

Influence of Mezzanine Floors on the Seismic Response of Open-Ground-Story Reinforced Concrete Mixed-Use Buildings

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Abstract:

This study investigates the influence of mezzanine-floor implementation on the seismic response of open-ground-story reinforced concrete (RC) mixed-use buildings. A comparative analytical assessment was conducted on two three-story RC frame configurations, with and without a mezzanine floor, using linear elastic time-history analyses under eleven earthquake ground motion records. The seismic response was evaluated in terms of modal periods, inter-story drift ratios, torsional and stiffness irregularities, base shear forces, and roof displacements. The mezzanine-integrated configuration reduced the fundamental period by 11.4%, indicating increased structural stiffness, redistributed inter-story drift demands within the lower stories, and reduced base shear demand for 9 of the 11 earthquake records. However, the maximum torsional irregularity coefficient increased to 1.586, exceeding the TBEC-2018 limit value of 1.20. Although the mezzanine floor reduced selected global response measures, it increased torsional irregularity and redistributed deformation demand within the lower stories. These findings indicate that reduction in global response measures should be evaluated together with local irregularity measures when assessing the seismic performance of mixed-use RC buildings.

1. Introduction

Reinforced concrete (RC) mixed-use buildings incorporating open commercial ground stories and residential upper floors are widely constructed in densely populated urban environments due to functional and economic demands. To maximize usable commercial space mezzanine floors are frequently incorporated within the ground story. Although architecturally advantageous, these additions may significantly modify the structural response of the building by altering mass distribution, lateral stiffness, and internal load-transfer mechanisms. Consequently, mezzanine-integrated RC buildings may become increasingly susceptible to unfavorable seismic response characteristics, including soft-story behavior, torsional amplification, and concentration of

deformation demands at lower stories under strong seismic excitation. Damage investigations following major earthquakes, including the 2023 Turkey–Syria earthquakes, have demonstrated that buildings with open ground stories, discontinuous infill walls, and mezzanine-related stiffness irregularities are particularly vulnerable to severe structural damage and soft-story collapse mechanisms [2–3].

The seismic vulnerability of RC buildings with vertical irregularities has been extensively investigated, particularly in relation to soft-story formation and stiffness discontinuities. Early field observations by Koç and Tuhta [4] indicated that commercial buildings incorporating mezzanine floors, cantilevered upper stories, and waffle slab systems frequently exhibit compromised structural performance due to abrupt changes in stiffness and

load-transfer mechanisms. Similarly, Akansel [4] demonstrated that irregularities associated with first-story infill wall distribution significantly increase collapse susceptibility in RC systems and emphasized that conventional code definitions may underestimate the severity of soft-story vulnerabilities. Abd-Alghany et al. [5] further reported that increased soft-story height and vertical stiffness irregularities substantially amplify lateral displacement and inter-story drift demands, while strengthening strategies such as shear walls and bracing systems can effectively mitigate these deficiencies.

The structural implications of mezzanine-floor implementation have also attracted increasing research attention in recent years. Loganantham and Shanmugasundaram [6] showed that the vertical location of mezzanine floors significantly influences structural dynamic characteristics, with improved seismic performance observed when the mezzanine is positioned near three-quarters of the story height. Investigating torsional response, Demirbaş and Şahin [7] reported that mezzanine additions accompanied by beam removal intensify torsional irregularities and increase column shear demands. In addition, Işık et al. [8] demonstrated that slab discontinuities reduce global lateral stiffness and seismic capacity, while Işık et al. [9] highlighted that mezzanine and band-window configurations may induce short-column effects that lead to elevated drift demands and brittle shear failures.

Recent studies conducted within the Turkish context have further emphasized the practical significance of these structural irregularities. Koç [10], based on extensive field investigations of RC buildings in Samsun, reported that mezzanine-induced irregularities remain widespread in practice, reflecting a persistent conflict between architectural requirements and seismic safety considerations. From a code-based perspective, Ulutaş [11] noted that certain provisions of the Turkish Building Earthquake Code (TBEC-2018) may still permit the formation of soft and weak stories in mixed-use RC buildings.

Post-earthquake damage assessments following recent seismic events in Turkey have further confirmed the detrimental effects associated with vertical stiffness irregularities in mixed-use RC buildings. Investigations conducted after the 2023 Turkey–Syria earthquakes revealed severe damage concentration in buildings containing commercial ground floors and mezzanine configurations [12–14]. Reported failure patterns included excessive inter-story drift concentration, torsional damage amplification, column shear failures, and soft-story collapse mechanisms associated with discontinuous

infill walls and abrupt stiffness variations between stories. These observations further emphasize the critical role of vertical irregularities in governing seismic damage distribution in RC mixed-use buildings.

However, despite the extensive body of research on soft-story behavior and structural irregularities, the isolated influence of mezzanine-floor implementation on the seismic response of low-rise mixed-use RC buildings designed according to TBEC-2018 provisions has not been systematically quantified. In particular limited studies have comparatively evaluated identical low-rise RC building configurations with and without mezzanine floors under consistent seismic excitation while maintaining equivalent geometric and material properties. Consequently, the extent to which mezzanine-induced irregularities alter modal characteristics, inter-story drift distribution, story shear demands, and torsional response remains insufficiently understood.

Accordingly, this study investigates the seismic behavior of a three-story RC mixed-use building with and without a mezzanine floor designed in accordance with TBEC-2018 provisions. Linear elastic time-history analyses are performed to evaluate the influence of mezzanine-induced structural irregularities on the dynamic response of the building under selected earthquake ground motions. By maintaining identical geometric configurations, material properties, and loading conditions between the reference and mezzanine-integrated models, the study isolates the specific influence of mezzanine-floor implementation on structural response characteristics. The comparative assessment focuses on variations in modal properties, inter-story drift ratios, story shear distribution, and torsional response resulting from the introduction of the mezzanine floor. The findings are expected to provide insight into the seismic implications of mezzanine-floor configurations and support the development of improved seismic design strategies for irregular mixed-use RC building systems.

2. Materials and Methods

2.1 Building Description and Structural Configuration

This study investigates the seismic response of low-rise reinforced concrete (RC) mixed-use buildings commonly observed in urban regions of Türkiye, with particular emphasis on the influence of mezzanine-floor implementation on structural behavior. Two three-dimensional structural models were developed using SAP2000 [15]: (i) a reference

model without a mezzanine floor and (ii) a modified model incorporating a mezzanine floor within the first story. Both configurations represent typical mixed-use RC building typologies in which the ground story is commonly utilized for commercial purposes, while the upper stories are designated for residential occupancy.

The geometric configuration of the structures was selected to represent realistic low-rise RC frame buildings frequently encountered in practice. Each building has a plan dimension of 12 m $\times$ 12 m, consisting of three bays in both the X and Y directions with a uniform bay spacing of 4 m. The ground-story height was defined as 5.0 m to represent commercial usage conditions, whereas the upper stories were modeled with uniform story heights of 3.0 m. In the mezzanine-integrated configuration, the mezzanine floor was positioned at mid-height within the ground story at an elevation of 2.5 m from the base level. To ensure a consistent comparative assessment, identical cross-sectional properties and material characteristics were assigned to both structural models. Columns were modeled with cross-sectional dimensions of 40 $\times$ 40 cm, while beams were defined with dimensions of 30 $\times$ 50 cm. Floor slabs were modeled as 12 cm thick shell elements. Material properties were assigned in accordance with TS500 provisions [16], including C30 concrete and S420 reinforcing steel. The principal geometric, material, and seismic design parameters adopted in the numerical models are summarized in Table 1. Three-dimensional views of the reference and mezzanine-integrated structural configurations are presented in Figure 1 and Figure 2, respectively, illustrating the overall structural layout, bay arrangement, and mezzanine-floor positioning.

