Approximate Natural Period Expression for Reinforced Concrete Tall Buildings in India – A proposal

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Abstract

Many tall buildings are being built in different Indian cities to cater to the demand generated by the large number of people migrating from rural areas to urban centres. The safety of such tall buildings is ensured by designing them for dynamic loads viz., wind and earthquake. To withstand these loads, the computation of the natural period becomes essential. The current Indian seismic code IS 1893 (2016) has outlined a couple of empirical expressions based on different structural systems to compute the natural period. These expressions have been developed using data obtained from experiments performed on low-to-midrise buildings. Thus, it is important to verify their applicability for tall structures before using them in practice. To achieve this, ambient vibration testing is done on 28 RC Tall buildings in Hyderabad and Mumbai, whose heights range from 50m to 150m. These tests' natural periods are compared with existing Indian and International codes. Based on the comparison, a new empirical expression of RC tall buildings is proposed.

Keywords:

Fundamental Natural Period; Tall Building; Ambient Vibration, IS 16700.

Introduction

In the last couple of decades, urbanisation in India has been occurring at an unimaginable pace, leading to the appearance of many tall buildings (>50m) to cater to this enormous demand. To ensure the structural safety of Tall buildings, the Bureau of Indian Standards (BIS) has released tall building code[1]. The design of tall buildings is usually different compared to low and mid-rise buildings. Buildings attract lateral loads (earthquake and wind) in addition to gravity loads (dead and live). Response of tall buildings to the earthquake ground motion significantly varies due to their flexibility. Also, depending on the height, wind load dominates earthquake load. The behaviour of tall buildings largely depends on structural form, stiffness and mass distribution in plan and elevation. The same is exhibited by dynamic characteristics such as natural period and mode shapes. In design, the natural period is used for the computation of design seismic force[2]and the computation of dynamic effects due to wind[3]. In design practice, it is quite common to use an empirical expression for obtaining the natural period.

IS 1893[2] has outlined the separate empirical expression of natural period for three categories, viz., bare frame buildings, building with structural wall and all other categories. These expressions are initially developed in the USA as a part of ATC3-06[4] Project. But, later they were found not to match well with the California natural periods database and were updated periodically. The earlier study[5] in India too observed that such expressions adopted from other countries do not go well with buildings in India due to considerable variations in construction practice. One more recent study[6] has highlighted the shortcoming of this expression given in IS 1893 to predict the natural period of tall buildings. Though IS 16700 is silent over a natural period approximate expression of a tall building, a draft version[7] of the upcoming revision of the same code proposes a new approximate empirical expression that needs to be validated based on the measured natural period of tall buildings.

The current study is conducted to assess the applicability of empirical expression for the natural period given in current seismic code[2] and, if found unsuitable, propose a new empirical expression of the natural period for tall buildings in India. [2,78]

Empirical Expression in Building Codes

The natural period of a building is usually linked with a number of storeys or height of a building or height and base dimension or height of a building and certain dimensions of structural walls present in the building. Historically, equation (1) was appeared first in ATC3-06[4], which was derived based on Rayleigh's method[8]. Where, T = Natural period in seconds and h is the height of a building in feet. The distinct values of 'a' were established based on the measured period of buildings that responded to 1971 San Fernando earthquake for Reinforced Concrete Moment Resisting Frame (RC MRF) and Steel Moment Resisting Frame buildings. Over time, the values of a and b are kept on revising in successive codes such as SEAOC-88[9] based on the accumulation of more such data in later years.

$$T = a\ h^{b} \tag{1}$$

NEHRP-94[10] linked the natural period with a number of storeys N and recommended an alternative expression for RC and steel MRF buildings as mentioned in equation (2). But, this expression applies to buildings having a maximum 12 number of storeys and whose floor-to-floor height is at least 10 feet.

$$T = 0.1\ N \qquad N \leq 12 \tag{2}$$

Following the trend of USA codes, India adopted the period height relationship as equation (1) and incorporated equation (3) for RC bare frame buildings in earlier[11] and current[3] versions[2] of the Indian seismic code. Where *h* is the height of a building in metres. Though this expression is only to be used for RC buildings without infill walls, but a recent amendment of seismic code states that for RC Structural Wall buildings, the natural period computed by the approximate period expression for structural wall building should not exceed the period obtained from this expression.

For RC MRF bare frame buildings: $T_a = 0.075h^{0.75}$ (3)

The period computed by taking input of building height (*h*) as well the base dimension (*d*) in the form of equation (4) was recommended in the previous version of IS 1893[11], which was intended for all building other than the bare frame. This expression appeared first in ATC3-06[4] with a value of 0.05 when *h* and *d* are in feet, which is equivalent to 0.09 when dimensions are in metres. As discussed by Crowley and Pinho[12], this expression comes from the equation of the frequency of vibration of a cantilever (considering shear deformation only), with the thickness of the wall considered more or less constant and thus only the width or length of the building is an input parameter, as presented in equation (5).

$$T_a = \frac{0.09\,h}{\sqrt{d}} \tag{4}$$

$$T = 4\sqrt{\frac{m}{\kappa G}}\frac{H}{\sqrt{A}} = \frac{\alpha H}{\sqrt{A}} = \frac{\alpha H}{\sqrt{D t_w}} = \frac{\alpha_1 H}{\sqrt{D}} \tag{5}$$

Where 'm' is the mass per unit length, 'G' is the shear modulus, 'κ' is the shape factor to account for the non-uniform distribution of shear stresses, 'D' is the length of the cantilever, and 't_w' is the thickness. Some codes use this expression specifically for buildings with both frames and shear walls, some use the equation for reinforced concrete MRF with masonry infill panels, but many specify it for use with any building except moment resisting space frames.

