Research & Design
www.jrede.org

Research Article

Effect of concrete strength and detailing properties on seismic damage for RC structures

Hayri Baytan Ozmen[*1a], Mehmet Inel[2b]

[1]*Department of Civil Engineering, Usak University, Usak, Turkey.*
[2]*Department of Civil Engineering, Pamukkale University, Denizli, Turkey.*

Article Info

Article History:

Received: 20 Oct 2024

Accepted: 2 Dec 2024

Keywords:

Concrete strength;
Lateral reinforcement;
Nonlinear analysis;
Seismic code;
Seismic performance

Abstract

This study investigates the effects of concrete strength, lateral reinforcement detailing and design code on the seismic performance of reinforced concrete (RC) buildings representative of existing residential structures. A total of 48 nonlinear inelastic models of 2, 4, and 7 storey buildings, designed per the 1975 and 1998 Turkish seismic codes, were analyzed using nonlinear static and dynamic methods. Capacity curves were obtained through inelastic static analysis, while displacement demands were calculated for 264 ground motion records using nonlinear dynamic analysis. The exceedance ratios of performance levels—Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)—were determined based on these demands. The findings reveal that the IO performance level is minimally affected by variations in material properties and detailing, as it primarily depends on structural strength. Paradoxically, in low-rise buildings, increased concrete strength and reinforcement can lead to higher IO exceedance ratios due to increased longitudinal reinforcement elongation at lower curvature values. The damage rate was found to be high in 4-storey buildings designed under the 1975 code showing higher exceedance ratios than 7-storey buildings due to relatively weaker structural systems and construction practices. In contrast, buildings designed per the 1998 code exhibited significantly lower exceedance ratios, highlighting the effectiveness of modern seismic design standards. The results underscore the importance of seismic detailing and retrofitting older buildings to improve resilience. This study may provide insights into the seismic behavior of RC buildings, offering guidance for structural engineers and policymakers in enhancing building safety.

1. Introduction

The seismic performance of reinforced concrete (RC) structures is a critical area of study in civil engineering, particularly in regions prone to earthquakes. The ability of these structures to withstand seismic forces is significantly influenced by various factors, including concrete strength, lateral reinforcement amount, and spacing. These factors may be considered as key parameters for the design of new structures or evaluation of existing ones. Concrete strength plays a pivotal role in determining the overall load-bearing capacity and ductility of RC elements. Higher concrete strength generally enhances the structural integrity and resilience of buildings during seismic events, as it allows for better energy dissipation and reduced deformation under lateral loads [1–3]. However, the effectiveness of increased concrete strength is dependent upon the adequacy of lateral

*Corresponding author: baytan.ozmen@usak.edu.tr
[a]orcid.org/ 0000-0001-6750-8632; [b]orcid.org/ 0000-0002-8323-259X;
DOI: http://dx.doi.org/10.17515/rede2024-005en1124rs

reinforcement, which serves to confine the concrete and allows the increased capacity to be effective by increased ductility.

Lateral reinforcement, typically in the form of stirrups or ties, is essential for enhancing the ductility and energy absorption capacity of RC structures. The spacing and amount of this reinforcement directly affect the confinement of the concrete core, which is critical for maintaining structural performance under seismic loading. Research has shown that insufficient lateral reinforcement spacing can lead to inadequate confinement, resulting in reduced load-carrying capacity and increased vulnerability to seismic damage [4]. For instance, studies have indicated that widely spaced transverse reinforcement can compromise the structural integrity of RC columns, leading to significant failures during seismic events [5]. Therefore, optimizing the amount and spacing of lateral reinforcement is crucial for improving the seismic resilience of RC structures.

The interaction between concrete strength and lateral reinforcement is complex and requires careful consideration in design practices. Analytical models and experimental studies have demonstrated that the combination of high concrete strength and appropriate lateral reinforcement can significantly enhance the seismic performance of RC columns and frames [6, 7]. For example, the use of high-strength steel bars in conjunction with high-strength concrete has been shown to improve the overall ductility and energy dissipation capabilities of RC elements, thereby reducing the likelihood of catastrophic failure during earthquakes [8, 9]. Furthermore, the design of lateral reinforcement must account for various factors, including axial loads and the specific seismic design category of the structure, to ensure that the reinforcement effectively contributes to the overall stability and resilience of the building [10, 11].