2 Structural Modeling Assumptions and Loading Conditions

Both structural models were assumed to possess fixed-base boundary conditions, and soil–

structure interaction effects were neglected in order to isolate the influence of superstructure irregularities on seismic response. Rigid diaphragm constraints were assigned at all floor and mezzanine levels to accurately represent in-plane floor stiffness and mass distribution.

Gravity loads and mass distributions were defined in accordance with the requirements of the Turkish Building Earthquake Code (TBEC-2018) [18] and TS500 provisions. Structural masses were automatically generated within SAP2000 based on tributary area calculations incorporating dead and live load contributions. The effective dead load assigned to the floor slabs was taken as 5.04 kN/m², including slab self-weight, superimposed dead loads, and partition wall effects. Live loads were assigned according to the intended occupancy type of each floor level, with separate residential and commercial loading conditions considered. For the mezzanine floor in the modified configuration, the same commercial loading assumptions were adopted to ensure consistency in the comparative assessment. The complete loading definitions used in the numerical models are summarized in Table 2.

2.3 Modal Analysis and Model Verification

Prior to nonlinear dynamic evaluation, modal analyses were performed for both structural configurations to assess their fundamental dynamic characteristics and verify the consistency of the numerical models. The first four vibration modes and their corresponding natural periods were extracted, as these modes predominantly govern the seismic response of low-rise RC frame structures.

Table 1. Structural and seismic analysis parameters of the studied RC building model

Parameter	Value
Number of stories	3
Story height(s)	Mezzanine: 2.50 m; ground floor: 2.50 m; typical floor: 3.00 m
Total building height	11.00 m
Concrete / reinforcement grade	C30 / S420
Building importance factor, <i>I</i>	1.0
Seismic design level	DD-2 (10% probability of exceedance in 50 years)
Soil class	ZD
Ductility level	High ductility
Effective ground acceleration coefficient, <i>A0</i>	0.30

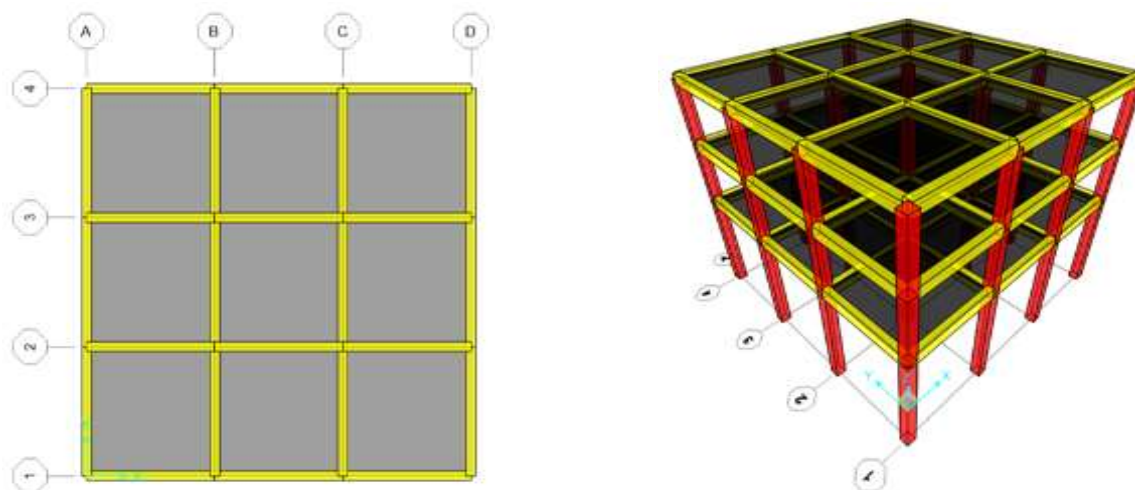


Figure 1. Plan view (left) and three-dimensional structural view (right) of the reference RC building model

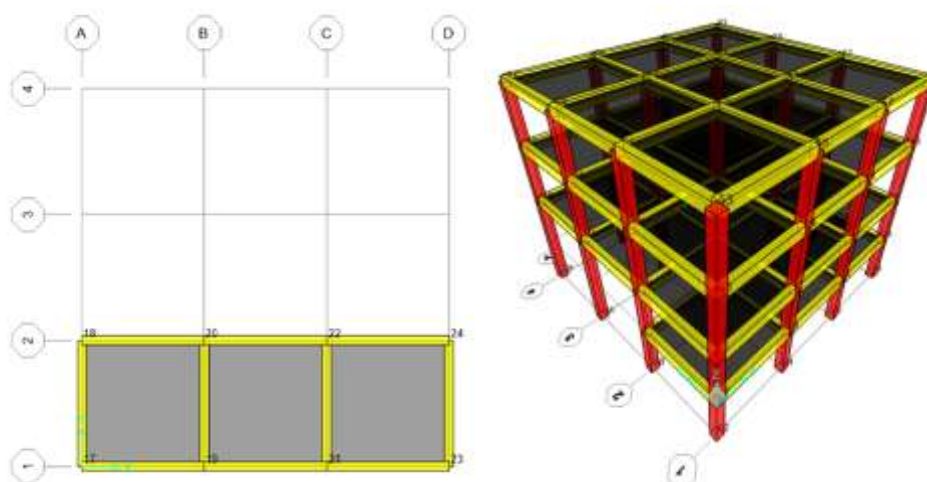


Figure 2. Plan view (left) and three-dimensional structural view (right) of the RC building model with mezzanine-floor configuration

Table 2. Gravity load parameters adopted in the numerical models

Load Type	Value
Residential floor live load	2.00 kN/m ²
Commercial floor live load	3.00 kN/m ²
Effective floor dead load (including self-weight and partitions)	5.04 kN/m ²
Interior wall load	4.15 kN/m ²
Exterior wall load	5.90 kN/m ²
Roof snow load	1.50 kN/m ²

The numerically obtained fundamental periods were further compared with empirical estimations prescribed by TBEC-2018 and ASCE 7-22 to evaluate the reliability of the developed analytical models. This comparison ensured that the dynamic characteristics predicted by the numerical simulations remained within acceptable ranges for comparable RC structural systems.

A linear elastic analysis framework was adopted to isolate the influence of mezzanine-induced stiffness irregularities on the global dynamic response of the structural systems without introducing uncertainties

associated with nonlinear material behavior and damage progression. Consequently, no staged construction procedures, member removal simulations, or nonlinear material degradation mechanisms were incorporated into the numerical models.

2.4 Ground Motion Selection

To evaluate the seismic response of the structural models under realistic earthquake excitation, a suite of 11 recorded ground motion pairs was selected for

linear time-history analysis. The record selection procedure was conducted in accordance with the recommendations of TBEC-2018 and widely adopted earthquake engineering practices. Selection criteria included moment magnitude (M_w), source-to-site distance, peak ground acceleration characteristics, and local site conditions to ensure representation of strong ground motion effects relevant to the considered seismic hazard level.

