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Evaluation and Comparison of the Seismic and Environmental Performance of Plane Trusses and Flat Space Frames: A Parametric Study on Soil and Climatic Influence

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Abstract: This study evaluates the analysis and design of two steel roof structures according to current practices in Turkey, including Eurocode 1 (2007) and the Turkish Building Earthquake Code of 2018 (TBEC 2018), with the aim of comparing the efficient roof system configuration from both a structural perspective and a structural behavior perspective. In this study, 8 structural models were examined, which investigated a combination of 2 different structural roof types, Plane Trusses (Type A) and Flat Space Frames (Type B), in two different climatic regions (Zone II and Zone IV), one seismic level, and two site classes (ZB and ZC). Structural modelling and analyses were analyzed and simulated using SAP2000 software. Calculations were carried out in accordance with the Turkish Steel Structures Design, Calculation and Construction Regulations (SDCCSS, 2016). The results indicate that the sensitivity of the structure to lateral loads is largely dependent on the classification of the lands and soil types, so that for type II lands, wind-induced displacements predominate, while for zone IV lands and site class (ZD), the behavior of the structure changes and becomes earthquake-oriented, with seismic displacements being predominant. Economically, Type A systems achieved the maximum weight for 20 m spans, and Type B systems recorded the minimum material consumption. Seismic displacements were recorded at higher levels for ZC site class, as well as for all models 2 and 4. This study shows that the choice of roof geometry significantly affects the total weight of the structure and consequently the cost of the project. The results of the analysis confirm that the performance of the Type B systems in limiting the lateral displacement in weak soils.

Keywords: Space truss system, Plane truss performance, Industrial buildings, Comparative analysis, Site class

Introduction

Roof structures are among the most significant structural members in buildings. They have a significant influence on load transfer. Recently, comparisons of plane trusses and space frames have attracted attention due to differences in seismic and environmental performance (Utami et al., 2025; Wang et al., 2025). Flat trusses, due to their simple structure, have been widely used in buildings. However, they have shown greater sensitivity to changes in soil conditions and seismic forces (Aydoğdu et al., 2023). On the other hand, space frames have shown better performance in buildings due to the use of multidimensional connecting members, which can help reduce material consumption (Utami et al., 2025). Studies have shown that the effects of optimization in design and material selection, including consideration of soil-structure interaction and climatic conditions, can significantly affect the final weight and stability of the structure (Prakash et al., 2024; Aydoğdu et al., 2023).

The use of optimization techniques such as Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) can lead to lighter, more robust structural systems (Carbas & Tunca, 2023). Furthermore, techniques such as curved-crease origami-inspired foldable nodes in space frames can lead to cost savings during construction and increased design flexibility (Lee et al., 2025). With regards to seismic activity and environmental sustainability in roof structure design, a parametric analysis of the effects of soil types and climate on plane trusses and space frames can provide a comprehensive guide to selecting the best possible structural system. This analysis is significant in modern engineering designs as it considers various loads and roof slopes (Baranyai, 2018; Cucuzza et al., 2023).

Method and Analysis

Structural Models and Design Parameters

In this study, we investigate the seismic and environmental performance of industrial buildings in Turkey under different environmental and seismic conditions, focusing on how soil and climate affect these structures. Eight computational models were developed to analyze two different steel roof systems. One is "Plane Trusses", a 2D truss structure used for sloping roofs (slope 11.31°) and the other is "Flat Space Frames", a 3D lattice structure. The dimensions of the buildings were considered constant as 42 m x 20 m x 8 m (length x width x height) and also two different climatic regions were selected with zone II in Tekirdag city and zone IV in Bursa city. The column bases were assumed fixed in the analyses and two soil profiles were considered for each model, including site classes ZB and ZC, which are equivalent to site classes D and C of the ASCE 7 code. A summary of the eight simulation scenarios is given in Table 1.

