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Research Article

Impact of composite columns on soft and weak storey irregularities in buildings without ground floor infill walls

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ABSTRACT

In buildings without infill walls on the ground floor, structural irregularities, such as soft and weak storey irregularities can significantly reduce their resilience to earthquakes. These irregularities arise from insufficient lateral stiffness and strength in the ground floor structure, leading to instability during seismic events. This study investigated the seismic performance of frame structures, focusing on two key factors: the lateral rigidity provided by infill walls and the potential benefits of replacing conventional columns with composite columns on the ground floor. The analysis was conducted in accordance with the Turkish Building Earthquake Code 2018 (TBEC-2018), which provides specific guidelines for designing structures to withstand seismic forces. The findings revealed that including the lateral rigidity of infill walls in the analysis increased the cracked cross-section's moment of inertia by 5%. While this addition enhanced the building's lateral load resistance, it also increased the rigidity irregularity coefficient by 33%, indicating a potential redistribution of seismic forces that could affect the overall stability. On the other hand, introducing composite columns on the ground floor helped reduce the rigidity irregularity coefficient by 20%, providing a more uniform response to lateral loads. However, this improvement came at the cost of a 29% increase in the strength irregularity coefficient, highlighting the challenges in balancing stiffness and strength irregularities. These findings emphasize the importance of carefully evaluating structural modifications to optimize seismic performance. While composite columns are effective in mitigating rigidity irregularities, their impact on strength irregularities must be managed to avoid compromising overall safety.

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1. Introduction

Earthquakes pose a major risk to 71% of Türkiye's population and affect 66% of the country's land, with over 24,500 kilometers of active fault lines, including 15,000 kilometers along critical areas. This makes designing earthquake resistant buildings a top priority. One of the most common types of damage in earthquake prone areas is what's called soft storey or weak storey damage. This happens when the ground floor of a building is taller and lacks infill walls to make it more functional for commercial use, leading to more horizontal movement during an earthquake. As a result, the building's structural system can suffer significant damage (Fig. 1).

Soft storey buildings are especially vulnerable to collapse in seismic zones because the lower levels have much less rigidity compared to the floors above, causing damage to worsen (Shahsahebi et al. 2020). Design standards like ASCE/SEI 41-17 (2017) consider a storey to be "soft" if its lateral rigidity is less than 70% of the floor above or 80% of the building's average rigidity.

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For example, in the 1985 Mexico City earthquake, about 8% of building collapses were linked to soft storey issues, and 42% involved corner buildings with both soft storey and torsional irregularities (Meli 1986). Likewise, the 1995 Kobe earthquake caused extensive destruction in buildings with soft storeys (Watanabe 1997). In 2011 Van, Türkiye earthquake, 75% of the 225 buildings with soft storey issues either collapsed or were severely damaged, highlighting the vulnerability of structures with weak ground floors and large differences in rigidity between storeys (Van Earthquake Report 2011a).

Fig. 1. Heavily damaged buildings whose ground storey columns collapsed due to the soft storey in the Van earthquake (Van Earthquake Report 2011b).

To address soft and weak storey issues in buildings, the rigidity differences between floors need to be reduced. Composite columns, which combine steel and concrete, offer more rigidity than regular reinforced concrete columns because of the added strength from the steel. This makes composite columns a great option for the ground floor to help fix these irregularities. Research has shown the structural benefits of composite columns. For example, Yazdi et al. (2021) studied buildings using concrete-filled steel tube (CFT) columns and found that these columns significantly reduced the likelihood of collapse in low to medium seismic areas. This shows that designing multi-storey buildings with composite columns can greatly improve their safety and earthquake resistance. Solak and Orhan (2023) stated that concrete-filled steel composite columns are a type of steel–concrete composite member that combine the excellent compressive strength of concrete with the high tensile strength of steel, offering superior performance compared to conventional bare steel columns and reinforced concrete columns.

In addition to composite columns, researchers have developed several innovative methods to create more flexible soft storeys in buildings. These include using gapped-inclined braces (GIB), hexabraced systems, and mass dampers (like TMDs and GMDs), which have been studied by experts such as Sahoo (2013), Beigi et al. (2015), Hessabi and Mercan (2016), and Fakhouri and Igarashi (2021). These techniques offer new ways to enhance building resilience in earthquake prone areas.

However, these methods tend to be expensive and are more suitable for areas with high earthquake risks. This study aims to find a solution for regions with lower seismic activity by using more traditional steel-concrete composite elements and evaluating how well they can create a flexible, ductile soft storey to prevent the collapse of multi-storey buildings. One of the most commonly used elements is the concrete encased steel composite column (CES). These columns are crucial in medium and high-rise buildings because they provide high load-bearing capacity, strong lateral strength, and good flexibility under earthquake forces (Sakino et al. 2004; Zhang et al. 2018).

CES columns have been extensively studied through numerous studies examining their performance under various conditions, including axial loads and a combination of axial and lateral forces. For example, a study conducted by Şermet et al. (2021) analyzed the behavior of concrete-encased steel composite column-reinforced concrete beam elements under cyclic seismic forces. The results showed that the composite elements increased ductility and improved the lateral displacement capacity of the structure without significant strength loss, thus increasing its seismic resistance.

