی در شرایط کاهش شدید مقاومت بتن نیز دچار فروریزش نشده و عملکرد لرزه‌ای و تاب‌آوری بهتری از خود نشان دادند. همچنین، مشخص شد که مدلهای ۸ طبقه حساسیت بیشتری نسبت به کاهش مقاومت فشاری بتن دارند. در مجموع، نتایج این پژوهش نشان می‌دهد که افزودن حداقل دیوارهای برشی می‌تواند به‌عنوان راهکاری عملی و مؤثر برای بهبود عملکرد لرزه‌ای و افزایش ایمنی ساختمان‌های بتن‌آرمه با قاب خمشی و بتن ضعیف مورد استفاده قرار گیرد.

کلمات کلیدی: بتن ضعیف، ساختمان بتنی، دیوار برشی، مفصل پلاستیک، فروریزش لرزه‌ای

Investigation Influence of Poor Concrete on Seismic Collapse of RC Buildings with and without Shear Walls

Mozhde Rezania[1], Nemat Hassani[2*], Hamid Bayesteh[3]

1-Phd Student, Department of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

M_Rezania@sbu.ac.ir

2- Associate Professor, Department of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

N_hassani@sbu.ac.ir

3-Assistant Professor, Department of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

h_bayesteh@sbu.ac.ir

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Abstract

Seismic collapse is a critical failure mode in reinforced concrete moment-resisting frame (RC-MRF) buildings, particularly those with poor construction quality and low concrete compressive strength. To address this issue, this study investigates the impact of adding minimal shear walls to improve lateral stiffness and prevent collapse. A reference model was created, simulating four levels of concrete strength deficiency: very slight to severe. Numerical analyses were conducted on 3-, 6-, and 8-story RC-MRF buildings, both with and without shear walls, under nonlinear dynamic loading. Key parameters such as story drift, plastic hinge development, and robustness index were examined. Results show that reduced concrete strength significantly increases story drift—especially at the first story in models without shear walls—resulting in widespread plastic hinge formation and increased risk of collapse. In contrast, models with shear walls did not experience collapse and showed improved seismic resilience, even under severe strength deficiencies. The study also found that the 8-story case was more sensitive to reductions in concrete strength. These findings highlight the effectiveness of minimal shear wall incorporation as a practical solution to enhance the seismic performance and safety of RC-MRF buildings with deficient concrete strength.

Keywords: Poor Concrete, Concrete Building, Shear Wall, Plastic Hinge, Seismic Collapse

***Corresponding Author: Nemat Hassani**

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1. Introduction

1.1. *Progressive Collapse*

One failure mechanism that has garnered significant attention over the past two decades—posing a serious threat to the stability of MRFs—is progressive collapse, which can ultimately lead to structural failure and total collapse [1]. Therefore, buildings should be designed to mitigate local failures by integrating structural members and redistributing loads through alternative load paths. This approach ensures that the structure possesses the necessary resistance to withstand abnormal loads, including dynamic effects [2]. The lateral forces induced by earthquakes significantly amplify the resultant stresses in structural members, potentially causing the failure of primary load-bearing components and initiating progressive collapse [3]. Structures with local failures are susceptible to impact-type progressive collapse, which may lead to a pancake-type failure[4, 5]. According to research by Ellingwood et al., and Gioncu et al., 2014 earthquakes may also cause progressive collapse, and many earthquake-related failures occur progressively[1, 6]. One advantage of designing structures to resist progressive collapse is that, in addition to providing the necessary resistance to earthquake forces, it can also ensure the safety of occupants following the failure of a primary load-bearing member [4]. Martin et al. conducted a study investigating structural damage caused by the 2023 Turkey earthquake. They reported that most buildings in Hatay and Kahramanmaraş collapsed due to a pancake failure mechanism, as depicted in Fig. 1. They identified poor concrete quality as the primary cause of these widespread failure[5].

Fig.1. Pancake collapse observed during the 2023 Turkey earthquake [5].

The ability of a structure to maintain stability under strong ground motions without collapsing is indicative of an adequate lateral force-resisting system capacity [5]. Investigating the relationship between a structure's nonlinear behavior and seismic response parameters, such as drift and member deformation, can serve as a criterion for assessing this phenomenon [6].

