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ORIGINAL PAPER

Fundamental period of RC buildings with infill walls in Nepal

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Abstract
The presence of infill walls in a building increases the stiffness and mass of the building leading to significant changes in the fundamental period. If this increase in stiffness is not considered, it may cause severe damages to the buildings during the earthquakes. This paper presents an analysis of the fundamental period of buildings considering the effect of infill walls. For this, a computer program was created to generate buildings with different configurations and calculate the fundamental period. It was found that besides the geometric parameters: number of stories and the height of the building, the bay span also had a significant effect on the fundamental period. Thus, a formula that takes into account those parameters was formulated for infilled reinforced concrete (RC) frames. The building codes must take parameters like bay span and the presence of infill walls into account for estimating the fundamental period.

Keywords Fundamental period · Seismic design · Infilled frames · Masonry wall · Nepali buildings · Computer modeling

Introduction

The fundamental period of a building is a key parameter used in the design of buildings. It appears in building code provisions of many countries to design base shear and lateral forces. However, until a building is designed its fundamental period cannot be determined. Hence, building codes provide empirical formulas. NBC 105 (1994) (Nepal National Building Code: Seismic Design of Buildings in Nepal) also provides formulas for the fundamental period of framed structures with no rigid elements limiting deflection. In Nepal, ordinary buildings up to three stories are designed according to NBC 205 (1994), while for other buildings, NBC 105 (1994) and Indian Standard (IS 456:2000) (2000) is used. The site observations carried out after the April 2015 Gorkha earthquake have shown that buildings suffered considerable damage by neglecting the infill wall as structural members (Dumaru et al. 2016). Infill walls increase the structural stiffness which has a direct impact on structural response. Increased stiffness decreases the time-period significantly and adds considerable demand in the structural requirement of the building due to increased base shear and lateral load. Since Nepal lies in a high seismic risk zone due to the convergence of Indian and Eurasian tectonic plates, it has a greater need to consider the effect of infill walls in the seismic response of buildings to prevent damage to buildings and loss of life and property. The fundamental period can be determined by analysis of buildings using software analysis, by using Rayleigh's method or using empirical formulas. The fundamental period explicitly depends on the distribution of mass and the stiffness imparted from structural as well as non-structural components. Also, other parameters such as symmetry, element size, loading pattern, number of stories, number of bays and bay span, story height, and openings in the shear walls and infill panels implicitly affect the period.

Problem statement and research objective

The NBC 105 (1994) has not clearly stated the formula for calculating the approximate fundamental period of RC buildings with masonry infill walls. The objective of this study is to study the various parameters of a building affecting its fundamental period and provide a formula that takes into account the influence of the unreinfroced masonry infill walls.

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Building code provisions

Building codes all around the world follow different approaches for estimating the fundamental period of the building. Depending upon the different factors affecting the seismic performance on different zones of the countries, the building codes contain some similar parameters and some varying parameters. One universal parameter found in all building codes is the height of the building. Besides, there are several other parameters such as infill walls, plan dimensions, openings in walls, soil type, etc. which are found in some codes while absent from others. Most of the formulas provided in building codes and research articles follow a common general formula: $T = C_t H^{\delta}$, where T is the fundamental period of the building, H is the total height of the building, and δ is a constant-coefficient.

The NBC 105 (1994) provides the following approximate formula of the fundamental time-period for preliminary member sizing:

$$\begin{aligned} &T = 0.85H^{3/4} \text{ for steel frames} \\ &T = 0.06H^{3/4} \text{ for concrete frames and} \\ &T = \frac{0.09H}{\sqrt{D}} \text{ for other structures,} \end{aligned} \tag{1}$$

where D is the base dimension of the building at the plinth level (in m) along the considered direction of the lateral force.

The formula provided by IS 1893 (2016) differs only in the case of concrete frames where the formula provided by IS code is:$T = 0.075H^{3/4}$.

According to ASCE (2017), the approximate formula of the fundamental period for moment-resisting frame systems of reinforced concrete in which the frames resist 100% of the required seismic force and are not enclosed or adjoined by more rigid components that will prevent the frame from deflecting when subjected to seismic forces is: $T_a = C_t h_n^x$, where $C_t = 0.044$, $x = 0.9$, and h_n is the height of the building (in m) above the base to the highest level of the structure.

Eurocode 8 (2004) uses $T = C_t H^{3/4}$ by providing a more accurate expression for the calculation of C_t, for masonry infilled reinforced concrete frames:

$$C_t = \frac{0.075}{\sqrt{A_C}},$$

$$A_C = \sum A_i \left(0.2 + \frac{l_{wi}}{H}\right)^2,$$

where C_t is the correction factor for masonry infilled reinforced concrete frames, A_C is the combined effective area of the masonry infill in the first storey, A_i is the effective cross-sectional area of the wall in the direction considered in the first storey, and l_{wi} is the length of the walls in the first storey in the direction under consideration.