In recent years, several studies (Hashemi et al., 2017a, 2017b; Elkady and Lignos 2018) have investigated the collapse mechanisms of multi-storey buildings through large-scale tests under realistic loading scenarios. However, limited research has focused specifically on addressing soft storey irregularities caused by composite columns in medium to high-rise structures. The objective of this study is to determine whether using steel-embedded composite columns solely at the ground floor level can reduce the soft or weak storey irregularities commonly observed in reinforced concrete buildings. For this purpose, a structural system consisting of composite columns on the ground floor and regular reinforced concrete columns on the upper floors was modeled, and its behavior under lateral loads was analyzed.

The analysis varied the ground floor height by 300, 350, 400, 450, 500 and 550 cm and considered various structural scenarios. These included whether the ground floor columns were made of reinforced concrete or composite materials and whether infill walls were present in the upper storeys. This approach allowed us to examine both the effects of composite columns on soft and weak storey irregularities and to assess the structural response at different ground floor heights. A total of 24 different frame configurations were modeled and analyzed. The ultimate goal of the study is to identify how the use of composite columns in medium to high-rise reinforced concrete buildings influences soft and weak storey irregularities at the ground level, with the aim of proposing an effective solution to mitigate these structural irregularities based on the findings.

2. Materials and Method

Soft and weak floor irregularities are given as B1 and B2 vertical irregularities in the Turkish Building Earthquake Code (TBEC-2018) section 3.6.

2.1. Weak storey irregularity

TBEC-2018 defines a weak storey as one where the strength irregularity coefficient η_{ci} less than 0.80. This coefficient is determined by comparing the total effective shear area of a given storey to that of an upper storey in either of two perpendicular earthquake directions. The calculations for the Strength Irregularity Coefficient are based on Eqs. (1) and (2):

$$\eta_{ci} = (\sum A_e)_i / (\sum A_e)_{i+1} < 0.80 \quad (1)$$

$$(\sum A_e)_i = (\sum A_w)_i + \left(\sum A_g\right)_i + (0.15 \sum A_k)_i \quad (2)$$

Here;

ΣA_e = The effective shear area at any storey in the direction of the earthquake being analyzed [m^2].

ΣA_g = It is the total of the cross-sectional areas of the structural system elements that function as a shear wall in the direction aligned with the earthquake being analyzed at any given storey [m^2].

ΣA_k = The total area of masonry infill walls (excluding gaps for doors and windows) on any storey that is aligned with the earthquake direction [m^2].

ΣA_w = The column cross section at any storey is the total of the effective web areas [m^2].

If flexible joints exist between brittle infill walls and frame elements, facade elements are attached to outer frames with flexible connections, or if the infill wall element is separate from the frame, then $A_k = 0$ is selected.

Coefficient of strength irregularity, considering the storey with the lowest value;

a. In the event of $0.60 \le \eta_{ci} \le 0.80$ the Structural System Behavior Coefficient from TBEC-2018 Table 4.1 will be multiplied by 1.25(η_{ci})min and applied to all storeys of the building in the direction of both earthquakes.
b. $\eta_{ci} < 0.60$ will never exist.
c. If $\eta_{ci} < 0.60$, the earthquake calculation will be repeated by increasing the strength and rigidity of the weak storey.

2.2. Soft storey irregularity

According to TBEC-2018, a soft storey is identified by calculating the average storey drift ratio at any specified i_{th} storey, excluding basement levels, and dividing this by the average inter-storey drift ratio at a neighboring higher or lower storey, for either of two perpendicular earthquake directions. This assessment shows that the coefficient η_{ki} exceeds 2.0.

The Rigidity Irregularity Coefficient is calculated using Eqs. (3) or (4):

$$\eta_{ki} = \left(\Delta_i^{(x)}/h_i\right)_{\text{avg}} / \left(\Delta_{i+1}^{(x)}/h_{i+1}\right)_{\text{avg}} > 2.0 \quad (3)$$

$$\eta_{ki} = \left(\Delta_i^{(x)}/h_i\right)_{\text{avg}} / \left(\Delta_{i-1}^{(x)}/h_{i-1}\right)_{\text{avg}} > 2.0 \quad (4)$$

Here;

h_i = The storey height of the i_{th} storey of the building [m].

$\left(\Delta_i^{(x)}\right)_{\text{avg}}$ = Average reduced inter storey drift at the i_{th} storey of the building [m].

The relative storey drifts will be calculated using TBEC-2018 Section 4.7.

2.3. Analysis models

In this study, 2D models were created because they are less complicated and allow for quicker analysis. This makes the calculations and modeling processes much more manageable. When dealing with structures where infill walls are present only on the upper floors and not on the ground floor, using a 2D model provides an effective, simplified way to better understand the building's overall rigidity and how it would behave during an earthquake.

In the analyses, a detailed 2D frame model was developed, consisting of a ground floor designed as a soft storey beneath five standard upper storeys, as illustrated in Fig. 2. This configuration allowed for a focused examination of soft storey behavior, especially in relation to varying ground floor heights and their impact on structural irregularities.

