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DETERMINATION OF FUNDAMENTAL TIME PERIOD OF BARE-FRAME BUILDING INCORPORATING NUMBER OF BAYS AND STOREY

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Abstract

The fundamental time period of a building plays a crucial role in determining the base shear during the seismic design of earthquake-resistant structures and is a vital parameter in modal analysis. For structural engineers, the basic knowledge of the fundamental time period is key for efficient and safe design of structures. There are various codes that give an empirical relationship to calculate the fundamental time period of buildings. All these relations are a function of height of the building. However, another influential parameter often overlooked is the number of bays, which directly affects both mass and stiffness, and consequently, the time period. In this study, the fundamental time period of buildings was analyzed incorporating height of building and number of storeys in x and y direction, and an empirical relationship incorporating these factors was created. Modal analysis was carried out in ETABS V17 where 81 models were created by varying storey from 1 to 9 and the number of bays from 2 to 4 in both directions. The storey height and bay spacing were taken as 3.5 m. A regular bare-frame building was analyzed without infill walls to isolate the effect of geometric parameters. Regression analysis was carried out for the time period obtained from the models to propose an empirical relation incorporating height of building and number of bays in both x and y direction using MATLAB code. The model yielded a coefficient of determination (R²) of 0.9902 and RMSE of 0.048 s, showing a strong correlation between predicted and analytical results. The obtained values were compared with empirical code-based expressions (NBC, Euro, IS) and showed deviations upto ±35%. This indicates that while height remains the dominant factor, inclusion of bay numbers improves accuracy, particularly for bare-frame structures. The study therefore provides empirical expression for fundamental time period of RC bare-frame buildings with number of bay and storey.

Keywords: Fundamental time period; Bare-frame building; Empirical relationship; Regular building; Number of bays

1. Introduction

In Seismic Design, one of the critical parameter is fundamental natural time period (T) of a building, which is the period of its first-mode free vibration. It influences the spectral acceleration demand, and the design base shear. Empirical formulas in seismic design codes commonly express T as a function of building height (H) or number of storeys (n), height-based relations in the form of:

$$T = C\,H^{a} \tag{1}$$

This has been widely adopted in international codes (Aninthaneni and Dhakal, 2017). Height is dominant because taller structures usually have lower lateral stiffness relative to mass, leading to longer periods (Ngab et al., 2021). However, research shows that other geometric and structural parameters—such as plan dimensions, number of bays/spans, infill stiffness, mass distribution and structural system type—also influence the fundamental period (Asteris et al., 2015, Yiğit et al., 2021). For instance, Yiğit et al. (2021) found that building width (or bay span) has an inverse correlation with T and that increasing width (or number of bays) tends to shorten the period due to increased lateral stiffness.

Goel and Chopra (1997), through regression analysis of building motion data recorded during eight California

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earthquakes between 1971 and 1994, developed refined empirical relationships for estimating the fundamental vibration period of moment-resisting frame (MRF) structures.The expressions are : For reinforced concrete MRFs :

$$T = 0.016\,H^{0.90} \tag{2}$$

For Steel MRFs :

$$T = 0.028\,H^{0.80} \tag{3}$$

Where H is the height of building taken in feet. Velani and Ramancharla (2017) conducted a significant study aimed at developing improved empirical formulas for estimating the fundamental natural period of tall reinforced concrete (RC) buildings in India and after conduacting ambient vibration tests on 21 RC buildings two new empirical formulas were proposed. For RC shear wall (SW) buildings:

$$T = 0.01\,H^{1.1} \tag{4}$$

For RC buildings above 20 storeys (60 m):

$$T = 0.09\,H^{1.1} \tag{5}$$

Where T is the fundamental period in seconds and H is the building height in meters. Ditommaso et al. (2013) studied 68 reinforced concrete buildings damaged in the 2009 L'Aquila earthquake and found, through ambient vibration tests, that code-based formulas greatly overestimate their fundamental periods. They proposed empirical relations based on regression analysis, such as:

$$T = \alpha\,H \tag{6}$$

More specifically for different damage levels spanning from 0 to 3 as lower to higher intensity.
For undamaged buildings, DL0-DL1,

$$T = 0.016\,H \tag{7}$$

For moderately damaged buildings, DL2-DL3,

$$T = 0.026\,H - 0.028\,H \tag{8}$$

Kose (2009), examined how certain factors such as building height, the number of bays, the ratio of shear wall area to floor area, the proportion of infilled panels to the total number of panels, and the type of frame impact structural performance. By applying a multiple linear regression model, the following equation was suggested:

$$\begin{aligned} T = 0.0935 + 0.0301\,H + 0.0156\,B + 0.0039\,F \\ - 0.1656S - 0.0232\,I \end{aligned} \tag{9}$$

Where, H = height of building in meters, B = number of bays F = frame type equals to 1 for frames with infills, 2 for frames with open first floor, 3 for bare frames. S = ratio in percentage of shear walls to total floor area I = area ratio of infill walls to total panels

Similarly, Bhuskade and Sagane (2017), conducted a comprehensive analytical study to investigate the effects of stiffness, mass, height, and column orientation. The study concluded that height-based empirical formulas alone may yield inaccurate or conservative estimates of the fundamental period, and that incorporating factors like base mass, stiffness distribution, and column orientation improves accuracy, especially for seismic design.

In the context of Nepal, empirical findings indicate that while building height remains the primary predictor of the period, the effect of base dimension or lateral dimension is small in multi-storey RC buildings (Shrestha and Karanjit, 2017). Their ambient vibration study of buildings in Kathmandu Valley found that simple height-only relations performed better than formulas including plan dimension. The period (T) and total building height (H) relationship obtained was of the form:

$$T = 0.012\,H^{1.134} \tag{10}$$

The relationship between the period, total building height, and base dimension (d) was found to be:

$$T = 0.03\,\frac{H^{0.94}}{d^{0.04}} \tag{11}$$

Rimal and Maskey (2019), studied how factors like storeys, bays, span length, and base dimensions affect the fundamental period of bare RC frame buildings in Nepal, beyond the height-based estimates in seismic codes. A total of 126 different fictitious RC frame buildings were modeled and through regression analysis revised empirical expressions are :

$$T = 0.084\,H^{0.82} \tag{12}$$

For height (H), base dimension (D), and bay number (B):

$$T = 0.030\,H^{0.82}\,D^{0.766}\,B^{-0.784} \tag{13}$$

Bhatt et al. (2019), investigated the influence of vertical mass and stiffness anomalies of infilled RC frame buildings on the fundamental period of infilled buildings through ETABS analysis of 6, 9, and 12 storey infilled buildings. The comparison was made of regular infilled frames, bare frames and irregular models per "IS 1893 (Part 1): Criteria for Earthquake Resistant Design of Structures — Part 1: General Provisions and Buildings", 2016. The time period of infill walls is also significantly reduced with additional stiffness. Generally, mass irregularity on upper storeys and stiffness irregularity on lower storeys are the most critical prolongation of the fundamental period,

Table 1. Fundamental time period provided by various building codes and research papers

IS, Eurocode & NBC (Codes)	$T = 0.075\,H^{0.75}$
Shrestha & Karanjit (2017)	$T = 0.012\,H^{1.134}$
Shrestha & Karanjit (2017)	$T = 0.03\,\dfrac{H^{0.94}}{d^{0.04}}$
Rimal & Maskey (2019)	$T = 0.084\,H^{0.82}$
Rimal & Maskey (2019)	$T = 0.030\,H^{0.82}\,D^{0.766}$
,	$B^{-0.784}$
Goel & Chopra (1997)	$T = 0.016\,H^{0.90}$