However, not all countries provide the height of buildings in the formula for the fundamental period. The National Building Code of Canada (2005) relates the fundamental period of the building with the number of storey above the ground as,

$$T = 0.1 \text{ N.}$$

Goel and Chopra (1997), in their paper, evaluated the existing formulas for the period of moment resisting frame structures through semi-empirical methods. They collected data of Californian RC buildings with heights ranging from 10 to 100 m from eight Californian earthquakes from the 1971 San Fernando Earthquake to the 1994 Northridge event. It was found that the general adopted formula: $T = C_t H^{3/4}$ underestimated the value of the fundamental period of the observed RC frames, particularly those above 16 stories. So, they provided an alternative formula for the time-period relating it to the total height of the building:

$$T = 0.0466H^{0.9}$$

A similar relation was semi-empirically derived by Hong and Hwang (2000) from 21 Taiwanese buildings subjected to moderate intensity earthquakes. The Taiwanese buildings were found to be stiffer than the Californian buildings, thus resulting in a lower estimation of the fundamental period. The formula derived is:

$$T = 0.0294H^{0.804}.$$

Previous researchers who studied the influence of the infill walls on the fundamental period of the RC buildings proposed different formulas based on the different building parameters.

Amanat and Hoque (2006) proposed the following equation:

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

where α_1, α_2 and α_3 are the modification factors for span length, number of spans, and amount of infill, respectively. These values are given in tabular format in the reference (Kose, 2009).

Crowley and Pinho (2006) obtained a simplified period-height relation for the cracked infilled RC buildings considering the typical Turkish buildings: $T = 0.055\ H$, where H is the total height of the building. Guler et al. (2008) used ambient vibration tests to compute the fundamental period of the Turkish buildings for elastic conditions and proposed an equation $T = 0.026\ H^{0.90}$, where H is the total height of the building above the basement. Another convenient expression for the fundamental period of the building is given by the equation

$$T = 0.1367 + 0.301H - 0.1663S - 0.0305I,$$

proposed by Kose (2009), where H denotes the height of a building in meters, S is the ratio of the percentage of shear walls to total floor area, and I is the area ratio of infill walls to total panels.

Shrestha and Karanjit (2017) conducted ambient vibration tests using geophones in 31 designed and free-standing RC framed buildings of Kathmandu Valley ranging from 3 to 18 storey. The period (T) and total building height (H) relationship obtained was of the form $T = 0.012H^{1.134}$. The relationship between the period, total building height, and base dimension (d) was found to be: $T = 0.03H^{0.94}/d^{0.04}$.

Methodology

The mathematical formulation of the fundamental period is fairly well known (Chopra 2017). In this paper, the fundamental period is obtained by formulating and solving the eigenvalue problem:

$$\left(K - M\Omega^2\right)\Phi = 0,$$

where, mass matrix (M) is a diagonal matrix whose elements are mass and moment of inertia (with the axis taken vertically through the centroid of the floor) for each floor by considering mass lumping at the floor level.

Stiffness matrix (K) is obtained by considering the stiffness of each column and each wall, in which the diaphragm is considered rigid. First, the stiffness of each member is expressed in its local coordinates and then it is transformed into global coordinates $\left[u_{x1}, u_{y1}, \theta_1, \ldots, u_{xn}, u_{yn}, \theta_n\right]$. The coordinates u_{xi}, u_{yi}, θ_i are the displacements of i th floor in x-, y-direction and rotation about the center of mass of the floor, respectively. The stiffness of a column is $K_c = \frac{12EI}{h^3}$ (E is the modulus of elasticity of column, I is the area moment of inertia, and h is the height of the floor) while the stiffness of the infill wall was taken as per IS code 1893 (2016) (Fig. 1).

Here, Ω^2 is the eigenvalue matrix whose diagonal elements correspond to the square of angular frequency (ω_i) of natural modes of the building. The fundamental time-period is then calculated using the smallest value among the angular frequencies ($T_i = 2\pi/\omega_i$).

To formulate and solve the above eigenvalue problem, computer programs were written by the authors in MATLAB and Common Lisp programming languages. The programs compute the mass matrix and stiffness matrix from the input Building Parameters and compute the fundamental period by solving the above eigenvalue problem. A sample calculation is shown in the Appendix.