The current Indian seismic code[2] explicitly introduced a separate expression (equation (6)) for RC structural wall system. Where A_w is total effective area of walls in first storey and can be computed by equation (7), A_{wi} is effective cross-sectional area of i^{th} wall in first storey, L_{wi} is length of structural wall at first storey along the direction under consideration, and N_W is the number of walls in the considered direction. This expression's shortcoming is that often the structural walls' length and thickness are not known to the designer at the initial stage. Hence, such an expression is bit tedious. The period computed by this expression is valid only if it is greater than equation (4) and less than equation (3). The measured period of buildings in the current study could not be compared with the natural period obtained by equation (6) due to unavailability of structural drawings.

$$T_a = \frac{0.075\, h^{0.75}}{\sqrt{A_W}} \geq \frac{0.09\, h}{\sqrt{d}} \tag{6}$$

$$A_w = \sum_{i=1}^{N_w} \left[A_{wi} \left\{ 0.2 + \left(\frac{L_{wi}}{h} \right)^2 \right\} \right];\ L_{wi}/h\ \leq 0.9 \tag{7}$$

The proposed revision[7] of IS 16700 introduces new approximate expressions for RC tall buildings. Equation (8) is one of them, which is introduced for structural systems except for RC MRF. This expression is more or less in line with American, Canadian and Korean building codes except for different values of a, which are mentioned in Table 1. But, it will be interesting to compare all of these equations with a measured period.[7]

$$T_a = 0.0672h^{0.75} \tag{8}$$

Literature on empirical expression for *T*

Efforts to check and improve the code suggested empirical expression are not new in India. Many past studies[5,6,13–15], based on ambient vibration, have been conducted from time to time to improve the period expression of RC buildings in India. Few other studies from India have also attempted to highlight the importance[16] and to improve the natural period expression based on analytical studies[17–19]. Similarly, many studies[20–31] around the globe have taken place in the last 30 years. But, current work focus on a detailed examination of studies carried out on RC buildings of height greater than 50 m (Table 2).

Lagomarsino[32] studied about 185 Italian buildings, out of which there were 52 RC buildings present. The study proposed equation (9) for RC buildings and revealed no correlation between the natural period and the direction of vibration.

$$T_a = h/55 \tag{9}$$

A team of Japanese researchers[33] created a database of 205 buildings collected from various institutions. And conducted a study to develop an empirical expression for the first mode, torsion mode, and damping of those buildings. For the Japanese buildings, equation

(10) is proposed to compute the natural period. Similarly, A Thai study[34] of 50 RC tall buildings in Bangkok proposed equation (11) for the natural period of these buildings, even though Thailand is not a seismically active region.

$$T_a = h/67 = 0.015\,h \tag{10}$$

$$T_a = h/54 = 0.0185\,h \tag{11}$$

Canadian researchers[35] proposed equation (12) for the natural period of RC structural wall (RCSW) buildings in Montreal after full-scale testing of 27 RCSW buildings. Revealing that the existing Canadian code expression is overestimating the natural period of RCSW buildings leads to possible consideration of unreasonably low seismic design loads.

$$T_a = 0.019\,h \tag{12}$$

A recent Korean study[36] proposed equation (13) for the natural period of tall Korean buildings by conducting an ambient vibration study of 58 RC buildings.[38]

$$T_a = h/51 = 0.0196\,h \tag{13}$$

Studies by Indian researchers[6,15] on tall buildings also have similar results. But, both the studies commented on the earlier version of Indian seismic code[11], and Tall building code[1] was not released then. Hence, the current study will be more valuable and relevant for India.

In summary, looking at all these proposals, it indicates that code suggested expressions are not suitable for tall buildings, since response of tall buildings is different than the low-rise and mid-rise buildings. The primary finding suggests that tall buildings in Asia exhibit similar natural periods, as evidenced by the equations proposed in literature[15,33,34,36]. Further, in the absence of buildings instrumented with permanent sensors, developing empirical expressions based on ambient vibration tests is quite common in earthquake and wind engineering disciplines. Thus, there is ample evidence to develop the empirical equation for tall buildings in India based on ambient vibration tests.

Measured Period of Tall buildings

28 number of RC tall buildings are tested in Hyderabad and Mumbai. Since the tall building is the focus, the shortest building in a database is of height 50.45 m and covers up to height 146.75m. The number of storeys covered is 17 to 42. All the buildings surveyed have a structural wall system as their gravity and lateral load-resisting system. Due to the unavailability of drawings and limited access to occupied buildings, the exact details of partition walls, such as their location, orientation, and material, are unknown. Except for one building, all of them are used as residential buildings. The basic dimensions of all buildings are given in Table 3, and one such sample building is shown in Figure 1. The plan geometry of buildings varies from symmetric about one axis to symmetric about both axis and asymmetric. Further, drawings of only two representative building plans are shown in Figure 2, and the rest listed in Table 3.