Table 1. General configuration and variables of the research models

Model ID	Roof System Type	Climate Region	Site Classes	Seismic Level (SDS)	Roof Slope (α)
A1	Plane Truss	II	ZB	SDS>0,75	11.31°
A2	Plane Truss	II	ZC	SDS>0,75	11.31°
A3	Plane Truss	IV	ZB	SDS>0,75	11.31°
A4	Plane Truss	IV	ZC	SDS>0,75	11.31°
B1	Space Frame	II	ZB	SDS>0,75	0.00°
B2	Space Frame	II	ZC	SDS>0,75	0.00°
B3	Space Frame	IV	ZB	SDS>0,75	0.00°
B4	Space Frame	IV	ZC	SDS>0,75	0.00°

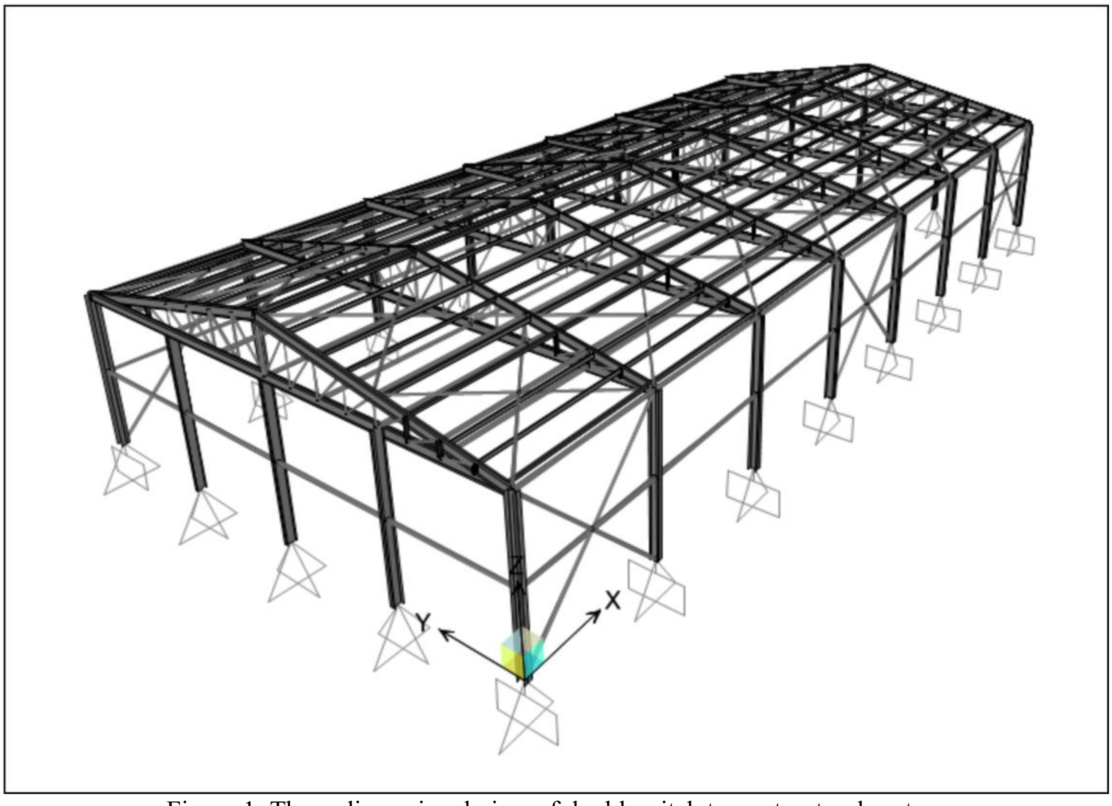

Figure 1. Three-dimensional view of double-pitch truss structural system

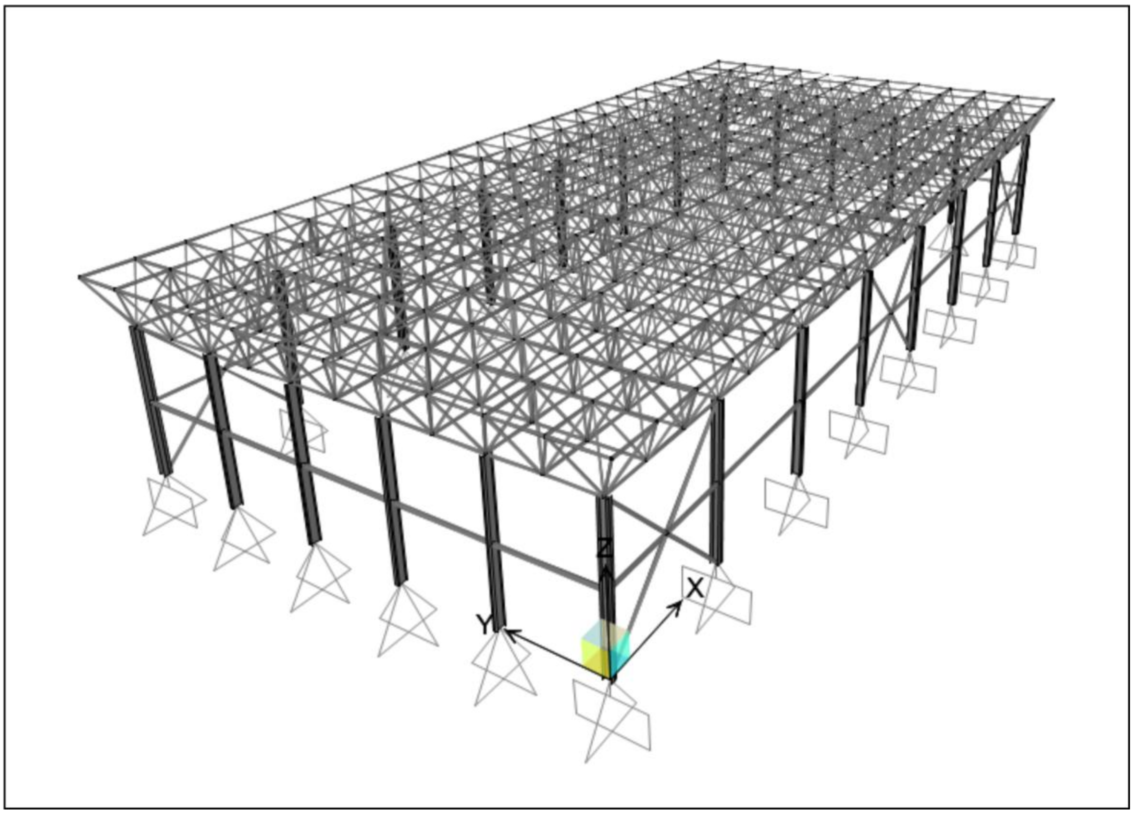

Figure 2. Three-dimensional view of the flat space frame system

Structural Modeling, Analysis, and Loading Conditions

In this study, geometric modeling and structural analyses were performed using SAP2000 software, considering linear material behavior for steel members. Gravity and wind loads were applied in accordance with Turkish Standard TS EN 1991-1-4 (Eurocode 1, 2007), and for seismic analyses, the Turkish Building Earthquake Code (TBEC, 2018) was used. The design of steel members was carried out according to the Turkish Specification for Design, Calculation and Construction of Steel Structures (SDCCSS, 2016) using the Load and Resistance Factor Design (LRFD) method. The main focus of this method is on the combination of loads and the safety factor for lateral loads and soil effects, which is aimed at investigating how soil and weather affect these structures. Since the purlins were modeled in the structure, the purlins load was not considered. A cladding load of 0.10 kN/m² was applied to the roof, and as dead load, cladding load and girt load, 0.30 kN/m2 was applied to the facade columns. Live loads were applied based on the intended use of the building and a temporary design load of 1.00 kN/m2 was applied. In order to consider the ambient temperature changes, thermal loads were applied to the structure. The structural members were designed considering temperature changes of ±20°C, which were considered to reflect the expected operational and climatic conditions.

In order to evaluate the structural response under snow loads, Bursa and Tekirdag were selected as sample industrial sites. Although these cities differe in altitude above sea level, they are classified to the same snow load category according to the Turkish Standard TS EN 1991-1-3 (Eurocode 1, 2007). Considering the roof slopes of 0° and 11.31°, the shape factor μ_i was taken as 0.8 according to TS EN 1991-1-4 (Eurocode 1, 2007). A summary of the parameters used for calculating the design snow load is given in Table 2, where the snow load was calculated using equation (1).

