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A simplified method for estimating the fundamental period of masonry infilled reinforced concrete frames

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Abstract. The fundamental period is an important parameter for seismic design and seismic risk assessment of building structures. In this paper, a simplified theoretical method to predict the fundamental period of masonry infilled reinforced concrete (RC) frame is developed based on the basic theory of engineering mechanics. The different configurations of the RC frame as well as masonry walls were taken into account in the developed method. The fundamental period of the infilled structure is calculated according to the integration of the lateral stiffness of the RC frame and masonry walls along the height. A correction coefficient is considered to control the error for the period estimation, and it is determined according to the multiple linear regression analysis. The corrected formula is verified by shaking table tests on two masonry infilled RC frame models, and the errors between the estimated and test period are 2.3% and 23.2%. Finally, a probability-based method is proposed for the corrected formula, and it allows the structural engineers to select an appropriate fundamental period with a certain safety redundancy. The proposed method can be quickly and flexibly used for prediction, and it can be hand-calculated and easily understood. Thus it would be a good choice in determining the fundamental period of RC frames infilled with masonry wall structures in engineering practice instead of the existing methods.

Keywords: fundamental period; masonry wall; infilled RC frame; theoretical method; hand-calculated; probability

1. Introduction

The construction method of filling masonry walls in reinforced concrete (RC) frames is widely and popularly used in multi-story buildings due to their advantage of easy material extraction, simple construction, good heat insulation and sound insulation performance (Penava *et al*. 2018, Peng *et al*. 2018, Surana *et al*. 2018, Parghi and Alam 2018, Zengin 2018, Marques *et al*. 2019). In the design of the infilled RC frame buildings, the lateral resistance of the masonry walls is generally neglected, even though the infill wall has a certain influence on the structural performance of them. Extensive experiments and analyses have been conducted to study the influence of masonry walls (Pujol and Fick 2010, Koutromanos *et al*. 2011, Fiore *et al*. 2012, Asteris *et al*. 2013, Smyrou *et al*. 2013, Petry and Beyer 2014, Penava *et al*. 2016, Perrone *et al*. 2017, Xin *et al*. 2017, Blasi *et al*. 2018, Mouzakis *et al*. 2018, Verderame *et al*. 2019). However, due to the lack of deeply understanding of the interaction behavior between the RC frame and the masonry walls, the seismic performance of such composite structures has not been clearly drawing conclusion. It is because of these limitations on seismic design, the infilled RC frame structures were damaged, destroyed, even collapsed under earthquakes, which caused tremendous deaths, injuries and economic losses (Zhao *et al*. 2009, Verderame *et al*. 2011, Belleri *et al*. 2014, Penna *et al*. 2014).

Seismic performance of building structures is not only related to the intensity of the earthquake, but also to the dynamic characteristics of the structures themselves (Koutas *et al*. 2014, Jiang *et al*. 2018). The design spectra curves are commonly used to determine the relationship between structural performance demands and the hazard levels of seismic (Newmark and Hall 1982). Also the base shear forces of the structures are calculated based on the design spectra curves and the fundamental periods of the structures. The fundamental period is an important parameter to determine the spectral acceleration of the building structures, which is used for determining the seismic response modification factor. Thus an accurate prediction of fundamental period is of great significance for seismic design and seismic risk assessment of building structures (Lee *et al*. 2000, Guler *et al*. 2008, Oliveira and Navarro 2010, Asteris *et al*. 2017a). The fundamental periods depend on the lateral stiffness and the structural mass of the buildings, which are closely related to the

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material properties, the section properties, the floor plans and the connection types of the structures. The fundamental periods can be evaluated by using the analytical methods (El-Dakhakhni *et al*. 2003, Asteris 2003, 2008, Puglisi 2009, Stavridis 2010, Nikoo *et al*. 2017, Doven and Kafkas 2017, De *et al*. 2018, Lemonis *et al*. 2019).

Empirical formulas on calculating the fundamental periods of building structures are recommended by the standards or design codes of many countries. These formulas were determined from regression analyses of a large number of numerical and experimental data. Most of these formulas are related to the height or story number of the buildings, and the constant values are suggested for the buildings with different structural types or different construction sites of the buildings. Though it is easily for calculating the fundamental periods of building structures in engineering practice. The fundamental period results calculated in these formulas are imprecise in most cases (ATC-06 1978, FEMA-450 2003, Eurocode 8 2004, NBCC 1995). Gallipoli *et al*. (2010) conducted a regression analysis on the height-period relationships based on the measured periods of 244 RC buildings, and the results were quite different from those mentioned in the codes. Thus it is recommended that the empirical formulas are needed to be refined with considering the effects of the other parameters except of the building height.