1.2. *Impact of Concrete Strength on Progressive Collapse*

Occurrence of progressive collapse is much more in reinforced concrete structures compared to those constructed with other materials [7]. As a result, despite significant advancements in design and construction technologies in recent years, reinforced concrete

(RC) structures still experience sudden damage during earthquakes and remain vulnerable to both moderate and severe seismic events [8]. Previous studies have shown that poor concrete quality can lead to severe damage and even structural collapse during earthquakes. uncertainty in concrete compressive strength is a critical factor that increases the risk of failure in RC structures. Lee and Mosalam utilized the first-order second-moment method to assess the effects of material strength deficiencies on the seismic response of reinforced concrete (RC) structures [11]. Qian (2021) experimentally investigated the influence of concrete strength on the behavior of T-beams [12]. Kim (2020) developed concrete failure curves while accounting for the uncertainty in concrete compressive strength [13]. Aamer (2017) experimentally and empirically studied the effect of concrete compressive strength on the seismic behavior of reinforced concrete (RC) frames and columns [14]. Baki et al. (2017) examined the effects of concrete strength on the seismic performance of structures under cyclic loading [15]. Rajeev (2011) investigated the effects of concrete material sensitivity on the seismic performance of six-story buildings [16]. Additionally, several researchers have explored solutions for retrofitting structures with inadequate concrete compressive strength [17-19]. Shen et al. evaluated the seismic behavior of existing low-rise buildings using pushover analysis. Through an investigation of various reinforced concrete column retrofitting methods, they concluded that increasing column strength—or simultaneously enhancing both strength and stiffness—is effective in reducing inter-story drift and improving overall structural performance[20]. Erberik highlighted the significance of concrete compressive strength in damaged buildings following the 1999 Düzce earthquake in Turkey [21]. Kocak conducted a study following the 1999 Marmara earthquake. By examining 220 buildings across various regions, Kocak assessed the earthquake risk in Istanbul. The concrete in only 27 buildings met the design compressive strength. These findings indicate a generally low quality of concrete compressive strength. Consequently, it became widely recognized that the ultimate strength of concrete significantly influences structural behavior [22]. Bayraktar, in order to determine the seismic performance of collapsed buildings from the 2011 Van earthquake, examined 90 collapsed RC buildings. The results showed that 47% of the buildings had an average compressive strength between 8 and 12 MPa, 26% had an average compressive strength between 4 and 8 MPa, and 20% had an average compressive strength between 12 and 16 MPa [23]. Caglar, by examining structural damage from the 2020 Elazığ earthquake in Turkey, identified poor concrete quality as one of the main causes of these damages. Almost all damaged buildings were constructed with very weak concrete, having a compressive strength between 6 and 12 MPa, which is significantly lower than the minimum code requirements. This concrete was produced manually or using inappropriate methods. It consisted of poorly graded aggregates, the addition of waste materials such as paper and wood, and insufficient cement, resulting in low-quality and low-strength concrete [24, 25]. One of the main causes of damage to RC buildings was the use of substandard concrete made from poorly graded aggregates and insufficient vibration during placement in Turkey [26]. Sedef et al. also stated in their paper that an investigation of buildings damaged in the 2023 Turkey earthquake revealed that the concrete used in these buildings did not meet the minimum standard strength of 14 MPa, with all having strengths less than 10 MPa. This was identified as one of the main causes of their failure [27]. Hosseini et al. reported that most of the concrete structures during the 7.3 magnitude earthquake in Kermanshah and Sar-e Pol-e Zahab in 2017 had a moment-resisting frame system, with only a few 4- or 5-story buildings utilizing shear wall systems. Investigations revealed that, in the moment-resisting frame system, most of the damage occurred in the columns, which was attributed to low concrete strength resulting from poor construction practices, particularly an inappropriate water-to-cement ratio. In contrast, the buildings with shear walls experienced less damage[28]. The results of investigations on moment-resisting frames (MRFs) constructed with low-strength concrete show significant flexural damage in beams, columns, and beam-column connections under lateral loads [29]. Considering that concrete deficiencies are common in typical buildings, this study focuses on standard residential buildings up to eight stories, using non-linear dynamic analysis.