Table 2. Design parameters for snow load calculation based on TS EN 1991-1-4 (Eurocode 1, 2007)

Parameter	Symbol	Value
Characteristic ground snow load	S_k	0.75 kN/m^2
Snow shape coefficient	μ_i	0.80
Exposure coefficient	C_e	1.00
Thermal coefficient	C_t	1.00
Design Snow Load	S	0.60 kN/m^2

$$S = \mu_e \times C_e \times C_t \times S_k \tag{1}$$

Seismic Load Modeling and Analysis

The seismic design of the structure was carried out in accordance with the Turkish Building Earthquake Code (TBDY 2018) considering the seismic hazard level DD-2, which indicates a moderate earthquake hazard, which is approximately in line with the Design Base Earthquake (DBE) in ASCE 7 standards. Two site classes, ZB and ZC, which are equivalent to the two site classes D and C of the American Society of Civil Engineers ASCE 7 code. The main seismic design parameters and coefficients used in the structural system are summarized in Table 3 and Table 4. The analyses were performed using the modal combination method and the results were verified against the Equivalent Seismic Load Method. The classification of this building according to the Turkish Building Earthquake Code (TBDY 2018) is BKS-3 category with an importance factor I=1.0, which is equivalent to the American Society of Civil Engineers code ASCE 7 Risk Category II. The building height is 8 meters (HN), which is earthquake design category 2 (DTS 2) according to the code and falls within the height range of 7.0 ≤ HN < 10.5 meters. Accordingly, the building height category (BYS) is considered to be 7. Seismic parameters were determined in accordance with TBDY 2018 and the guidelines of the Turkish Steel Structure Design Code (SDCCSS-2016) were used for load combinations, modeling and analysis of steel members. In order to consider the nonlinear effects of the structure and its energy absorption capacity, seismic force reduction factor (R) and overstrength factor (D) were considered in accordance with SDCCSS-2016 for the X and Y directions. Vertical seismic effects ($E_d(Z)$) were included in the load combinations as recommended by the code.

Table 3. Seismic design parameters and structural response factors [20]

Description	Symbol	Value
Earthquake Ground Motion Level	-	DD-2
Local Soil Class	-	ZC
Short-period design spectral acceleration	SDS	1.003
1.0s period design spectral acceleration	SD1	0.342
Building Importance Factor	I	1.0
Seismic Design Category	DTS	1
Building Height Class	BYS	7
Response Modification Coefficient (X / Y)	R	5 / 8
Overstrength Factor (X / Y)	D	2 / 3

Table 4. Seismic design parameters and structural response factors [20]

Description	Symbol	Value
Earthquake Ground Motion Level	-	DD-2
Local Soil Class	-	ZD
Short-period design spectral acceleration	SDS	0.752
1.0s period design spectral acceleration	SD1	0.182
Building Importance Factor	I	1.0
Seismic Design Category	DTS	1
Building Height Class	BYS	7
Response Modification Coefficient (X / Y)	R	5 / 8
Overstrength Factor (X / Y)	D	2 / 3

Wind Load Modeling and Analysis

For all eight structural models, wind loads were determined according to TS EN 1991-1-4 (Eurocode 1, 2007). The peak velocity pressure (q_p) was Calculated to be 1.08 kN/m^2 for structures in Region II and 0.51 kN/m2 for Region IV, as shown in Table 5. The net wind pressure (W_{net}) on the surface of the structure was calculated using Formula 2. In this formula, $C_{p,net}$ represents the net pressure coefficient, and q_p represents the wind velocity pressure at height z. The surface of the wall and roof was divided into standard pressure zones A to E, and $C_{p,net}$ and branch dimensions of e/4 and e/10 were used to accurately determine the spatial change in wind suction and pressure. The external pressure coefficients (C_{pe}) were applied depending on roof geometries for pitched and flat roof systems. For the pitched roof models with a slope angle of 11.31°, the external pressure coefficients (C_{pe}) were determined for both wind directions (θ = 0° and θ = 90°), i.e., the two directions (X and Y) in accordance with TS EN 1991-1-4 (Eurocode 1, 2007). Since this regulation provides values for roof slopes of 5° and 15°, linear interpolation was used to obtain the coefficients for the actual roof angle. Due to the fluctuating nature of the wind, positive and negative pressure effects were considered. For the wind perpendicular to the overhang (θ = 0°), the roof was divided into four standard pressure zones (F to I), while for the wind direction parallel to the overhang (θ = 90°), the roof was divided into five main zones (F to G), all of which were mainly subjected to suction, and critical pressure values were observed near the edge zones (F and G). The peak velocity pressure (q_p) was significantly higher in zone II than in zone IV, indicating more severe wind effects in this region. For each direction, external pressure coefficients (C_{pe}) and internal pressure coefficients (C_{pi}) were considered. Internal pressure coefficients were calculated based on the size and distribution of openings in industrial structures to ensure that the combined effect of external suction and internal pressure on the roof and wall cladding is correctly accounted for in the structural analysis.

