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Fundamental period equations for plan irregular moment-resisting frame buildings

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Abstract:
The fundamental natural period of oscillation is a critical parameter in evaluating the design base shear of buildings. Worldwide seismic design codes typically employ height-based empirical formulas to estimate this period for various building categories, without distinguishing between regular and irregular buildings. This study proposes a formula specifically for reinforced concrete (RC) moment-resisting frame (MRF) buildings with dominant re-entrant corner type plan irregularity. A total of 190 re-entrant corner dominant building models with different shapes (C-, L-, T-, and PLUS-type), heights, and floor configurations were prepared, and eigenvalue analysis (EVA) was conducted. The fundamental natural period of oscillation for each model was evaluated and compared with the height-based formulas from seismic design codes and the period–height relationship proposed in existing literature. A nonlinear regression model, using a multi-variable power function, is proposed to estimate the fundamental natural period for these re-entrant corner dominant building models. This model considers the A/L ratio in both directions of the building, along with its height. Both unconstrained and constrained regression analyses were performed to derive a formula that best fits the fundamental natural period data. The study recommends that the unconstrained best-fit minus one standard deviation curve can conservatively define the fundamental natural period of oscillation for re-entrant corner dominant RC building models. The equation defining this curve has the potential to replace the existing seismic design code-based period-height formula.

Keywords:
fundamental natural period; plan irregularity; re-entrant corner; regression analysis

1 Introduction

Earthquake ground motion comprises different frequencies, and it causes buildings to oscillate depending on their mass and stiffness distribution across the height. It is well known from the fundamentals of the dynamics of structures that when these frequencies are close to or equal to the fundamental frequencies of the buildings, the dynamic response of the building is amplified which leads to damage to the buildings. Therefore, estimating the fundamental natural period of oscillation (natural frequencies) of a building is crucial. The fundamental natural period of oscillation of a building can be estimated via eigenvalue analysis (EVA) of the mass and stiffness properties of the building under free vibration. However, this type of an analysis is tedious and time-consuming for buildings with a large number of degrees of freedom, and it requires computer programming. Rational simplifying assumptions aid in significantly reducing the number of degrees of freedom to a great extent for buildings that are regular, symmetric, and have a uniform mass distribution. The degrees of freedom of buildings with various types of irregularities cannot be reduced to a certain extent to capture their dynamic response characteristics.

Seismic design codes worldwide recommend using the fundamental EVA approach to determine the building's fundamental natural period of oscillation. However, they also propose an empirical formula for the natural period: (1) to provide a conservative estimate, ensuring higher lateral load estimation than exact analysis; (2) to offer a method easily accessible to designers for code-based lateral load estimation; (3) to accommodate a variety of building stocks; and (4) to simplify the procedure for estimating the fundamental natural period of oscillation. The seismic design code offers a generalized empirical formula, largely dependent on geometric parameters such as the building's height (h) or the height and base dimension (d). This formula can effectively estimate the fundamental natural period of oscillation for buildings that are symmetric, with uniform mass and stiffness distributions, and can be modelled as a single-degree-of-freedom system. However, for buildings with significant irregularities or complex geometries, which require 3D modelling, the fundamental natural period of oscillation may not be accurately estimated using this code-based formula.

This study proposes a regression-analysis-based formula for the fundamental natural period of oscillation for RC buildings with dominant re-entrant corners in both X- and Y-directions. A total of 190 RC building models with re-entrant corners of different shapes, heights, and floor configurations were developed. EVA of these finite element (FE)-based models was performed to obtain the fundamental natural periods of oscillations. Unconstrained and constrained regression analyses were performed to propose a new nonlinear power function-based formula for the fundamental natural period of oscillation that includes a re-entrant corner descriptor, *A*/*L* in both the X- and Y- directions, along with the height of the building.

2 Literature review

Various analytical, numerical, and experimental studies have been conducted to propose a fundamental natural period for the oscillation formula using regression analysis. These studies provide a comparison between the fundamental natural period of oscillation estimated using the proposed period-height formula and that of the seismic design code-based formula to review the accuracy of the fundamental natural period of oscillation estimation of the latter. A brief summary of the literature review related to the fundamental natural period of oscillation estimation is presented in the following sections: (1) the proposed periodic height formula for irregular buildings and (2) the code-based fundamental natural period of oscillation formula.

2.1 Proposed period-height formula for irregular buildings

Goel and Chopra [1] measured the fundamental natural period of the oscillation of MRF buildings and compared them using a seismic design code-based formula. It was found that the code-based fundamental natural period of oscillations was shorter than the measured fundamental natural period of the oscillations of the MRF buildings. An improved fundamental natural period of the oscillation formula with a lower bound of 15,9 percentile value was proposed for RC and steel MRF buildings. Asteris et al. [2] investigated the fundamental natural period of oscillation of buildings with masonry-infilled walls. The number of stories, span length, stiffness of the infill wall panels, location of soft stories, and soil-type parameters were assumed to significantly influence the fundamental natural period of oscillation of RC buildings. Masi and Vona [3] examined the fundamental natural period of the oscillation of RC-framed buildings in the elastic, yield, and highly damaged states. Building models were carefully considered to account for cracking, masonry infills, and elevation irregularities; however, other characteristics, such as stairs and plan irregularities, were not considered. A comparison of the fundamental natural period of oscillations obtained through EVA and the experiment showed a large difference between them.

Ahmed et al. [4] proposed a new formula for irregularly braced steel-frame buildings based on 176 prototype steel buildings with vertical, horizontal, and combined irregularities. It was observed that the bracing systems and building irregularities affected the fundamental natural period of oscillation of buildings with the same height. Loghmani et al. [5] stated that the fundamental natural period of the oscillation of a building, defined by its height or number of stories, is independent of whether the building is regular or irregular. A new formula for the fundamental natural period of oscillation was proposed for regular and irregular buildings using an artificial neural network. Crowley and Pinho [6] used a seismic-design-code-based fundamental natural period of the oscillation formula to conduct linear static and dynamic analyses of buildings. The modal response spectrum method yielded a realistic lateral load distribution owing to the higher contributory modes. The period-height relationship was obtained from models which used gross stiffness-based EVA in the form of the power expression suggested by Goel and Chopra [1]. The oldest empirical relationship in Equation (1) appeared in ATC3-06 and was derived based on Rayleigh's method [7].

$$T = \alpha H^{\beta} \quad (1)$$

where *T* denotes fundamental natural period of oscillation, α and β are coefficients, α depends on structure type, and *H* height of the building (in m).