2. Numerical Models

A reference model with a compressive strength of 30 MPa is established as a baseline. Four additional models with lower concrete strengths are developed. In these models, all geometric and reinforcement parameters are identical to the reference model, except for the reduced compressive strength. Four levels of concrete strength reduction are considered: very mild (25 MPa), mild (20 MPa), moderate (15 MPa), severe (10 MPa). To examine the influence of building height, models with three, six, and eight stories are analyzed. Consequently, five MRF models, with and without shear walls, are analyzed for each level of concrete strength and building height. Subsequently, to assess the behavior of buildings with weak concrete, they were modeled in 3D and subjected to nonlinear Dynamic analysis. The plans of the models are shown in Fig. 2. Figs. 3 and 4 present the 3D views of the models without and with shear walls.

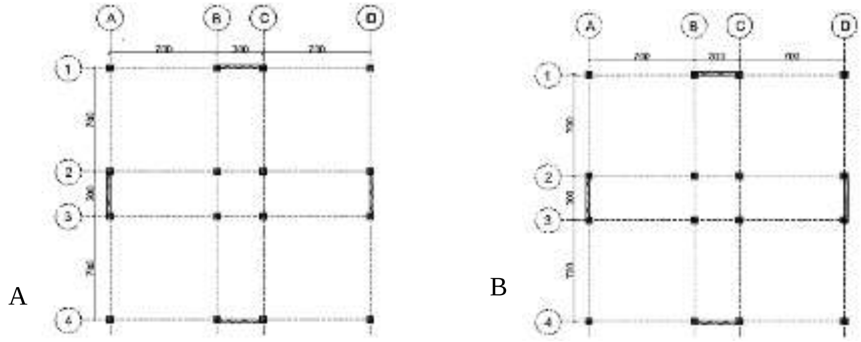
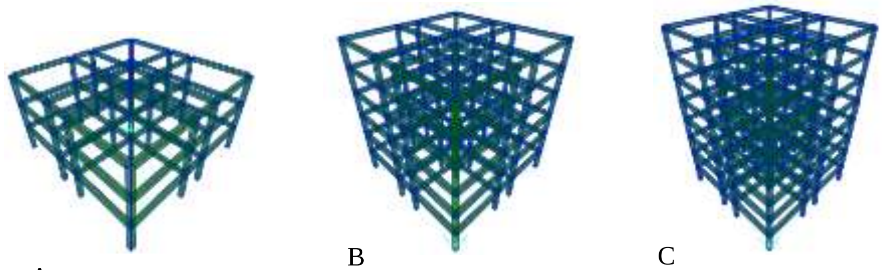
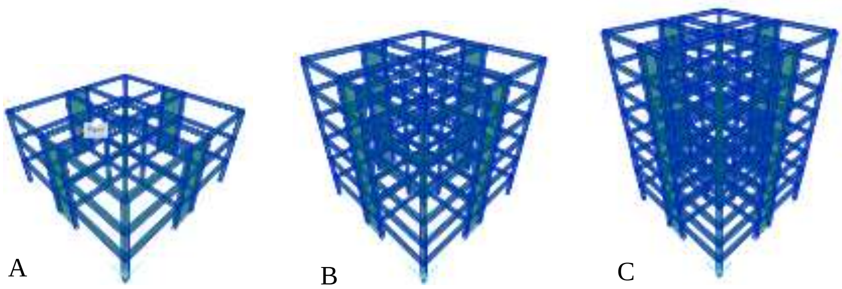


Fig. 2. Plan of the models, A: MRF, B: MRF with shear walls



A B C

Fig. 3. The 3D of MRF models, A: 3-story, B: 6-story, C: 8-story



A B C

Fig. 4. The 3D of MRF with shear walls models, A: 3-story, B: 6-story, C: 8-story

The studied models are assumed to be located in a high seismicity region with residential occupancy and soil type II. The story height is taken as 3.2 meters. The design floor loads include a dead load of 500 kg/m² and a live load of 200 kg/m². The reinforcing steel is assumed to be ST52 with a yield strength of Fy = 4000 kg/cm². To account for the variation in concrete compressive strength, the modulus of elasticity is calculated for each strength level and incorporated into the numerical models as in Table 1.

Table 1: Material properties of concrete

Compressive strength (MPa)	Modulus of elasticity (MPa)
30	27691.5
25	25277.9
20	22608.9
15	19580.6
10	15987.5

The cross-sectional details are summarized in Table 2. The sections are assumed to be confined, and the wall sections include boundary elements as shown in Figure 5.