For flat roof models, external pressure coefficients ($C_{pe,10}$) were determined assuming sharp edges and the zoning parameter was defined by the formula e = min(b, 2h) which was calculated according to the structural information e = 16m.

$$W_{net} = q_p(z) \times (c_{pe} - c_{pi}) \tag{2}$$

Table 5. Summary of wind design parameters

Parameter	Symbol	Region II (A1-B2)	Region IV (A3-B4)
Basic wind velocity	v_b	28 m/s	28 m/s
Roughness factor	$c_r(z)$	0.96	0.49
Turbulence intensity	$I_v(z)$	0.2	0.48
Exposure coefficient	$c_e(z)$	2.21	1.04
Peak velocity pressure	$q_p(z)$	1.08 kN/m^2	0.51 kN/m^2

The selected cross-sections for all model A-1 and B1 are summarized in Tables 6.

Table 6. Sections for Models A-1 and B-1

Structural Element	Model A-1 Sections	Model B-1 Sections
Compression Pipe (Y)	CHCF139.7X5	CHCF139.7X5
Compression Pipe (X)	-	CHCF168.3X5
Roof Bracing	CHCF88.9X3.5	-
Facade Bracing	CHCF114.3X5	CHCF114.3X3.6
Main Column	HE280B	HE280B
Wind Column	IPE360	IPE360
Gable Post	HE100A	-
Truss Member	CHCF60.3X3.6	CHCF76.1X2.5
Roof Purlin	UPN120	-
Bottom Chord	IPE330 (Beam)	CHCF88.9X3.2
Top Chord	IPE330 (Beam)	CHCF88.9X3.2
Total Weight	56.48 tons	39.67 tons

Results and Discussion

Seismic Interstory Drift Analysis

As you can see in Figure 3, for two structural system models, namely Model A (plate truss) and Model B (space frame), the relative displacement index of the stories (Δ/h) in seismic zones II and IV and soil classes ZB and ZC in the critical Y direction has been compared. Based on the results we obtained, all configurations have fully complied with the 0.008 limit set by the TBDY-2018 regulations. Data analysis shows that, with the transition from seismic zone II to IV and the weakening of the site class from ZB to ZC, lateral displacement has increased in both models. Although in most cases, due to the higher rigidity of the space frame system, Model B has recorded less drift than Model A, in critical conditions IV-ZC, both Models A and B have approached the upper limits; So that Model A responded with a value of 0.0069 (86% of the allowable limit) and Model B responded with a value of 0.0063 (79% of the allowable limit). Therefore, the results obtained confirm that the space frame system provides greater lateral stability and a wider safety margin in softer soils and areas with high seismic risk.