which affects seismic behavior. Despite this evidence, many building codes, including those used in Nepal("NBC 105: Nepal National Building Code, Part 5: Earthquake Resistant Design", 2020) still provide simplified period formulas based primarily on height, and rarely incorporate plan layout parameters such as number of bays explicitly (Masi and Vona, 2022). Considering that number of bays affects both mass and lateral stiffness through its influence on span length, column spacing and structural system redundancy, neglecting it may lead to less-accurate period predictions—especially in framed buildings without infill walls (bare-frame). Therefore, this study aims to determine the fundamental period of bare-frame buildings by explicitly incorporating both the number of storeys (height) and the number of bays (plan configuration). A parametric set of 81 models is developed, varying storey count from 1 to 9 and bay count from 2 to 4 in both principal directions. The outcomes are expected to contribute to more accurate estimation of the fundamental period during early design stages of moment-resisting bare-frame buildings, thereby improving seismic performance, safety and economy.

2. Methodology

2.1. Study Scope and Model Definitions

To evaluate the influence of both number of storeys and number of bays on the fundamental natural period (T) of bare frame buildings, a parametric modelling study was conducted. A total of 81 building configurations were developed by varying two key parameters:

- Number of storeys (n_s) ranging from 1 to 9.
- Number of bays in both X and Y directions (n_b) ranging from 2 to 4.
- All models assumed a uniform storey height of 3.5 m and bay spacing of 3.5 m in both principal directions. The buildings were modelled as reinforced concrete moment resisting bare frames (i.e., no infill walls) for consistency in isolating the effect of these geometric parameters on period with M25 grade concrete and Fe500 steel.
- The size of slab was kept of same thickness 125 mm.
- The columns were kept square with sizes 350 mm × 350 mm for storey 1 to 3, 400 mm × 400 mm for storey 3 to 6, and 500 mm × 500 mm for storey 6 to 9.
- Beam sizes were 250 mm × 355 mm for storey 1 to 3, 300 mm × 400 mm for storey 3 to 6, and 350 mm × 450 mm for storey 6 to 9.

2.2. Modelling and Software

The structural models were implemented in ETABS, a widely used finite element structural analysis package capable of modal/eigenvalue analysis. All models assumed rigid diaphragms at floor levels, fixed base supports, consistent material properties (e.g., concrete strength, steel reinforcement) and consistent section dimensions across models to isolate the effect of storey and bay variation. Similar modelling strategies (using modal analysis to determine the fundamental period) have been adopted in prior research (Aninthaneni and Dhakal, 2017, Shrestha and Karanjit, 2017). A representative diagram of bare-frame building as modeled in ETABS is shown in Figure 1.

2.3. Analysis Procedure

For each of the 81 models the following steps were carried out:

1. Definition of geometry (number of storeys, number of bays, uniform storey height, bay spacing).
2. Assignment of material and structural properties (e.g., concrete grade, steel grade, beam/column sizes) held constant across models.
3. Application of appropriate mass and stiffness definitions: Floor slabs treated with rigid diaphragm assumption; mass assigned to account for dead load only as per design code practice.
4. Execution of modal (Eigenvalue) analysis to determine the fundamental (first mode) period T_1. Modal participation and mass participation checks were performed to ensure the fundamental mode was meaningful for lateral response.
5. Extraction of T_1 for each model and compilation of data in tabular form to observe variations with ns and nb.
6. Comparative evaluation of the computed periods against empirical code based expressions (e.g., height based formulas) and regression analysis to derive a new empirical relation incorporating both ns and nb.