Table 2: Sections Used in the Numerical Models

Building Type	Structural System	Story Level	Sections Used	
3-Story		1st – 3rd	Beam	B45×45

	MRF (Moment Resisting Frame)		Column	C45×45-20T16
	MRF + Shear Wall	1st – 3rd	Beam	B40×40
			Column	C40X40-12T16
			Wall	Wall20
6-Story	MRF	1st – 3rd	Beam	B50X50
			Column	C50X50-16T20
		4th – 6th	Beam	B45X45
			Column	C45X45-16T16
	MRF + Shear Wall	1st – 6th	Beam	B45X45
			Column	C40X40-12T16
			Wall	Wall25
8-Story	MRF	1st – 5th	Beam	B55X55
			Column	C55X55-22T20
		6th – 8th	Beam	B45X45
			Column	C45X45-16T20
	MRF + Shear Wall	1st – 5th	Beam	B50X50
			Column	C50X50-20T20
			Wall	Wall35
		6th – 8th	Beam	B45X45
			Column	C45X45-16T20
			Wall	Wall35

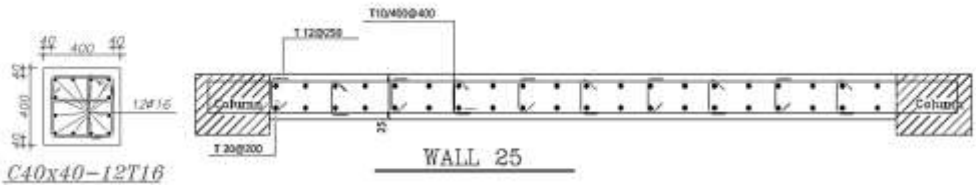


Fig.5. Column and Wall Section

The models are named using the format (Story number) F/W (Compressive strength). 'F' indicates models without shear walls, and 'W' indicates models with a shear wall system.

3. Validation of the Numerical Model

To assess the accuracy of the developed numerical model, the results of nonlinear time history analyses for a 6-story frame under the Kocaeli earthquake were compared with values reported in the reference study[30]. Figure 6 shows the base shear force versus time for the 6-story frame, illustrating the variation of base shear over time. The validation results indicate that the base shear trends in both data sets are almost aligned, and the overall structural response is similar in both cases. Discrepancies mainly occur over short time intervals and account for only a few percent of the maximum response. This close agreement demonstrates the high accuracy of the numerical model in predicting the structural response under seismic excitation and confirms its validity for further analyses.

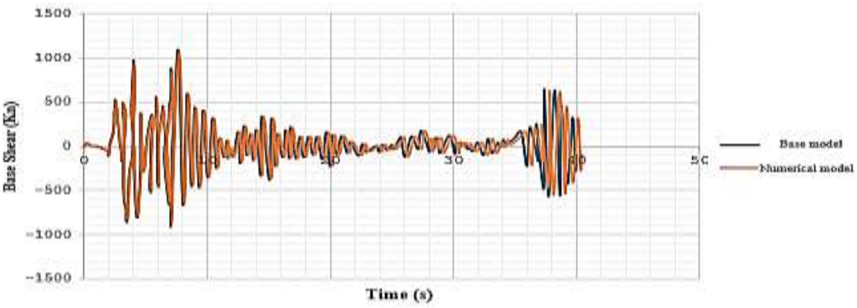


Fig. 6. Comparison of Base Shear Time Histories: Numerical vs. Reference Model

4. Nonlinear time-history analysis

The structural response is evaluated by considering both material and geometric nonlinearities using nonlinear time-history analysis. Typically, natural accelerograms are employed for time-history analysis. These accelerograms represent ground motions that have been previously recorded at specific locations. Efforts are made to select records with characteristics that closely match the site conditions. In this study, earthquake records listed in Table 3 were utilized. These records were obtained from the Pacific Earthquake Engineering Research Center (PEER) database**.**