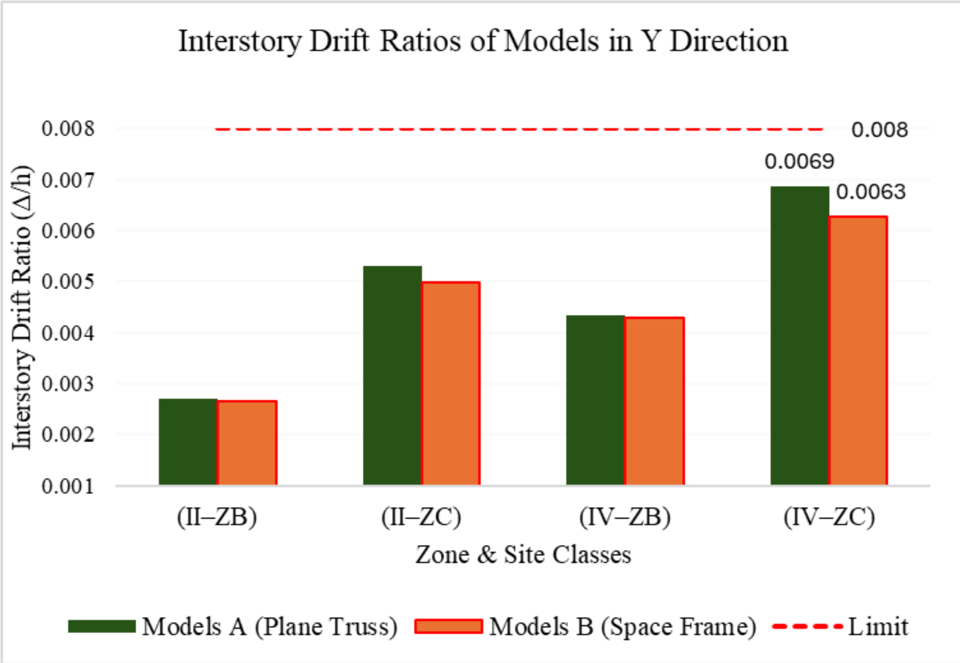

Figure 3. Interstory drift ratios of Models A & B in Y direction

Wind-Induced Structural Response

Figure 4 shows the lateral displacement values of columns under wind load for different models. Based on Chapter 15 of the SDCCSS–2016 regulation, the calculated displacement for all models is less than the permissible limit of h/150 (20 mm). The results show that all models under wind load are within the acceptable range for performance and occupant comfort. None of the columns exceeds the permissible displacement limit.

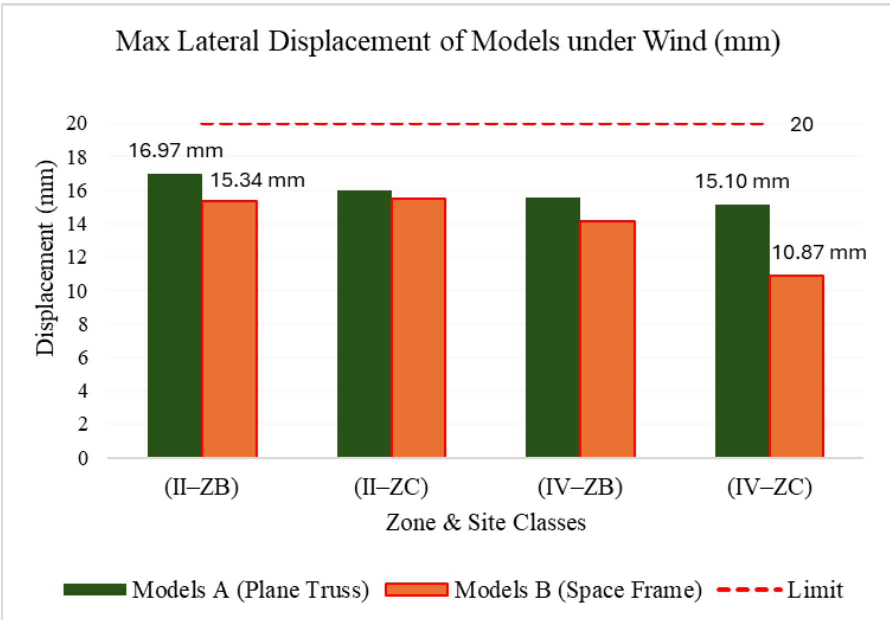

Figure 4. Wind-induced lateral displacement of Models A & B in Y-direction

Using the data in Table 7 and Equation 2 to examine the effect of structure type, we calculated the percentage reduction in lateral displacement when changing from model A to model B, which is:

$$\%\ Reduction = \frac{\delta_A - \delta_B}{\delta_A} \times 100 \quad (3)$$

The results, reported in Table 7, show significant effects on displacement reduction from changes in structure type, climate region, and site class.

Table 7. Percentage reduction in lateral displacement when switching from Plane Truss (Model A) to Space Frame (Model B) under wind load

Zone & Site Classes	% Reduction A → B
II–ZB	9.6%
II–ZC	3.0%
IV–ZB	8.9%
IV–ZC	28.0%

Effect of Climatic Regions on Structural Performance

As shown in Figures 5 and 6, in both models A and B, for cases A2 and B2, the wind-induced displacement is larger than the earthquake-induced displacement and controls the structural behavior due to the relatively high wind pressure in zone II (q_p = 1.08 kN/m^2). In contrast, in models A4 and B4, despite the wind pressure decreasing to 0.51 kN/m^2 in zone IV, the increase in seismic force intensity has led the earthquake-induced displacement (about 18.42 mm) to dominate as the critical design case. However, the displacement values in all models remain within the permissible limits set by the regulations.