Ambient vibration is measured using a portable 'IT Kyoshin' vibration sensor. The sensor can simultaneously measure the vibration along all three directions with an accuracy of range +0.25g to -0.25g in resolving power $5x10^{-3}$ cm/sec^2. The vibration data sensed by sensors are transferred with the help of an ethernet cable and stored in the laptop. An external power supply is needed for the sensor to work. A single-point observation at the rooftop or maximum accessible floor level is recorded for 15-45 minutes. To measure the true lateral period whenever possible, the sensor is kept near the centre of the building and readings are taken at the rate of 100 data points per second. To capture the period along the two major principal directions of building, the sensor is aligned and levelled in such a way that two horizontal axes of the sensor become parallel to the longitudinal and transverse directions of the building.

The raw data collected from the site is processed in a lab to compute the natural period of the building. A generalised MATLAB[37] code is written to do the entire computation. As a first step, 15 minutes of undisturbed raw data is divided into 15 numbers of 1 minute data. A baseline correction is performed using standard MATLAB function developed by Hrovat[38]. Furthermore, a digital bandpass filter is used to remove unwanted noise from the captured data. The cut-off frequency is selected based on the probable natural period of a building. These two processes lead to 15 corrected acceleration time histories of one-minute data. Fourier spectrum is generated for each time history data and the average FFT is computed from these 15 FFT data, as shown in Figure 3. This step ensures the removal of unwanted noise, which could not have been removed in the filtering process. From this average FFT fundamental natural period of the building is identified based on the power spectrum peak picking method in one direction. A similar operation is carried out for other lateral direction. The natural period identified for all buildings by this procedure is tabulated in Table 3.

Proposed Equation

As discussed earlier, buildings tested in the current study qualify for equation (3). But, due to the unavailability of drawings, code based natural period for the structural wall system could not be computed. Hence, the measured period of tall buildings is compared with equation (5) in Figure 4a. This is equally important since amendment number 2 of IS 1893 has imposed lower bound (equation (5)) and upper bound (equation (2)) values of the natural period computed using equation (3). The period computed by equation (3) must be greater than equation (5) and should not be more than equation (2). Figure 4a indicates that the code recommended period expression (equation (5)) for other buildings underestimates the period for buildings having $h/d^{0.5}$ greater than 20. For buildings having $h/d^{0.5}$ less than 20, the code recommended expression sometime underestimates and sometime overestimates the period value. Another challenge with period expression having a lateral dimension of building as input is that the natural period measured has a huge difference for the two buildings with the same $h/d^{0.5}$ ratio, which is not captured by the current expression.

Figure 4b shows the IS 1893[2] recommended upper bound value (equation (1)) of the natural period along with the proposed expression (equation (5)) for tall buildings with other structural systems. The proposed equation (5) of draft IS 16700[7] is found to be better compared to RC bare frame equation (1). But, computation of base shear from the proposed equation will give lower base shear as it overestimates the natural period compared to the measured period. The proposed equation is found to be unconservative when it is compared with measured period data. Hence, there is a need to find an alternate equation that can reduce the gap between the actual period and the predicted period.

A comparison of the measured period with other code expressions is presented in Figure 4c. KBC[39] expression is precisely the same as RC bare frame expression given in IS 1893. The slight difference arises due to the third digit difference in coefficient value a between the two expressions. Similarly, ASCE 7-16[40] and NBCC[41] standards are nearly identical, and they are the most conservative of all the expressions compared in this study. But, they too fail to predict the natural period of tall buildings in India as they are giving good results only in the vicinity of a building of height 75 m. Before 75 m, they are overestimating the natural period, and above 75 m, they are underestimating the period. The natural period expression suggested by European code[42] for wind design stands out differently from all other expressions. This is due to the power a of h in the expression is one. But, European code expression, too, does not match with a measured period. This comparison leads to one more conclusion that natural period expression generated from the observed building periods of other countries will not be valid for tall buildings in India. Hence, it is suggested to develop empirical expressions based on the data obtained in India.

To investigate the influence of lateral dimensions of buildings on fundamental natural period, the plan aspect ratios of buildings and their natural period along both directions are plotted in Figure 5a and Figure 5b, respectively. Figure 5a indicates that except for four buildings, the rest all buildings have a plan aspect ratio of less than two. This could be a trend in tall buildings in India, and the same can be verified in future by collecting more such data. But, despite having an aspect ratio of more than one, most of the building's natural periods are close to each other, as shown in Figure 5b. This indicates that height plays an important role in the natural period, and the influence of a lateral dimension of buildings on the natural period is relatively less. This observation matches the previous studies[29,32,43,44], and hence new natural period empirical expression linked with the height of the building is explored in a next section.