Table 3. Ground-motion records input to the building models

Earthquake	Record	Duration (sec)	Year	Mag.	Rjb (km)	Rrup (km)	Vs30 (m/sec)
Bam	4054	9.5	2003	6.6	46.2	46.22	574.88
Tabas	137	21.3	1978	7.35	119.77	120.8	377.56
Kobe	1102	7.7	1995	6.9	49.91	49.91	609
Loma	572	10.6	1989	6.93	26.5	27.1	430
Northridge	953	12.4	1994	6.69	18.2	19	350
San Fernando	165	11.2	1971	6.61	22.3	23.5	360
Chichi	1516	18.7	1999	7.62	35.7	37.2	410

4.1. *Plastic hinge mechanism*

Stages of plastic hinge formation and assignment, considering 5% damping in nonlinear dynamic analysis, have been carried out. The formation stages of plastic hinges and the relative lateral displacement values of stories under selected accelerograms have been extracted. Based on the control of the results of nonlinear time history dynamic analysis, examples of plastic hinge formation under the BAM earthquake accelerogram for models with strength of 30 (reference) and 10 (severe poor) MPa are shown in figures 7 to 9 both without and with shear walls. As observed, in the three-story moment frame model with 10 MPa, the columns of the first story enter the collapse mechanism. On the other hand, the shear wall model, there is no hinge in columns. For the six-story models, formation of plastic hinges in columns of the cases without shear wall are growing, while there is no hinge in column in cases with shear walls. In the eight-story moment frame structure, it is observed for 10 MPa, all columns of the first story and some beams enter the collapse mechanism, which will result in the complete collapse. In the shear walled model, only two columns exceeded the C limit, demonstrating significantly better performance.

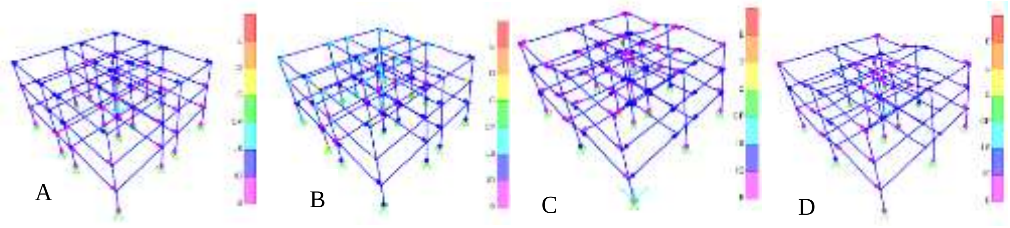


Fig. 7. Plastic hinges in 3-story models under Bam record. A) 3F30 B) 3F10 C) 3W30 D) 3W10

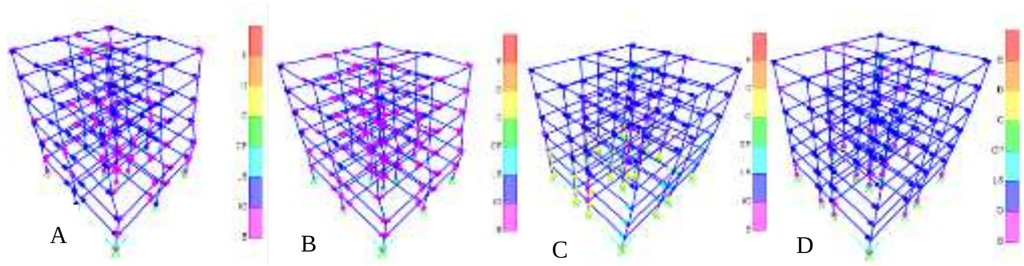


Fig. 8. Plastic hinges in 6-story models under Bam record. A) 6F30 B) 6F10 C) 6W30 D) 6W10

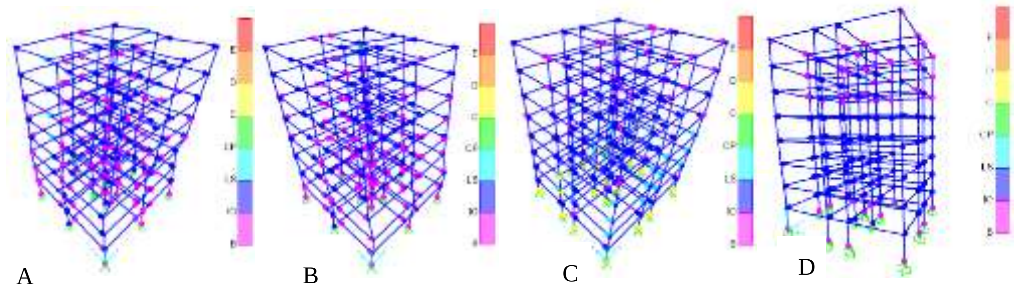


Fig. 9. Plastic hinges in 8-story models under Bam record. A) 8F30 B) 8F10 C) 8W30 D) 8W10