Table 1 lists the period-height relationship proposed by various researchers for the fundamental natural period of building stocks [8]. Two forms of expressions are proposed: (1) a power expression and (2) number of stories for the fundamental natural period estimation.

Table 1. Period–height relationship for fundamental natural period proposed by researchers

Authors	Fundamental natural period formula proposed	Building description
Goel and Chopra (1997) [1]	$T= 0{,}023H^{0{,}9}$	RC MRF (Ht. 300 ft.)
Chopra and Goel (2000) [9]		
Guler et al. (2008) [10]	$T= 0{,}026H^{0{,}9}$	RC MRF mid-rise (Ht. up to 30 m)
Hong and Hwang (2000) [11]	$T= 0{,}029H^{0{,}804}$	RC MRF mid-rise (Ht. up to 80 m)
Crowley and Pinho (2004) [12]	T= 0,1H	RC MRF (Ht.- 2 m to 28 m)
Crowley and Pinho (2006) [13]	T= 0,055H	RC MRF Cracked infill (Ht.- 2 m to 24 m)

Verderame et al. [14] evaluated the period–height relationship for building models in the transverse and longitudinal directions subjected to gravity load design. Design acceleration of 0,05 g; 0,07 g, and 0,10 g were considered for period–height relation evaluation. The constants for the period–height relation given in Eq. (1); α and β were calibrated with the periods measured on some buildings during the 1971 San Fernando earthquake. The value of β that appeared in ATC3-06 (ATC, 1978) is 0,75, where α is 0,06. The said relationship is computed via Rayleigh method with seismic design assumptions; (i) horizontal forces are linearly distributed along the height, (ii) mass distribution is constant along the height, (iii) deformed shape is linear, and (iv) base shear is proportional to $1/T^{\gamma}$. By satisfying these conditions, the period can be expressed as:

$$T = \alpha H^{1/(2-T\gamma)} \tag{2}$$

The value of γ is 2/3 as per US code (UBC 1997) [14]. The coefficients of the power law formulation in Eq. (1) were evaluated using ordinary least-squares regression. The effective mass and translational stiffness were correlated with the plan extension of the building, and these variables were expected to have predictive power with respect to the period. An expression, including the plan area, is considered as:

$$T = \alpha H^{\beta} S^{\gamma} \tag{3}$$

where S denotes product of the two principal plan dimensions of the building: L_x and Ly. Relationships in the transverse and longitudinal directions were obtained using least-squares regression. It was concluded that by adding the building typology parameter S, the standard error was reduced by 60 % when compared with the formulation which only accounts for the height of the building.

Hadzima-Nyarko et al. [15] proposed new expressions for the fundamental period of regular RC frames by considering the direction of the structures and by performing nonlinear regression analysis using a genetic algorithm on 600 different models of RC-framed structures. There is a scope for further improvement in the period height equation provided by seismic design codes, which depend on building height or the number of stories, as height alone is inadequate for explaining period variability. The authors proposed seven expressions for estimating the elastic period which, in addition to the number of floors, considered the number of bays parallel to the considered direction, the ratio between the number of bays in the longitudinal and transverse directions, and the product between the number of bays in the longitudinal and transverse directions. The expressions for the fundamental natural period of oscillation are defined as:

$$T = C_1 N^{C_2} \tag{4}$$

$$T = C_1 N^{C_2} \cdot B^{C_3} \tag{5}$$

$$T = C_1 N^{C_2} + C_3 B^{C_4} \tag{6}$$

$$T = C_1 N^{C_2} \left(\frac{B_x}{B_y}\right)^{kC_3} \tag{7}$$

$$T = C_1 N^{C_2} + C_3 \left(\frac{B_x}{B_y}\right)^{kC_4} \tag{8}$$

$$T = C_1 N^{C_2} \left(B_x B_y\right)^{C_3} \tag{9}$$

$$T = C_1 N^{C_2} + C_3 \left(B_x B_y\right)^{C_4} \tag{10}$$

where N denotes number of stories, B number of bays in the building parallel to the considered direction, B_x number of bays in the longitudinal direction, B_y number of bays in the transversal direction, k constant with a value of 1 when the period in the longitudinal direction is to be determined and k is –1 when the period in the transversal direction is to be determined, and C_1, C_2, C_3 and C_4 are unknown parameters that should be determined.

Amanat and Hoque [16] demonstrated a practical way to evaluate the fundamental natural period of RC frames using rational approaches, such as modal analysis, and eliminated the necessity of imposing code limits. Three parameters that influenced the period were identified:

(i) span length, (ii) number of spans, and (iii) number of in-filled panels. Including these parameters, the fundamental natural period of the proposed oscillation formula is as follows:

$$T = \alpha_1 \alpha_2 \alpha_3 C_t H^{3/4} \tag{11}$$

where α_1 denotes modification factor for span length, α_2 modification factor for number of spans and α_3 modification factor for amount of infill, C_t numerical co-efficient, and H height of the building above the base.

An empirical formula to obtain the fundamental period of oscillation for multistorey RC frame buildings considering the total height (H), total breadth (B), total mass (total weight W), and number of bays of the building frames as shown in Eq. (12) was proposed to perform a multiple regression analysis on a dataset of EVA to modify the fundamental period–height formulae commonly used by seismic design codes [17].

$$T = 0{,}879 \frac{H^{0{,}43} m^{0{,}65} W^{0{,}18}}{B} \tag{12}$$

Subsequently, parameter, the total load on the frame, was eliminated from Eq. (12), assuming that to some extent, it is a function of the frame's global dimension. Another equation was proposed by performing multiple regression analysis with parameters: total height, total breadth, and number of bays of the frame of the building, as shown in Eq. (13). The results obtained using this formula are similar to those obtained using Eq. (12).