The new empirical expressions and existing ones are evaluated based on statistical analysis. The new equations are developed using regression analysis, and the proposed models are evaluated based on the standard error of estimate S_e (equation (15)) and coefficient of determination R^2 (equation (9)). S_e helps in measuring the accuracy of the prediction made by a regression model, and for a very large value of data points, it approaches the standard deviation of the measured periods from the best-fit equation. And R^2 is a statistical value that measures the degree of interrelation and dependence between two variables, which varies between zero (indicating no correlation) and one (indicating perfect correlation). Here, for *'n'* number of sample size, $'T_i'$ and $'\bar{T}_i'$ are *'i^{th}'* measured natural period and computed natural period from the regression model, respectively.

$$S_e = \sqrt{\frac{\sum(\log T_i - \log \bar{T}_i)^2}{n-2}} \tag{14}$$

$$R^2 = 1 - \frac{n\sum(\log T_i - \log \bar{T}_i)^2}{\left(n\sum \log {T_i}^2\right) - (\log T_i)^2} \tag{15}$$

The new relation of the natural period based on height as only input (equation (1)) is explored by transforming both variables by means of a logarithm. The resulting data is plotted on a “log-log” scale, where a linear model is then fitted by equation (16). Where $y = \log(T)$ and $x = \log(H)$. The parameter 'a_1' and 'a_2' are determined by minimizing the squared error between the measured period and computed periods, and then 'a' was back calculated from the relationship $a_1 = \log(a)$.

$$y = a_1 + a_2 x \tag{16}$$

The stated procedure gives the values of a and b of equation (1) to represent the best fit. But, for computing the base shear demand, the code obtained natural period should give lower values. This is obtained by lowering the best-fit line by S_e without changing the slope (equation (17)). Similarly, for displacement based design of tall buildings, the code estimated natural period should be higher so that displacement demand will be more from displacement spectra[45]. Hence, increasing the best-fit line by S_e without changing the slope (equation (18)) is done.

$$\log a_{low} = \log C_t - S_e \tag{17}$$

$$\log a_{upper} = \log C_t + S_e \tag{18}$$

To start with, unconstrained regression analysis is performed to get values of a and b, as mentioned in equation (1). The first trial gave $S_e = 0.142$ and $R^2 = 0.88$. In the second iteration, the power b is rounded to 1.35 and constrained regression led to almost similar values of S_e and R^2. In the third iteration, the power b is made unit and this causes an increase in S_e and a decrease in R^2. The details of all these three trials are summarised in Table 4.

Similarly, constrained regression analysis is carried out by using a and b values of code expressions to compute S_e values. Such constrained regression analysis is carried out for building codes of India[2,7], USA[40], Canada[41,46,47], Europe[42], and Korea[39]. Among all these, ASCE 7-16 recommended expression was found to have the least S_e values. The Se values generated for all these expressions can be found in Table 5.

As discussed in the previous section and outlined in Table 4 and Table 5, among all iterations, equation (19) gives the least S_e = 0.142 and highest R^2=0.88 value. Hence, for the conservative design of tall buildings, for base shear computation, equation (20) is proposed for the Indian tall building code IS 16700[1]. In future, if displacement based design becomes popular in India, a designer can use equation (21) to arrive at displacement based on design displacement spectra. All these three equations are plotted in **Error! Reference source not found.** Figure 6a.

$$T_a = 0.0035h^{1.35} \tag{19}$$

$$T_a = 0.0030h^{1.35} \tag{20}$$

$$T_a = 0.0040h^{1.35} \tag{21}$$

The proposed equation has a power of 1.35, which essentially arises since the measured natural periods of tall buildings are elongated nonlinearly with an increase in height. This indicates that for the same structural wall system, the buildings tend to become flexible with an increase in height. Accumulating more such data for buildings with the same and different structural systems will provide more insight into this aspect. The power b of the proposed equation does not match with many of the past literature[15,32–36], except one[6], which has b = 1.10. The possible reason could be a difference in construction practices among all these countries. But, it is interesting to note that none of the code recommended expressions (Table 1) around the world have b greater than or equal to one, except the Wind code of Europe[42], which is quite common in literature recommending new expressions for RC buildings[6,15,32–36]. India can still go ahead with this new proposal since $b=1.35$ computes realistic natural periods, which will tend to give lesser base shear values than existing standards. The proposed expression is plotted with past literature in Figure 6**Error! Reference source not found.**b.

Discussions and Conclusions

The current study focused on developing empirical expression of the natural period for RC tall buildings by measuring actual natural periods by ambient vibration test. For this purpose, 28 number of RC tall buildings are surveyed in the city of Hyderabad and Mumbai, which fall into seismic zone II and III, respectively. An extensive literature study was done to understand the current code natural period expressions around the globe and how they are getting revised. Comparing the measured period with the existing international building code recommended expressions and proposed equations of similar global studies reveals that those equations are unsuitable for tall buildings in India. A similar observation is made while comparing the measured period with existing Indian code expressions and suggested expression stated in an upcoming revision of the tall building code.