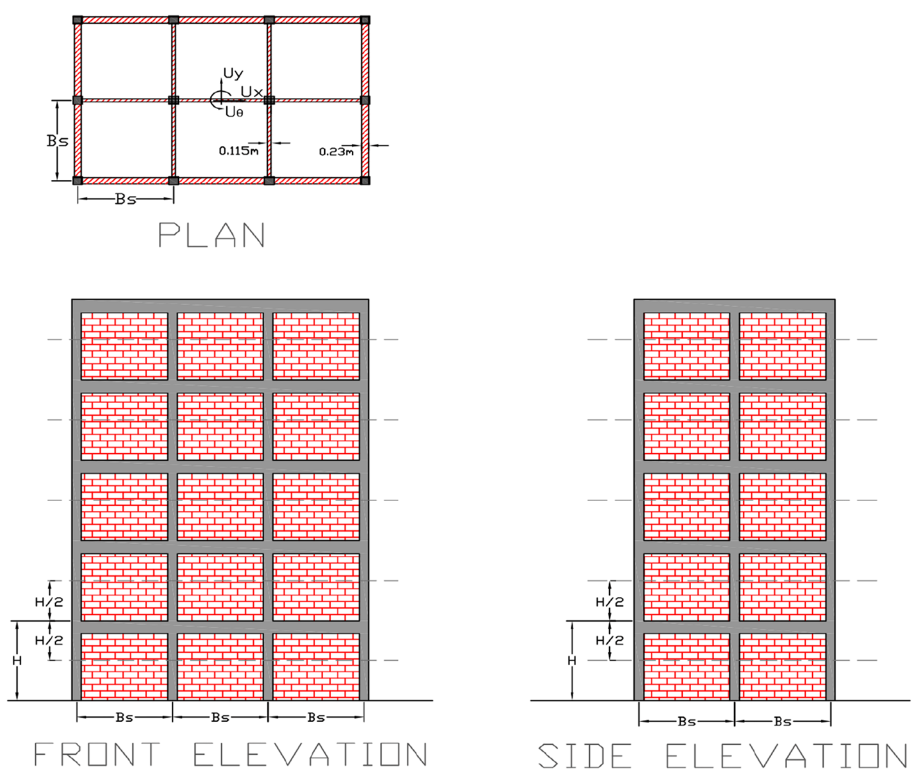

Fig. 1 Showing global coordinates and lumping of mass at the floor level

Table 1 Ranges of the values for building's geometrical parameters

Parameters	Values/range
Number of stories (N)	1–16
Story height (h)	3 m, 3.5 m, 4 m
Bay Span (B_s)	3 m, 3.5 m,…, 6 m
Number of Bays $\left(B_x, B_y\right)$	(2,2), (2,3), (2,4), (2,5), (3,3), (3,4), (3,5), …, (5,5)

Table 2 Variation of Beam and Slab size with Bay Span (B_s)

Bay span (m)	Beam size (width) (m)	Beam size (depth) (m)	Slab thickness (m)
3	0.230	0.375	0.125
3.5	0.240	0.400	0.125
4	0.260	0.430	0.125
4.5	0.280	0.460	0.125
5	0.300	0.500	0.150
5.5	0.330	0.530	0.150
6	0.360	0.560	0.150

Building parameters

Using the computer programs a collection of 3360 building models, with varying geometrical parameters as listed in Table 1 were generated and their fundamental time-period was calculated. The buildings considered were symmetrical, and all the exterior infill walls were of uniform 0.230 m thickness while all the interior infill walls were of 0.115 m thickness.

The sizes and strengths [Tables 2, 3] for the members were varied according to building parameters and their design was done according to IS 456:2000 (2000) by following a well-known book on RCC design (Punmia and Jain 2007). The stability of a few of the structures was verified using SAP2000 (Fig. 2).

Other building parameters are listed in Table 4:

In addition to the mass of structural members of the building, an additional 2.0 KN/m^2 live load and 1.5 KN/m^2 dead load (floor finish) were added to all floors except the roof.

Modeling of infill wall

Strut modeling of infill walls was done per IS code 1893 (2016). The unreinforced masonry walls were modeled assuming equivalent diagonal struts whose ends were considered to be pin-jointed to the RC frame. Since the walls were considered to be without any openings, the width of the diagonal strut was calculated by the following formula:

$$\text{Width, } b = 0.175 * \propto^{-0.4} * L, \text{where,} \propto = h * \sqrt[4]{\frac{E_b * t * \sin(2\beta)}{4 * E * I_{col} * h}}$$

, L is the length of the diagonal strut, h is the clear height of the unreinforced brick masonry, E_b is the modulus of elasticity of unreinforced brick masonry, t is the thickness ot the infill wall, β is the angle of inclination of the diagonal strut with the horizontal, E is the modulus of elasticity of the RC moment-resisting frame, and I_{col} is the area moment of inertia of the column (Fig. 3).

Table 3 Square columns with sizes varying with the number of stories N and bay span B_s

N	Bay span (m)						
	3	3.500	4	4.500	5	5.500	6
4	0.300	0.300	0.300	0.300	0.300	0.350	0.350
5	0.300	0.300	0.300	0.350	0.350	0.400	0.400
6	0.300	0.300	0.350	0.350	0.400	0.450	0.450
7	0.300	0.350	0.350	0.400	0.450	0.450	0.500
8	0.300	0.350	0.350	0.400	0.400	0.450	0.500
9	0.300	0.350	0.400	0.400	0.450	0.500	0.500
10	0.350	0.350	0.400	0.450	0.450	0.500	0.550
11	0.350	0.400	0.400	0.450	0.500	0.550	0.550
12	0.350	0.400	0.450	0.500	0.500	0.550	0.600
13	0.400	0.400	0.450	0.500	0.550	0.600	0.600
14	0.400	0.450	0.500	0.500	0.550	0.600	0.650
15	0.400	0.450	0.500	0.550	0.600	0.600	0.650
16	0.400	0.450	0.500	0.550	0.600	0.650	0.700

For $N \leq 3$ column size of 0.3 by 0.3 m was taken (all dimensions are in meters)