The selected earthquake records include both significant Turkish earthquake events and internationally recognized strong-motion records. The

selected dataset encompasses earthquake magnitudes ranging from M_w 6.54 to M_w 7.90, thereby ensuring representation of diverse seismic intensity measures and frequency-content characteristics. Turkish earthquake records incorporated into the study include the Kocaeli (1999), Düzce (1999), and Erzincan (1992) earthquakes, among others. International records include the Kobe (1995), Chi-Chi (1999), and Imperial Valley-02 (1940) earthquakes. Detailed information regarding the selected ground motion records is provided in Table 3.

Table 3. Ground motion records adopted for linear time-history analysis

No	Ground motion event	RSN	Magnitude (M_w)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Imperial Valley-02	6	6.95	0.233	31.30	18.45
2	Kocaeli	1176	7.51	0.286	70.87	63.12
3	Superstition Hills-02	719	6.54	0.126	12.82	5.49
4	Düzce	1602	7.14	0.776	62.90	19.67
5	Erzincan	821	6.69	0.445	93.84	29.35
6	Northridge-01	949	6.69	0.329	29.29	9.50
7	Kobe	1101	6.90	0.311	45.04	27.43
8	Kocaeli	1158	7.51	0.321	56.11	31.87
9	Chi-Chi	1194	7.62	0.155	41.62	29.54
10	Denali	2114	7.90	0.324	94.23	45.89
11	Düzce	1605	7.14	0.434	78.70	48.74

Note: RSN denotes the record sequence number obtained from the PEER ground motion database; M_w represents moment magnitude; PGA, PGV, and PGD denote peak ground acceleration, peak ground velocity, and peak ground displacement, respectively.

2.5 Ground Motion Processing and Scaling Procedure

Prior to dynamic analysis, all selected ground motion records were preprocessed using Seismosignal software [19]. Baseline correction procedures were applied to eliminate potential signal drifts and numerical inconsistencies in the acceleration time histories. No filtering or spectral matching procedures were performed in order to preserve the original frequency content and physical characteristics of the recorded ground motions.

Following preprocessing, all earthquake records were scaled according to the simplified scaling procedure specified in TBEC-2018. The square root of the sum of squares (SRSS) of the two horizontal ground motion components was utilized to determine the resultant horizontal response spectra. Scaling coefficients were computed such that the average response spectrum of the selected record set within the period range of $0.2T_p$ – $1.5T_p$ was not less than 1.3 times the target design spectrum specified by TBEC-2018.

The scaling procedure was conducted for the ZD site class under the DD-2 earthquake hazard level. A

single scale factor was uniformly applied to both horizontal components of each earthquake record to maintain the original relationship between the orthogonal ground motion components. The scaling coefficients were calculated using spreadsheet-based numerical procedures, and the adjusted records were subsequently implemented in the time-history analyses.

This scaling methodology preserves the inherent frequency characteristics of the selected ground motion records while ensuring compatibility with the target TBEC-2018 design spectrum. Consequently, the adopted procedure enables a consistent and code-compliant representation of seismic demand for comparative evaluation of the reference and mezzanine-integrated structural systems. The average scaling coefficients obtained for the mezzanine-integrated and reference models were 2.171 and 2.176, respectively, indicating a consistent scaling process between the two structural configurations. The compatibility between the mean response spectra of the scaled earthquake records and the target DD-2 design spectrum is illustrated in Figures 3 and 4 for the mezzanine-integrated and reference models, respectively.

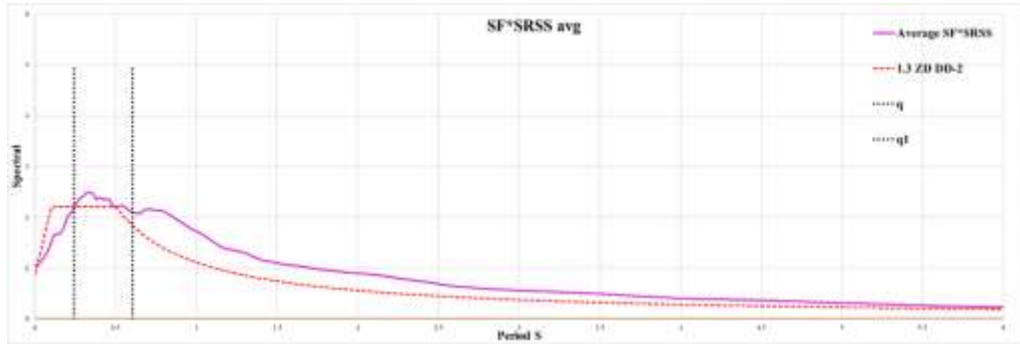


Figure 3. Comparison between the mean response spectrum of the 11 scaled earthquake records for the mezzanine-integrated model and the target DD-2 design spectrum. The scaled mean spectrum demonstrates satisfactory compatibility with the target spectrum over the considered period range

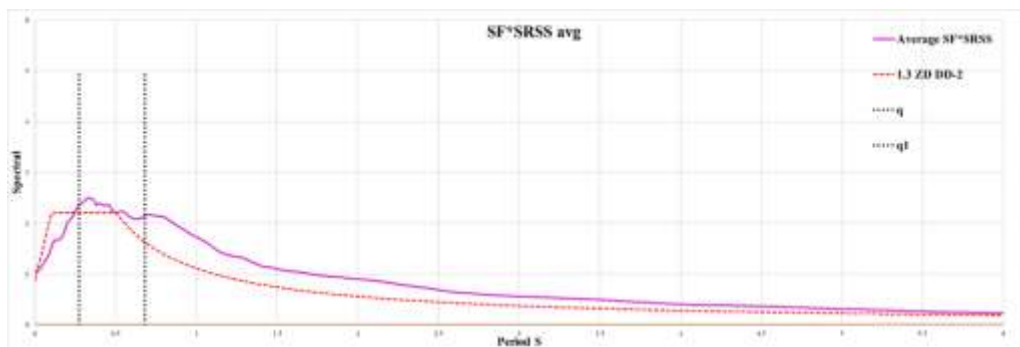


Figure 4. Comparison between the mean response spectrum of the 11 scaled earthquake records for the reference model and the target DD-2 design spectrum. The scaled mean spectrum demonstrates satisfactory compatibility with the target spectrum over the considered period range.

2.6 Seismic Response Parameters

To quantify the influence of mezzanine-floor implementation on structural seismic performance, several global dynamic response parameters were extracted from the linear time-history analyses. The evaluated response quantities included fundamental natural periods, modal response characteristics, inter-story drift ratios, story shear distributions, and torsional response behavior. These parameters were selected because they directly reflect the influence of vertical stiffness irregularities on the global seismic response and deformation characteristics of low-rise RC structural systems. The response parameters obtained from the reference and mezzanine-integrated models were comparatively evaluated to identify the

extent to which mezzanine-floor implementation modifies structural behavior under seismic excitation.