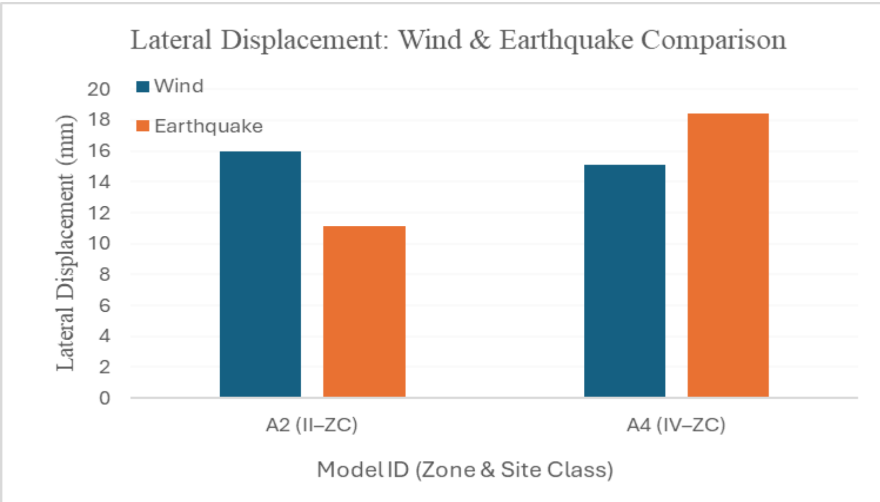

Figure 5. Comparison of wind and earthquake displacements for A2 and A4 models

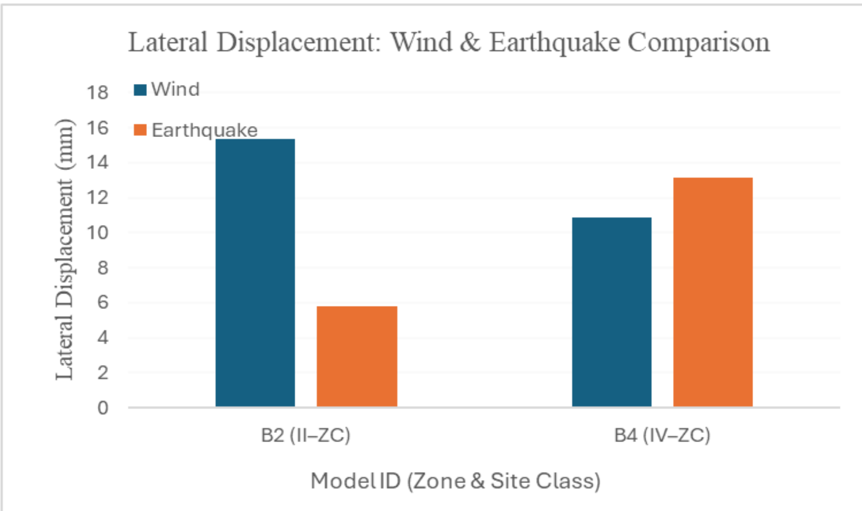

Figure 6. Comparison of wind and earthquake displacements for B2 and B4 model

Weight Comparison of Structural Models

Looking at the results extracted from the total weight of the models, a significant technical and economic advantage is seen in the B-type configurations; so that replacing the plate truss system (Model A) with a space frame (Model B) in all scenarios has led to a significant weight reduction of about 30%. For example, while Model A1 weighs 56.48 tons, Model B1, with the same application and dimensions, weighs only 39.67 tons. This significant weight difference, together with the earlier drift results, shows that the space frame system, due to its three-dimensional behavior, not only provides higher lateral stiffness but also greatly reduces steel consumption by optimally distributing forces within the members. Also, the relative stability of weight in all four climatic and seismic zones (A1 to A4) indicates that the design of sections in these mid-rise structures was mostly influenced by combinations of gravity loads and minimum regulatory requirements, and changes in seismic and wind parameters did not cause severe fluctuations in the total weight of the structure. A comparison of the total structural steel weight (tons) between the flat truss (Model A) and space frame (Model B) configurations is shown in Figure 7. The weights and percentage reduction are also shown in Table 8.