Amanat and Hoque (2006) clarified that the fundamental periods were significantly affected by the number of spans and infilled walls and the span length. Kose (2009) proposed a new empirical formula with considering the effects of the building height, configurations of the frame as well as the masonry walls. Ricci *et al.* (2011) established 3D numerical models with varying structure configurations (building height, surface area, ratio between plan dimensions) and infill characteristics, and period formulas were proposed based on the regression analysis of numerical results. Hatzigeorgiou and Kanapitsas (2013) found that the flexibility of soil elongates the fundamental period, and considered the soil-structure effect in addition to the height, the length and infill walls of the buildings. Perrone *et al.* (2016) considered the effects of the building height, the flat/deep beam, the infills Young modulus, the openings in the infills and setbacks, and proposed simplified formula for period estimation. Masi and Vona (2009) evaluated the fundamental period of RC frames with different structural characteristics (number of stories, irregularity in elevation, presence and position of infills etc.). Al-Balhawi and Zhang (2017) proposed empirical formulas to predict the elastic periods of different types of models, and considered the effects of the number of storeys, the number and length of bays, plan configurations, mechanical properties of infills and the openings in infills etc. Asteris *et al.* (2015a, b, 2016a, 2017b) investigated the effects of several parameters on the fundamental period estimation of RC frame with masonry wall structures, and an empirical expression was proposed including the effects of the height, the number of span, the span length and the configurations of the frame and the masonry walls. These analytical methods are still based on the regression analysis of the period data of some typical structures, and it still lacks of theoretical basis and in-depth analysis of the mechanical behavior between the frame-walls in RC structures. Although the finite element method (FEM) results have high precision, it still takes effort in modelling the buildings and professional controlling the FEM software, which seems to be time-consuming for structural engineers.

In this paper, a theoretical method is developed to predict the fundamental period of the RC frame infilled masonry walls. Firstly, the theoretical model of the masonry infilled RC frame structures is developed based on single diagonal strut model (Asteris *et al.* 2011) and the parallel spring model (Aninthaneni and Dhakal 2016, 2017). The mechanical behavior of such composite structures under lateral forces and different configurations are considered into the proposed model. Then, the fundamental period results predicted by the theoretical method are compared to the FEM results in the FP4026 Research Database (Asteris 2016b). A correction coefficient is proposed to control the errors between the estimated values and the FEM values. The corrected formula is verified by shaking table tests on two masonry infilled RC frame structures (Žarnić *et al.* 2001). Finally, a probability-based method for estimating fundamental period is proposed, which allows the structural engineers to flexibly select an appropriate period value under a certain safety redundancy.

2. A simplified model for modelling the masonry infills

The masonry walls are connected with the beams and the columns of the RC frames, the interaction between the frames and the masonry infill walls would increase the lateral stiffness and the lateral resistance of the RC frame structures. The nonlinear behaviors of the masonry infill walls as well as the interaction action should be considered in the numerical analysis of the RC frame with masonry wall structures. There are two main approaches for modelling infilled walls, including the microscopic model (Tzamtzis and Asteris 2003) and the macroscopic model (Fiore *et al.* 2016). The microscopic model was commonly developed based on the finite element method, and the infilled walls were meshed as several elements. The modelling process of the microscopic model is complex and time-consuming, and the calculation convergence of the model is not so good. The macroscopic model is a simplified method, the infilled walls were always simplified as two crossed diagonal struts or a single diagonal strut, and the nonlinear behavior of the walls was inputted by an idealized nonlinear material model. Due to the complexity and high non-linearity of the microscopic numerical model of the masonry walls structures, the macroscopic models are generally used to simulate the seismic behavior of RC frames with masonry wall structures. The simplified single diagonal strut model is one of them, which is depicted in Fig. 1. It has been proven to be the most popular over the years (Asteris *et al*. 2017a).

The concept that considering the effect of infill walls as diagonal braces was proposed by Polyakov (1960) Then, Holmes (1961) conducted an in-depth study based on

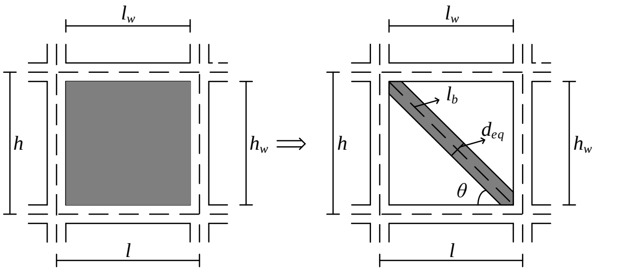


Fig. 1 Diagram of the simplified single diagonal strut model

several full-scale tests, and estimated an infill wall as an articulated diagonal strut with the same material and thickness of the infill wall. Smith (1966) and Smith and Cater (1969) found that the width of the equivalent diagonal strut was related to the wall-frame contact length, and proposed the wall-frame relative stiffness parameter λ_h to predict the width of the diagonal strut d_{eq}. The wall-frame relative stiffness parameter can be calculated by:

$$\lambda_h = \sqrt[4]{\frac{E_w t_w \sin 2\theta}{4EIh_w}}h \tag{1}$$

where E_w, h_w and t_w are the elastic modulus, the height and the thickness of the infill wall, respectively; E and I are the elastic modulus and the inertia moment of the column; $\theta = \tan^{-1}(h_w / l_w)$ is the inclined angle between the diagonal strut and the beam; l_w is the length of the infill wall, which is equal to the clear length of the RC frames; h is the story height of the RC frames.

Mainstone and Weeks (1970) and Mainstone (1974) summarized the experimental and analytical data and proposed the calculation of the width of the equivalent diagonal strut d_{eq}:

$$d_{eq} = 0.175\lambda_h^{-0.4} l_b \tag{2}$$

where l_b is the length of the estimated diagonal strut. Eq. (2) was adopted by the FEMA-274 (Federal Emergency Management Agency 1997) and the FEMA-306 (Federal Emergency Management Agency 1998), and it was also commonly used for simulating the behavior of RC frames with masonry infill wall structures. The cross-sectional area of the equivalent strut is $A_w = t_w d_{eq}$. Therefore, the initial stiffness of the masonry wall can be defined as the axial stiffness of the equivalent diagonal strut:

$$K_w = A_w E_w / l_b \tag{3}$$

This simplified model was adopted by Asteris (2003) to calculate the lateral stiffness of the masonry infilled frame. After that, the simplified model made contributions to the research on the influence of column shear failure (Cavaleri *et al.* 2017), out-of-plane response of the filling frame (Asteris *et al.* 2017c), influence of openings and vertical loads on the infilled frame (Asteris *et al.* 2016c), and period prediction of infilled frame structures (Asteris and Nikoo 2019). These equations (Eqs. (1)-(3)) were accepted by the majority of researchers engaged in the analysis of infilled frame analysis.