$$T = \frac{0{,}475 H^{0{,}547} m^{0{,}103}}{B^{0{,}271}} \tag{13}$$

To obtain a simple relationship involving the two main global parameters of frame, height, and breadth, a nonlinear regression analysis was performed to derive Eq. (14) [17]. Each expression, Eq. (12), Eq. (13), and Eq. (14) show good agreement between the predicted and actual values of the fundamental period of the building oscillation.

$$T = \frac{0{,}428 H^{0{,}545}}{B^{0{,}185}} \tag{14}$$

A simple height-based formula provided by Eq. (15) showed low agreement with finite element results when compared with the previous three formulas.

$$T = 0{,}28 H^{0{,}54} \tag{15}$$

An ambient vibration measurement was performed on 24 newly constructed residential detached RC buildings in Turkey [18]. A new empirical period–height relationship was obtained, as shown in Eq. (16). The obtained equation can be used for the force-based design of infilled RC-frame buildings.

$$T = 0{,}0195 H \tag{16}$$

The fundamental natural periods of oscillation of irregular eccentrically braced tall steel frame structures were obtained for vertical geometric irregularities and combined irregularities [19]. The three-variable power model expressed in Eq. (17) is developed.

$$T = 0{,}042 (H)^{0{,}85} \left(\frac{H_{av}}{H}\right)^{0{,}6} \left(\frac{D_{av}}{D}\right)^{0{,}35} \tag{17}$$

An empirical fundamental natural period of the oscillation formula of 3D RC buildings was proposed for bare and infill frames, considering the height, length, infill panels, and concrete shear walls. The formula was modified by ignoring the influences of the infill, concrete shear walls, soil flexibility, and building length, as shown in Eq. (18) [20]. Specifically, H_{av} and D_{av} are the average values of the height and dimension of the braced frame in the direction parallel to the applied force for the irregular structure, where D denotes the dimension of the structure in the direction of the applied force.

$$T=0{,}073(H)^{0{,}745} \tag{18}$$

Ambient vibration testing was performed on 28 tall RC buildings situated in the Indian cities of Hyderabad and Mumbai, with heights ranging from 50 to 150 m. The fundamental natural periods of the oscillation values obtained from the test were compared with the seismic design code-based results. A new empirical expression for tall RC buildings has been proposed [21]. An improved formula for the fundamental natural period of oscillation of RC MRF buildings was proposed based on a regression analysis of the data available from the motions recorded during eight earthquakes in California. It was also concluded that the fundamental natural period of the oscillation formula of the US and Egyptian codes should be modified as a function of the number of stories (n) [22]. Using the shear wall displacement, a closed-form period of the oscillation solution based on Rayleigh's method is proposed to determine the fundamental natural period of the oscillation. It was also observed that the code-based formula is inadequate for estimating the fundamental period of a shear wall building [23].

A simplified formula for the fundamental natural period of oscillation was proposed for masonry-infilled reinforced concrete frames. This formula is based on a simple concept of engineering mechanics [24]. The effects of the number of stories, number of spans, span length, stiffness of the infill wall panels, and percentage of openings with the infill panel on the fundamental natural period of oscillation were studied, and a formula for the fundamental natural period of oscillation was proposed using regression analysis [25]. The compilation of expressions for the fundamental natural period of oscillation for masonry-infilled RC frames from the seismic standards of different countries is provided with classification [26]. An advanced machine-learning algorithm was applied to masonry-infilled RC frames, and the corresponding fundamental natural period of oscillation was obtained. A comparison was also made between the values of the fundamental natural period of oscillation obtained through the algorithm and those provided in the literature [27].

2.2 Code-based fundamental natural period of oscillation formula

Seismic design codes provide a simplified empirical formula to estimate the fundamental period of oscillation (T) based on the overall height of buildings, as provided in Eq. (1). In Eq. (2), γ is considered as 2/3 as established in US code (UBC, 1997) [28].

$$T = \alpha H^{0.75} \tag{19}$$

The value of numerical coefficient (α) is specified by seismic design codes. The period-height relationship suggested by the seismic design codes and guidelines is listed in Table 2, where N denotes number of storeys.

Table 2. Code-based fundamental natural period of oscillation formula

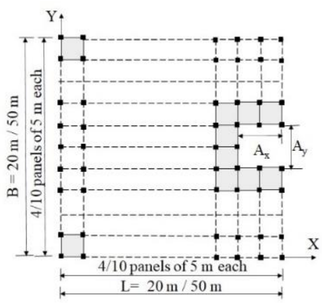
Name of country code/guideline	Fundamental natural period of oscillation formula
ATC3-06 (ATC, 1978) [6]	T= 0,06$H^{0,75}$
Taiwan and Venezuela [29]	T= 0,07$H^{0,75}$
Cuba; Israel Standard and Korea [29]	T= 0,073$H^{0,75}$
India [28]; Eurocode 8; Italian Technical Code; UBC [2]; Algeria; Philippines; Switzerland [29]; Canada [30] and Nepal [31]	T= 0,075$H^{0,75}$
FEMA450-2003 [2] and Bangladesh [32]	T= 0,075$H^{0,75}$
USA [29]	T= 0,10N
Costa Rica [2]	T= 0,08N

It is evident from the literature review that the fundamental natural period of the oscillation formula proposed by various researchers as well as that recommended by seismic design codes is mostly a function of the height of the building and does not account for the distinction between regular and irregular buildings. A research gap exists in proposing a fundamental natural period of the oscillation formula for plan irregular buildings for a realistic distribution of lateral forces on buildings.

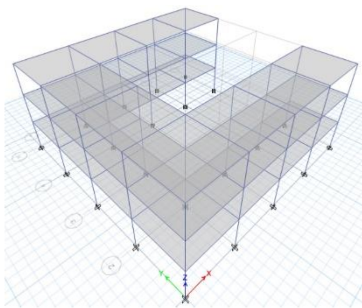
3 Re-entrant dominant plan irregular building models

Irregular buildings are broadly classified into two categories: (1) plan irregularities and (2) vertical irregularities. Buildings with plan irregularities, such as asymmetry, re-entrant corners, and nonparallel lateral force-resisting systems, are commonly used in the field. Of these, RC buildings with re-entrant corners are widely constructed for reasons such as natural ventilation and illumination, limited land availability, rapid urbanisation, and aesthetics. In this study, 190 RC building models with MRF and re-entrant corner-type plan irregularities were developed. Of these, 164 models had plan dimensions of 50 × 50 m with heights varying from 3 m to 30 m, comprising single-storey to ten-storey buildings.