The moment-curvature relationship, which describes how a beam or column deforms under bending, is influenced by both the amount of reinforcement and the concrete strength [7, 12]. Structures with well-designed reinforcement layouts tend to exhibit more favorable moment-curvature characteristics, enabling them to withstand larger deformations without experiencing significant damage [13, 14]. This is particularly important in the context of modern seismic design, where the goal is to ensure that structures can endure substantial forces while maintaining their integrity and functionality.

The implications of these interactions extend beyond individual elements to the overall performance of entire structures. The seismic response of multi-storey buildings, for instance, is heavily influenced by the design and detailing of RC columns and beams, which must work in concert to provide adequate lateral stability [15–17]. As such, a comprehensive understanding of how concrete strength and lateral reinforcement affect seismic damage is essential for engineers tasked with designing safe and resilient structures. This understanding not only informs design codes and standards but also guides the development of innovative materials and reinforcement techniques aimed at enhancing the seismic performance of RC buildings.

The aim of the study is to evaluate the effect of concrete strength, seismic code and lateral reinforcement detailing properties on the behavior of reinforced concrete structures and seismic damage risk for different performance levels. For this purpose, 2, 4 and 7 storey reference buildings without any irregularities representing the existing building stock in Turkey were modeled as residential buildings according to the 1975 and 1998 codes [18, 19].

The building characteristics used in scope of the study were created through an inventory study on approximately 500 existing buildings. In scope of the study by Ozmen et. al [20], the values of some structural properties that are thought to have an effect on the strength and strain behavior of reinforced concrete structures in the building stock were examined. The buildings were divided into subgroups according to their construction years and number of storeys and a total of 475 buildings and 40351 columns and 3123 beams selected from these buildings were taken into consideration. The properties of these buildings were converted into numerical values (column area/building area, partition wall amount/building area, element size and reinforcement amount, etc.). In this way, 2-storey building models representing 1-2 storey buildings, 4-storey building models for 3-5 storey buildings and 7-storey building models for 6 and more storey buildings were created in accordance with the average values of approximately 34 parameters reflecting existing building characteristics.

The year 1998 is important for Turkey being the year for a seismic code change and a corner for the common use of higher strength concrete in buildings. For each building group, two different earthquake codes (1975 and 1998), two different concrete compressive strengths and two different lateral reinforcement conditions were considered. Concrete compressive strength of 16 MPa (medium quality) and 10 MPa (low quality) for pre-1998 structures and 25 MPa (good quality) and 16 MPa (medium quality) for post-1998 are considered. For each model, two different lateral reinforcement conditions were taken into consideration: reinforcement arrangement in accordance with the regulations in the confinement zones and 200 mm spacing and without stirrups. For the infill walls, two different cases were analyzed, one in which the structures had an amount of load-bearing infill walls suitable for the inventory study and one in which the load-bearing properties of the infill walls were not taken into account. SAP2000 program was used in the analyses [21].

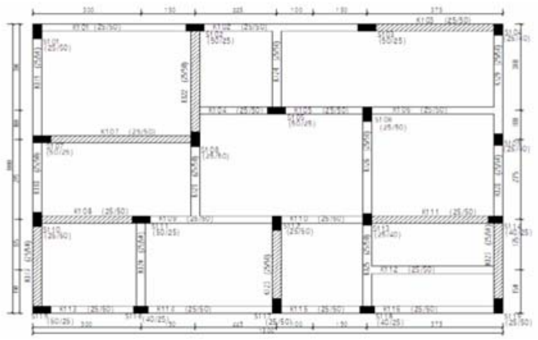
According to the 2018 Turkish Earthquake Code, the displacement capacity values of these models at the Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance levels are determined [22]. The capacity curves of the models were reduced to "Single Degree of Freedom" (SDOF) by bi-linearization [22]. Nonlinear displacement demands of the SDOF models were calculated by nonlinear time domain analysis using 264 real earthquake records with different peak ground acceleration values and soil properties. Using the seismic demand and capacity values of the models, we calculated the ratio of instances where the seismic demand exceeded the model capacities. This was done by dividing the number of earthquakes that surpassed the relevant capacity by the total number of earthquakes analyzed. Through the analyses conducted in this study, we quantitatively assessed how various parameters—such as the number of storeys, the building codes considered, the material types, and the detailing conditions—affect the damage rates at different earthquake intensities for each performance level of the buildings. The results obtained from this analysis can enhance methods for estimating earthquake damage and assist in prioritizing risk assessments for structures.