Hence, the characteristics of sampled buildings are studied in detail, and it is found that the lateral dimension of buildings has the least influence on the natural period compared to the height of the building. With this insight, various unconstrained and constrained regression analysis is carried out to establish the relation between natural period and height alone. Based on the standard error of estimate and coefficient of determination of various proposals following new approximate expressions are proposed:

a) For forced based design to compute base shear, $T = 0.0030 H^{1.35}$

b) For displacement based design to compute target displacement, $T=0.0040H^{1.35}$

Where, T = Natural period in (sec) and H = Height of building in (m). Forced based design expression '*a)*' will be useful for buildings qualifying as per IS 16700[1], and for the design of code-exceeding buildings (as described by Annexure A of IS 16700[1]) the expression '*b)*' will be of a great use where design is carried out to achieve the desired performance of structure when building attains target displacement during a seismic event. Using these expressions will lead to better prediction of periods, thereby computing realistic design force.

The current proposal is made based on testing 28 number of buildings using ambient vibration study. Till India gets sufficient instrumented buildings that can capture periods of buildings shaken due to earthquake ground motion, the current expression holds good. Of course, the confidence level on expression will increase as the period database is expanded, covering buildings from different parts of the country. This expression can also be validated during real earthquakes. In future, the empirical expression should be revised from time to time. It is also suggested to derive separate empirical expressions for each structural system.

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Tables

Table 1: Natural period expressions in International codes

Country	**Building Code Name**	**Structural System**	**Expression**
USA	ASCE 7-16 [40]	RC SW	$T_a = 0.0488\ h^{0.75}$
Canada	NBCC [41,46,47]	For SW and Other structure	$T_a = 0.05\ h^{0.75}$
Europe	EN 1991 1-4 [42]	RC Multi-storey building H > 50m	$T_a = h/46$
Korea	KBC 2009 [39]	RC MRF	$T_a = 0.073\ h^{0.75}$
RC SW: Reinforced Concrete Structural Wall SW: Structural Wall RC MRF: Reinforced Concrete Moment Resisting Frames			

Table 2: Natural period expression proposed in past literature

Country	**Authors**	**No. of Buildings**	**Height Range: (m)**	**Expression**
Italy	Lagomarsino [32]	52	Up to 200	$T_a = h/55$
Japan	Satake et al. [33]	25	12 - 170	$T_a = h/67 = 0.015\ h$
Thailand	Warnitchai [34]	50	20 - 210	$T_a = h/54 = 0.0185\ h$
Canada	Gilles and McClure [35]	27	20 – 195	$T_a = 0.019\ h$
India	Velani and Ramancharla [15]	32	46.21 – 146.75	$T_a = 0.013\ h$
India	Velani and Ramancharla [6]	19	63 – 146.75	$T_a = 0.009\ h^{1.10}$
Korea	Ha et al. [36]	58	24.2 - 305	$T_a = h/51 = 0.0196\ h$

Table 3: Fundamental Natural Periods of RC Tall Buildings (>50m) Measured by Ambient Vibration

Serial No.	**Building ID**	**Plan Shape**	**Number of Storey**	**Building Height**	**Dimensions**		**Plan Aspect Ratio**	**Natural Period (sec)**	
			N	**H (m)**	**Longer 'L'(m)**	**Shorter 'D' (m)**		**Along L**	**Along D**
1	HYB39	Rectangle	17	50.81	45.82	42.75	1.07	0.738	0.620
2	HYB44	Rectangle	17	51.15	27.27	27.14	1.00	0.569	0.700
3	HYB45	Rectangle	17	51.15	28.00	24.00	1.17	0.593	0.688
4	HYB46	Rectangle	17	51.15	27.27	27.14	1.00	0.630	0.688
5	HYB47	Rectangle	17	51.15	27.27	27.14	1.00	0.625	0.682
6	HYB51	Rectangle	17	51.15	27.27	27.13	1.01	0.616	0.645
7	HYB52	Rectangle	17	51.15	40.53	28.00	1.45	0.569	0.650
8	HYB43	Plus	17	52.98	43.11	40.38	1.07	0.751	0.694
9	MUM05	L	20	58.60	30.74	19.91	1.54	0.987	0.811
10	MUM02	Rectangle	21	63.00	49.07	24.80	1.98	1.154	1.137
11	HYB12	Rectangle	22	65.60	28.94	26.56	1.09	0.920	0.963
12	HYB13	Rectangle	22	65.60	44.55	28.97	1.54	0.910	0.952
13	HYB53	L	22	66.00	27.00	27.00	1.00	1.050	1.050
14	MUM14	Rectangle	22	66.00	26.40	23.30	1.13	1.204	1.365
15	HYB18	Rectangle	22	66.00	81.08	25.45	3.19	1.154	1.078
16	HYB23	Rectangle	17	66.23	67.64	24.45	2.77	1.154	0.871
17	MUM01	Rectangle	23	69.00	49.07	24.80	1.98	1.388	1.122
18	MUM15	Rectangle	25	71.86	24.67	13.63	1.81	1.545	1.107
19	MUM03	L	25	75.00	48.19	40.62	1.19	1.365	1.412
20	MUM16	Rectangle	26	77.86	37.60	16.80	2.24	1.545	1.222
21	HYB20	Rectangle	27	81.00	73.43	20.58	3.57	1.280	1.170
22	HYB32	T	26	83.60	50.46	42.31	1.19	1.122	1.138
23	HYB42	Plus	28	86.37	43.11	40.38	1.07	1.154	1.388
24	HYB19	Rectangle	24	87.14	80.26	46.03	1.74	1.241	1.204
25	MUM08	Oval	31	90.95	52.54	35.18	1.49	1.638	1.517
26	MUM06	T	37	119.60	46.39	29.72	1.56	2.340	1.780
27	MUM07	Y	37	137.70	51.54	37.85	1.36	2.642	2.340
28	HYB31	Z	42	146.75	33.34	29.50	1.13	3.033	3.033