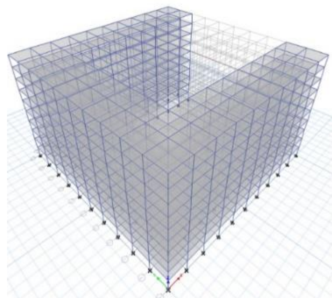
The remaining 26 building models had plan dimensions of 2 × 20 m with a height of 9 m, representing 3-storey RC building stocks. Building models have re-entrant corner-type plan irregularities defined by plan irregularity descriptors (PIDs) [33] in the form of projections of the building on the overall plan dimension, *A*/*L*, in both directions. This type of a PID is most commonly used in various seismic design codes to identify re-entrant-type plan irregularities. Figure 1 shows the plan layout and elevation of C-, L-, T-, and PLUS-shaped building models resulting from the bidirectional re-entrant corners considered in this study.



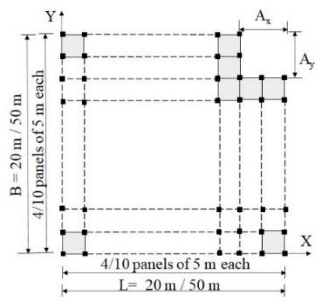
(a) Plan



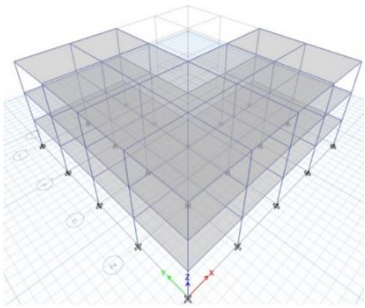
3-D view of a three-storey building



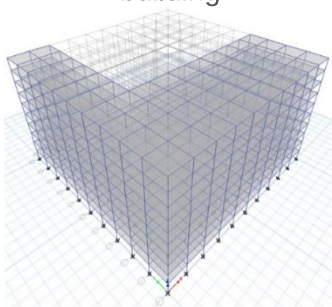
3-D view of a ten-storey building



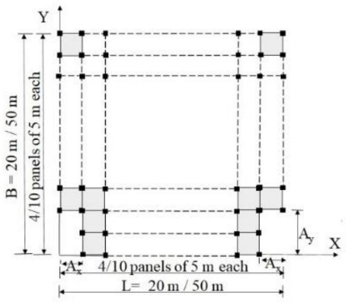
(b) Plan



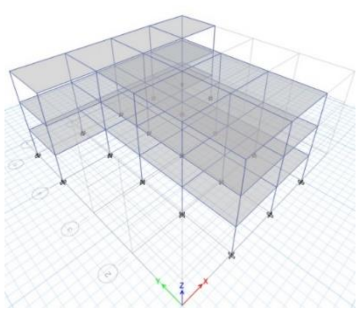
3-D view of a three-storey building



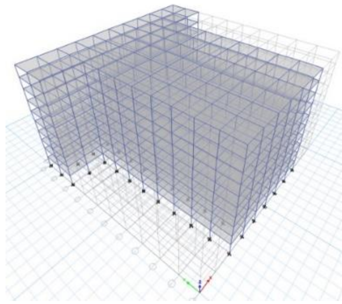
3-D view of a ten-storey building



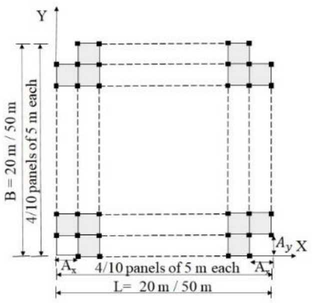
(c) Plan



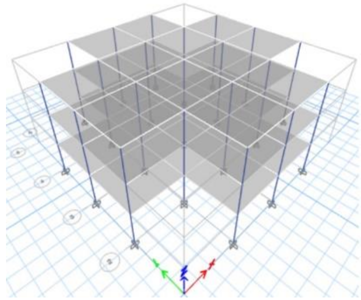
3-D view of a three-storey building



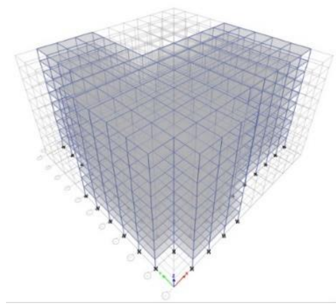
3-D view of a ten-storey building



(d) Plan



3-D view of a three-storey building



3-D view of a ten-storey building

Figure 1. Plan layout and 3-D view of RC building models: (a) C- shaped; (b) L- shaped; (c) T- shaped, and (d) PLUS- shaped

Table 3. Data set of fundamental period of oscillation of building models for 20 × 20 m plan dimensions

Building type & height (m)	$\left(\frac{A_x}{L}, \frac{A_y}{B}\right)$ **Fundamental period of oscillation** (sec)				**No. of models**
C-shaped; 9 m	(0,50;0,25) 0,781	(0,5;0,5) 0,809	(0,25;0,50) 0,817	(0,25;0,25) 0,837	4
L-shaped; 9 m	(0,5;0,5) 0,819	(0,583;0,350) 0,81	(0,417;0,41) 0,807	(0,350;0,583) 0,810	17
	(0,75;0,25) 0,828	(0,75;0,50) 0,752	(0,75;0,75) 0,759	(0,563;0,45) 0,786	
	(0,25;0,25) 0,842	(0,25;0,50) 0,835	(0,333;0,333) 0,828	(0,375;0,375) 0,824	
	(0,5;0,5) 0,738	(0,39;0,39) 0,780	(0,42;0,42) 0,806	(0,36;0,36) 0,799	
	(0,33;0,33) 1,096	--	--	--	
T-shaped; 9 m	(0,25;0,75) 0,785	(0,25;0,50) 0,819	(0,25;0,25) 0,835	(0,50;0,25) 0,828	4
PLUS-shaped; 9 m	(0,25;0,25) 0,819	--	--	--	1