2. Modelling assumptions and model properties

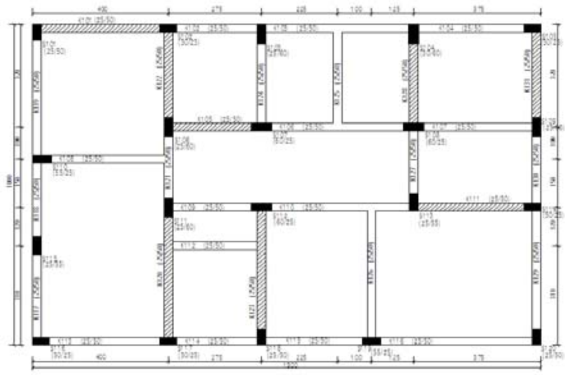
In the study, 3-D modeling of a total of 48 buildings with 3 different plan and different values of the examined parameters were made. The plan views of the models are given in Fig 1. Considering the two principal directions of the buildings, 96 analysis results were evaluated within the scope of the study.

In order to determine the seismic behavior and performance of the considered buildings, nonlinear models were prepared in accordance with the 2018 Turkish seismic code [22]. Non-linear inelastic behavior was determined by means of plastic hinges placed at the ends of the elements. In order to define a plastic hinge, the coordinates of points B, C, D, E (and IO, LS, CP for performance criteria) given in Fig. 2 should be determined.

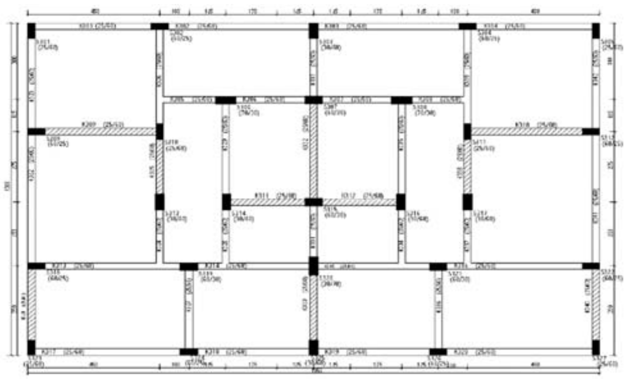
To accurately assess the performance of flexural plastic hinges in reinforced concrete structures, it is essential to understand the moment-curvature relationship. This relationship describes how the curvature of a structural element changes in response to applied moments. To establish this relationship, the strain-strength characteristics of reinforced concrete must be evaluated at critical sections of each structural element. By analyzing these sections, we can determine how much deformation the flexural plastic hinges can endure before failure occurs. This analysis utilizes the moment-curvature relationship derived from the material's deformation-strength characteristics and established ductility criteria. The identification of flexural joints involves calculating the moment-curvature relationships for the critical sections of each member. This calculation is performed using specialized confinement analysis software developed by the authors, known as SEMAp [23]. This software allows for a detailed examination of how the confinement of concrete affects its performance under load, thereby providing numerical insights into the behavior of flexural joints in reinforced concrete structures.



a) Two storey building plan



b) Four storey building plan



c) Seven storey building plan

Fig. 1. Plan views of the buildings considered in the study. Shaded areas represent walls with load bearing ability.

For concrete material, the Mander confined concrete model is used [24]. Using these moment-curvature relationships, ultimate deformation criteria and plastic joint length, the plastic rotational capacity and joint properties of each member were determined. Damage capacity limit values for flexural joints are given in Table 1.

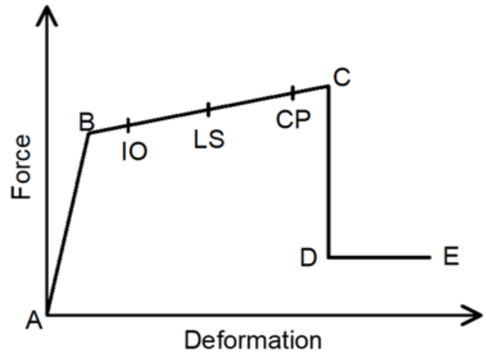


Fig. 2 Typical force and deformation relation of a plastic hinge

In addition to flexural joints, shear joints are also defined in columns and beams. Unlike flexural joints, no ductility is calculated for shear joints and it is assumed that the elements reach the collapse state as soon as they reach their shear capacity. Shear capacities were calculated according to TS500 [25]. In order to take into account the effect of the infill walls on the structural behavior of the structure, each model was prepared in two different forms, with and without considering the walls as load-bearing elements. The effect of the walls is reflected by using equivalent diagonal pressure struts. The properties of the pressure struts were determined in accordance with FEMA-356 and TBSC-2018 [22, 26].