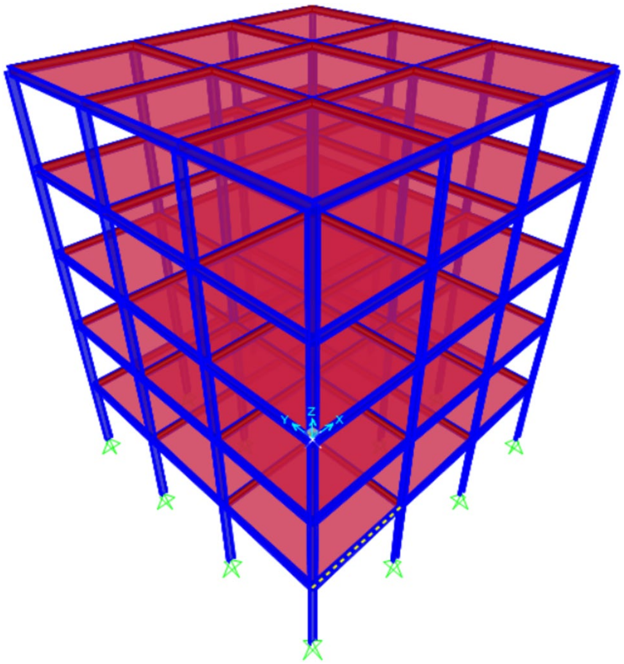

Fig. 2 SAP2000 model of a building. The structural stability of a few models was verified using SAP (Note that infill walls are not shown in the model figure to prevent clutter)

Table 4 Other building parameters

Parameter	Value
Characteristic compressive strength (f_{ck})	25 MPa for $N \leq 7$ and 30Mpa for $N > 7$
Modulus of elasticity for concrete E	$E = 5000\sqrt{f_{ck}}$ MPa
Modulus of elasticity for walls	$E_w = 2650MPa$
Tensile yield strength of steel	500 MPa
Width of Infill walls	Exterior walls: 230 mm, interior walls: 115 mm

Results and discussion

Sensitivity analysis

To understand the sensitivity of the time-period with the building parameters, the maximum variation in time-period due to variation in individual parameters was checked. The result is given in Table 5.

The principal component affecting the fundamental period, i.e. the total height of the building (*H*), is obtained when the number of stories (N) and story height (h) are considered together. This is the reason why all the building codes have a formula that depends either on total height H or the number of stories N. Apart from N and h, bay span (B_s)

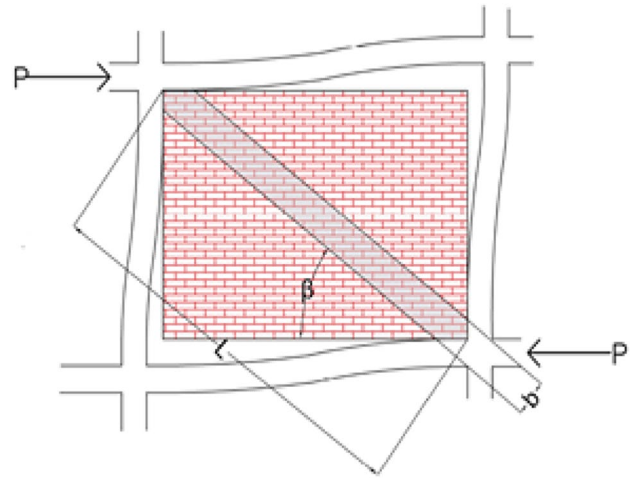

Fig. 3 Equivalent diagonal strut of unreinforced masonry infill wall

Table 5 Maximum variation in time-period

Varied parameter	Max time-period variation	Values of other parameter for Max variation
N	1.08	$h=4.0$, $B_s=3$, $(B_x, B_y)=(2, 5)$
H	0.35	$N=16$, $B_s=4$, $(B_x, B_y)=(2, 5)$
B_s	0.31	$N=16$, $h=4$, $(B_x, B_y)=(2, 2)$
N and H	1.10	$B_s=3.0$, $(B_x, B_y)=(2, 5)$
B_x and B_y	0.047	$N=16$, $h=4.0$, $B_s=3$

results in more variation in time-period (0.31 s) compared to bay sizes (0.047 s). The variation due to height, bay span, and bay sizes increases as the number of stories increase. Subsequently, the exact magnitudes of these variations will change with changes in strengths and sizes of members [Tables 2, 3, 4] and other building parameters (Bureau of Indian Standards, 2016). But the relative order of importance of these parameters is as observed above.

Regression analysis

Formula with total height only

Regression analysis with widely used formula $T = C_t H^b$ gives the following best-fit formula (in sense of least square fit):

$$T = 0.0368H^{0.788}.$$

The coefficient of determination R^2 of the regression is 95.1%, with root mean square error (RMSE) 0.0553.

Tweaking the coefficients for convenience of use results in a slight increase in RMSE to 0.0554.

$$T = 0.035H^{0.8} \tag{2}$$

The use of this formula can give, in the worst case, to a maximum percentage difference $\left(\frac{T_{\text{formula}} - T_{\text{program}}}{T_{\text{fromula}}}\right)$ of 29%, i.e. the actual time-period returned by our computer analysis would differ by up to 29% from the time-period returned by the formula. The deviation of the actual time-period from the time-period given by the formula increases with an increase in height of the building. A comparison of this formula with other formulas is shown in Fig. 4.

Formula considering bay span

Figure 5 shows that only the use of story height is insufficient to encompass the variation in the period. Apart from H, bay span is the most influential parameter. Hence, variation with bay span was checked which shows (Fig. 6) that the time-period decreases with an increase in bay span, and the rate of decrease is more rapid with an increase in the number of stories. Previous studies (Asteris et al. 2015; Amanthaneni and Dhakal 2016) have shown that the fundamental period increases with the increase in bay span because for a given frame configuration of given column size, the lateral stiffness decreases and, consequently the period increases. But, when the buildings are designed, an increase in bay span also requires bigger columns as given in Table 3 and consequently we found that the stiffness increases and the fundamental period decreases for designed buildings.