3. Results and Discussion

3.1 Modal Period Comparison

The first four natural vibration periods obtained from the modal analyses for the reference and mezzanine-integrated structural configurations are summarized in **Table 4**. A consistent reduction in modal periods is observed for the mezzanine-integrated model across all considered vibration modes, indicating an overall increase in structural stiffness resulting from the introduction of the mezzanine floor. The corresponding model deformation characteristics for both structural configurations are illustrated in **Figure 5**.

Table 4. Comparison of the first four natural vibration periods of the reference and mezzanine-integrated structural configurations

Mode No	With mezzanine floor (s)	Without mezzanine floor (s)
T1	0.482	0.544
T2	0.471	0.544
T3	0.384	0.455
T4	0.142	0.145

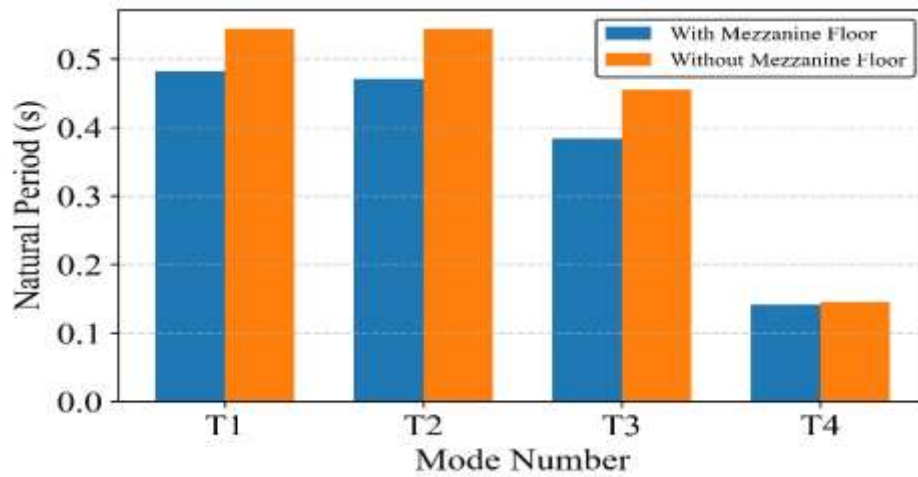


Figure 5. Modal period comparison for the first four vibration modes of the reference and mezzanine-integrated structural configurations

For the fundamental vibration mode (T1), the natural period decreased from 0.544 s in the reference model to 0.482 s in the mezzanine-integrated configuration, corresponding to a reduction of approximately 11.4%. Similar reductions were observed for the second and third vibration modes, with decreases of 13.4% and 15.6%, respectively. By contrast, the fourth mode exhibited only a minor reduction of approximately 2.5%, suggesting that the influence of the mezzanine floor is more pronounced in the lower vibration modes that predominantly govern the global seismic response of low-rise RC frame structures.

From a structural dynamics perspective, the reduction in natural periods indicates that the mezzanine floor contributes additional stiffness to the overall lateral load-resisting system. The introduction of an intermediate slab level within the commercial ground story modifies the vertical stiffness distribution and alters the effective modal characteristics of the structure. Consequently, the structural system exhibits shorter vibration periods and modified dynamic interaction characteristics under earthquake excitation.

Since structures with shorter natural periods may attract different acceleration-sensitive seismic demands depending on the spectral characteristics of

the input ground motion, the observed reduction in modal periods may also influence the distribution of seismic force demand and deformation response throughout the structure. These changes in modal properties are consistent with the response trends discussed in the subsequent sections, particularly regarding variations in drift concentration, torsional response, and stiffness irregularity.

Overall, the results demonstrate that mezzanine-floor implementation significantly modifies the global dynamic characteristics of the building and therefore plays an important role in governing its seismic response behavior.

3.2 Inter-Story Drift Ratio Response

The inter-story drift ratio (IDR) responses obtained from the linear time-history analyses for both structural configurations under the selected earthquake records are summarized in Table 5. Representative drift distribution patterns observed along the building height are further illustrated in Figure 6. A clear distinction is observed between the seismic deformation responses of the reference model and the mezzanine-integrated configuration in both the X and Y directions.

Table 5. Inter-story drift ratio (IDR) results for both structural configurations under the selected earthquake records in X and Y directions.

Model		With Mezzanine Floor				Without Mezzanine Floor		
Story		Mezzanine	Story1	Story2	Story3	Story1	Story2	Story3
Elevation (m)		2.5	5	3	3	5	3	3
Location		Top	Top	Top	Top	Top	Top	Top
RSN6	X	0.039	0.061	0.057	0.029	0.086	0.051	0.025
	Y	0.061	0.040	0.047	0.023	0.076	0.047	0.024
RSN1176	X	0.046	0.091	0.078	0.039	0.111	0.068	0.033
	Y	0.060	0.041	0.055	0.029	0.117	0.069	0.033
RSN719	X	0.013	0.017	0.016	0.008	0.026	0.017	0.009
	Y	0.015	0.010	0.013	0.006	0.023	0.014	0.007

RSN1602	X	0.060	0.096	0.092	0.047	0.156	0.095	0.046
	Y	0.147	0.102	0.137	0.071	0.237	0.144	0.071
RSN821	X	0.059	0.129	0.109	0.056	0.153	0.090	0.042
	Y	0.091	0.060	0.070	0.032	0.149	0.086	0.040
RSN949	X	0.046	0.089	0.071	0.035	0.125	0.075	0.036
	Y	0.070	0.050	0.070	0.036	0.079	0.047	0.023
RSN1101	X	0.040	0.159	0.066	0.032	0.119	0.071	0.034
	Y	0.105	0.145	0.101	0.052	0.216	0.129	0.062
RSN1158	X	0.039	0.073	0.067	0.035	0.081	0.049	0.024
	Y	0.086	0.058	0.080	0.039	0.104	0.063	0.031
RSN1194	X	0.025	0.044	0.039	0.020	0.057	0.034	0.016
	Y	0.066	0.045	0.057	0.029	0.063	0.038	0.019
RSN2114	X	0.064	0.107	0.092	0.044	0.169	0.099	0.046
	Y	0.081	0.054	0.068	0.035	0.090	0.052	0.024
RSN1605	X	0.069	0.100	0.096	0.049	0.166	0.099	0.047
	Y	0.129	0.087	0.114	0.059	0.224	0.131	0.062

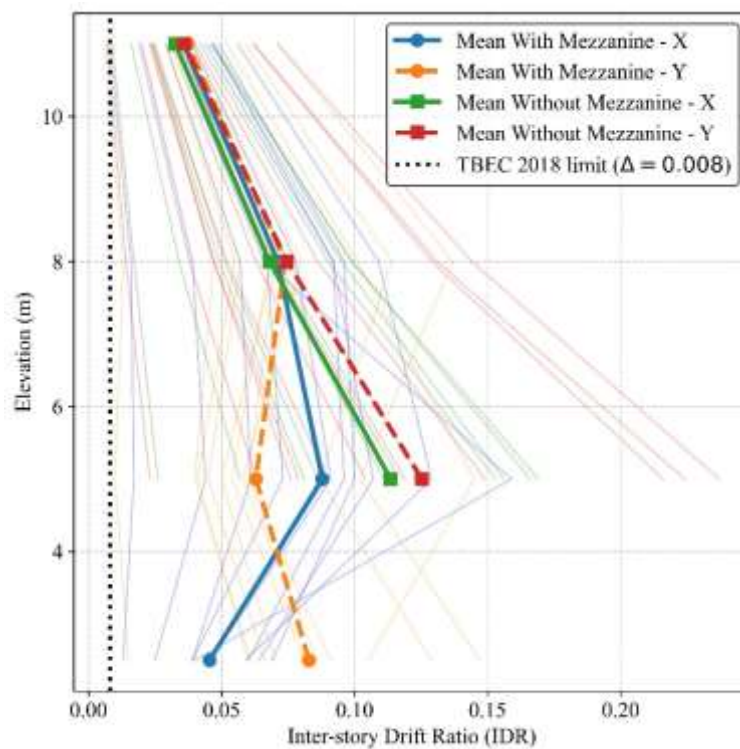


Figure 6. Inter-story drift ratio (IDR) profiles for all earthquake records together with the mean profile and the TBEC 2018 drift limit ($\Delta = 0.008$). Thin lines represent individual earthquake records, while thick lines denote the mean response profile