Table 1 Flexural joint damage limit criteria

Point	Concrete Strain	Steel Strain
B	Determined by yield strength and flexural rigidity	
IO	(ε_c) =0.0035	(ε_s) = 0.01
LS	(ε_{cc})= 0.0035+0. 010·(ρ_c/ρ_s) ≤0.0135	(ε_s)= 0.04
CP	(ε_{cc})= 0.0040+0.014·(ρ_c/ρ_s) ≤0.0180	(ε_s)= 0.06
C-D	(ε_{cc})= 0.03	(ε_s)= 0.5·ε_{su}
E	(ε_{cc})= 0.04	(ε_s)= ε_{su}

In Table 1; ε_c: concrete strain, ε_{cu}: strain at the most outer fiber of concrete, ε_{cc}: strain at the most outer core fiber of the concrete, ρ_s: volumetric ratio of lateral reinforcement present, ρ_c: volumetric ratio of lateral reinforcement required by code, ε_s: reinforcing steel strain, ε_{su}: reinforcing steel ultimate strain value.

3. Determination of nonlinear displacement demands

The buildings modeled in 3-D were subjected to non-linear static analysis considering the vertical load effects and capacity curves were obtained. For 96 models, displacement capacity values at Immediate Occupancy, Life Safety and Collapse Prevention performance levels were obtained according to 2018 Earthquake Regulation. The capacity curves of 3-D models were reduced to "Single Degree of Freedom" (SDOF) models using bi-linearization. Nonlinear displacement demands of the SDOF models were calculated by nonlinear time domain analysis using 264 real earthquake records with different maximum ground acceleration values [27]. The obtained building displacement capacities were compared with the displacement demands. A total of 264 ground motion records were used to calculate the nonlinear displacement demands. All earthquake records were obtained from PEER website [28]. The maximum ground acceleration values of the earthquakes and acceleration records used in the analysis are given in Table 2.

Table 2. The seismic events and the PGA values of the records considered in the study

No	Earthquake	# records	PGA Range (g)
1	Cape Mendocino 1992/04/25 18:06	4	0.385-0.662
2	Chi-Chi, Taiwan 1999/09/20	56	0.119-0.655
3	Coalinga 1983/05/02 23:42	4	0.227-0.592
4	Coyote Lake 1979/08/06 17:05	3	0.228-0.434
5	Duzce, Turkey 1999/11/12	2	0.348-0.535
6	Erzincan, Turkey 1992/03/13	1	0.496
7	Friuli, Italy 1976/05/06 20:00	1	0.351
8	Gazli, USSR 1976/05/17	1	0.608
9	Imperial Valley 1940/05/19 04:37	2	0.215-0.313
10	Imperial Valley 1979/10/15 23:16	33	0.160-0.704
11	Irpinia, Italy 1980/11/23 19:34	11	0.201-0.602
12	Kobe 1995/01/16 20:46	8	0.212-0.693
13	Kocaeli, Turkey 1999/08/17	17	0.137-0.550
14	Landers 1992/06/28 11:58	4	0.152-0.417
15	Livermore 1980/01/24 19:00	1	0.229
16	Loma Prieta 1989/10/18 00:05	38	0.159-0.701
17	Mammoth Lakes 1980/05/27 14:51	1	0.408
18	Morgan Hill 1984/04/24 21:15	2	0.423-0.711
19	N. Palm Springs 1986/07/08 09:20	7	0.205-0.694
20	Northridge 1994/01/17 12:31	34	0.185-0.657
21	Parkfield 1966/06/28 04:26	5	0.357-0.652
22	San Fernando 1971/02/09 14:00	1	0.324
23	Spitak, Armenia 1988/12/07	1	0.199
24	Superstitn Hills(B) 1987/11/24 13:16	10	0.181-0.682
25	Tabas, Iran 1978/09/16	2	0.328-0.406
26	Victoria, Mexico 1980/06/09 03:28	2	0.587-0.621
27	Westmorland 1981/04/26 12:09	7	0.155-0.651
28	Whittier Narrows 1987/10/01 14:42	5	0.199-0.426
29	Whittier Narrows 1987/10/04 10:59	1	0.374
	Total	264	

While comparing earthquake displacement demands and building displacement capacities, earthquake records were divided into 3 groups to reflect the 3 earthquake intensity levels (0.2g, 0.4g and 0.6g) in the seismic codes. The average ground acceleration values of the records with peak ground acceleration values around 0.2g, 0.4g and 0.6g values were divided into 3 groups to reflect these values and used in the comparison. These groups can be considered as ground motions with different return periods. The values related to the acceleration record groups used are given in Table 3. Since there are few acceleration records with high PGA values (0.5g-0.7g) in the literature, fewer acceleration records were used in this group.