4.2. *Robustness indicator*

As previously explained, robustness is defined as a structure's ability to withstand localized failure without compromising overall stability. The results of this indicator are shown in Table 4 and Fig.10. The results indicate that as the concrete strength decreases from 30 MPa to 10 MPa, the robustness index decreases by 13%, 20%, and 26% in the 3F, 6F, and 8F models, respectively. In contrast, in the 3W, 6W, and 8W models, the robustness index decreases by 6%, 7%, and 9%, respectively. These findings suggest that, with increasing model height, the impact of concrete strength reduction on the robustness index becomes more pronounced.

Table 4: Robustness index for models in nonlinear time-history analysis

Compressive strength (MPa)	Robustness index					
	3F	3W	6F	6W	8F	8W
30	1	1	1	1	1	1
25	0.99	0.99	0.95	0.99	0.98	0.99
20	0.96	0.98	0.87	0.97	0.92	0.95
15	0.94	0.97	0.84	0.95	0.85	0.93
10	0.87	0.94	0.8	0.93	0.74	0.91

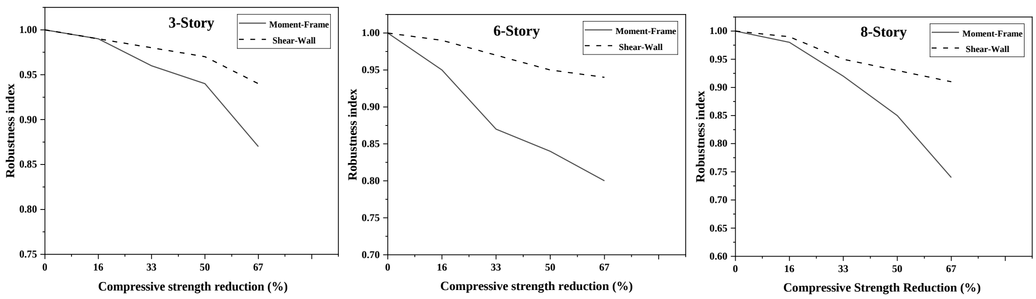


Fig. 10. Relative base force of 3, 6 and 8-Story model under non nonlinear time-history analysis

4.3. Displacements

Fig. 11 shows the inter-story drift in models 3F10, 6F10, and 8F10 is 2.1, 2.0, and 1.9 times greater than in models 3F30, 6F30, and 8F30, respectively. The drift in models 3W10, 6W10, and 8W10 is 1.75, 1.6, and 1.45 times greater than in models 3W30, 6W30, and 8W30, respectively. Similar trends were observed for both first-story displacement and roof displacement. Fig. 12 show that the first-story displacement ratio for 10 MPa, increases by 1.36, 2, and 2.2 times in the 3F, 6F, and 8F models, respectively. However, the inclusion of shear walls effectively mitigates this effect, reducing the displacement ratios to 1.36, 2, and 2.1, respectively. These findings underscore the critical role of shear walls in enhancing seismic resilience and improving structural stability. As shown in Fig. 13, for 10 MPa, the maximum displacement in the 3F, 6F, and 8F models increases by 2, 1.7, and 1.56 times, respectively. By enhancing lateral stiffness, improving load-bearing capacity, and optimizing seismic force distribution, shear walls effectively limit structural displacements and reduce torsional effects, thereby improving overall seismic performance. The results show for 10 MPa, the maximum displacement in the 3W, 6W, and 8W models increases by only 1.26, 1.4, and 1.45 times, respectively.

In the final summary, the relative story displacement of the various models was compared to that of the reference model (Fig. 14). The results show that in models with moment-resisting frames, the increase in relative displacement due to the reduction in concrete strength is more pronounced than in models with shear walls. Furthermore, the increase in relative displacement becomes more significant as the building height increases, indicating that the 8-story case is more vulnerable to the effects of reduced concrete strength.