So, a new formula is proposed by the authors (with $R^2 = 99.0\%$ and RMSE = 0.0247):

$$T = aH^b - c\left(NB_s\right)$$

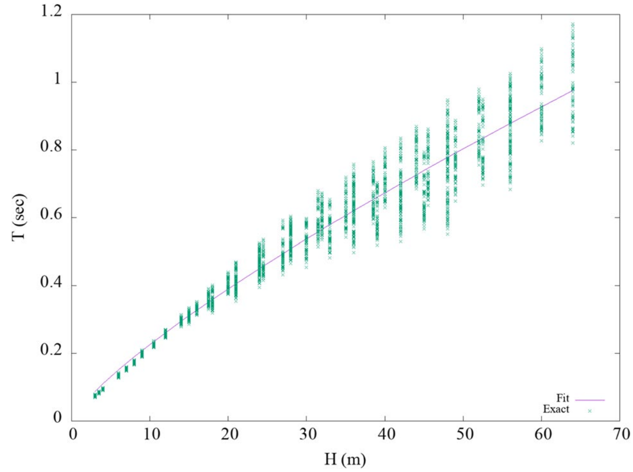

Fig. 5 Fundamental Period vs Total Height of the Building. Cross represents the actual data points from program, and the line is the best-fit Eq. (2)

$$T = 0.0445H^{0.817} - 0.00458\left(NB_s\right) \tag{3}$$

Tweaking the formula for convenience of use results to (with $R^2 = 98.9\%$ and RMSE = 0.0252)

$$T = 0.045H^{0.82} - 0.005NB_s \tag{4}$$

Although the new formula (Eq. 4) has a similar maximum percentage difference (= 28%) with the previous formula (Eq. 2) it has significantly lower RMSE and on average this formula gives values closer to the time–periods obtained from computer analysis. Figure 7 shows how the proposed equation fits the data.

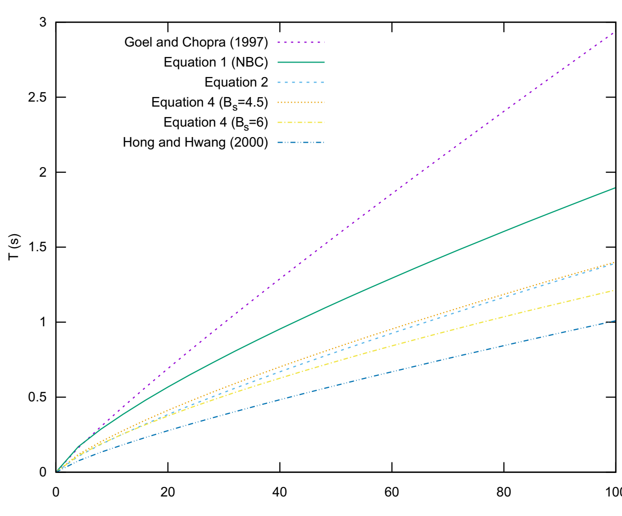

Fig. 4 Comparison of existing formulas and proposed formulas

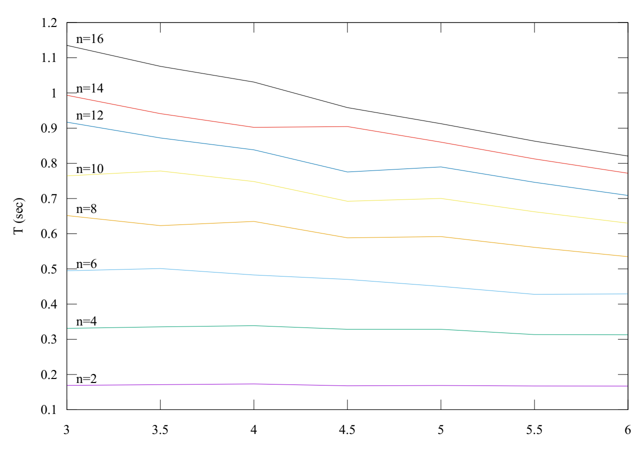

Fig. 6 Time–period vs bay span for different values of N (Other parameters were kept constant at $h = 4$, $(B_x, B_y) = (2, 2)$)