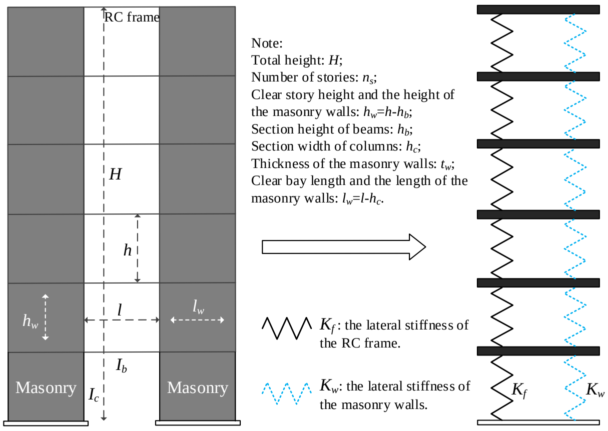


Fig. 2 Parallel spring model diagram for a masonry infilled RC frame structures

Asteris *et al.* (2011) compared the structural response of the pseudo-dynamic loading results of the RC frames with masonry wall structures modeled by the multi-strut model as well as the single strut model. It was found that the single diagonal strut model was also reliable, and it has less input parameters and a simple analysis process. By contrast, the multi-strut model has complicated pre- and post-processing even though they are more accurate. The single strut model was more useful to predict the elastic behaviour, although it is not able to predict the shear failure in the columns due to the masonry infills. Therefore, the simplified single diagonal strut model is used to predict the initial stiffness of the RC frames with masonry infills.

3. Theoretical model for fundamental period prediction of RC frame with infill walls

3.1 Parallel spring model

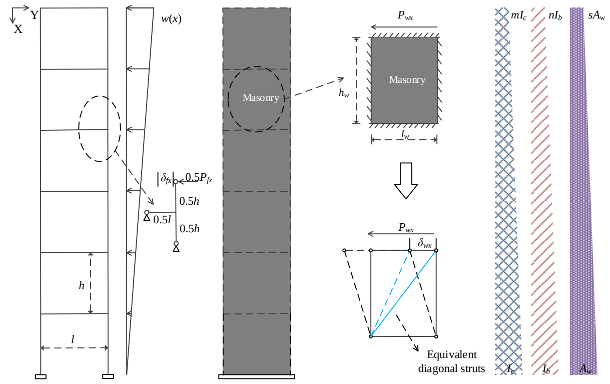
The parallel spring model was proposed by Aninthaneni and Dhakal (2016, 2017) to estimate the lateral stiffness as well as the fundamental period of frame and concentrically braced frame buildings. In this paper, the parallel spring model is used to consider the contributions of the RC frame and the infill walls, and the lateral stiffness of the RC frame is directly calculated. The lateral stiffness of the infill walls is calculated by the single strut model, because the bend-shear deformation behavior of the masonry wall is hard to be calculated directly.

A multi-span multi-story masonry infilled RC frame structure is simplified as a parallel spring system, as shown in Fig. 2. The lateral stiffness of the system is supported by the RC frame and the masonry walls, and the distributions of the lateral shear force depend on the contributions of them.

As an idealized theoretical model, some assumptions are presented for determining the lateral stiffness of the parallel spring system:

(1) The points of contra-flexure (POC) are assumed at the mid-height and mid-length of the columns and beams in each story, respectively. The effects of vertical loads and

(2) masonry walls on shifting the position of POC are neglected.



(a) Frame system (b) Masonry system (c) Section properties

Fig. 3 Deformation diagram of the masonry infilled RC frame structures

(3) The lateral deformation of the building is assumed to vary linearly along the story height, thus the principle of superposition can be used for the model.

(4) All the beam-column and the column-base connections are assumed as rigid connections. Moreover, the compression deformations of the columns and the beams are neglected.

(5) The initial imperfection of the components as well as the buildings is neglected.

(6) The in-plane stiffness of the RC slabs is assumed rigid enough, and compressive deformation of the RC slabs is also neglected.

3.2 Initial lateral stiffness calculations

A masonry infilled RC frame structure is divided as a RC frame sub-system and a masonry wall sub-system, as shown in Fig. 3. According to the assumption (2) in Section 3.1, the lateral load $w(x)$ is a linear function of the building height. The continuous function of the lateral force $w(x)$ about the distance x from the top of the frame, and it is equal to the sum of the lateral force on the RC frame sub-system $w_f(x)$ and the masonry wall sub-system $w_w(x)$:

$$\begin{aligned} w(x) &= w_f(x) + w_w(x) = w(1-\frac{x}{H}) \\ w_f(x) &= w_f(1-\frac{x}{H}); w_w(x) = w_w(1-\frac{x}{H}) \end{aligned} \tag{4}$$

where H is the total height of the building.