Table 3. The acceleration set properties considered in the study

Acceleration Set	Quantity	Min. (g)	Max. (g)	Avg. (g)
0.2g	93	0.119	0.274	0.200
0.4g	108	0.300	0.506	0.400
0.6g	63	0.500	0.711	0.601

4. Analysis results

To assess the impact of the analyzed parameters, we calculated the exceedance probability for each performance level. This probability represents the likelihood that the structural displacement demand will exceed the capacity associated with a specific performance level for a particular set of acceleration records.

Table 4. Exceedance ratios for different cases

1975 Code		C10s200	C16s200	C10sCode	C16sCode
0.2g/IO	S2	0.105	0.046	0.110	0.059
	S4	0.866	0.801	0.874	0.833
	S7	0.769	0.753	0.772	0.755
0.4g/LS	S2	0.009	0.000	0.005	0.000
	S4	0.465	0.218	0.343	0.141
	S7	0.428	0.146	0.118	0.014
0.6g/CP	S2	0.067	0.008	0.036	0.000
	S4	0.746	0.500	0.647	0.393
	S7	0.512	0.258	0.194	0.071
1998 Code		**C16s200**	**C25s200**	**C16sCode**	**C25sCode**
0.2g/IO	S2	0.024	0.024	0.027	0.024
	S4	0.374	0.427	0.309	0.239
	S7	0.390	0.446	0.446	0.422
0.4g/LS	S2	0.000	0.000	0.000	0.000
	S4	0.005	0.002	0.000	0.000
	S7	0.046	0.000	0.000	0.000
0.6g/CP	S2	0.000	0.000	0.000	0.000
	S4	0.135	0.048	0.000	0.000
	S7	0.163	0.016	0.000	0.000

For the correspondence of performance level and acceleration group, the performance requirements commonly considered for residential buildings was used. According to this, residential structures should have low damage for frequent ground motions (Immediate Occupancy for earthquakes with an average PGA of 0.2g); meet life safety requirements for the design earthquake load (Life Safety for earthquakes with an average PGA of 0.4g). For rare ground motions, total collapse should be prevented (Pre-Collapse for earthquakes with an average PGA of 0.6g). These values are given in Table 4 according to the number of storeys for different structural case, performance levels and code. “S2”, ‘S4’ and ‘S7’ in the tables indicate the number of stories as 2, 4 and 7. The value after “C” indicates the concrete strength in MPa and the “200” after “s” indicates that the lateral reinforcement spacing is 200 mm. In this case, it is assumed that there are no stirrups in the section. The expression “sCode” indicates that the lateral reinforcement case is in compliance with the relevant code. Under the “Ratio” column, the exceedance ratio of the case in question is given.

5. Results and discussion

When the obtained results are analyzed, following conclusions may be drawn: The exceedance ratio of the Immediate Occupancy performance level is much less affected by changes in concrete strength, lateral reinforcement quantity and detailing when compared to the other performance levels. This is an expected result since this level is at the beginning of the nonlinear behavior. Since concrete strength and amount of lateral reinforcement are more effective on deformation capacity rather than strength, they are not effective on IO, which is mostly determined by strength.

For Immediate Occupancy performance levels, increasing concrete strength and lateral reinforcement can paradoxically lead to higher exceedance rates in certain cases. This occurs because these improvements result in higher longitudinal reinforcement elongation at lower curvature values, while also requiring more lateral reinforcement due to increased concrete strength (as per code regulations). This effect is particularly pronounced in low-rise buildings, where the ductility of beam and column sections is highly sensitive to longitudinal reinforcement elongation. Similar observations have been reported in previous research [29].

For both code cases and all performance levels, the damage rate increases rapidly as the number of storeys increases. It has been observed in many previous studies and post-earthquake investigations that the seismic performance of low-rise buildings is better than high-rise buildings [30–32]

For the 1975 code models, it is seen that 4-storey buildings have a greater risk than 7-storey buildings. One of the reasons for this situation is that 4-storey 1975 code buildings have relatively weaker structural systems. These buildings are partially constructed in a poorer manner due to their low number of storeys due to construction culture in Turkey [20]. In addition, the period values of these structures have values closer to the dominant period of the acceleration records. It is stated that the relative (not absolute) drift demands of these buildings are higher than those of 7-story buildings [33]. For the 1998 code models, it is seen that the increase in the number of storeys and the increase in the damage ratio are parallel.