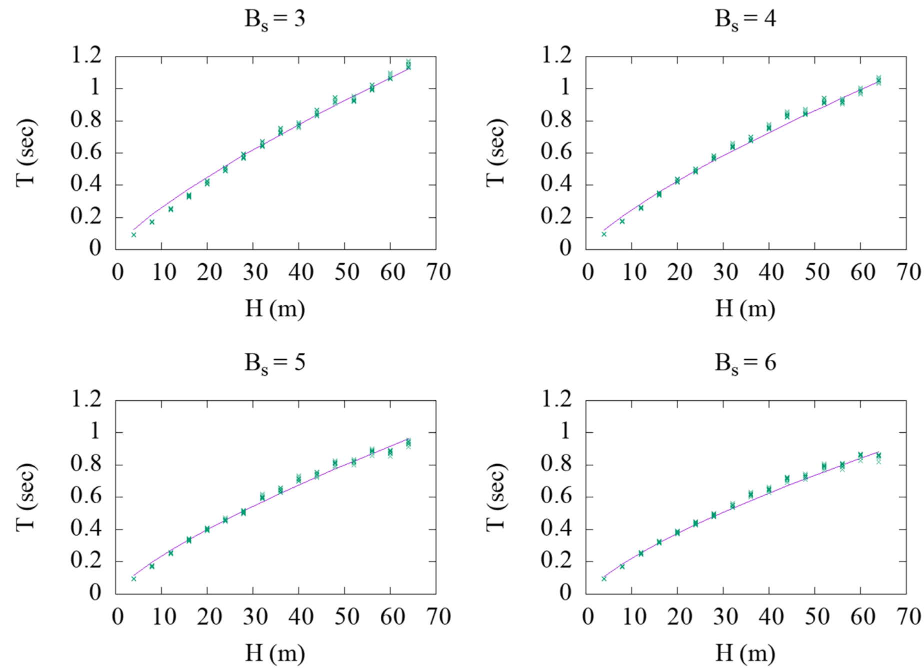

Fig. 7 Eq. (4) is plotted along with the exact data points for bay spans 3 m, 4 m, 5 m, and 6 m. H is the total height of the building (story height $h = 4$)

Effect of different bay spans

The building models used for Sensitivity Analysis and Regression Analysis were symmetrical buildings with equal bay spans in both directions, but in practice, the bay spans can vary. Thus, extra building models were generated with different bay spans (B_{sx},B_{sy}) on the two sides (in the range 3–6 m (by step size 0.5 m)). Although expression for the equivalent bay span to use in Eq. (4) was not found. The fundamental period of the buildings with different bay spans was compared with the ones with equal bay spans ($B_S = \max(B_{SX}, B_{SY})$) in both directions. It was found that in 98% of cases, the fundamental period of buildings with different bay spans was higher than that of buildings with the same bay span. And for the 2% cases where the fundamental period was lower, the difference was only 2% on average and 9% at max.

Formula	Max % difference	R^2	RMSE
$T = 0.04H^{0.78}$	30.9	0.9377	0.6685
$T = 0.05H^{0.82} - 0.006\ NB_s$	29.6	0.9879	0.2948

Non-typical buildings

In the above sections, analysis of typical buildings (i.e. buildings with member sizes and other parameters as listed in [Tables 2, 3, 4]) was done. In this section, the analysis of buildings with different considerations is presented.

Thicker infill walls

To check the dependence of wall thickness on the fundamental period, the analysis was redone with infill walls of both external and internal thickness 0.230 m. Similar results are obtained but with slightly higher coefficients.

Without stiffness from infill walls

To get an idea of the effect of the stiffness of infill walls, the stiffness provided by infill walls in typical buildings was removed i.e. $E_w = 0$ MPa was used instead of 2650 MPa (See Sample Calculation, Appendix). The statistical values of the variable ζ are listed below:

$$\zeta = \frac{T_{E=2650}}{T_{E=0}} \times 100\% ,$$

Lower bound	Mean	Upper bound	Standard deviation
20%	51%	84%	15%

This shows that for a typical building if the analysis is done incorrectly without considering the stiffness of infill walls, the fundamental period is highly overestimated. The proper estimate of the fundamental period would be on average 0.51 times (or about half) of the fundamental period estimated without considering the effect of stiffness of infill walls. This overestimation would suggest a smaller base shear force and could lead to structural damage during actual earthquakes.

Comparison with Nepal National Building Code (NBC 105 (1994))

The formula recommended by NBC 105 (1994) for estimating the fundamental period of a building is $T = 0.06H^{3/4}$. Figure 8 shows that the proposed Eq. (4) fits the data very well whereas it is clear from Fig. 9 that the NBC 105 (1994) formula (Eq. 1) very much overestimated the fundamental period. Moreover, a comparison of Eq. (1) with the data generated by neglecting the stiffness of infill walls indicates (from Fig. 10) that the fundamental period from the NBC 105 (1994) formula would only be safer when the infill walls did not provide any structural stiffness.

Conclusion

The fundamental period is one of the most important parameters affecting the seismic design of buildings. In this study, the significant parameters affecting the fundamental period have been investigated and the regression equation for infilled reinforced concrete frame structures has been developed taking into account the bay span along with the number of stories and height of the building. In addition to the members' weights, additional 1.5 kN/m^2 (dead load) and 2 kN/m^2 (live load) were taken at all floors except at the roof. The diagonal strut modelling was done as an additional assumption to include the effect of the infill walls according to the IS 1893 (2016). In order to get more accurate results, nonlinear finite element modelling of the unreinforced masonry infill walls (Crisafulli 1997) could be done considering the relevant size of openings in masonry walls and flexibility of the foundation soil. Although the developed relation for the fundamental period is relatively new, the generated equation is correct for specific conditions that are common in Nepal.