Besides, the linear variations of the section properties along the building height are considered in this model. The functions of the inertia moment of the beams I_b and the columns I_c and the sectional area of the masonry walls A_w are varying along the distance x from the top of the frame, and the functions are:

$$\begin{aligned} I_{cx} &= I_c[m+(1-m)\frac{x}{H}] \\ I_{bx} &= I_b[n+(1-n)\frac{x}{H}] \\ A_{wx} &= A_w[s+(1-s)\frac{x}{H}] \end{aligned} \tag{5}$$

where m, n and s are the constants about variations of the section properties. The lateral force of the RC frame sub-system P_{fx} and the masonry wall sub-system P_{wx} at the distance x from the top of the building are obtained by integrating the Eq. (4) over the distance x. The equations are:

$$P_{fx} = w_f(x-\frac{x^2}{2H}); P_{wx} = w_w(x-\frac{x^2}{2H}) \tag{6}$$

The deformation diagrams of the RC frame and the masonry wall subject to the lateral forces are shown in Fig. 3. The lateral deformation of the RC frame sub-system δ_{fx} at the distance x from the top of the building can be calculated by:

$$\begin{aligned} \delta_{fx} &= \frac{P_{fx}h^3}{12\sum E_c I_{cx}} + \frac{P_{fx}h^2 l}{12\sum E_b I_{bx}} \\ &= \frac{w_f(x-x^2/2H)h^3}{12\sum E_c I_c[m+(1-m)x/H]} \\ &+ \frac{w_f(x-x^2/2H)h^2 l}{12\sum E_b I_b[n+(1-n)x/H]} \end{aligned} \tag{7}$$

The Eq. (7) can also be expressed as an integral form:

$$\begin{aligned} d\delta_{fx} &= \frac{w_f h^3}{12\sum E_c I_c}\left(\frac{(x-x^2/2H)(1-\beta_{bh})^3}{[m+(1-m)x/H]}\right. \\ &\left.+\lambda_f\frac{(x-x^2/2H)(1-\beta_{cl})^3}{[n+(1-n)x/H]}\right)dx \end{aligned} \tag{8}$$

where h and l are the story height and the span length of the RC frame, respectively; E_c and E_b are the elastic modulus of the columns and beams, respectively; $\beta_{bh}=h_b/h$ and $\beta_{cl}=h_c/l$ are the beam depth (h_b) to the story height (h) ratio and the column depth (h_c) to the span length (l) ratio, respectively; λ_f is the ratio of the columns stiffness to the beams stiffness at the same story, and it can be calculated by:

$$\lambda_f = \frac{\sum E_c I_c / h}{\sum E_b I_b / l} \tag{9}$$

Thus, the lateral displacement of the RC frame at the top story can be calculated by integrating Eq. (8) over the height of the building

$$\begin{aligned} \Delta_f &= \int_0^H d\delta_{fx} = \\ &\frac{P_f h^3 n_s}{12\sum E_c I_c}\left[\eta_m(1-\beta_{bh})^3 + \lambda_f \eta_n (1-\beta_{cl})^3\right] \end{aligned} \tag{10}$$

where n_s is the story number of the building; η_m and η_n are the nonuniform factors due to the section properties variation of the columns and the beams with the height of the building. Aninthaneni and Dhakal (2017) developed the calculation equation for these factors as:

$$\eta_i(i=m,n,s) = \frac{1.5(1-i)^2+(1-i)i(2\ln i+1)+i^2\ln i}{(1-i)^3} \tag{11}$$

Particularly, $\eta_m=\eta_n=0.67$ when the section properties remain uniform ($m=n=1$).

The equivalent single diagonal strut model in Section 2 is used to calculate the lateral stiffness of the masonry wall sub-system. The lateral deformation of the masonry wall sub-system δ_{wx} at the distance x from the top of the building can be calculated by:

$$\delta_{wx} = \frac{P_{wx} l_b^3}{l_w^2 \sum A_{wx} E_w} = \frac{w_w l_b^2}{0.175 l_w^2 \sum E_w t_w \lambda_h^{-0.4}} \left(\frac{(x - x^2/2H)}{[s + (1-s)x/H]} \right) \tag{12}$$

where h_w, l_w, t_w are the height, the length and the thickness of the masonry walls, respectively.

The wall-frame relative stiffness parameter λ_h can be obtained by the Eq. (1), and it can be expressed as:

$$\lambda_h = \sqrt[4]{\frac{E_w t_w \sin 2\theta}{4 E_c I_c h_w}} h \tag{13}$$

where $\theta=\tan^{-1}(h_w/l_w)$ is the angle between the diagonal strut and the beam. Eq. (12) can also be expressed by the integral form:

$$d\delta_{wx} = \frac{w_w l_b^2}{0.175 l_w^2 \sum E_w t_w \lambda_h^{-0.4}} \left(\frac{(x - x^2/2H)}{[s + (1-s)x/H]} \right) dx \tag{14}$$

Thus, the lateral displacement of the masonry walls at the top story can be calculated by integrating Eq. (14) over the height of the building:

$$\Delta_w = \int_0^H d\delta_{wx} = \frac{\eta_s P_w l_b^2 n_s}{0.175 l_w^2 \sum E_w t_w \lambda_n^{-0.4}} \tag{15}$$