Building models were developed in the FE-based commercially available software ETABS (V18) [34] and were designed for gravity loading: Dead Load (DL) and Live Load (LL) of 3 kN/m^2 at typical floors; 1,5 kN/m^2 at the roof, and a Floor Finish (FF) load of 1 kN/m^2. The seismic parameters considered for the study were seismic zone-v (Peak Ground Acceleration-PGA-0,36 g), response reduction factor of 5, Special Moment-Resisting Frame (SMRF),

medium stiff soil, and a damping coefficient of 0,05. Details of the RC building models with re-entrant-type plan irregularities on the shape, *A*/L ratios, height of the model, fundamental natural period of oscillation evaluated using eigenvalue analysis and number of the models are summarized in Table 3 for building models of plan dimension 20 × 20 m and total height of 9 m. Where, A_x/L denotes ratio of the length of the projection to the overall plan dimension in direction X, and A_y/B denotes ratio of the length of the projection to the overall plan dimension in direction Y.
Table 4 reports details of RC building models on similar lines as that mentioned in Table 3 for building models of plan dimension 50 × 50 m and total height of 30 m. Table 4 comprises of large data set of fundamental periods of oscillation for RC building models with variety of A_x/L and A_y/B ratios of re-entrant corner.

Table 4. Data set of fundamental period of oscillation of building models for 50 × 50 m plan dimensions

Building type & height (m)	$\frac{A_y}{B}$ / $\frac{A_x}{L}$	**0,1**	**0,2**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**No. of models**
		Fundamental period of oscillation (sec)								
C-shaped; 30 m	0,2	1,458	1,457	1,457	1,456	1,455	1,454	1,454	1,453	24
	0,4	1,457	1,455	1,453	1,451	1,449	1,447	1,445	1,443	
	0,6	1,456	1,453	1,449	1,445	1,441	1,437	1,432	1,429	
L-shaped; 30 m	0,2	1,458	1,457	1,456	1,455	1,453	1,452	1,451	1,450	32
	0,4	1,457	1,455	1,452	1,449	1,447	1,444	1,442	1,440	
	0,6	1,456	1,452	1,448	1,444	1,440	1,436	1,433	1,432	
	0,8	1,455	1,450	1,445	1,440	1,435	1,437	1,430	1,432	
PLUS-shaped; 30 m	0,2	1,455	1,454	1,452	1,450	1,448	1,446	1,444	1,443	32
	0,4	1,453	1,466	1,446	1,442	1,438	1,435	1,432	1,431	
	0,6	1,451	1,446	1,441	1,435	1,429	1,423	1,421	1,423	
	0,8	1,448	1,443	1,437	1,431	1,426	1,423	1,426	1,439	

	$\frac{A_y}{B}$ / $\frac{A_x}{L}$	**0,1**	**0,2**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	
		Fundamental period of oscillation (sec)								
T-shaped; 30 m	0,1	1,458	1,457	1,455	1,454	1,453	1,452	1,451	1,45	32
	0,2	1,457	1,454	1,452	1,449	1,446	1,444	1,441	1,44	
	0,3	1,455	1,452	1,448	1,443	1,438	1,434	1,43	1,429	
	0,4	1,454	1,449	1,443	1,436	1,416	1,408	1,414	1,418	

	$\frac{A_x}{L}$ / $\frac{A_y}{B}$	**0,11**	**0,12**	**0,13**	**0,14**	**0,15**	**0,16**	**0,17**	**0,18**	**0,19**	
		Fundamental period of oscillation (sec)									
L-shaped; 30 m	0,1	1,458	1,457	1,388	1,392	1,42	1,45	1,449	1,448	1,459	9
	$\left(\frac{A_x}{L},\frac{A_y}{B}\right)$	**0,11**	**0,12**	**0,13**	**0,14**	**0,15**	**0,16**	**0,17**	**0,18**	**0,19**	
L-shaped; 30 m		1,456	1,453	1,382	1,393	1,331	1,455	1,453	1,451	1,46	9

	$\left(\frac{A_x}{L},\frac{A_y}{B}\right)$ **Fundamental period of oscillation** (sec)				
L-shaped; 30 m	(0,1;0,1) 1,458	(0,3;0,3) 1,454	(0,5;0,5) 1,443	(0,7;0,7) 1,43	4
PLUS-shaped; 30 m	(0,1;0,1) 1,456	(0,2;0,2) 1,449	(0,3;0,3) 1,431	(0,4;0,4) 1,379	4

In order to have comprehensive data set inclusive of varying height, 18 building models of plan dimension 50 × 50 m with height of the model varying from 3 to 27 m were developed for C-and L-shaped re-entrant corner RC building. Table 5 shows details of RC building models on shape, *A*/*L* ratio, height of the model, fundamental natural period and number of models.

Table 5. Data set of fundamental period of oscillation of building models for 50 × 50 m plan dimension with varying height of the buildings

Building Type	$\left(\frac{A_x}{L}, \frac{A_y}{B}\right)$	3 m	6 m	9 m	12 m	15 m	18 m	21 m	24 m	27 m	No. of models
		Fundamental period of oscillation (sec)									
C-shaped	(0,4;0,5)	0,240	0,425	0,451	0,611	0,773	0,936	1,122	1,246	1,339	9
L-shaped	(0,5;0,5)	0,242	0,426	0,451	0,611	0,772	0,935	1,071	1,243	1,335	9

Building models were prepared without considering masonry-infilled walls because they are treated as non-structural elements for the analysis and design of buildings. Additionally, there are very limited guidelines available for the modelling of masonry infill in the Indian seismic design code, except for the latest revision of the seismic design code, which recommends that the infilled wall should be modelled as a diagonal strut member. The sizes of the beams and columns designed using the Indian code IS 456:2000 [35] for the various building models are listed in Table 6.

Table 6. Details of beam and column sizes for building models

Numbers of storeys	Size of columns	Size of beams
1	350 x 350 mm	300 x 300 mm
2	400 x 400 mm	
3 to 6	450 x 450 mm	300 x 450 mm
7	450 x 450 mm (1-3 storeys); 400 x 400 mm (4-7 storeys)	
8	500 x 500 mm (1-3 storeys); 400 x 400 mm (4-8 storeys)	
9	550 x 550 mm (1-3 storeys); 450 x 450 mm (4-6 storeys); 400 x 400 mm (7-9 storeys)	

The building models were developed as a space frame comprising beams, columns, and slab (diaphragm) elements. Beams and columns were modelled as line elements with their sectional properties, whereas slabs were modelled as area elements with uniform thickness. The slab is defined as membrane element as membrane element with rigid diaphragm transfers lateral forces to vertical load resisting systems. As mentioned earlier, the masonry infill was not included in the model. The model has a fixed boundary condition at the base and is assigned gravity and lateral loads with the design inputs specified in Table 7. The material model was linear because a linear static analysis was performed.