The model was designed to evaluate the impact of varying ground floor heights on the overall behavior of the building frame. Six ground floor heights were tested: 300, 350, 400, 450, 500, and 550 cm, providing a range to analyze how increased heights influence the stability and flexibility of the structure. To ensure consistency, the height of each upper floor was fixed at 300 cm, allowing any observed performance differences to be directly linked to changes in the ground floor. The ground floor was modeled without infill walls to simulate the soft floor effect typical in designs requiring open spaces, such as parking areas or lobbies. In contrast, all upper floors, including balconies, were constructed with infill walls to represent typical multi-storey building conditions. These walls add rigidity to the upper floors, further highlighting the ground floor's flexibility and providing clear insights into how the structure responds to loads differently across its height. This configuration enables a focused analysis of how varying ground floor heights influence the building's performance under lateral forces like wind or earthquakes.

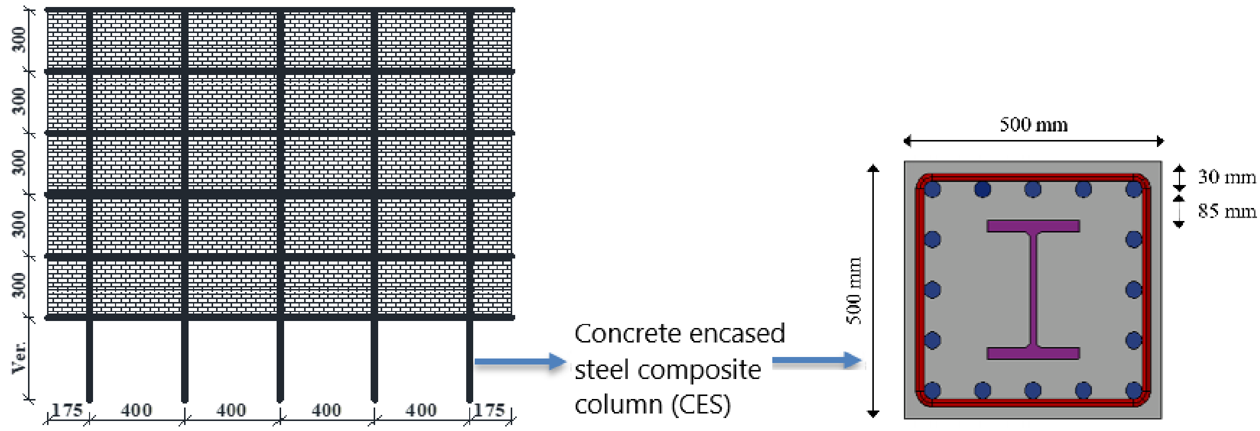

Fig. 2. Frame analysis model.

The model includes reinforced concrete columns sized 50x50cm and beams sized 25x50cm. For composite columns, the HE240M steel profile is used. The structural elements are made from C30/37 grade concrete and S275 grade steel, ensuring the model accurately represents commonly used construction materials. Pumice concrete blocks are used for the infill walls. The loading conditions are set as follows: a dead load (G) of 0.575 tf/m is applied to all beams, and live loads (Q) are set at 0.20 tf/m for interior beams and 0.50 tf/m for cantilever beams. The load from the infill walls is 0.35 tf/m.

The study explores six different ground floor heights 300, 350, 400, 450, 500, and 550 cm resulting in a total of 24 unique model variations. Table 1 summarizes the main features, groupings, and abbreviations for each of these models, making it easy to compare and understand their different configurations.

Table 1. Summary of the analyzed models.

No.	Ground storey height (cm)	Ground storey with RC. col. models	Ground storey with RC. col. and wall rigidities included	Ground storey with composite column models	Ground storey with C. col. and wall rigidities included
		Group 1	Group 2	Group 3	Group 4
1	300	B300C	B300D	C300C	C300D
2	350	B350C	B350D	C350C	C350D
3	400	B400C	B400D	C400C	C400D
4	450	B450C	B450D	C450C	C450D
5	500	B500C	B500D	C500C	C500D
6	550	B550C	B550D	C550C	C550D

2.4. Earthquake parameters and design information

The two-dimensional frame analysis uses specific earthquake parameters to assess the structural response to seismic forces. These earthquake parameters, detailed in Table 2, include essential factors such as the seismic zone, soil type, peak ground acceleration (PGA), and response modification factors. These factors are selected based on regional seismic standards to simulate realistic earthquake loading conditions that the building might experience. By applying these parameters, the model provides insights into how the structure's stiffness and stability would perform under potential earthquake scenarios.

Along with the earthquake parameters, the specific design details of the building's structural elements are outlined in Table 3. This table provides clear specifications for key features, such as material strengths, column and beam dimensions and reinforcement details. It also covers the layout of the structural system, including how beams connect to columns, the base of each column, and any special reinforcements added for better flexibility under stress.

These details help ensure that the model closely resembles real construction practices, leading to accurate and dependable simulation results that can guide structural assessments. Together, Tables 2 and 3 give a complete picture of both the earthquake forces the building is designed to withstand and the structural elements that help it do so. This combined information allows for a well-rounded evaluation of how the building would likely respond to seismic events.

Table 2. Earthquake parameters.

Building location			
Latitude	41.059128	Longitude	28.968130
Map spectral acceleration coefficients			
S_S	0.825	S_1	0.239
S_{DS}	0.990	S_{D1}	0.359
PGA	0.340	PGV	21.946

Table 3. Design information.