In the reference configuration, the maximum IDR values were predominantly concentrated at the first story, indicating a pronounced soft-story tendency at the commercial ground level. Peak drift ratios in the Y direction reached 0.237 under RSN1602, 0.224 under RSN1605, and 0.216 under RSN1101. Similar trends were observed in the X direction, where maximum first-story drift ratios reached 0.169, 0.166, and 0.156 under RSN2114, RSN1605, and RSN1602, respectively. These results indicate substantial deformation concentration at the lower level resulting from the open ground-story configuration.

By comparison, the mezzanine-integrated configuration exhibited a more distributed drift profile along the building height. Significant drift demands

developed not only at Story 1 but also at the mezzanine elevation. The highest drift ratios in the mezzanine-integrated configuration were observed at Story 1, reaching 0.159 in the X direction under RSN1101 and 0.145 in the Y direction. However, substantial drift concentrations also occurred at the mezzanine level, particularly in the Y direction, where peak values of 0.147 and 0.129 were recorded under RSN1602 and RSN1605, respectively.

This response behavior indicates that the mezzanine floor modifies the lateral stiffness distribution by introducing an intermediate stiffness discontinuity within the commercial story. As a result, seismic deformation demands become redistributed across

multiple vertical levels rather than remaining concentrated solely at the original ground-story level. Although both structural configurations exceeded the drift limitations prescribed by TBEC-2018 under several ground motion records, the results suggest that the mezzanine floor primarily alters the vertical distribution of deformation demand rather than uniformly increasing or decreasing global drift response. In several cases, the presence of the mezzanine reduced peak drift concentrations at the original first-story level relative to the reference configuration. However, this reduction was accompanied by increased drift accumulation at the mezzanine elevation.

From a structural response perspective, this behavior is significant because it suggests that mezzanine-floor implementation may partially redistribute lower-story deformation demand while simultaneously introducing localized deformation concentrations within the commercial story region. Such behavior may contribute to nonuniform seismic response characteristics and localized structural vulnerability under strong ground motion excitation.

These observations are consistent with previous studies reporting that mezzanine implementation and vertical stiffness discontinuities can substantially alter deformation distribution patterns in mixed-use RC buildings. The results therefore support the conclusion that mezzanine-floor implementation modifies the development of soft-story response characteristics by redistributing lateral deformation demands across multiple structural levels.

3.3 Torsional Irregularity Response

The torsional irregularity coefficients (η_{bi}) obtained for both structural configurations under the selected earthquake records are presented in Table 6, while the corresponding torsional response distributions are illustrated in Figure 7. According to TBEC-2018, torsional irregularity occurs when η_{bi} exceeds the limiting value of 1.20.

Table 6. Torsional irregularity coefficients (η_{bi}) obtained for the with-mezzanine and without-mezzanine models under the selected earthquake records in X and Y directions

Model		With Mezzanine Floor				Without Mezzanine Floor		
Story		Mezzanine	Story1	Story2	Story3	Story1	Story2	Story3
Elevation (m)		2.5	5	3	3	5	3	3
RSN6	X (η_{bi})	1.046	1.397	1.107	1.079	1.045	1.079	1.121
	Y (η_{bi})	1.282	1.277	1.224	1.22	1.044	1.069	1.105
RSN1176	X (η_{bi})	1.097	1.561	1.326	1.307	1.002	1.021	1.039
	Y (η_{bi})	1.096	1.099	1.086	1.104	1.151	1.162	1.173
RSN719	X (η_{bi})	1.047	1.336	1.078	1.087	1.017	1.058	1.103
	Y (η_{bi})	1.107	1.097	1.072	1.011	1.034	1.067	1.097
RSN1602	X (η_{bi})	1.043	1.374	1.038	1.018	1.094	1.100	1.097
	Y (η_{bi})	1.101	1.106	1.086	1.090	1.130	1.155	1.180
RSN821	X (η_{bi})	1.030	1.510	1.231	1.164	1.111	1.089	1.040
	Y (η_{bi})	1.251	1.258	1.251	1.248	1.120	1.106	1.096
RSN949	X (η_{bi})	1.018	1.487	1.186	1.177	1.062	1.089	1.124
	Y (η_{bi})	1.146	1.174	1.267	1.267	1.132	1.162	1.129
RSN1101	X (η_{bi})	1.061	1.500	1.165	1.171	1.022	1.031	1.040
	Y (η_{bi})	1.159	1.159	1.169	1.173	1.031	1.035	1.038
RSN1158	X (η_{bi})	1.025	1.472	1.204	1.192	1.043	1.043	1.042
	Y (η_{bi})	1.158	1.150	1.152	1.163	1.093	1.089	1.089
RSN1194	X (η_{bi})	1.086	1.507	1.262	1.219	1.039	1.044	1.046
	Y (η_{bi})	1.209	1.206	1.186	1.168	1.036	1.018	1.002
RSN2114	X (η_{bi})	1.218	1.586	1.349	1.299	1.293	1.294	1.294
	Y (η_{bi})	1.291	1.277	1.265	1.235	1.220	1.224	1.227
RSN1605	X (η_{bi})	1.078	1.403	1.141	1.101	1.036	1.031	1.025
	Y (η_{bi})	1.161	1.143	1.075	1.044	1.121	1.117	1.113

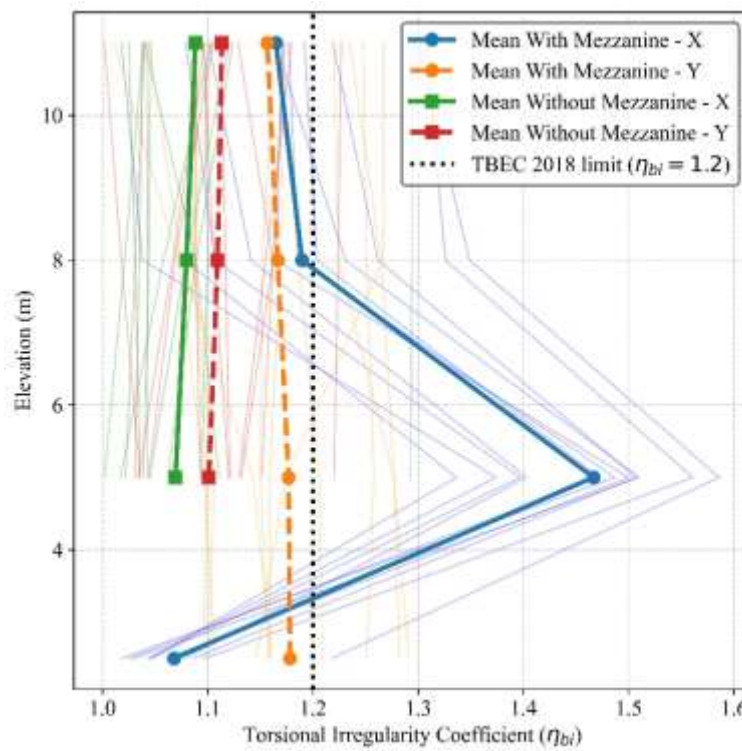


Figure 7. Torsional irregularity coefficient (η_{bi}) profiles for all earthquake records together with the mean response profile and the TBEC 2018 limit ($\eta_{bi} = 1.2$). Thin lines represent individual earthquake records, while thick lines denote the mean response profile