It is observed that the 1975 code models have significantly high damage ratios for all performance cases. For 2 and 7 storey buildings, low damage ratios are obtained only for LS and CP when both concrete strength and lateral reinforcement amount are positive. These ratios increase significantly with the decrease of material and/or lateral reinforcement properties. Considering that the models used in the study do not have any irregularities, the high exceedance ratios become more striking.

For the 1998 code models, the exceedance ratios are at very low levels. Especially for LS and CP cases, zero or near zero values are obtained unless both concrete strength and lateral reinforcement amount are low. This can be considered as an indication that the 1998 code models have superior seismic performance. Despite the unfavorable concrete strength and lateral reinforcement values, the low exceedance rates can be attributed to the fact that the models do not contain irregularities and the unfavorable concrete strength value is chosen at a value that is not too low such as C16. When the displacement demands of these models were examined, it was also determined that in most cases the demand values were very close to the capacity values.

It is determined that the IO performance level exceedance rates are high in both regulations, except for 2-storey buildings. Although the 1998 code values are more favorable than the 1975 code, the exceedance rates in the range of 24-45% can be considered high. The effect of concrete strength and lateral reinforcement detailing on the damage rate generally increases as the performance level and the number of storeys increase and is greater for the 1975 code models with lower strength than for the 1998 code models. As an expected result, the effect of material and detailing properties on the performance increases with the increase in the nonlinear displacement demand of the structures.

Concrete strength and lateral reinforcement detailing have a significant effect on the damage rate. For example, for the 1975 code models, for 0.4g/LS, the damage rate of 4-storey models decreases from 47% to 14% and for 7-storey models from 43% to 1%. For 0.6g/CP, there are reductions from 75% to 39% for 4-story models and from 51% to 14% for 7-story models.

In the 1998 code models, the exceedance rates for most of the performance levels other than IO are zero or close to zero, making it more difficult to evaluate. However, in 4 and 7 storey models, the values decrease rapidly between C16s200 and C16sCode ratios and reach zero for other cases, indicating that concrete strength and lateral reinforcement detailing are effective on the damage rate.

6. Conclusions

This study investigates the seismic behavior of reinforced concrete buildings, specifically focusing on the effects of concrete strength and lateral reinforcement detailing. A total of 48 nonlinear inelastic models representing 2-, 4-, and 7-storey residential buildings were analyzed using both static and dynamic methods. The capacity curves were derived through linear inelastic static analysis, and displacement demands were calculated using nonlinear inelastic time domain analysis across 264 acceleration records. The study aimed to assess how variations in concrete strength and lateral reinforcement influence the exceedance rates of different performance levels, particularly Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

- The exceedance ratio for the IO performance level is minimally affected by changes in concrete strength and lateral reinforcement, as IO is primarily governed by strength rather than deformation capacity.
- Paradoxically, increasing concrete strength and lateral reinforcement can lead to higher IO exceedance rates in low-rise buildings. This is attributed to increased longitudinal reinforcement elongation at lower curvature values, necessitating additional lateral reinforcement.
- Damage rates increase with the number of storeys, with low-rise buildings generally exhibiting better seismic performance than high-rise structures.
- For the 1975 code models, 4-storey buildings showed higher exceedance rates than 7-storey buildings due to weaker structural systems, higher relative drift demands, and construction practices.
- The 1998 code models showed superior seismic performance, with near-zero exceedance rates for LS and CP under most conditions, even with low concrete strength.

- High exceedance ratios for the 1975 code models highlight the significance of modern seismic design practices and improved detailing requirements.
- At CP performance levels under high-intensity ground motion (0.6g), significant reductions in exceedance rates were observed when transitioning from inadequate to code-compliant detailing emphasizing the effect of considered parameters in highly nonlinear behavior.
- Concrete strength and lateral reinforcement detailing are crucial for improving seismic performance, particularly for older code models. Their impact becomes more pronounced at higher performance levels (LS and CP) and for taller buildings.

This study highlights the critical influence of material properties, lateral reinforcement detailing, and building height on the seismic performance of RC structures. While modern seismic design codes have significantly improved performance outcomes, older code-compliant buildings remain vulnerable under higher seismic demands. The findings emphasize the need for retrofitting strategies and stricter enforcement of seismic design standards to ensure the resilience and safety of the built environment.

Acknowledgement

This study was supported by TUBITAK Scientific Research Project No. 107M569.

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