Building usage classification	3	Earthquake design class	1
Building importance level	1	Building height class	5
Seimic ground motion level	DD-2	Normal performance target	Controlled damage
Evaluation/design approach	Strength based design	Slab type	Beam slab
Ductility level	High	Rx/Dx	8/3
Diaphragm type	Rigid		
Ground class	ZC	Density of soil	2.10 tf /m^3
Bearing capacity of soil	20 tf /m^2	Coefficient of soil reaction	2,400 tf /m^3

2.5. Software

ideCAD Static is a comprehensive professional Structural BIM software specifically developed for modeling, finite element analysis, code-compliant design, performance evaluation and strengthening of structural systems. Earthquake loads were determined using ideCAD Static v.10.20, following the Equivalent Earthquake Load Method and the Linear Earthquake Calculation principles outlined in Section 4.7 of TBEC-2018.

CSiCol is a comprehensive software package used for the analysis and design of columns, effectively addressing the design of columns in any type of concrete, reinforced concrete or composite sections. CsiCol was used to determine the composite column sections.

2.6. Method for calculating wall rigidity

It has been observed that infill walls significantly increase the rigidity of the structure and cause a noticeable reduction in the building period (Zengin 2021). In this study, the infill walls are not represented in the analytical model as an equivalent diagonal strut with hinged ends, as is commonly done in the literature. Instead, a more practical approach is taken by mathematically incorporating them into the effective lateral rigidity of the storey through the use of moments of inertia and modulus of elasticity. Macro modelling of infill walls with equivalent struts can be seen in Fig. 3.

TBEC-2018 does not consider the rigidity of infill walls when assessing soft storey irregularities. However, it is evident that rigidly connected infill walls, which account for 15% of the strength in weak storey calculations, will still influence soft storey irregularity to some extent based on their stiffness. Therefore, in the calculations for soft storey irregularities, the rigidity of the infill walls is set at 5% instead of 15%, reflecting a value equivalent to the moment of inertia of the cracked cross-section (Tezcan et al. 2007). The modulus of elasticity for the walls was determined using Eq. 5, developed with the FlatJack Method (Ulukaya and Yüzer 2017).

$$E_w = 0.11.E_h^{1.35}.E_t/(1.84.E_h + E_t) \quad (5)$$

Here;
E_h = The elasticity modulus of the mortar [MPa].
E_t = Wall elasticity modulus [tf /cm^2].

The modulus of elasticity for the wall binder mortar was determined using Equation 12.1 from the Regulation on Design, Calculation, and Construction Principles of Steel Structures (TSC). The elasticity formula for masonry mortar is presented in Eq. (6).

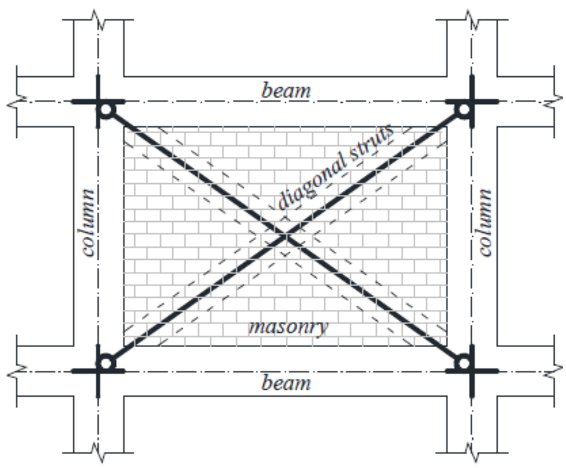

Fig. 3. Macro modelling of infill walls with equivalent struts (Lima and Martinelli 2014).

$$E_c = 0.043.w_c^{1.5}.\sqrt{f_{ck}} \quad (6)$$

Here;
w_c = The density of the mortar [kg /m³].
f_{ck} = Characteristic compressive strength of the mortar [MPa].

The modulus of elasticity (E_t) for pumice concrete block infill walls is determined to be 70 tf/cm^2, with the characteristic strength of the mortar at 8 MPa and a density of 2,000 kg/m^3. According to TBEC-2018, the effective bending rigidity factor for the walls was accepted as 0.50, as indicated in Table 4.2. The effective lateral drift rigidity of the walls (k_w) was calculated using Eq. (7), excluding the lateral drift rigidity of the walls on the cantilever beams.

$$k_{wx} = (12.E_w.I_{wx})/h^3 \quad (7)$$

2.7. Composite column design approach

For this study, CES composite columns was chosen, where a steel section is surrounded by reinforced concrete, are extensively used as key load-bearing components in high-rise structures. In accordance with TSC Section 12.3.1.5(a), the distance between the steel core and the nearest longitudinal rebar must be at least 1.5 times the diameter of the rebar and no less than 40 mm. The HEM240 profile, which has the largest cross-section meeting these criteria, was selected.