For the mezzanine-integrated configuration, the most critical torsional response consistently occurred at Story 1, where η_{bi} values significantly exceeded the code limitation under the majority of the selected ground motion records. In the X direction, peak torsional irregularity coefficients reached 1.586, 1.561, 1.510, and 1.507 under RSN2114, RSN1176, RSN821, and RSN1194, respectively. Similar exceedances were also observed in the Y direction, although with comparatively lower magnitudes. The concentration of torsional irregularity at the first-story level suggests that the mezzanine floor introduces substantial asymmetry in stiffness and mass distribution within the commercial story. Consequently, rotational response demand becomes amplified under lateral seismic excitation. By contrast, the reference configuration generally exhibited lower torsional irregularity coefficients in both principal directions. In the X direction, η_{bi} values remained relatively close to unity for most earthquake records, indicating a comparatively uniform lateral displacement distribution across the structural plan. However, localized exceedances were still observed under stronger ground motion records, particularly under RSN2114. The concentration of torsional irregularity at the lower-story level is consistent with the drift concentration patterns discussed in the previous section and confirms that the mezzanine configuration intensifies lower-story seismic vulnerability through the combined influence of soft-

story tendencies and torsional amplification effects. From a structural mechanics perspective, these findings indicate that the mezzanine floor acts as an internal discontinuity within the open commercial story, disrupting the uniform transfer of lateral seismic forces and producing localized stiffness imbalance. Such behavior is particularly critical in mixed-use RC buildings where the ground story already possesses reduced lateral stiffness due to architectural openness. Overall, the results demonstrate that mezzanine-floor implementation may substantially increase the likelihood of torsion-sensitive seismic response characteristics and localized deformation concentration within mixed-use RC building systems.

3.4. Story Stiffness Irregularity (Soft-Story) Response

The story stiffness irregularity coefficients (η_{ki}) obtained for both structural configurations are presented in Table 7, while the corresponding stiffness irregularity distributions are illustrated in Figure 8. According to TBEC-2018 provisions, a story is classified as exhibiting soft-story irregularity when η_{ki} exceeds the limiting value of 2.0. For the reference configuration, the most critical stiffness irregularity consistently occurred at the story immediately above the commercial ground story (Story 2 in the analytical model notation) in both principal directions. The corresponding η_{ki} values frequently approached or

exceeded the code limitation. Maximum values of 2.164 and 2.149 were obtained in the X and Y directions under RSN949 and RSN2114, respectively. This behavior indicates that the stiffness contrast between the flexible commercial ground story and the comparatively stiffer upper residential stories

becomes highly pronounced, resulting in significant vertical stiffness discontinuity within the lower structural levels. In the mezzanine-integrated configuration, the stiffness irregularity response became more complex due to the introduction of the intermediate mezzanine level. The

Table 7. Story stiffness irregularity coefficients (η_{ki}) obtained for both structural configurations under the selected earthquake records in X and Y directions

Model		With Mezzanine Floor				Without Mezzanine Floor		
Story		Mezzanine	Story 1	Story 2	Story 3	Story 1	Story 2	Story 3
Elevation (m)		2.5	5	3	3	5	3	3
RSN6	X (η_{ki})	0.859	0.860	1.879	–	1.725	2.145	–
	Y (η_{ki})	1.525	0.821	2.031	–	1.653	2.051	–
RSN1176	X (η_{ki})	0.715	0.986	1.200	–	1.661	2.074	–
	Y (η_{ki})	1.468	0.738	1.916	–	1.708	2.126	–
RSN719	X (η_{ki})	0.974	0.830	1.921	–	1.628	2.01	–
	Y (η_{ki})	1.495	0.763	1.891	–	1.678	2.088	–
RSN1602	X (η_{ki})	0.823	0.788	1.909	–	1.648	2.057	–
	Y (η_{ki})	1.454	0.725	1.946	–	1.680	2.085	–
RSN821	X (η_{ki})	0.675	0.958	1.860	–	1.672	2.042	–
	Y (η_{ki})	1.519	0.861	2.151	–	1.718	2.133	–
RSN949	X (η_{ki})	0.755	0.988	2.012	–	1.711	2.164	–
	Y (η_{ki})	1.444	0.766	1.935	–	1.720	2.013	–
RSN1101	X (η_{ki})	0.714	0.932	2.081	–	1.692	2.123	–
	Y (η_{ki})	1.451	0.719	1.951	–	1.681	2.098	–
RSN1158	X (η_{ki})	0.776	0.893	1.898	–	1.638	2.035	–
	Y (η_{ki})	1.454	0.735	2.053	–	1.649	2.044	–
RSN1194	X (η_{ki})	0.797	0.938	1.920	–	1.690	2.102	–
	Y (η_{ki})	1.465	0.768	1.984	–	1.618	2.009	–
RSN2114	X (η_{ki})	0.780	0.992	2.025	–	1.719	2.136	–
	Y (η_{ki})	1.467	0.789	1.902	–	1.731	2.149	–
RSN1605	X (η_{ki})	0.898	0.849	1.882	–	1.671	2.082	–
	Y (η_{ki})	1.448	0.719	1.868	–	1.696	2.117	–

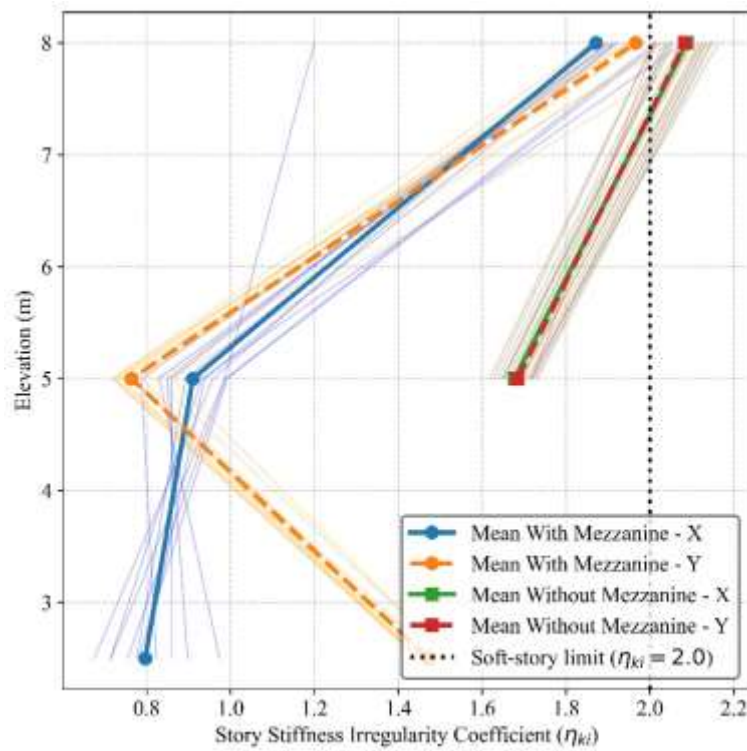


Figure 8. Soft-story irregularity profiles for all earthquake records together with the mean profile and the TBEC 2018 limit ($\eta_{ki} = 2.0$). Thin lines represent individual earthquake records, while thick lines denote the mean response profile