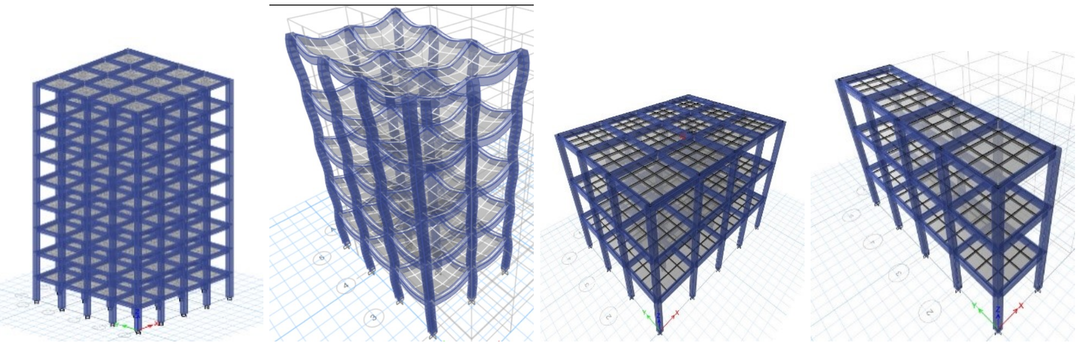

Figure 1. Typical 3D model of bare-frame building from ETABS for a) 9 storey 4x4 bays, b) 5 storey 2x3 bays, c) 3 storey 4x3 bays and d) 3 storey 4x1 bays

2.4. Regression and Empirical Relation Development

Following data extraction, regression analysis was conducted to quantify the relationship between T_1 and the independent variables (number of storeys and number of bays). A candidate functional form of the empirical equation was assumed in the form:

$$T = k \cdot (n_s)^a \cdot (n_{bx})^c \cdot (n_{by})^d \tag{14}$$

where k, a, c and d are regression constants to be determined. Multiple regression (log–log form) was used to estimate a, c and d, and the resulting model statistical strength (R², standard error) was assessed. Similar regression based approaches are documented in literature (Yiğit et al., 2021, Asteris et al., 2015) which show that plan dimension parameters (such as number of bays or width) can significantly improve period estimation accuracy.

2.5. Assumptions, Limitations and Sensitivity

- Bare frame condition: All models exclude masonry infill walls, acknowledging that infills increase stiffness and reduce period (Dhakal et al., 2020). Thus, results apply strictly to infill free frames.
- Uniform bay spacing and storey height: To isolate the direct effect of n_s, n_{bx} and n_{by}, these were held constant; hence results may not directly extend to varying storey heights or irregular bay sizes.
- Rigid diaphragm and fixed base: These assumptions simplify the model and may under represent soil foundation interaction or diaphragm flexibility effects, which could lengthen the period (Dhakal et al., 2020).
- Material properties constant: Variation in material (e.g., modulus of elasticity, cracking) was not considered, although these can influence period.
- Linear elastic modal analysis: Only the first mode period was recorded; higher modes, non linear behavior, or soil structure interaction was not accounted for.

3. Result and Discussion

3.1. Fundamental Periods of Parametric Models

The fundamental periods (T_1) of the 81 bare-frame models were obtained from modal analysis in ETABS. As expected, T_1 increases with number of storeys because taller structures have lower lateral stiffness relative to mass (Aninthaneni and Dhakal, 2017). For the same number of storeys, increasing the number of bays in X or Y direction slightly decreases the period due to increased lateral stiffness, consistent with findings by Yiğit et al. (2021). Table 1 presents the extracted periods. The discrepancy between modal time period and time period from proposed equation was +/-10%.

3.2. Regression Analysis and Proposed Empirical Relation

A multiple log–log regression was performed on the fundamental period data (T) obtained from 81 ETABS models by varying the number of storeys (n_s) and bays in both directions (n_{bx}, n_{by}). The best-fitting functional form was found to be:

$$T = 0.2017 \times (n_s)^{0.8269} \times (n_{bx})^{0.0275} \times (n_{by})^{0.0289} \tag{15}$$

The resulting coefficients of determination were $R^2_{\ln T} = 0.9902$ for the log-scale regression and $R^2_T = 0.9801$ on the linear scale, with an RMSE of 0.048 s. This high coefficient of determination demonstrates that the proposed relation reliably predicts the fundamental time period of bare-frame buildings using only geometric parameters. The exponent of n_s (0.827) indicates that the number of storeys, which directly reflects the height of the structure, is the dominant influencing parameter for the fundamental period. In contrast, the exponents associated with the number of bays in both X and Y directions (≈ 0.03) show relatively minor contributions, implying that lateral plan dimensions