When determining the material properties of the composite column, the modulus of elasticity was calculated based on the Poisson ratio and the unit weight ratios of concrete and steel. The effective cross-sectional areas were then derived from the ratio of the elastic modulus using Eqs. (8–11).

$$E_{comp} = E_c.V_c + E_s.V_s \quad (8)$$

$$\upsilon_{comp} = \upsilon_c.V_c + \upsilon_s.V_s \quad (9)$$

$$w_{comp} = w_c.V_c + w_s.V_s \quad (10)$$

$$A_{comp} = A_c - A_s + r_{Esc}.A_s \quad (11)$$

Here;
$E_{comp,c,s}$ = Elastic modulus of composite section, considering concrete and steel [tf /m²].
$\upsilon_{comp,c,s}$ = Poisson ratios of composite section, considering concrete and steel.
$w_{comp,c,s}$ = Density of composite section, considering concrete and steel [tf /m³].
$A_{comp,c,s}$ = Areas of composite section, considering concrete and steel [cm²].
$V_{c,s}$ = Concrete and steel volume ratios.
r_{Esc} = The ratio of the modulus of elasticity of steel to that of concrete.

The HE240M profile is placed within the reinforced concrete column, with its body aligned parallel to the frame direction (along the x direction). Material and cross-sectional properties were determined using the CSiCol v.10 program, minimizing reinforcement contributions. These values from CSiCol v.10 were then input into ideCAD Static v.10.20, where they were linearly analyzed using the equivalent earthquake load method. Earthquake loads were calculated, and irregularity assessments were conducted. The cross-section of the composite column is shown in Fig. 4, with its properties listed in Table 4.

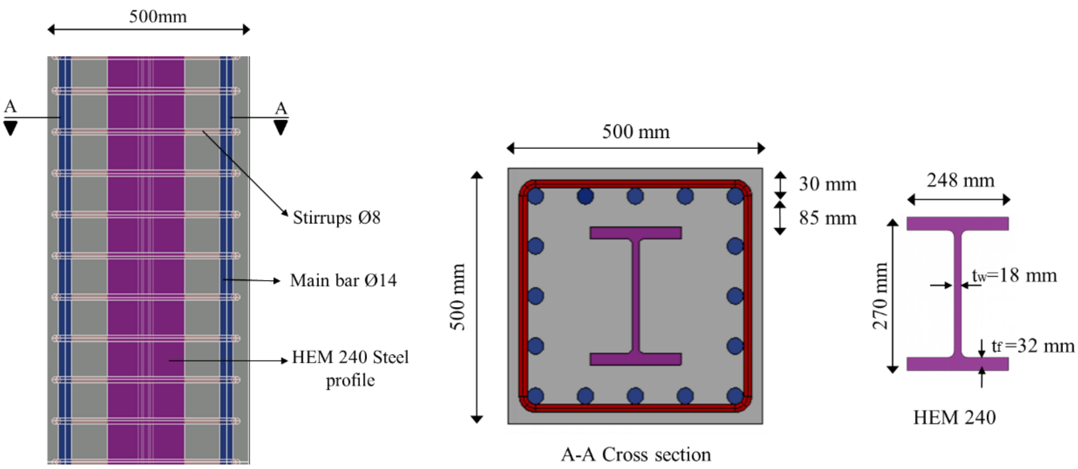

Fig. 4. Longitudinal and cross-section of the composite column.

Table 4. Properties of the composite column cross-section.

Modulus of elasticity (tf/m²)	4,544,000.00	Cross-sectional area (cm²)	3,573.85
Poisson's ratio	0.21	Shear area – SA_2 (cm²)	3,167.81
Density (tf/m³)	2.93	Shear area – SA_3 (cm²)	2,501.20
Moment of inertia – I_{22} (cm⁴)	651,418.10	Moment of inertia – I_{33} (cm⁴)	564,572.06

Note: Since the methods in this study are designed for buildings without infill walls on the ground floor, the irregularities in the storeys above the ground floor are not examined.

3. Results and Discussion

3.1. Soft storey irregularity controls

In models with reinforced concrete columns, increasing the height of the ground storey results in a decrease in column rigidity, which contributes to the formation of soft storey irregularities. As the ground storey height rises, columns become less rigid, making the structure more susceptible to lateral displacements during an earthquake. This reduction in rigidity can lead to soft storey behavior, a condition in which one storey is significantly more flexible than the others, affecting the building's overall stability. To quantify this effect, the soft storey irregularity coefficient (η_{ki}) was calculated for each storey using Eqs. (3) and (4), with results shown in Tables 5–12. The analysis of the 1st Group models, based on TBEC-2018 Section 3.6, initially focused on detecting these irregularities in the ground storey. According to these results, soft storey irregularities appeared in models with ground storey heights of 450 cm or greater, where columns reduced rigidity led to irregularity.

In Tables 5 and 6, soft storey irregularities are marked, with 'None' indicating no irregularities and 'Yes' indicating their presence. These findings illustrate the importance of controlling ground storey height to prevent soft storey conditions, as increased height directly impacts lateral rigidity and the building's earthquake resilience.

Table 5. Group 1 soft storey irregularity controls.

Storey No.	B300C			B350C			B400C		
	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control
5	–	0.48	None	–	0.48	None	–	0.48	None
4	2.07	0.71	Yes	2.07	0.71	Yes	2.07	0.70	Yes
3	1.41	0.82	None	1.42	0.82	None	1.42	0.81	None
2	1.22	0.89	None	1.22	0.89	None	1.23	0.89	None
1	1.12	0.95	None	1.12	0.69	None	1.13	0.53	None
Z	1.05	–	None	1.45	–	None	1.90	–	None

Table 6. Group 1 soft storey irregularity controls (continued).