The equilibrium and compatibility of the parallel spring model, as well as the relationship between lateral force and lateral displacement, which can be explained as:

$$P_i = P_{fi} + P_{wi}; \delta_i = \delta_{fi} = \delta_{wi} \tag{16}$$

$$\frac{P_i}{K_i} = \frac{P_{fi}}{K_{fi}} = \frac{P_{wi}}{K_{wi}}; K_i = K_{fi} + K_{wi} \tag{17}$$

The lateral stiffness of a multi-span masonry infilled RC frame structure can be calculated by the ratio of the shear force to the lateral displacement at the top story. The displacement of the RC frame and the masonry walls are given in Eq. (10) and Eq. (15). Finally, the lateral stiffness of the masonry wall infilled RC frame structures can be calculated by:

$$K_{str} = \frac{12 n_c E_c I_c}{h_w^3 n_s (\eta_m + \lambda_f \beta \eta_n)} + \frac{0.175 l_w^2 E_w n_w t_w \lambda_h^{-0.4}}{\eta_s l_b^2 n_s} \tag{18}$$

where n_c and n_w are the number of the columns and the masonry walls at the same story; β is a factor due to the size effect of the beams and the columns, and it can be calculated by:

$$\beta = \left(\frac{1-\beta_{cl}}{1-\beta_{bh}}\right)^3 \tag{19}$$

3.3 Initial lateral stiffness calculations

A multi-story frame building can be considered as a multi-degree of freedom (MDOF) system, thus there are many possible vibration modes of the building. As stated by Aninthaneni and Dhakal (2016, 2017), the period of the first order vibration mode calculated by the MDOF system can be expressed by an equivalent single-degree of freedom (SDOF) system. Thus the fundamental period of the infilled RC frame structure in orthogonal directions can be calculated by:

$$T = 2\pi \sqrt{\frac{M_{eff,i}}{K_{eff,i}}} \tag{20}$$

where $M_{eff,i}$ is the modal mass of the first order vibration mode in the i direction, and it can be calculated by the mass participation coefficient and the total mass of the building, and the mass participation coefficient depends on the shape of the vibration mode and the mass distribution along the height of the building; $K_{eff,i}$ is lateral stiffness of the equivalent SDOF system. According to the suggestion by Aninthaneni and Dhakal (2016, 2017), the lateral stiffness of the infilled building $K_{str,i}$ in the i direction is used instead of the $K_{eff,i}$, and the total mass of the building $M_{str,i}$ is used instead of the $M_{eff,i}$. Thus the simplified formula for predicting the fundamental period of the masonry infilled RC frame structure in the i direction is:

$$T = 2\pi \sqrt{\frac{M_{str,i}}{K_{str,i}}} \tag{21}$$

4. Period prediction and formula correction

4.1 The FP4026 research database

The FP4026 Research Database was reported by Asteris (2016) based on a systematic analytical research on the fundamental period of the masonry infilled RC frame structures. A total of 792 cases of masonry fully-infilled RC frames in the FP4026 Research Database are selected in this paper, and the selected period data of these structures are used to validate the prediction results of the proposed theoretical model. These cases took into account the main geometrical and material parameters, including: the total height of the building, the number of span, the span length, the elastic modulus and the thickness of the masonry wall and the section size of the column. These structures were designed according to Eurocode 8 (CEN 2004), and an elevation view of these frames is shown in Fig. 4.

The story number in these cases was ranges from 1 to 22, the story height was constant and equal to 3.00m. The number of span varied between 2, 4 and 6, and these buildings were designed with four types of span length

Table 1 Information of the buildings in the FP4026 Research Database

Items	Variables
Number of story, n_s	From 1-story to 22-story
Story height, h	3.00 m
Number of bay or masonry walls, n_w	2, 4 and 6
Bay length, l	3.00 m, 4.50 m, 6.00 m and 7.50 m
Elastic modulus of masonry walls, E_w	1.50 GPa, 3.00 GPa, 4.50 GPa, 8.00 GPa and 10.00 GPa
Thickness of masonry walls, t_w	0.15 m and 0.25 m
Dead loads	1.50 kN/m2 + 0.90 kN/m2
Live loads	3.50 kN/m2
Elastic modulus of concrete, E_c or E_b	31.00 GPa
Section dimension of beam	0.25 m × 0.60 m

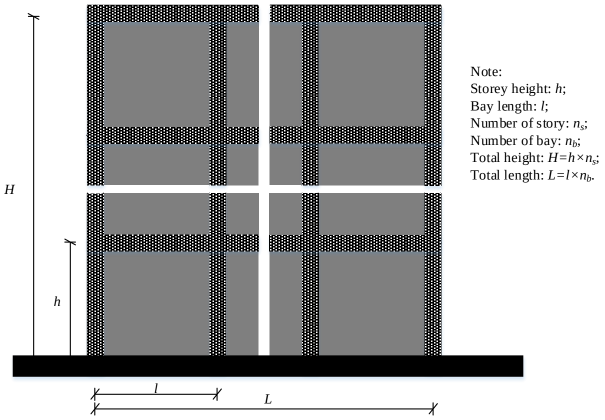


Fig. 4 An elevation view of the masonry infilled building in the FP4026 Research Database (Asteris 2016)