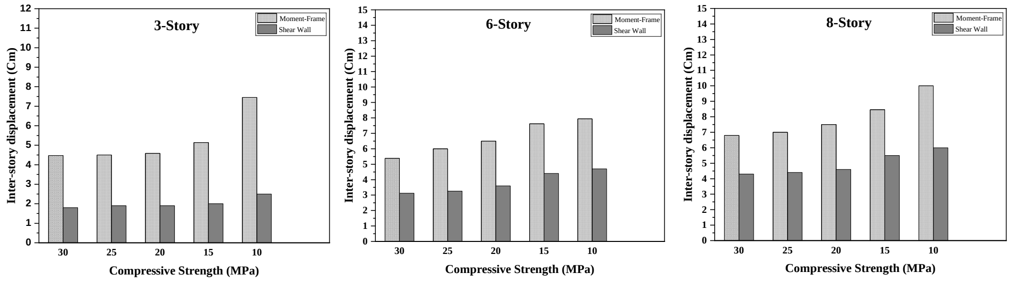


Fig. 11. Inter-story displacement curve for 3, 6 and 8 story models (10 to 30 MPa)

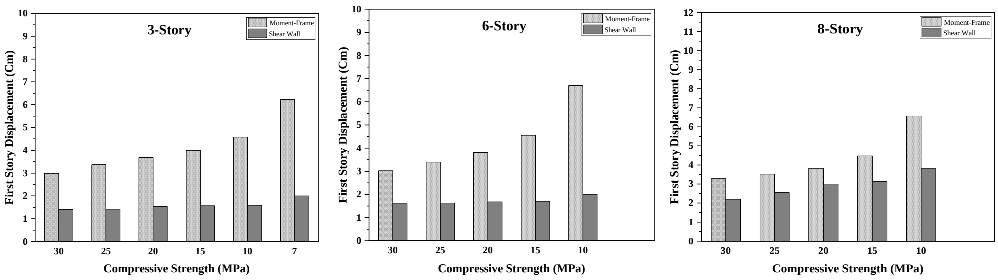


Fig. 12. First story drift curve for 3, 6 and 8 story models (10 to 30 MPa)

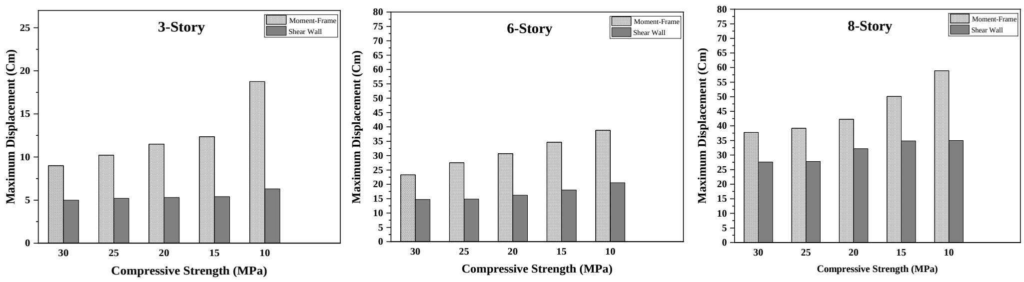


Fig. 13. Maximum displacement curve for 3, 6 and 8 story model (10 to 30 MPa)