Table 4: Results from Regression analysis

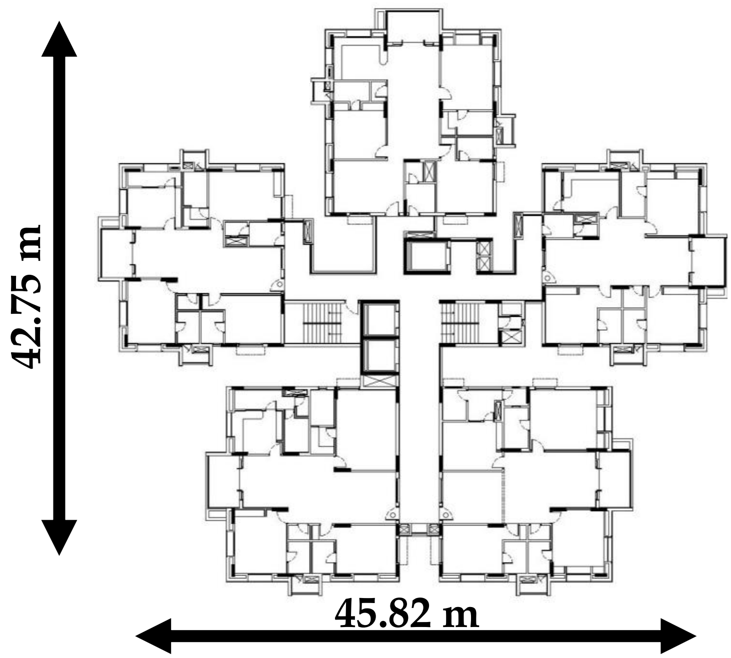
Regression Analysis Type	**Period Expression**			**S_e**	**R^2**
	Best Fit	**Best Fit – 1 σ**	**Best Fit + 1 σ**		
Unconstrained	$T_a = 0.0034\ H^{1.3562}$	$T_a = 0.0029\ H^{1.3562}$	$T_a = 0.0039\ H^{1.3562}$	0.142	0.88
Constrained, b = 1.35	$T_a = 0.0035\ H^{1.3562}$	$T_a = 0.0030\ H^{1.35}$	$T_a = 0.0040\ H^{1.35}$	0.142	0.88
Constrained, b = 1.00	$T_a = 0.0153\ H$	$T_a = 0.0128\ H$	$T_a = 0.0183\ H$	0.177	0.82

Table 5: Standard error in Code expressions with measured data

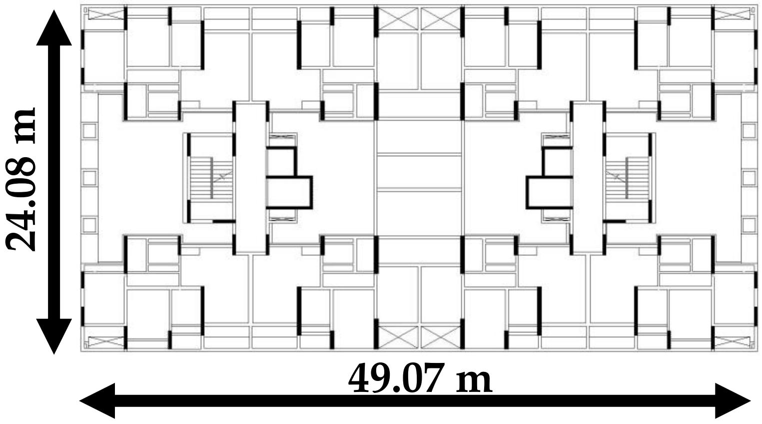
Country	**Code Name**	**Period Expression**	**S_e**
India	IS 1893 [2]	$T_a = 0.075\ H^{0.75}$	0.583
India	IS 16700 Draft[7]	$T_a = 0.0672\ H^{0.75}$	0.482
USA	ASCE 7-16 [40]	$T_a = 0.0488\ H^{0.75}$	0.249
Canada	NBCC 2020 [41,46,47]	$T_a = 0.050\ H^{0.75}$	0.260
Europe	EN 1991-1-4 Wind 4 [42]	$T_a = H/46$	0.399
Korea	KBC 2009 [39]	$T_a = 0.073\ H^{0.75}$	0.558