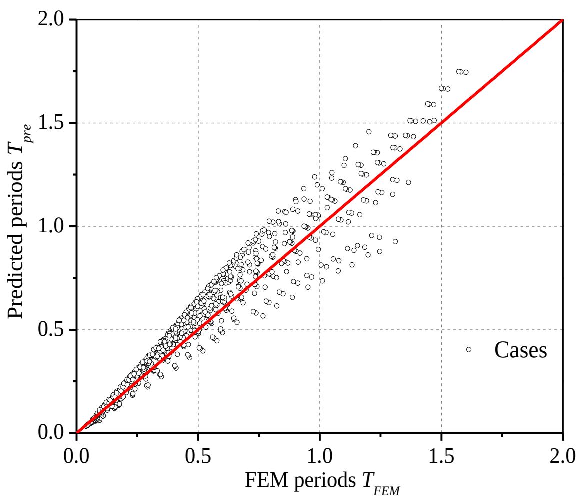


Fig. 5 Comparison of the predicted theoretical periods and the FEM periods

(3.00m, 4.50m, 6.00m, and 7.50m). The span length in the perpendicular direction kept as 5m for all cases. The number of masonry wall was consistent with the number of span. In order to investigate the influence of the stiffness of the masonry walls, five types of the elastic modulus of masonry wall (1.50 GPa, 3.00 GPa, 4.50 GPa, 8.00 GPa, 10.00 GPa) and two types of the thickness of two masonry wall (0.15m, 0.25m) were considered in these buildings. The elastic modulus of concrete was constant value of 31GPa. The dead load was 1.50 kN/m^2 + 0.90 kN/m^2, and the live load was 3.50 kN/m^2, a combination of the dead load and the live load (D + 0.5L, where D = dead load, L = live load) was used to consider the structural mass. The cross-sectional dimensions of the RC beams were 0.25 m × 0.60 m. The detailed dimensions of the square column were listed in the file of the FP4026 Research Database (Asteris 2016). The parameters of buildings are summarized in Table 1, and other information can be found in the FP4026 Research Database (Asteris 2016).

4.2 Theoretical period results of the 792 buildings

Taking the basis of Eq. (21), the theoretical results on fundamental period of the 792 buildings can be calculated. A comparison between the theoretical/predicted results (T_{pre}) and the results derived from the finite element method (T_{FEM}) is shown in Fig. 5. It can be found that the errors of these buildings are distributed around the diagonal line, and the maximum error is about 40%. The error is generated due to the assumptions presented in Section 3.1, including: (1) the lateral deformation of these buildings is estimated as linear relationship with the story height in the proposed method, but the distribution of the lateral deformation is complicated in a practical masonry infilled RC frame building; (2) the MDOF system is considered by an equivalent SDOF system in the proposed method, and the effective mass is replaced by total seismic weight in first order vibration mode; (3) the section properties of columns are not linearly varied. However, the fundamental period predicted by the theoretical model could consider the difference between the buildings with different configurations on the RC frame and the masonry walls, which parameters could not be considered in the design codes of many countries. Besides, the changing trend of the fundamental period results predicted by the theoretical model is quite similar with the FEM results. And the proposed theoretical model can be easily-understood and hand-calculated. Thus it could be a good choice for structural design of RC frame structures with masonry walls once a correction coefficient is considered.

Generally, it is commonly accepted that it is difficult to calculate the precise fundamental period of the frames and the wall infilled frame structures (Aninthaneni and Dhakal 2016, 2017), and a simple correction coefficient is desired to consider the different between the predicted results and the FEM results. Thus the corrected formula can then be used in engineering practice. The errors are relating to the following parameters, including: the total height of the building H, the ratio of the columns stiffness to the beams stiffness λ_f and the wall-frame relative stiffness parameter λ_h. Thus, a correction coefficient φ_{str} is proposed to correct

the former formula in Eq. (21). To simplify the coefficient and to make it easily calculated, a multiple linear regression analysis is carried out to obtain the correction factor, which is estimated as:

$$\varphi_{str} = \frac{A}{\lambda_f} + B\lambda_h + CH + D \tag{22}$$

where A, B, C and D are constant parameters needed to be determined according to the regression analysis.

In the design codes of many countries, the basic form of the empirical formula to calculate the fundamental period of building structures is:

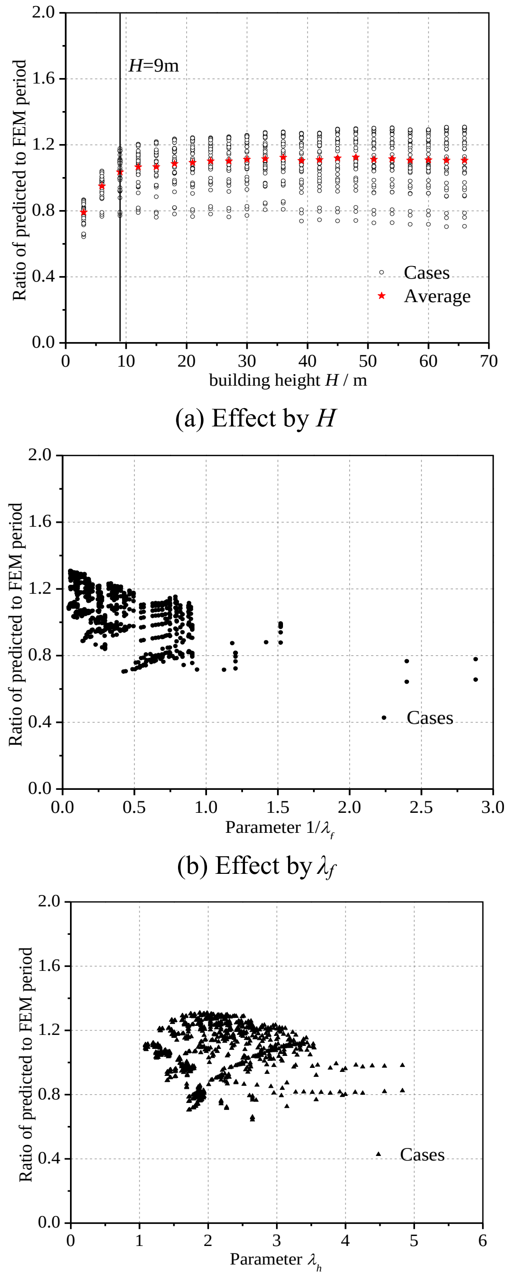
$$T = C_t H^x \tag{23}$$

where C_t and x are constants depending on the structural type, and H is the total height of the buildings.