The well-established literature and seismic design codes of various countries, including the Indian seismic design code, recommend that irregular buildings should be analysed using 3-D modelling with a flexible diaphragm. In this study, 3-D building models were analysed using EVA to evaluate the fundamental natural period of oscillation and the associated mode shape. All building models were found to have the first and second modes of vibration as translational modes in the principal direction, followed by the rotational mode of vibration. The fundamental natural period of oscillation, corresponding to the first translational modes of vibration, is considered to propose a new fundamental natural period of oscillation formula. As per the formula, the lowest and largest mass participation produces the maximum seismic force on the building models.

Table 7. Design inputs of RC building models

Gravity Loading Definition	
Impose load (Live load)	3 kN/m² for a Typical floor
	1,5 kN/m² for Roof floor
Floor finish	1 kN/m²
Seismic Loading Definition	
Seismic zone factor	0,36 (∵ seismic zone-v)
Importance factor	1,2
Response reduction factor	5 (∵ Special Moment-Resisting Frame)
Soil type	Medium stiff
Damping	5 % of critical damping
Fundamental natural period of oscillation estimation	Code-based formula; Programme calculated
Seismic Analysis Method	
Equivalent Static Method (ESM)	---
Response Spectrum Method (RSM)	
Numbers of participating modes	Up to mass participation ≥ 90%
Participating modes	$\left[\{\emptyset_{ik}\}_x \ \{\emptyset_{ik}\}_y \ \{\emptyset_{ik}\}_\theta\right]$ at the floor i in mode k Where, x, y = Translational degrees of freedom θ = Rotational degree of freedom
Material Definition	
Concrete	f_{ck} = 25 MPa for $M25$ grade
Steel	f_y = 415 MPa for HYSD
Material model	Linear

4 Evaluation of code-based and proposed period–height relationship

The fundamental natural period of oscillation of the RC building models was calculated using the seismic design codes of different countries, including the Indian seismic design code. Figure 2 (a) shows the fundamental natural period of oscillation of building models from EVA as discrete data points with a graph legend of the present study (EVA), while those obtained from the seismic design code-based formula for the bare-frame building are shown in the form of a trendline for better visualisation and comparison. It is evident that all seismic design codes yield a lower fundamental natural period of oscillation for re-entrant corner-type plan irregular buildings. However, they became substantially conservative as the height of the building increases beyond 15 m. This is due to the fact that building models become flexible with height due to mass and stiffness distribution, which cannot be captured by the code-based formula as it depends only on the height of the building model. Additionally, the code-based formula for the fundamental natural period of oscillation estimation does not differentiate between regular and irregular building models, whereas the latter type of building model has different dynamic properties, and thereby, different fundamental natural periods of oscillation and associated mode shapes. The Costa Rican seismic design code yields the most conservative estimate of the fundamental natural period of oscillation for re-entrant irregular corner-type buildings. Various researchers proposed a period–height relationship for building stocks, realising that the seismic design code-based formula for the fundamental natural period of oscillations cannot have generalised applicability to buildings with different configurations, structural systems, damage states, and frames with masonry walls because the dynamic properties of each building varies.

Figure 2 (b) shows a graphical representation of Table 1 when compared to the values obtained using the period–height formula proposed by various researchers. It is evident that the period–height relationships proposed by Chopra and Goel (2000) [9] and Crowley and Pinho (2006) [13] agree well with the original fundamental natural period of the oscillation dataset. Other period–height relationships yield an underestimation of the fundamental natural period of oscillation, leading to higher seismic forces on the building models. It can be observed that the period–height relationship proposed by Crowley and Pinho (2004) [12] highly overestimates the fundamental natural period of oscillation, while the proposed relationship by Hong & Hwang (2000) [11] and Guler et al. (2006) [10] substantially underestimate the fundamental natural period of oscillation.

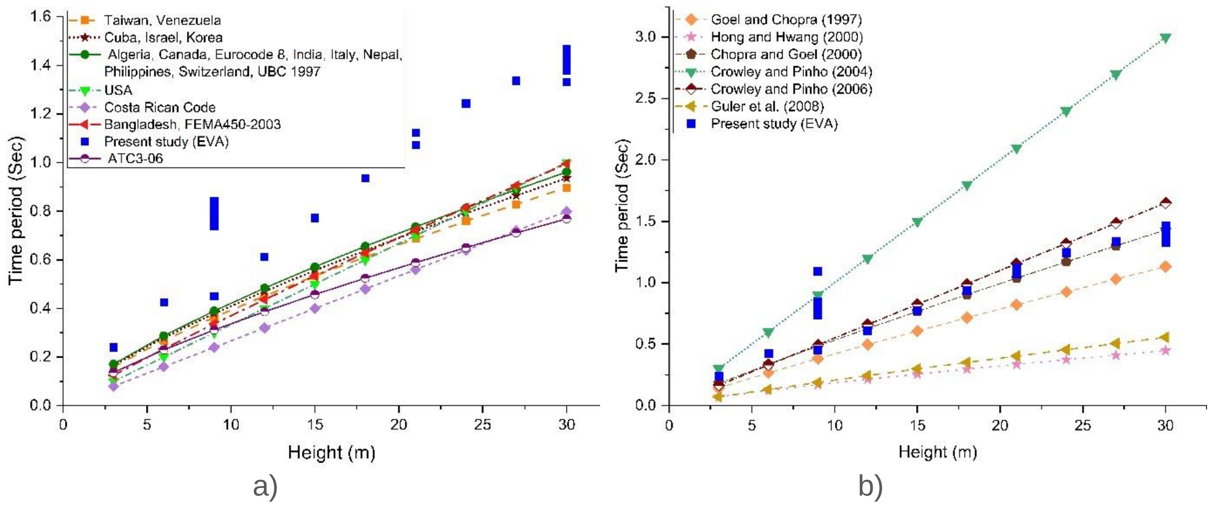


Figure 2. Comparison of EVA-based fundamental natural period of oscillation data set with: a) data set of seismic design code formula, and b) data set of period–height relationship proposed by researchers