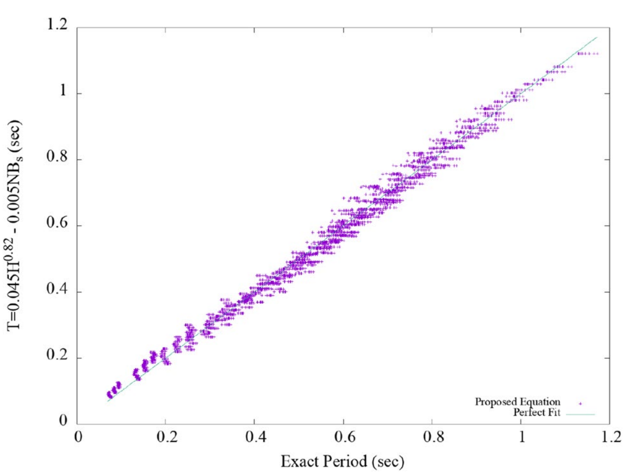

Fig. 8 Fundamental period from Eq. (4) (fitted T) is compared with the period obtained from the computer program (exact T)

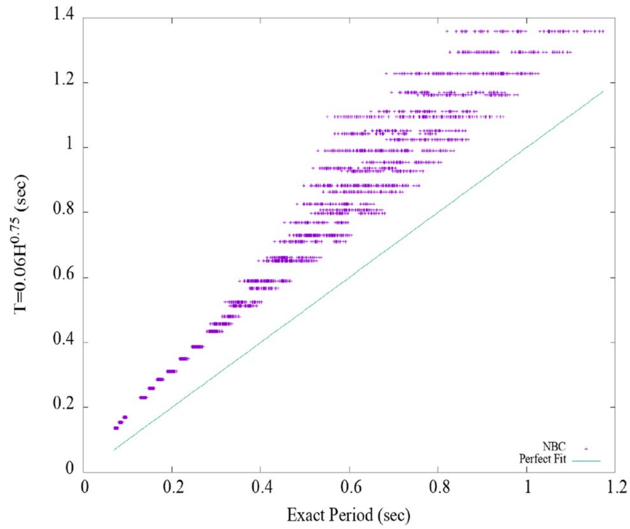

Fig. 9 Fundamental period from NBC 105 (1994) Eq. (1) compared with actual period

Moreover, the results depend on the assumption used for modeling (i.e. story height, gravity loads, bay span, roof characterization, and so on). It is also noted that for actual use of the proposed equation, calibration with empirical data might be necessary.

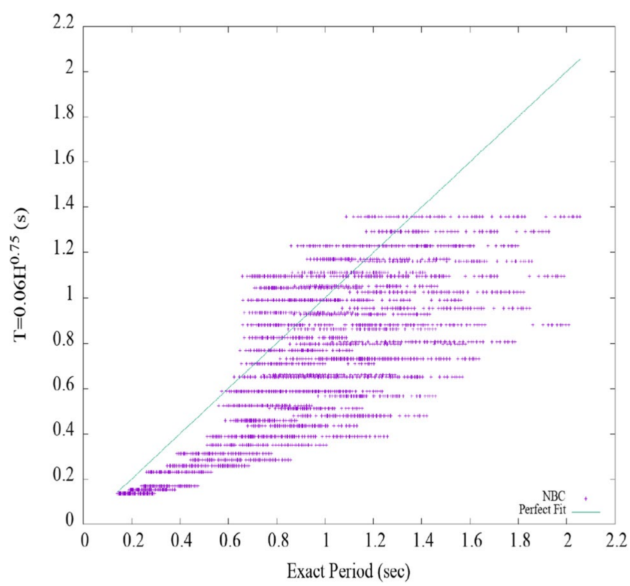

Fig. 10 Fundamental Period from NBC 105 (1994) Eq. (1) compared with the time-period obtained by the analysis which does not consider stiffness of infill walls

Appendix

Sample calculation performed by the computer program

To elaborate on the method that the computer program uses, a sample calculation is presented here:

In the following steps, the fundamental period of the building with the below-mentioned geometry will be calculated.

Geometry

Number of stories ($N = 3$), story height ($h = 3$), bay span ($B_s = 5$) and two bays along each axis ($B_x = 2, B_y = 2$).

Member sizes and strength

Column size 0.3 m by 0.3 m, Beam Depth 0.500 m, Beam Width 0.300 m, Wall Thickness 0.230 m, Slab thickness 0.150 m, Column Elasticity $5000\sqrt{25}\text{MPa} = 2.500 * 10^{10}\text{Pa}$, Wall Elasticity $2.65 * 10^9$ Pa, Concrete Unit Weight 25 kN, Masonary Unit Weight 20 kN or Concrete Density = 2548.420 kg/m^3 and Masonry Density = 2038.736 kg/m^3.

Mass matrix

Mass calculation for Floor 1 and 2.

Total extra load of (3.5 kN/m^2 = 356.779 kg/m^2 (live load + floor finish)) on the floor is added on slab and subtracted from column and wall area.

1. Each column = 2548.420*0.300*0.300*2.850 − 356.779*0.300*0.300 = 621.560 kg
2. Columns total = 621.560*9 = 5594.04 kg
3. Each beam span = 2548.420*4.700*0.300*0.350 = 1257.645 kg
4. Beams total = 1257.645*12 = 15,091.74 kg
5. Each wall span = 2038.736*4.700*0.230*2.500 − 356.779*4.700*0.230 = 5124.006 kg
6. Walls total = 5124.006*12 = 61,488.072 kg
7. Slab = 2548.420*10.300*10.300*0.150 + 10.300*10.300*356.779 = 78,404.944 kg

Total mass = 160,578.796 kg.