The structural engineers could select proper values of C_t and x to determine the fundamental period of building structures. Asteris *et al.*(2017a) compared the fundamental period results of the empirical formula and the FEM for some case buildings in FP4026 Research Database already. It was found that the maximum error of the empirical formula was more than 200%. In the theoretical model proposed in this paper, the parameters A, B, C and D can be selected instead of the former two parameters in determining the fundamental periods of building structures.

4.3 Correction formula

Due to the total height of the buildings H is considered as the key parameter to determine the fundamental period of building structures. Thus relating curves between H and the ratios of the predicted to FEM periods are depicted in Fig. 6(a) for the selected 792 cases. When the building height H≤9m, the building height has a great influence on the ratio. When the building height H>9m, the building height has little influence on the ratio. The reason of this phenomenon is: the point of contra-flexure (POC) of the columns at the first story is not at the midpoint position if the stiffness of the beams is not absolute rigid. Thus the former assumption has a great impact on the low-rise buildings. The RC frame was dominated by shear deformation, and the infill walls were dominated by bend-shear deformation. In the proposed method, the bend-shear deformation of the infill walls was simplified as the axial deformation of the single diagonal strut according to the suggestion by Asteris *et al.*(2017a). Schultz (1992) also suggested a special modification on lateral stiffness for the low-rise frame buildings. In addition,



(a) Effect by H

(b) Effect by λ_f

(c) Effect by λ_h

Fig. 6 Ratios of the predicted theoretical periods to the FEM periods

it can be found that the ratios of the predicted period to the FEM period of the buildings with the same height are discrete, which is caused by the difference in configurations on the RC frame and the masonry infilled walls. Thus the ratio of the columns stiffness to the beams stiffness λ_f as well as the wall-frame relative stiffness parameter λ_h are also important for the correction coefficient. The ratios of the predicted to FEM periods due to the effects of these parameters are presented in Figs. 6(b)-(c). The effects of stiffness parameters and building height on the ratios are reflected in the value of constant parameters A, B and C respectively.

Therefore, the calculation of the correction coefficient includes two parts with considering the building height of

Table 2 Results of the parameters in Eq. (22)

Building height	A	B	C	D
H≤9	-0.064535	0.059307	0.038044	0.604387
H>9	-0.612027	0.201774	0	0.885839

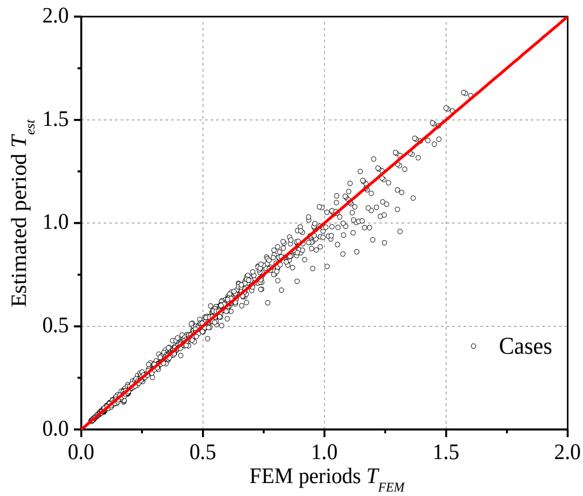


Fig. 7 Comparison of the estimated periods and the FEM periods

H≤9m and H>9m. The *stepwise* function in the mathematical software *Matlab 2016a* is used to obtain the values of the parameters of A, B, C and D in Eq. (22), and the values are listed in Table 2. The findings indicate that: when H≤9m, the effects of stiffness parameters (λ_f and λ_h) and building height H should be considered; when H>9m, the effects of stiffness parameters are mainly considered. Then the correction coefficient φ_{str} can be calculated. Thus the corrected formula for fundamental period estimation of the masonry infilled RC frame buildings in the i direction is:

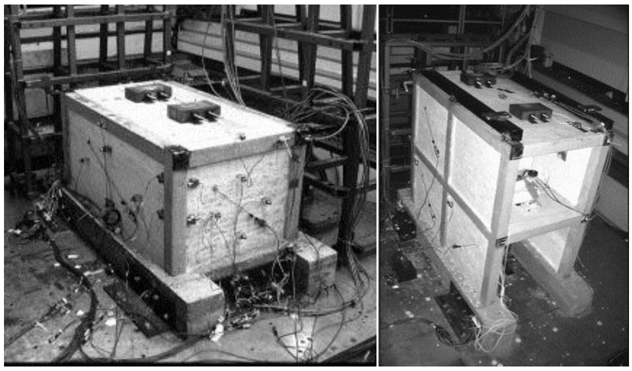
$$\hat{T}_{str,i} = \frac{2\pi}{\varphi_{str,i}} \sqrt{\frac{M_{str,i}}{K_{str,i}}} \tag{24}$$

The fundamental periods of the 792 buildings are calculated according to the corrected formula, and the estimated period results (T_{est}) are compared to the FEM results (T_{FEM}) from the database, as shown in Fig. 7. It can be found that the corrected results have better accuracy guarantee compared to the results calculated by Eq. (21). The maximum error of these 792 buildings with different configurations is less than 30%, and most of the errors are less than 15%, indicating the accuracy of the corrected formula is quite good.