Table 2. Fundamental period of models from modal analysis

h (m)	n_s	n_{bx}	n_{by}	T (s)	h (m)	n_s	n_{bx}	n_{by}	T (s)
3.5	1	4	4	0.211	17.5	5	3	2	0.840
3.5	1	4	3	0.208	17.5	5	2	4	0.852
3.5	1	4	2	0.202	17.5	5	2	3	0.840
3.5	1	3	4	0.208	17.5	5	2	2	0.820
3.5	1	3	3	0.203	21.0	6	4	4	1.030
3.5	1	3	2	0.198	21.0	6	4	3	0.999
3.5	1	2	4	0.202	21.0	6	4	2	1.032
3.5	1	2	3	0.198	21.0	6	3	4	1.031
3.5	1	2	2	0.191	21.0	6	3	3	1.000
7.0	2	4	4	0.398	21.0	6	3	2	1.019
7.0	2	4	3	0.394	21.0	6	2	4	1.032
7.0	2	4	2	0.387	21.0	6	2	3	1.019
7.0	2	3	4	0.394	21.0	6	2	2	0.995
7.0	2	3	3	0.387	24.5	7	4	4	0.979
7.0	2	3	2	0.380	24.5	7	4	3	0.987
7.0	2	2	4	0.387	24.5	7	4	2	1.002
7.0	2	2	3	0.380	24.5	7	3	4	0.987
7.0	2	2	2	0.355	24.5	7	3	3	0.975
10.5	3	4	4	0.586	24.5	7	3	2	0.990
10.5	3	4	3	0.582	24.5	7	2	4	1.002
10.5	3	4	2	0.574	24.5	7	2	3	0.990
10.5	3	3	4	0.582	24.5	7	2	2	0.970
10.5	3	3	3	0.573	28.0	8	4	4	1.128
10.5	3	3	2	0.566	28.0	8	4	3	1.139
10.5	3	2	4	0.574	28.0	8	4	2	1.160
10.5	3	2	3	0.566	28.0	8	3	4	1.139
10.5	3	2	2	0.551	28.0	8	3	3	1.125
14.0	4	4	4	0.678	28.0	8	3	2	1.147
14.0	4	4	3	0.677	28.0	8	2	4	1.160
14.0	4	4	2	0.674	28.0	8	2	3	1.147
14.0	4	3	4	0.677	28.0	8	2	2	1.124
14.0	4	3	3	0.667	31.5	9	4	4	1.279
14.0	4	3	2	0.664	31.5	9	4	3	1.293
14.0	4	2	4	0.674	31.5	9	4	2	1.320
14.0	4	2	3	0.664	31.5	9	3	4	1.293
14.0	4	2	2	0.647	31.5	9	3	3	1.278
17.5	5	4	4	0.854	31.5	9	3	2	1.306
17.5	5	4	3	0.853	31.5	9	2	4	1.320
17.5	5	4	2	0.852	31.5	9	2	3	1.306
17.5	5	3	4	0.853	31.5	9	2	2	1.280
17.5	5	3	3	0.841					

slightly increase the period when the number of bays increases. This weak dependence is consistent with the findings of Shrestha and Karanjit, 2017, who observed that height-based relations generally provide reliable estimates for Nepalese RC buildings, but plan parameters offer marginal refinement.

3.3. Comparison with Code-Based Relations and Research paper

For comparison, code-based formulas such as those from “NBC 105: Nepal National Building Code, Part 5: Earthquake Resistant Design”, 2020, “EN 1998-1: Eurocode 8 — Design of Structures for Earthquake Resistance — Part 1: General Rules, Seismic Actions and

Rules for Buildings", 2004,"IS 1893 (Part 1): Criteria for Earthquake Resistant Design of Structures — Part 1: General Provisions and Buildings", 2016, express the fundamental period primarily as a function of height (H) and when time period from derived relation was compared with above code error was found to be ± 35%. When comparison was made with time period obtained by Goel and Chopra, 1997 and Shrestha and Karanjit, 2017, similar result was obtained with discrepancy of ± 35%. Similarly, when compared with RRimal and Maskey, 2019, the discrepancy lowered to ± 20%.