Storey No.	B450C			B500C			B550C		
	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control
5	–	0.48	None	5	–	0.48	None	5	–
4	2.07	0.70	Yes	4	2.07	0.70	Yes	4	2.07
3	1.42	0.81	None	3	1.42	0.81	None	3	1.42
2	1.23	0.88	None	2	1.23	0.88	None	2	1.23
1	1.13	0.41	None	1	1.13	0.41	None	1	1.13
Z	2.43	–	Yes	Z	2.43	–	Yes	Z	2.43

The lateral drift rigidity of the wall, calculated as 85.28 tf/cm from the analysis, was incorporated into the effective drift rigidity of the ground storey in the second group of analysis models, as presented in Table 1. By adding this wall rigidity component, the models were then examined for soft storey irregularities, focusing on whether this added rigidity affected the ground storey's stability across varying heights.

Soft storey irregularities were identified in models with ground storey heights of 400 cm and above, indicating a noticeable impact of the wall's added rigidity on the structural behavior. Specifically, the inclusion of wall lateral drift rigidity led to an approximately 33% increase in the rigidity irregularity coefficient for the ground storeys across all tested heights, when compared to the results from the first group analysis models where wall rigidity was not accounted for.

A clear difference was observed between the two groups of models: in the first group, where wall stiffness was excluded, soft storey irregularities only began to appear at a ground storey height of 450 cm. However, in the second group, where wall stiffness was included in the calculations, these irregularities appeared at the lower height of 400 cm. This suggests that the added lateral drift rigidity from the walls amplified the stiffness irregularity coefficient, making the structure more prone to soft storey irregularities even at reduced ground storey heights.

These results, as shown in Tables 7 and 8, highlight the importance of considering wall rigidity in structural designs, as it plays a crucial role in the seismic performance and stability of buildings with varying ground storey heights.

Table 7. Group 2 soft storey irregularity controls.

Storey No.	B300C			B350C			B400C		
	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control
5	–	0.48	None	5	–	0.48	None	5	–
4	2.07	0.71	Yes	4	2.07	0.71	Yes	4	2.07
3	1.41	0.82	None	3	1.41	0.82	None	3	1.41
2	1.22	0.89	None	2	1.22	0.89	None	2	1.22
1	1.12	0.71	None	1	1.12	0.71	None	1	1.12
Z	1.40	–	None	Z	1.40	–	None	Z	1.40

Table 8. Group 2 soft storey irregularity controls (continued).

Storey No.	B450C			B500C			B550C		
	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control
5	–	0.48	None	5	–	0.48	None	5	–
4	2.07	0.70	Yes	4	2.07	0.70	Yes	4	2.07
3	1.42	0.81	None	3	1.42	0.81	None	3	1.42
2	1.23	0.88	None	2	1.23	0.88	None	2	1.23
1	1.13	0.31	None	1	1.13	0.31	None	1	1.13
Z	3.23	–	Yes	Z	3.23	–	Yes	Z	3.23

In the third group of analysis models (Table 1), the effect of using composite columns on the ground floor was investigated to assess their effectiveness in reducing the soft story irregularity. This assessment was based on the criteria outlined in Section 3.6 of TBEC-2018, which states that the wall lateral drift stiffness is not included in the analysis.

The results of the calculations indicated a significant improvement in structural performance; specifically, the stiffness irregularity coefficient for models featuring composite columns in the ground storey was found to be approximately 20% lower than that of the first group analysis models, which did not take wall lateral drift rigidity into account. This reduction suggests that the incorporation of composite columns enhances the overall stability of the structure by effectively addressing issues related to soft storey irregularity.

Further analysis revealed that the soft storey irregularity was particularly pronounced at a ground storey height of 500 cm. This finding emphasizes the importance of height considerations in structural design, particularly in seismic zones where soft storey irregularity can lead to significant vulnerabilities. The detailed results of this analysis, including comparative data and specific findings, are thoroughly documented in Tables 9 and 10, providing a comprehensive overview of the effectiveness of composite columns in reducing soft storey irregularity in the ground storey.

Overall, these findings contribute valuable insights into the design practices for tall structures, particularly in regions subject to seismic activity, highlighting the role of composite columns in enhancing structural integrity and performance.

Table 9. Group 3 soft storey irregularity controls.

Storey No.	B300C			B350C			B400C		
	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control	η_{ki}(+)	η_{ki}(-)	Control
5	–	0.48	None	5	–	0.48	None	5	–
4	2.07	0.71	Yes	4	2.07	0.71	Yes	4	2.07
3	1.41	0.82	None	3	1.41	0.82	None	3	1.41
2	1.22	0.89	None	2	1.22	0.89	None	2	1.22
1	1.12	1.18	None	1	1.12	1.18	None	1	1.12
Z	0.84	–	None	Z	0.84	–	None	Z	0.84

Table 10. Group 3 soft storey irregularity controls (continued).