5 Proposed fundamental natural period of oscillation formula for re-entrant dominant RC buildings

In this section, a new fundamental natural period formula is proposed for re-entrant corner-dominant plan irregular RC building stocks to improve the height-based time–period relationships proposed by various researchers and seismic design codes, as discussed in Section 4. The proposed time period formula includes the PID and *A*/*L* ratio in both directions, in addition to the height of the building stock. Given that the fundamental natural period of oscillation of the building stock is assumed to be influenced by more than one parameter (height), a nonlinear regression model in the form of a multiple-variable power equation is proposed, as shown in Eq. (20).

$$T = \alpha(h)^{\beta}\left(\frac{A_x}{L}\right)^{\gamma}\left(\frac{A_y}{B}\right)^{\delta} \tag{20}$$

where, T denotes fundamental natural period of oscillation (sec); h height (m) of the building; α, β, γ and δ multiple regression variables; A_x & A_y denote projection of building in X- and Y- directions, respectively and L & B are overall plan dimension of building in X- and Y- directions, respectively.

Referring to Fig. 2(a), it is sufficient to realise that the nonlinear model proposed by Eq. (20) can be fitted well with the original fundamental natural period of the oscillation data on linearization of the nonlinear regression model. Eq. (20) can be rewritten as follows:

$$y = \alpha + \beta x_1 + \gamma x_2 + \delta x_3 \tag{21}$$

In which, y=log(T), α=log(α), x_1=log(h), x_2=log(A_x/L) and x_3=log(A_y/B).

Multiple linear regression was used to determine regression variables, α, β, γ, and δ, by minimising the squared error, resulting in the formulation of the matrix form as follows:

$$\begin{bmatrix} n & \sum x_{1i} & \sum x_{2i} & \sum x_{3i} \\ \sum x_{1i} & \sum {x_1}^2{}_i & \sum x_{1i}\, x_{2i} & \sum x_{1i}\, x_{3i} \\ \sum x_{2i} & \sum x_{1i}\, x_{2i} & \sum {x_2}^2{}_i & \sum x_{2i}\, x_{3i} \\ \sum x_{3i} & \sum x_{1i}\, x_{3i} & \sum x_{2i}\, x_{3i} & \sum {x_3}^2{}_i \end{bmatrix} \begin{Bmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{Bmatrix} = \begin{Bmatrix} \sum y_i \\ \sum x_{1i} y_i \\ \sum x_{2i} y_i \\ \sum x_{3i} y_i \end{Bmatrix} \tag{22}$$

Eq. (22), which contains simultaneous linear equations, was solved using the Gauss elimination method. The standard error of the estimation of the computed fundamental natural period of the oscillation dataset is as follows:

$$S_e = \sqrt{\frac{\sum_{i=1}^{n}[y_i - (\alpha + \beta x_{1i} + \gamma x_{2i} + \delta x_{3i})]^2}{(n-4)}} \tag{23}$$

where, y_i=log(T_i) = computed fundamental natural period of oscillation value; [log(α)+(β·log(h_i))+(γ·log(A_x/L)$_i$)+(δ·log(A_y/B)$_i$)] denotes computed value of the *i*-th data; *n* is total numbers of computed fundamental natural period data points. Furthermore, S_e represents the scatter in the data and converges to standard deviation for large values of *n* data points, *n*, from the best-fit equation. The regression variables determined using the solution to Eq. (22) and is substituted into Eq. (20) yields the unconstrained best-fit equation.

$$T = 0{,}186(h)^{0{,}6}\left(\frac{A_x}{L}\right)^{-0{,}01}\left(\frac{A_y}{B}\right)^{0{,}001} \tag{24}$$

However, the code-based fundamental natural period of the oscillation formula should provide lower values in order to remain conservative. Therefore, the best-fit line, determined using Eq. (24) should be reduced by S_e without changing the slope. Furthermore, α_L, the lower value of α, can be determined as:

$$log(\alpha_L) = log(\alpha) - S_e \tag{25}$$

As discussed earlier, as S_e approaches standard deviation for large numbers of data, *n* and *y* is lognormal, α_L is minus one standard deviation or 15,9 percentile value. This implies that 15,9 % of calculated fundamental natural period of oscillation fall below the curve defined by α_L, i.e., best-fit-1σ curve. A total of ten numbers of building models have fundamental natural period of oscillation lower than best-fit-1σ curve amounting to 5,26 % re-entrant corner dominant building models. The maximum variation in the fundamental natural oscillation period of these building models, compared to the best-fit 1σ curve, is relatively small (approximately 2.93%). This observation holds for models with an *A*/*L* ratio of either (0,5;0,4) or (0,5;0,5), representing building models that are common among the widespread building stocks analysed in the study. The codes also specify the upper limit of the fundamental natural period of oscillation obtained through rational analysis. This was achieved by raising the best-fit line using S_e without changing its slope. Thus, α_U, the upper value of α, can be obtained as:

$$log(\alpha_U) = log(\alpha) + S_e \tag{26}$$

Eq. (26) corresponds to best-fit+1σ curve for the original fundamental natural period of oscillation data. Newly proposed fundamental natural period of oscillation formula is compared with height-based seismic design code formula of various countries which use the value of 0,75; 1,00 and 0,90; respectively, for regression variable, β, by performing nonlinear constrained regression analysis. Table 8 summarises the results of the unconstrained and constrained regression analyses performed to propose the fundamental natural period of the oscillation formula along with the standard error of the estimate (S_e), standard deviation (SD), co-efficient of variance (CoV), co-efficient of determination (r^2), and correlation coefficient (*r*).