3.4. Influence of Geometric Parameters

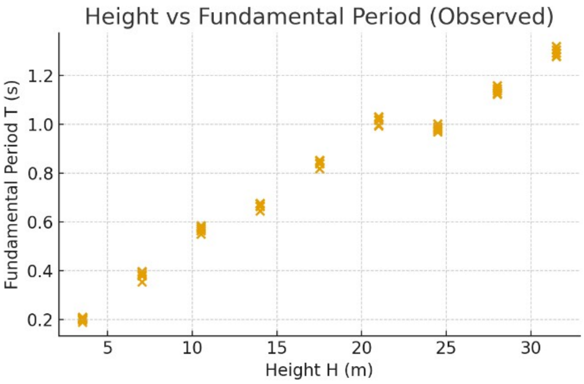

Figure 2. Relationship between building height (H) and fundamental time period (T). The fundamental period increases with height, showing near-linear dependence.

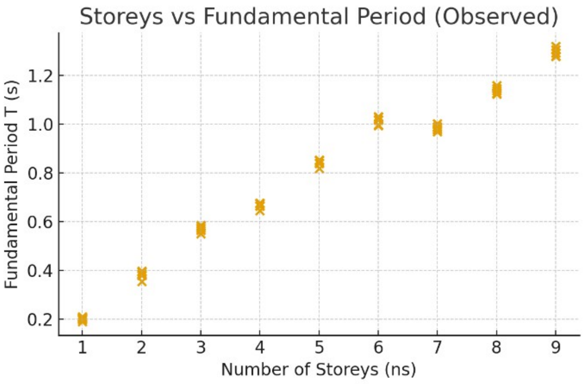

Figure 3. Variation of fundamental time period (T) with number of storeys (n_s). The trend confirms that taller buildings exhibit longer time periods.

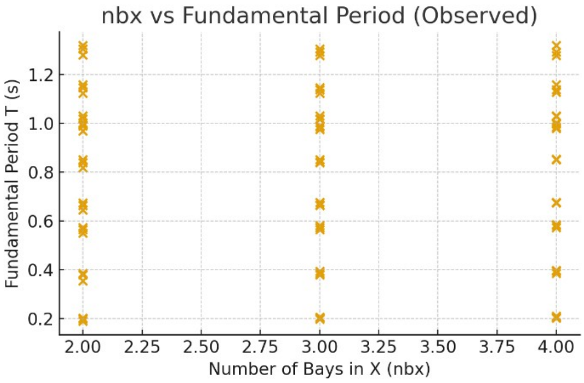

Figure 4. Effect of number of bays in X-direction (nbx) on fundamental time period. Increasing bays slightly increases T due to mass and flexibility effects.

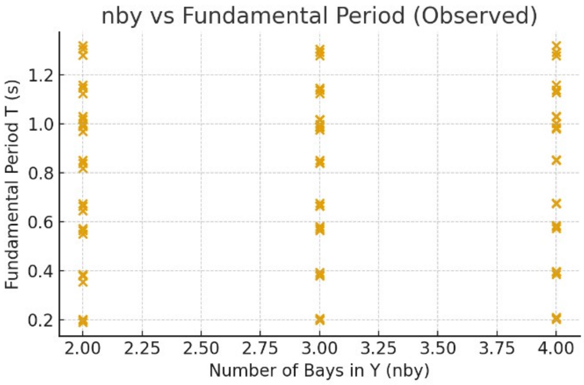

Figure 5. Effect of number of bays in Y-direction (nby) on fundamental time period. The influence is minor but consistent with structural stiffness behavior.