Storey No.	B450C			B500C			B550C		
	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control
5	–	0.48	None	5	–	0.48	None	5	–
4	2.07	0.70	Yes	4	2.07	0.70	Yes	4	2.07
3	1.42	0.81	None	3	1.42	0.81	None	3	1.42
2	1.23	0.88	None	2	1.23	0.88	None	2	1.23
1	1.13	0.51	None	1	1.13	0.51	None	1	1.13
Z	1.95	–	None	Z	1.95	–	None	Z	1.95

In the fourth group analysis models, the calculations were re-conducted to incorporate both wall lateral drift rigidity and the integration of composite columns in the ground storey. This dual approach aimed to further enhance the structural performance by addressing two critical aspects of design: the rigidity provided by the walls against lateral drift and the strength characteristics of composite columns.

The results of this comprehensive analysis demonstrated a significant reduction in the stiffness irregularity coefficient, which decreased by approximately 20% compared to the second group analysis models. The second group had already included ground storey reinforced concrete columns along with wall lateral drift rigidities; thus, the additional benefits of using composite columns highlight their effectiveness in enhancing the overall stability and rigidity of the structure.

Soft storey irregularity was specifically noted at a ground storey height of 450 cm, indicating that while incorporating composite columns and wall lateral drift rigidity improved performance, certain height configurations still posed challenges related to soft storey irregularity. This observation underscores the importance of carefully considering storey heights during the design process, as variations can influence the structural response under lateral loads.

The detailed findings from this analysis are systematically presented in Tables 11 and 12, which provide a thorough breakdown of the numerical data and comparative results between the different model groups. These tables serve as a vital resource for understanding the implications of incorporating both composite columns and wall lateral drift rigidity in structural design, particularly in relation to mitigating soft storey irregularities.

Ultimately, the insights gained from this fourth group analysis contribute to the broader discourse on optimizing building design for resilience against lateral forces, such as those encountered during seismic events. The combination of composite columns with wall lateral drift rigidity emerges as a promising strategy for improving the performance of structures, especially in high-risk areas, and could inform future design standards and best practices in civil engineering.

Table 11. Group 4 soft storey irregularity controls.

Storey No.	B300C			B350C			B400C		
	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control
5	–	0.48	None	5	–	0.48	None	5	–
4	2.07	0.71	Yes	4	2.07	0.71	Yes	4	2.07
3	1.41	0.82	None	3	1.41	0.82	None	3	1.41
2	1.22	0.89	None	2	1.22	0.89	None	2	1.22
1	1.12	0.89	None	1	1.12	0.89	None	1	1.12
Z	1.12	–	None	Z	1.12	–	None	Z	1.12

Table 12. Group 4 soft storey irregularity controls (continued).

Storey No.	B450C			B500C			B550C		
	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control	$\eta_{ki}(+)$	$\eta_{ki}(-)$	Control
5	–	0.48	None	5	–	0.48	None	5	–
4	2.07	0.70	Yes	4	2.07	0.70	Yes	4	2.07
3	1.42	0.81	None	3	1.42	0.81	None	3	1.42
2	1.23	0.88	None	2	1.23	0.88	None	2	1.23
1	1.13	0.39	None	1	1.13	0.39	None	1	1.13
Z	2.59	–	Yes	Z	2.59	–	Yes	Z	2.59

3.2. Weak storey irregularity controls

In the analysis, the same data set was utilized to calculate both soft storey and weak storey irregularities. It's important to note, however, that according to the TBEC-2018 guidelines, ground storey heights are not considered when assessing weak storey irregularity. Instead, the evaluation focuses exclusively on the effective shear areas of the structural elements involved. This distinction highlights the different parameters that influence soft and weak storey irregularities in building design.

In this context, the benefits associated with the use of composite columns in ground storeys become particularly evident. The effective shearing area increases with the incorporation of composite columns due to the addition of structural steel profiles, which enhance the overall strength and stability of the building. As a result, the analytical models can be thoroughly examined based on whether the ground storey columns are made of reinforced concrete or composite materials, allowing for a clearer comparison of their respective performances.

The analysis revealed a noteworthy increase in the strength irregularity coefficient, calculated using Equation 1, when the ground storey columns were designed as composite. Specifically, this coefficient increased by approximately 29% when compared to models utilizing reinforced concrete columns. This substantial change caused the strength irregularity coefficient to rise from 0.66 to 0.85, ultimately surpassing the critical limit of 0.80 established by TBEC-2018. Such an increase in the coefficient indicates a significant shift in the structural behavior, suggesting that composite columns not only enhance the effective shearing area but also improve the overall load-carrying capacity of the ground storey.

The results of this analysis are comprehensively displayed in Table 13, which provides detailed numerical data and comparisons between the various models. This table serves as a valuable resource for understanding the implications of using composite columns in terms of both soft storey and weak storey irregularities.

Overall, these findings emphasize the importance of material choice in structural design, particularly in the context of enhancing shear capacity and addressing irregularities. The increase in the strength irregularity coefficient with the use of composite columns indicates that careful consideration of material properties and structural configurations can lead to improved resilience against lateral forces, such as those encountered during seismic events. This insight is crucial for informing best practices and design strategies in the field of civil engineering, particularly for buildings in areas susceptible to seismic activity.

Table 13. (a) Controls for weak storey irregularity in models with ground storey reinforced concrete columns; (b) Weak storey irregularity in models with composite columns in the ground storey.