most critical irregularity remained concentrated near Story 2, where several records produced η_{ki} values approaching or exceeding the code limitation. The maximum value of 2.151 was observed under RSN821 in the Y direction. However, the mezzanine level and Story 1 generally exhibited comparatively lower stiffness irregularity coefficients. This behavior indicates that the mezzanine floor partially redistributes the vertical stiffness transition across multiple levels rather than concentrating the stiffness discontinuity exclusively at the original ground-story level. A key observation is that although the mezzanine floor does not eliminate soft-story tendencies, it alters both the severity and vertical location of stiffness irregularity within the structure. While the abrupt stiffness contrast at the original first-story level becomes partially reduced, an additional intermediate stiffness transition is simultaneously introduced within the commercial story region. From a structural mechanics perspective, the mezzanine floor therefore acts as an intermediate stiffness-modifying component that redistributes, rather than eliminates,

stiffness irregularity effects. Consequently, localized irregular seismic response characteristics may still develop within the lower-story region. These findings confirm that mezzanine-floor implementation significantly influences the formation and distribution of soft-story response characteristics in low-rise mixed-use RC buildings.

3.5. Base Shear Force Response

The peak base shear forces obtained from the linear time-history analyses in both principal directions are summarized in Table 8. Comparative variations in base shear demand between the two structural configurations are further illustrated in Figure 9. Overall, the mezzanine-integrated configuration generally exhibited reduced base shear demand in the X direction relative to the reference model. Among the selected earthquake records, nine records produced lower peak base shear forces in the mezzanine-integrated configuration.

Table 8. Comparison of peak base shear forces in the X and Y directions for the two structural configurations under the selected ground motion records

No	Ground motion event	With mezzanine F_X (kN)	Without mezzanine F_X (kN)	Change in F_X (%)	With mezzanine F_Y (kN)	Without mezzanine F_Y (kN)	Change in F_Y (%)
1	Imperial Valley-02	6187	6285	-1.56	6024	5592	7.72
2	Kocaeli	7478	8100	-7.68	6771	8636	-21.59

3	Superstition Hills-02	1987	1889	5.15	1569	1720	-8.78
4	Düzce	10454	11278	-7.30	16824	17292	-2.71
5	Erzincan	10933	11237	-2.71	11292	11077	1.94
6	Northridge-01	8747	9151	-4.42	7128	5791	23.09
7	Kobe	7769	8753	-11.25	12464	15792	-21.07
8	Kocaeli	6309	5840	8.03	9347	7582	23.27
9	Chi-Chi	4170	4215	-1.06	7140	4575	56.05
10	Denali	11851	12541	-5.50	7784	6675	16.62
11	Düzce	11819	12135	-2.61	15407	16493	-6.58

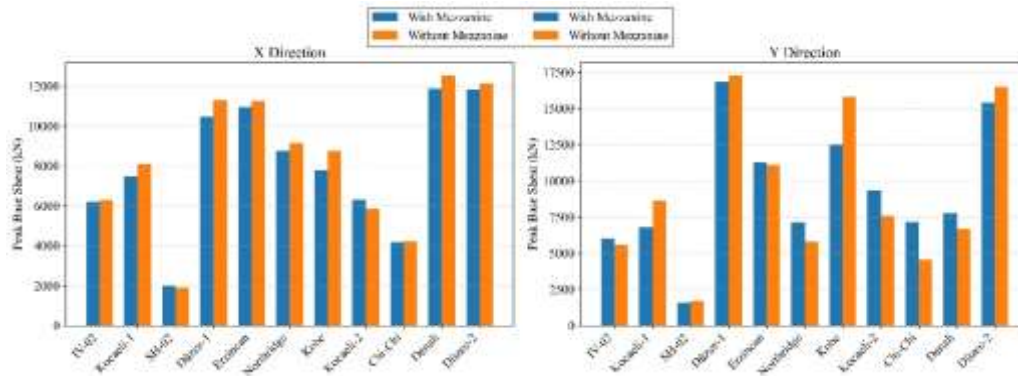


Figure 9. Comparison of peak base shear forces in the X and Y directions for the structural models with and without mezzanine floor under the selected ground motion records

The most significant reduction occurred under the Kobe earthquake record, where the peak base shear decreased by approximately 11.25%. Similar reductions were observed under the Kocaeli, Düzce, and Denali records.

In contrast, the Y-direction response exhibited more variable behavior. Although several records produced reduced base shear demand, substantial increases were observed under certain ground motions. The most significant increase occurred under the Chi-Chi earthquake record, where the peak base shear increased by approximately 56.05%.

These variations indicate that the influence of mezzanine-floor implementation on global force demand is highly dependent on excitation direction and ground-motion frequency characteristics.

From a structural dynamic perspective, the observed differences may be attributed to modifications in the vertical mass–stiffness distribution and modal participation characteristics caused by the mezzanine floor. The introduction of the intermediate mezzanine level alters the internal force-transfer mechanism within the commercial story and consequently changes the interaction between the structure and the imposed seismic excitation.

Importantly, reductions in global base shear demand should not be interpreted as direct indicators of improved seismic performance. As demonstrated in the preceding sections, the mezzanine-integrated configuration simultaneously exhibited increased

torsional irregularity and localized drift concentration at lower structural levels.

This observation highlights that reductions in global force demand may occur concurrently with amplification of localized deformation demand and torsional response irregularities. Therefore, global force-based response parameters should be evaluated together with local deformation-based indicators when assessing the seismic response characteristics of irregular mixed-use RC buildings.

3.6 Maximum Roof Displacement Response

The maximum roof displacements obtained from the linear time-history analyses for both structural configurations are summarized in **Table 9**, while the comparative displacement response trends are illustrated in **Figure 10**. For the X-direction response, the mezzanine-integrated configuration exhibited mixed displacement trends relative to the reference model. Moderate displacement increases were observed under several earthquake records, whereas reductions were obtained under others.

The most significant reductions in X-direction roof displacement were observed under the Düzce, Kobe and Denali earthquake records. Conversely, increases were observed under selected records including Kocaeli and Erzincan.

In the Y-direction, the mezzanine-integrated configuration generally exhibited reduced roof displacement demand for most earthquake records.

Significant reductions were observed under the Kobe, Kocaeli, Erzincan, and Düzce records. However, localized displacement increases were also recorded under certain motions, particularly under the Chi-Chi and Northridge-01 records. This behavior indicates that roof displacement response remains strongly dependent on the frequency content and directional characteristics of the selected earthquake excitation.