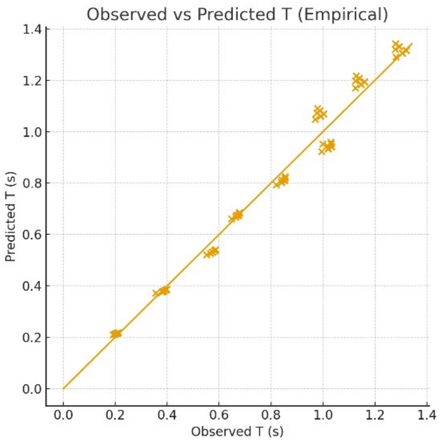

Figure 6. Comparison between observed and predicted fundamental time periods using the proposed empirical relation. A strong linear correlation ($R = 0.98$) is observed.

Figure 3 clearly illustrates that the fundamental period increases almost linearly with storey number, consistent with code trends and physical expectation: as height increases, stiffness decreases relative to mass. Figure 4 and Figure 5 show that varying the number of bays from 2 to 4 slightly increases T, attributed to increased total mass and

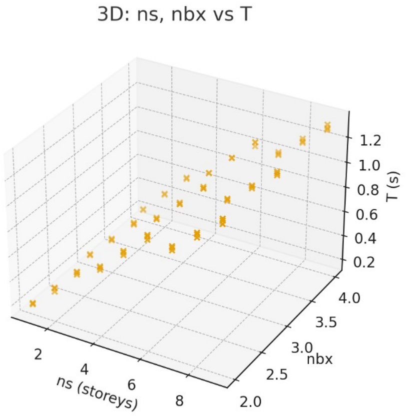

Figure 7. 3D plot showing the combined influence of number of storeys (n_s) and bays (nbx) on fundamental time period (T). The surface illustrates dominance of storey count.

flexible deformation across larger plan dimensions. The 3D surface plot (See Figure 7) further highlights that while the storey count dominates, the bay numbers contribute secondary adjustments.

3.5. Discussion

The results reaffirm that building height (or storey count) is the principal factor governing the fundamental period of moment-resisting RC frames. However, incorporating the number of bays modestly enhances prediction accuracy, particularly for bare-frame models where infill stiffness is absent. The small positive exponents of n_{bx} and n_{by} indicate that increasing the number of bays slightly lengthens the period—consistent with trends reported by Yiğit et al. (2021) and Asteris et al. (2015). The empirical model thus provides a practical balance between simplicity and accuracy. It can be implemented in preliminary design to estimate the time period without full modal analysis, particularly when code-based height-only formulas yield conservative estimates.

4. Conclusion

The study was able to establish that the basic time period of bare-frame RC buildings is mainly dependent on the number of storeys, which explains that building height is the most important variable that dictates seismic behavior.

- In both X and Y directions, addition of number of bays led to a small but significant increase in prediction accuracy, showing that plan configuration does contribute to the control of mass and stiffness distribution even in standard bare-frame buildings.
- The result of the empirical relation proposed through the regression analysis on 81 ETABS models has produced a high coefficient of determination ($R^2 = 0.99$) and low RMSE (= 0.048 s) which confirms the reliability of this empirical relationship in predicting time periods in preliminary design.
- Variation in the number of bays shows a noticeable effect on time period even at the same height. For instance, at 5 storeys (17.5 m), the period increases from about 0.82 s to 0.85 s as bays increase from 2×2 to 4×4, and at 7 storeys (24.5 m) it rises from roughly 0.97 s to 1.00 s. This confirms that increasing bay numbers slightly lengthens the time period due to added mass and flexibility.
- An increase in the number of bays resulted in a slight rise in the fundamental time period, attributed to increased mass and flexibility. Comparison with empirical expressions indicated that the proposed model deviates up to ±35% from code-based formulas, while the deviation reduces to approximately ±20% when compared with research-based models.
- The results were compared with existing code-based and research-based formulas to find out that height-based expressions are generally conservative on bare-frame structures, whereas the proposed model maintained the same discrepancy of up to 10% and this gave a refined and practical estimate of the rationality.

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