Table 8. Fundamental natural period of oscillation formula with unconstrained and constrained regression analysis

Type of Regression	Proposed Formula		
	Best-fit (S_e; SD; CoV in %; r^2 and r)*	Best-fit-1σ	Best-fit$+1\sigma$
Unconstrained	$T=0,186(h)^{0,6}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$ (0,069; 0,3; 23,07; 0,95; 0,97)	$T=0,159(h)^{0,6}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$	$T=0,218(h)^{0,6}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$
Constrained with $\beta=0,75$	$T=0,116(h)^{0,75}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$ (0,102; 0,36; 26,99; 0,92; 0,96)	$T=0,092(h)^{0,75}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$	$T=0,147(h)^{0,75}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$
Constrained with $\beta=0,90$	$T=0,072(h)^{0,9}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$ (0,153; 0,41; 30,37; 0,86; 0,93)	$T=0,051(h)^{0,9}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$	$T=0,103(h)^{0,9}\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$
Constrained with $\beta=1,00$	$T=0,053h\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$ (0,19; 0,44; 32,35; 0,82; 0,91)	$T=0,034h\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$	$T=0,082h\left(\frac{A_x}{L}\right)^{-0,01}\left(\frac{A_y}{B}\right)^{0,001}$

It is clearly observed from Table 8 that the value of S_e is substantially high for β=0,75;1,00; and 0,90; used by seismic design code of various countries. Consequently, the value of β=0,60 suggests that the fundamental natural period of oscillation formulas in seismic design codes do not accurately estimate the fundamental natural period of oscillation for building models with dominant re-entrant corner plan irregularities. Therefore, fundamental natural period of oscillation estimation for re-entrant dominant plan irregular building models can be best represented by unconstrained best-fit-1σ curve.
Figure 3 shows a comparison of the fundamental natural period of the oscillation obtained from the proposed new fundamental natural period of the oscillation formula with the original fundamental natural period of the oscillation data and seismic design code-based formula. It has been observed that unconstrained best-fit curve fits well with original fundamental natural period of oscillation data set. The seismic-design-code-based formula yielded a highly conservative estimation of the fundamental natural oscillation period.

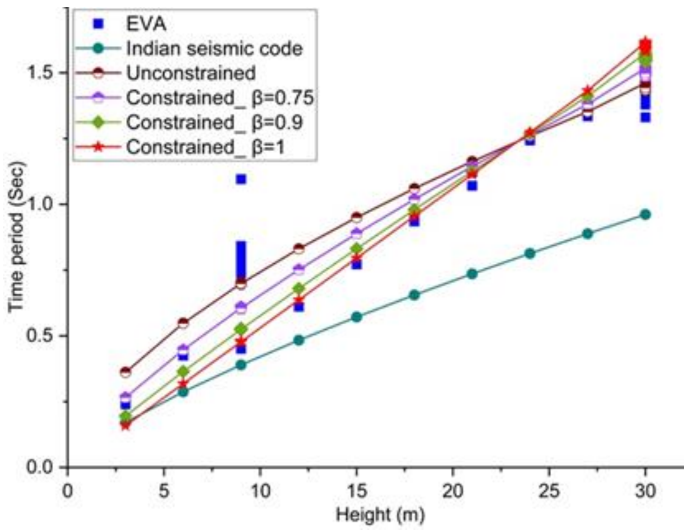


Figure 3. Comparison of fundamental natural period of oscillation values of proposed formulas

Figure 4 shows original fundamental natural period of oscillation data set with lower and upper bound represented by best-fit-1σ curve and best-fit+1σ curve, respectively, obtained through regression analysis. It is evident that best-fit-1σ curve effectively and conservatively represents fundamental natural period of oscillation for re-entrant corner dominant plan irregular building models. Inclusion of additional parameters, A_x/L and A_y/B, governed by regression analysis variables, γ and δ, enhances the fit of the best-fit-1σ curve with the original data set of the fundamental natural period of oscillation, especially as the building height increases. This is due to the –ve value of regression variable, γ, and +ve value of regression variable, δ.

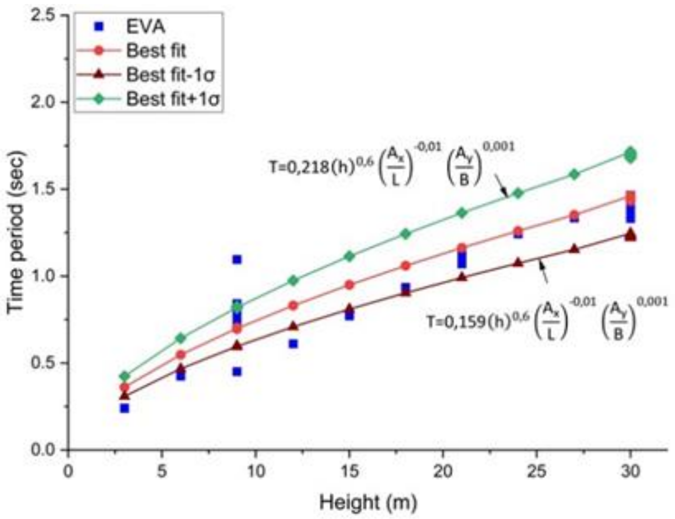


Figure 4. Regression analysis of fundamental natural period of oscillation data

6 Conclusions

The fundamental natural period of building oscillations is crucial in the seismic analysis and design of RC buildings. Currently, there is a significant need to revise the seismic design code-based formula for this period. The existing formula primarily considers building height and fails to adequately address irregular RC buildings, particularly those with re-entrant corner-type plan irregularities. To address this, 190 models of such irregular RC buildings, featuring various shapes (C, L, T, and PLUS), heights, and floor configurations, were developed for analysis. An Eigenvalue Analysis (EVA) was conducted to evaluate their fundamental natural periods of oscillation. These findings were then compared with the periods obtained from the seismic design codes of various countries, as well as with the period-height formula proposed in existing literature. A set of proposed formulas for the fundamental natural period of oscillation includes parameters specific to the re-entrant corners of RC buildings, alongside building height. These equations represent the EVA-based dataset accurately, with the unconstrained equation showing the best agreement and least statistical error indices. Seismic design code-based formulas tend to yield highly conservative estimates of the fundamental natural period, especially for taller buildings. The newly proposed formula, derived from unconstrained regression analysis and best-fit-1σ, aligns well with the EVA data. It performs favourably compared to the period-height formulas from various countries' seismic guidelines and existing literature. These fundamental period formulas could be further refined by incorporating other types of plan and vertical irregularities, allowing for a more comprehensive approach in seismic analysis and design.

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