Storey No.	Storey height (cm)	η_{ci}		Control	
		(a)	(b)	(a)	(b)
5	300	1.00	1.00	None	None
4	300	1.00	1.00	None	None
3	300	1.00	1.00	None	None
2	300	1.00	1.00	None	None
1	300	1.00	1.00	None	None
Z	Variable	0.66	0.85	Critical*	None

*For $0.60 \leq \eta_{ci} \leq 0.80$, the Structural System Behavior Coefficient given in Table 13, should be multiplied by the value of $1.25(\eta_{ci})$min and applied to the entire building in both earthquake directions.

3.3. Ground storey displacements

As the height of the ground floor increases, the observed displacements in both reinforced concrete and composite column models also rise significantly. This phenomenon can be attributed to the fact that greater heights lead to increased flexibility within the structure, resulting in larger displacements under lateral loads, such as those imposed by wind or seismic activity.

When comparing the two types of models, it is evident that reinforced concrete structures experience more displacement than those utilizing composite columns. This distinction suggests that composite columns enhance the overall rigidity of the structure, thereby effectively mitigating displacement. The differences in ground floor displacement become increasingly pronounced as the height of the ground floor rises. For instance, at a height of 300 cm, the displacement difference between the two models is measured at 0.97 cm. However, this disparity grows substantially as the height increases to 550 cm, where the difference reaches 3.88 cm (Table 14).

This growing divergence emphasizes the enhanced performance of composite columns in taller structures. The ability of composite columns to maintain lower displacement levels becomes increasingly critical as the structure's height increases, making them an effective solution for minimizing displacement in high-rise buildings. This characteristic is particularly advantageous in seismic zones, where excessive displacement can lead to structural failure or significant damage. Furthermore, the findings underscore the importance of considering column material selection when designing taller structures. The flexibility associated with increased height necessitates robust design strategies to ensure structural integrity and safety. Composite columns, with their superior rigidity and lower displacement characteristics, provide a viable alternative to traditional reinforced concrete columns, especially in applications where minimizing lateral movement is paramount.

In summary, the relationship between ground floor height and displacement highlights the significant role that column materials play in structural performance. As building heights continue to increase, the use of composite columns emerges as a preferred choice for engineers seeking to optimize structural rigidity and minimize displacement, thereby enhancing the overall safety and performance of tall buildings. This insight not only informs current design practices but also suggests pathways for future research and development in the field of civil engineering.

Table 14. Reduced ground storey displacements.

Ground storey height (cm)	Ground storey displacements (cm)		Difference in ground storey displacement (cm)
	Reinforced concrete models	Composite column models	
300	5.76	4.79	0.97
350	8.82	7.38	1.44
400	12.64	10.64	2.00
450	17.21	14.60	2.61
500	22.50	19.26	3.24
550	28.47	24.59	3.88

Fig.5 indicates that as the height of the ground floor increases, the structures become more flexible, which reduces the effectiveness of relative floor drift reduction. Buildings with shorter ground floors have a greater advantage in minimizing drift during earthquakes and exhibit higher reduction rates. In contrast, taller ground floors experience larger drifts, making drift reduction measures less effective.

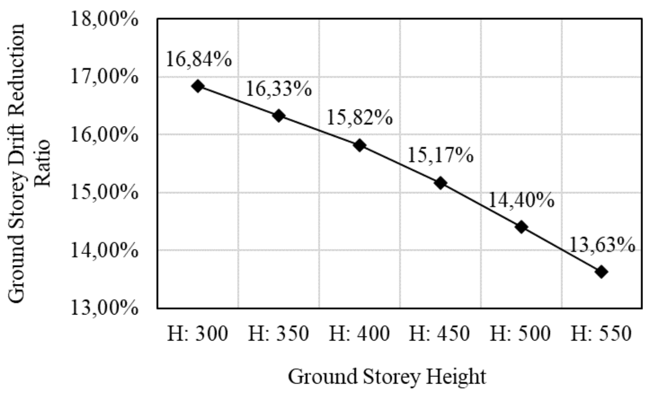

Fig. 5. The use of composite columns decreases the displacement rates of the ground floor.

4. Conclusions

This study looks at how adding wall rigidity impacts soft and weak storey irregularities in buildings without infill walls on the ground storey, and whether composite columns can help fix these problems. It finds that composite columns reduce stiffness differences and ground storey displacements, though longer columns lead to more displacements. Overall, using composite columns is a practical solution to prevent ground or soft storey collapses during earthquakes.

Although TBEC-2018 Information Annex 3A advises avoiding weak and soft storey configurations as much as possible, Section 3.6.2.1 states that A1 and B2 type irregularities only influence the choice of earthquake calculation method according to Section 4.6. As a result, soft storey irregularities are not considered in dynamic analyses. However, as demonstrated in the calculations, including the lateral drift rigidity of infill walls in mathematical calculations even using approximate methods significantly alters the results for soft storey irregularity. Therefore, earthquake codes should include procedures for incorporating wall rigidities into soft storey irregularity assessments. Composite columns in ground storeys can help prevent soft and weak storey issues in structures where infill walls are not used in the ground storey but are present in the upper storeys.

Finally, the impact of using composite columns solely in the ground storey on the selection of the building behavior coefficient and how this should be specifically addressed requires separate examination.

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Author Contributions

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Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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