And from the distribution of mass from the floor plan, the centroids and the mass moment of inertia about the centroid is calculated to be:

XC	5.000	X-coordinate of centroid
YC	5.000	Y-coordinate of centroid
MASS	160,578.798	Total mass
IXX	1,734,595.484	Moment of inertia along X-direction from the centroid
IYY	1,734,595.484	Moment of Inertia along Y-direction from the centroid
IPC	3,469,190.968	Polar Moment of Inertia

Mass calculation for 3rd floor

- Each column = 2548.420*0.300*0.300*1.350 = 309.633
- Each beam span = 2548.420*4.700*0.300*0.350 = 1257.645
- Each wall = 2038.736*4.700*0.230*1.000 = 2203.874
- Slab = 2548.420*10.300*10.300*0.150 + 10.300*10.300*0.000 = 40,554.283

MASS	84,879.207
IPC	1,838,611.448

Finally, we get the mass matrix:

160,578.798	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	160,578.7981	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	3,469,190.968	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	160,578.7981	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	160,578.7981	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	3,469,190.968	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	84,879.2070	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	84,879.2070	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1,838,611.448

Stiffness matrix

- Area moment of inertia of a column $I_c = \frac{1}{12}0.3^4 = 6.75*10^{-4}$
- K of column $= 12\frac{E_c I_c}{h^3} = 75*10^5$

Infill wall (length $l = 5 - 0.3 = 4.7$ m, height = 3–0.5 = 2.5 m).

- $L_{ds} = 5.323$
- $\theta = 0.489$
- $\alpha = 3.289$
- $w_{ds} = 0.579$
- $t_{ds} = \max\left(\frac{h}{12}, \frac{l}{12}, b = 0.23\right) = 0.392$
- Strut's stiffness $K = \frac{t_{ds} w_{ds} E_w}{l_{ds}} \cos^2\theta = 8.794*10^7$

For a single frame in X-direction (single floor).

- Stiffness from walls = $8.794*10^7*2 = 17.58*10^7$

- Stiffness from columns $= 75*10^5 * 3 = 2.25 * 10^7$
- Total stiffness $= k_1 = k_2 = k_3 = 19.84 * 10^7$

Local stiffness matrix (K_{lx1}).

396,755,259.2	– 198,377,629.6	0.0
– 198,377,629.6	396,755,259.2	– 198,377,629.6
0.0	– 198,377,629.6	198,377,629.6

Local coordinate to the global coordinate transformation matrix A_{x1} (for the first frame along X-axis).

1.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	1.0	0.0	5.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	5.0

Finally, Stiffness matrix is obtained $K = \sum \left[A_{xi}^T K_{lxi} A_{xi} + A_{yi}^T K_{lyi} A_{yi}\right]$.

1,190,265,777.6	0.0	– 0.0000009537	– 595,132,888.8	0.0	0.00000047684	0.0	0.0	0.0
0.0	1,190,265,777.6	0.0	0.0	– 595,132,888.8	0.0	0.0	0.0	0.0
– 0.0000009537	0.0	39,675,525,920	0.00000047684	0.0	– 19,837,762,960	0.0	0.0	0.0
– 595,132,888.8	0.0	0.00000047684	1,190,265,777.6	0.0	– 0.0000009537	– 595,132,888.8	0.0	0.00000047684
0.0	– 595,132,888.8	0.0	0.0	1,190,265,777.6	0.0	0.0	– 595,132,888.8	0.0
0.00000047684	0.0	– 19,837,762,960	– 0.0000009537	0.0	39,675,525,920	0.00000047684	0.0	– 19,837,762,960
0.0	0.0	0.0	– 595,132,888.8	0.0	0.00000047684	595,132,888.81	0.0	– 0.0000004768
0.0	0.0	0.0	0.0	– 595,132,888.8	0.0	0.0	595,132,888.81	0.0
0.0	0.0	0.0	0.00000047684	0.0	– 19,837,762,960	– 0.0000004768	0.0	19,837,762,960

Once we have the stiffness and mass matrix we can solve the eigenvalue problem $\left(K - M\Omega^2\right)\Phi = 0$.

- Eigenvalues $\left\{\omega_i^2\right\} = 13{,}587.9, 7273.8, 974.4, 20{,}947.9, 11{,}212.6, 1502.0, 974.4, 13{,}587.9, 7273.8$
- Time-periods (sorted) $T_i = 2\pi/\omega_i = 0.2012, 0.2012, 0.1621, 0.0736, 0.0736, 0.0593, 0.0539, 0.0539, 0.0434,$

Hence, the fundamental period is 0.2012s.

Author contributions KBT conceived of the presented idea. PS carried out sample verification of buildings for member sizes using SAP2000. BP and PD wrote programming languages in LISP and MATLAB. BP made programs for the regression analysis, sensitivity analysis, and curve fitting in LISP. PD and PS conducted curve fitting and regression analysis in MATLAB and Excel. KBT supervised the findings of this work. BP, PD and PS wrote manuscript with the support from KBT. KBT reviewed the final manuscript and made subsequent corrections.

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Code availability The code of the program used for fundamental period calculation is available at a Github repository (https://github.com/bpanthi977/fundamental-period) of the author. Another repository has the code used for regression analysis and exploration of generated data. (https://github.com/bpanthi977/fundamental-period-workbook).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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