Figures

Figure 1: Sample of Tall building (HYB18) surveyed in the current study



(a) HYB39



(b) MUM01

Figure 2: Sample plans of buildings surveyed

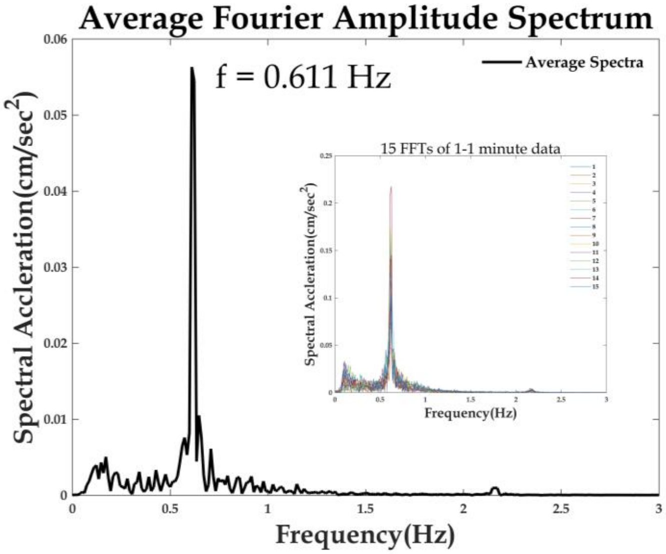
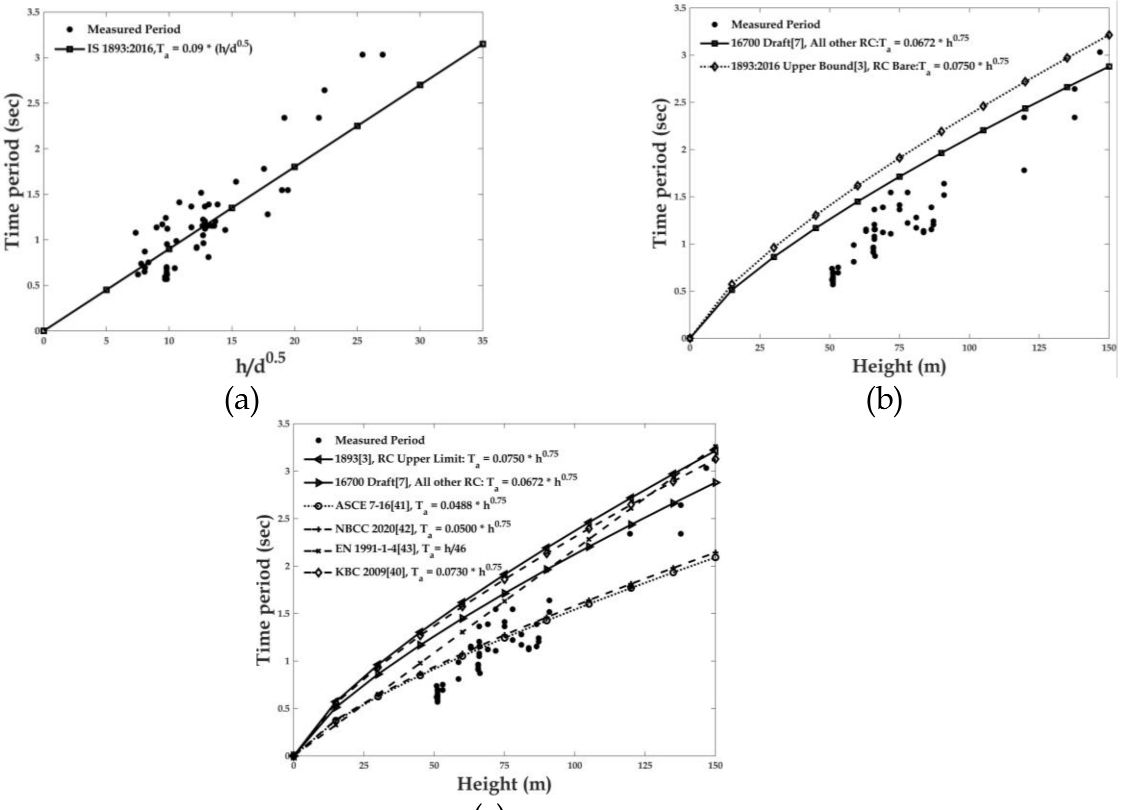


Figure 3: Mean Spectra of Sample building



(a) (b)

(c)

Figure 4: Measured period compared with (a) IS 1893 [2] *expression for other structures; (b) RC bare frame expression of IS 1893* [2] *and all other structural systems of draft revision*[7]*; (c) With few International Standards*