From a global response perspective, the results indicate that mezzanine-floor implementation modifies the lateral deformation characteristics of the structure by altering the vertical stiffness distribution and modal participation behavior.

Nevertheless, reductions in maximum roof displacement should not be interpreted independently as indicators of improved structural seismic performance. Despite reductions in global displacement response under several records, the mezzanine-integrated configuration simultaneously exhibited increased torsional irregularity and localized drift concentration at lower structural levels. These findings demonstrate that global displacement-based response parameters must be evaluated together

with local deformation indicators, including inter-story drift ratios, torsional irregularity coefficients, and stiffness irregularity response, in order to achieve a comprehensive assessment of the seismic behavior of mezzanine-integrated RC mixed-use buildings.

Finally, it should be noted that the present study is limited to linear elastic time-history analyses and therefore does not explicitly capture nonlinear material degradation, strength deterioration, or collapse mechanisms that may develop under severe seismic excitation. Consequently, the findings should be interpreted as representative of relative changes in elastic seismic response associated with mezzanine-floor implementation rather than direct prediction of nonlinear collapse mechanisms, strength deterioration, or post-yield damage progression.

Overall, the findings demonstrate that mezzanine-floor implementation significantly modifies the seismic response characteristics of low-rise mixed-use RC buildings by altering stiffness distribution, modal behavior, deformation concentration patterns, and

Table 9. Comparison of maximum roof displacements in the X and Y directions for the two structural configurations under the selected ground motion records

No	Ground motion event	With mezzanine U_x (mm)	Without mezzanine U_x (mm)	Change in U_x (%)	With mezzanine U_y (mm)	Without mezzanine U_y (mm)	Change in U_y (%)
1	Imperial Valley-02	188.18	186.51	0.90	159.03	168.94	-5.86
2	Kocaeli	260.36	243.18	7.60	172.42	253.84	-32.07
3	Superstition Hills-02	53.72	59.04	-9.01	41.29	51.31	-19.53
4	Düzce	296.57	342.71	-13.46	425.88	520.23	-18.14
5	Erzincan	365.33	330.18	10.65	237.04	318.24	-25.51
6	Northridge-01	249.11	272.34	-8.53	209.86	172.01	22.01
7	Kobe	225.42	259.06	-12.98	308.08	468.26	-34.21
8	Kocaeli	218.86	176.76	23.82	245.01	226.77	8.04
9	Chi-Chi	129.83	124.42	4.34	183.84	137.19	34.01
10	Denali	312.56	363.84	-14.09	222.40	192.83	15.34
11	Düzce	314.27	359.30	-12.53	363.35	482.491	-24.69

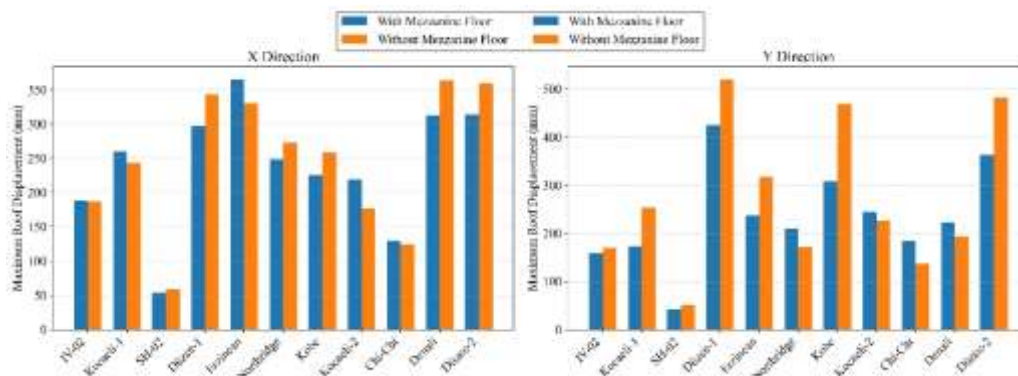


Figure 8. Comparison of maximum roof displacements in the X and Y directions for the structural models with and without mezzanine floor under the selected ground motion records

torsional response characteristics. Although the mezzanine-integrated configuration contributed to localized reduction in certain global response parameters under selected earthquake records, it simultaneously intensified torsional irregularity and redistributed deformation demand within the lower-story region. These results indicate that mezzanine-floor implementation may alter rather than eliminate soft-story vulnerabilities, thereby introducing complex irregular seismic response mechanisms that should be carefully considered in the seismic assessment and design of mixed-use RC building systems.

4. Conclusion

This study investigated the influence of mezzanine-floor implementation on the seismic response characteristics of a low-rise mixed-use reinforced concrete (RC) building with an open commercial ground story through a comparative analytical assessment of a reference structural configuration and a mezzanine-integrated configuration subjected to eleven earthquake ground motion records.

The results demonstrated that the introduction of the mezzanine floor significantly modified the global dynamic characteristics of the structure by increasing its overall lateral stiffness. The fundamental vibration period decreased from 0.544 s to 0.482 s, corresponding to an 11.4% reduction, while the second and third modal periods decreased by 13.4% and 15.6% respectively. These reductions indicate that the mezzanine level substantially alters the modal properties and dynamic seismic behavior of the building.

The deformation analyses revealed that the reference configuration exhibited pronounced soft-story behavior, with severe drift concentration at the first-story level, where peak inter-story drift ratios reached 0.237 in the Y direction and 0.169 in the X direction under selected earthquake records. In contrast, the mezzanine-integrated configuration redistributed deformation demand across both the mezzanine and first-story levels, indicating that the mezzanine floor modifies the vertical distribution of seismic demand rather than eliminating soft-story response mechanisms.

A critical finding of the study is the significant amplification of torsional response associated with the mezzanine-integrated configuration. The torsional irregularity coefficient reached a maximum value of 1.586 in the X direction, substantially exceeding the TBEC-2018 limit value of 1.20. This response suggests that the mezzanine floor introduces localized stiffness and mass asymmetry within the commercial story region, thereby

increasing the susceptibility of the structure to torsion-sensitivity seismic behavior.

Although the mezzanine-integrated configuration generally reduced certain global response parameters, including base shear demand for 9 out of 11 earthquake records and roof displacement demand by up to 34.21% under selected ground motions, these reductions did not necessarily correspond to improved seismic performance. The simultaneous increase in torsional irregularity and localized deformation concentration indicates that reductions in global force-based response parameters may coexist with increased local structural vulnerability.

Overall, the findings demonstrate that mezzanine-floor implementation alters rather than eliminates seismic vulnerability in open-ground-story mixed-use RC buildings by redistributing stiffness discontinuities and deformation demands while simultaneously amplifying torsional response effects. The results further highlight the importance of evaluating both global and local seismic response indicators, particularly inter-story drift concentration, torsional irregularity, and stiffness discontinuity, in the seismic assessment and design of mezzanine-integrated RC building system.

Finally, it should be noted that the present study was limited to linear elastic time-history analyses and therefore does not explicitly capture nonlinear material degradation, strength deterioration, or collapse mechanisms under severe seismic loading. Future studies incorporating nonlinear analytical procedures and experimental validation are recommended to further investigate damage concentration, post-yield behavior, and collapse vulnerability in mezzanine-integrated mixed-use RC buildings.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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