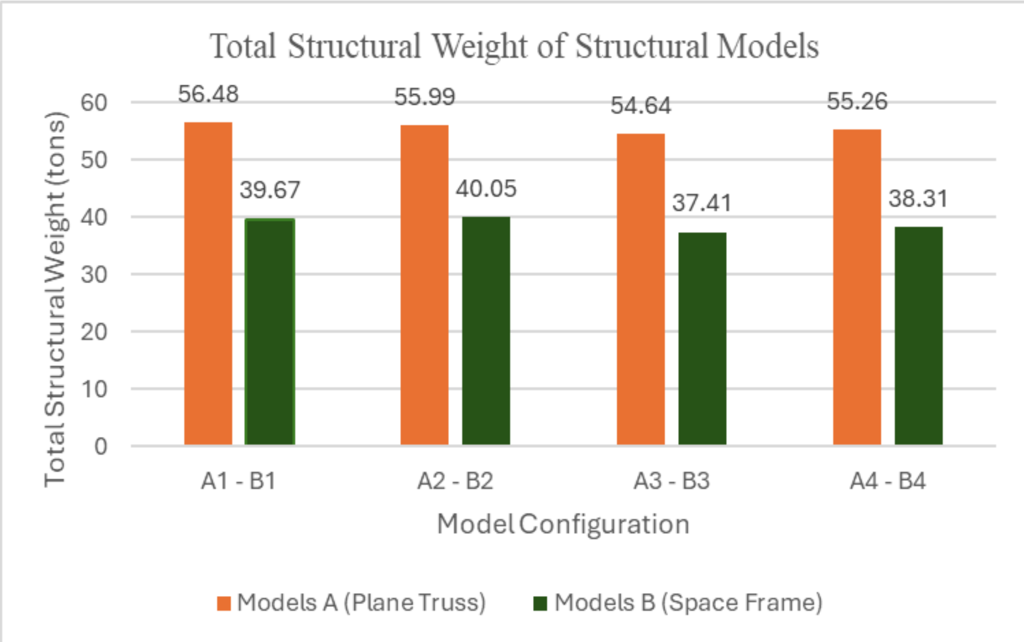

Figure 7. Comparison of total structural steel weight (tons) between Plane Truss (Model A) and Space Frame (Model B) configurations.

Table 8. Plane truss vs. Space frame: Weights and reduction percentages

Model ID	Plane Truss (A) (ton)	Space Frame (B) (ton)	Weight Reduction (%)
A1–B1	56.48	39.67	29.77%
A2–B2	55.99	40.05	28.47%
A3–B3	54.64	37.41	31.53%
A4–B4	55.26	38.31	1.04

Conclusion

In this study, the behavior of two structural systems, plate truss (Model A) and space frame (Model B), under wind and earthquake loads, was investigated under different conditions. The lateral displacement of all models under wind and earthquake loads was less than the code limit. Comparison of the models showed that the space frame performs better at controlling lateral displacement and, in some cases, achieves a significant reduction compared to the plate truss. Also, regional conditions showed a clear effect on the results. In region II, due to higher wind pressure, the wind effect was shown to be dominant in the models, while in region IV, with decreasing wind pressure and increasing earthquake effect, the seismic load plays a more decisive role. On the other hand, the soil type (site classes ZB and ZC) also affects the displacement and, in some cases, especially in the space frame model, reduces it. Overall, the results show that the choice of structural system and consideration of regional conditions can significantly affect the structure's behavior and displacement.

Recommendations

According to the results of this study, it is recommended to use a space frame system due to its performance in controlling lateral displacement, especially under wind loading conditions. Moreover, in designing structures, it is very significant to take into consideration the regional conditions and the classification of the soil, since these factors can affect structural behavior. As recommendations for future studies, it is suggested that the impact of other factors, such as the height of the structure, geometric irregularities, and nonlinear behavior, should be further investigated in order to have a more comprehensive understanding of the structural behavior.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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