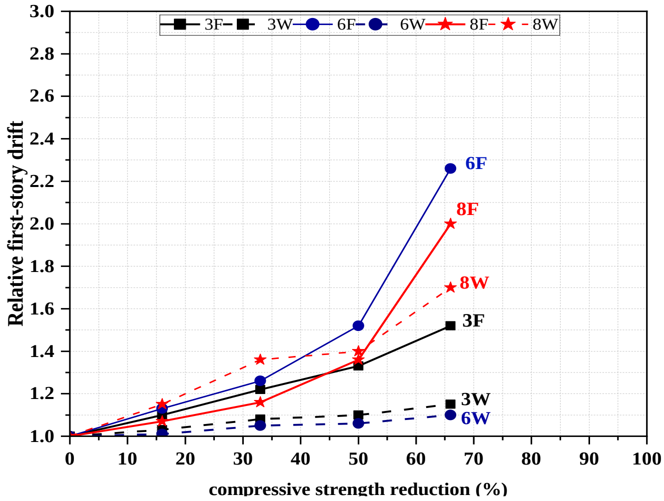


Fig. 14. Relative first-story displacement curve for 3, 6 and 8 Story models

5. Discussion on results

As shown in Table 5, the load-bearing capacity of frame-only models exhibited a significant reduction compared to frame models with shear walls. Specifically, in the 3F and 6F models, when the concrete strength was reduced to 10 MPa and 20 MPa, respectively, the first-story columns approached the collapse threshold. However, In the corresponding models with shear walls, even reduction in concrete strength to 10 MPa, the structure still exhibits satisfactory behavior. In the 8F model, the structure approached the collapse threshold when the concrete strength was reduced to 25 MPa. In contrast, in the 8W model, the structure remained at the life-safety performance level even with a concrete strength reduction to 10 MPa. A reduction in concrete strength from 30 MPa to 10 MPa resulted in a 68%, 63%, and 57% decrease in inter-story displacement (compared to frame-only models) for the 3W, 6W, and 8W models, respectively. Similarly, the maximum displacement in the same models decreased by 45%, 49%, and 38%, respectively. When the concrete strength was reduced from 30 MPa to 7 MPa, the first-story displacement in the 3W, 6W, and 8W models increased by factors of 1.36, 2, and 2.1, respectively. In contrast, in the models with shear walls, these factors were 1.11, 1.22, and 1.73. Furthermore, a reduction in concrete strength from 30 MPa to 5 MPa led to a 13%, 20%, and 26% decrease in the robustness index for the 3W, 6W, and 8W models, respectively. In comparison, the reduction in the robustness index for the same models with shear walls was limited to 6%, 7%, and 9%.

Table 5: Summary of results

Nonlinear dynamic analysis — MRF

FC \ Story-number	Robustness indicator 3	Robustness indicator 6	Robustness indicator 8	Plastic hinges 3	Plastic hinges 6	Plastic hinges 8	First-story displacement 3	First-story displacement 6	First-story displacement 8	Inter-story displacement 3	Inter-story displacement 6	Inter-story displacement 8	Maximum story displacement 3	Maximum story displacement 6	Maximum story displacement 8
30	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
25	Good	Good	Good	Good	Good	Moderate	Good	Good	Good	Good	Good	Moderate	Good	Good	Good
20	Good	Moderate	Moderate	Good	Moderate	Poor	Good	Good	Good	Good	Moderate	Poor	Good	Good	Good
15	Moderate	Moderate	Moderate	Good	Poor	Poor	Good	Moderate	Moderate	Good	Poor	Poor	Good	Moderate	Moderate
10	Moderate	Poor	Poor	Good	Poor	Poor	Moderate	Poor	Poor	Moderate	Poor	Poor	Moderate	Moderate	Moderate

Nonlinear dynamic analysis — MRF+ Wall

FC \ Story-number	Robustness indicator 3	Robustness indicator 6	Robustness indicator 8	Plastic hinges 3	Plastic hinges 6	Plastic hinges 8	First-story displacement 3	First-story displacement 6	First-story displacement 8	Inter-story displacement 3	Inter-story displacement 6	Inter-story displacement 8	Maximum story displacement 3	Maximum story displacement 6	Maximum story displacement 8
30	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
25	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
20	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
15	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
10	Good	Moderate	Moderate	Good	Good	Good	Good	Good	Moderate	Good	Good	Moderate	Good	Moderate	Moderate

Good performance | Moderate performance | Poor performance

6. Conclusions

This paper investigates influence of poor concrete on the seismic collapse of reinforced concrete moment-resisting frames in residential low-rise buildings, both without and with shear walls. The concrete compressive strength was decreased to almost 70 percent compared to the reference model for 4 cases of very slight, slight, moderate and severe for 3, 6, and 8-story models with and without shear walls. The study employs dynamic analyses with direct earthquake records for all models. The main concluding points may be summarized as follows:

- All the models without shear walls are so susceptible to destructive plastic hinge formation even with a slight decrease in concrete compression strength.
- The shear walled models demonstrate good seismic performance even with a severe reduction in concrete compression strength.
- The maximum drifts in the models with shear walls are significantly lower than those of the models without shear walls.
- Shear walls also effectively reduced sensitivity of the models to increased inter-story displacements (drifts), particularly in 3 and 6-story models.
- Analysis of the robustness index reveals an increased sensitivity to reduced concrete strength in 8-story mode.

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