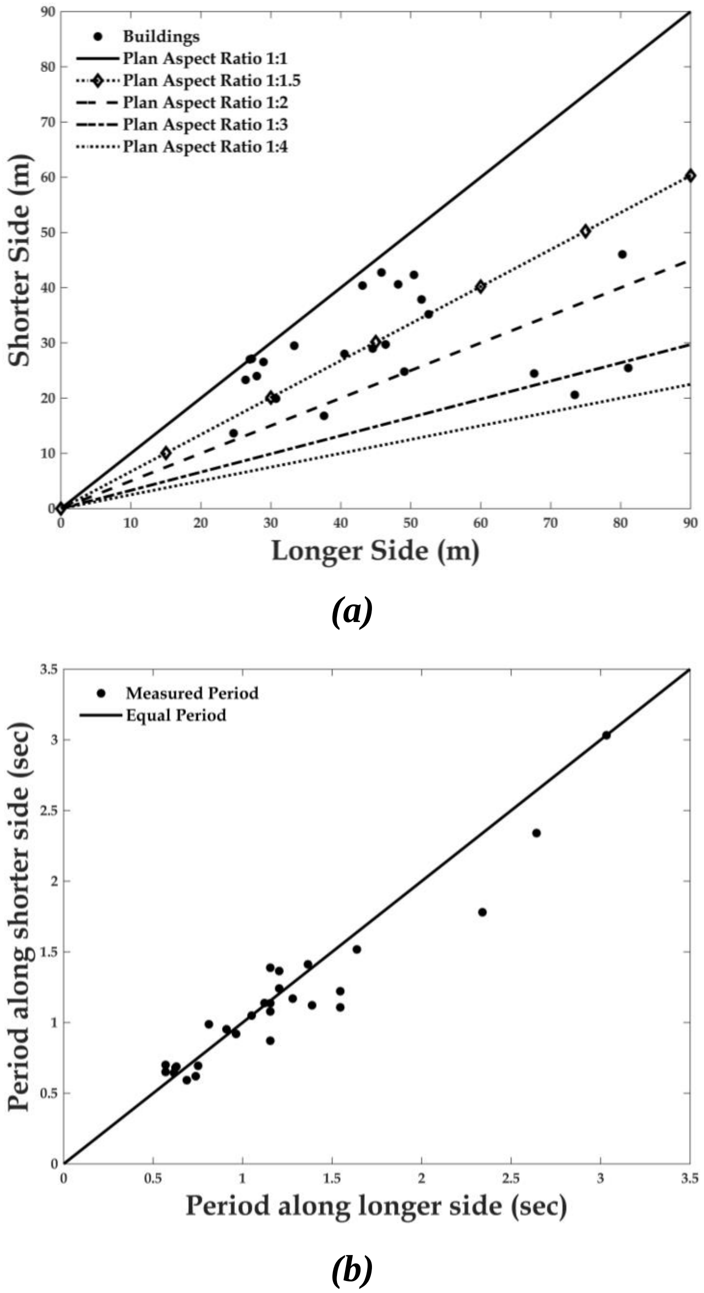
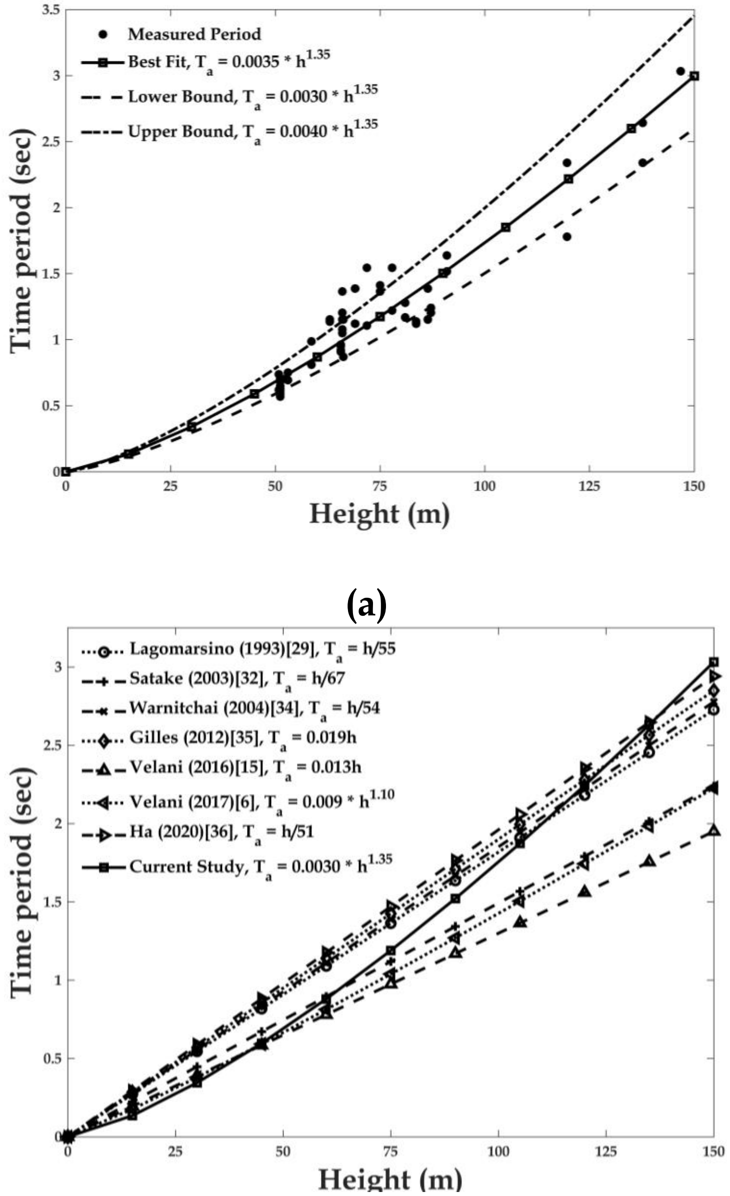


Figure 5: Influence of lateral dimensions (a) Plan aspect ratios of buildings under consideration; (b) Relation between measured period along two principal lateral dimensions



(a)

(b)

Figure 6: Proposed expression (a) Best fit curve; (b) Comparison with other published empirical expressions of RC Tall buildings