5. Verification and suggestion

5.1 Verification by shaking table test results

In order to validate the accuracy of the proposed theoretical model and the corrected formula, shaking table tests on two RC frames infilled with masonry are selected, which were conducted by Žarnić *et al.* (2001). The



(a) (b)

Fig. 8 Shaking table tests conducted by Žarnić *et al.* (2001). (a) B-mode, (b) H-model

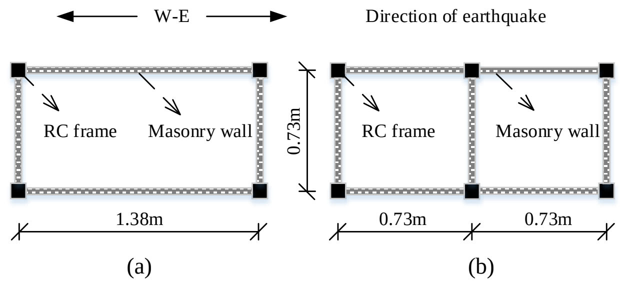


Fig. 9 Floor plans for the specimens. (a) B-mode, (b) H-model

Table 3 Specimens information in Žarnić *et al.* (2001)

Items	B-model	H-model
story height, h	0.64m	0.64m
Bay length, l	1.38m	0.73m
Beam/column side length	0.08m	0.08m
Thickness of masonry walls, t_w	0.03m	0.03m
Elastic modulus of concrete, E_c or E_b	11.70GPa	11.70GPa
Elastic modulus of masonry walls, E_w	0.59GPa	0.59GPa
Gravity loads (dead load + live load)	0.5kN/m^2 + 2kN/m^2	0.5kN/m^2 + 2kN/m^2

specimens were designed following the actual building regulations, and the test setup of the models was shown in Fig. 8. The first specimen (B-model) was designed as a single-span single-story box-type structure, and the second one (H-model) was designed as a double-span double-story structure, the floor plans of these models are shown in Fig. 9. The story height of these specimens was 0.64m. The span length was 1.38m and 0.73m for the B-model and the H-model, respectively. The RC beams and columns of these specimens were square section (side length was 0.08m), and the elastic modulus of the concrete was 11.70GPa. The thickness of the masonry walls was 0.03m and the elastic modulus was 0.59GPa. The gravity load of the specimens included a dead load of 0.5 kN/m^2 and a live load of 2 kN/m^2. The parameters of these models are summarized in Table 3. More details can be found in the study of Žarnić *et al.* (2001).

Table 4 Period results of the proposed formula and compared to the test result

Specimen	H / m	λ_f	λ_h	φ_{str}	T_{est} / s	T_{test} / s	Error / %
B-model	0.64	4.31	2.22	0.75	0.037	0.037	2.3
H-model	1.28	1.71	2.39	0.76	0.053	0.043	23.2

The first frequencies of the specimens measured by the shaking table test were 26.8 HZ and 23.2 HZ for the B-model and the H-model, respectively. The building information of these models are input to the corrected formula Eq. (24) to estimate the fundamental period in the W-E direction. Table 4 shows the calculation parameters and the estimated periods T_{est} are compared with the test results T_{test}. The errors between the estimated value and the test value are 2.3% and 23.2% for the B-model and the H-model, respectively. It is indicated that the proposed correction formula has good precision. The reasons for the errors including: (1) the initial imperfection of the specimens; (2) as Žarnić mentioned, there were some spurious motions during the test; (3) lack of the connection information of the specimen components. In addition, there are some uncertainties in the whole test process, just as the error of B-model is only 2.3%, while the error of H-model is 23.2%. These uncertainties are reflected in the test setup, the material characteristics, the construction process, measurement error and so on.

5.2 Design suggestion

Generally, the fundamental period is an important parameter for seismic design and seismic risk assessment of building structures (Jiang *et al.* 2018; Jiang *et al.* 2019; Jiang *et al.* 2020). The inherent fundamental period of a practical building is usually estimated by engineers taking the basis of numerical tools or experiences. However, there are many uncertainty factors are involved in the prediction of the fundamental period, because it depends on the lateral stiffness as well as the structural mass of the buildings. Though the reliability theory has been applied to the codes in many countries, the empirical formula on fundamental period was always a determined value. Thus the lateral force of the building structures may be underestimated if the fundamental period is not correct. Therefore, this paper proposes a probability-based method to determine the fundamental period in engineering practice. A flexible and reliable interval of the fundamental period estimation is suggested to the structural engineers. The engineers could select a proper value of the fundamental period according to a certain confidence rate, and then realize a conservative design of building structures with certain safety redundancy.

In this paper, a statistical analysis is performed to obtain the distribution and uncertainty of the period results taking basis of the estimation on period of the 792 cases. The period results obtained from the FEM are treated as the true values. The cumulative distribution probability of the ratio of the estimated period T_{est} to the FEM results T_{FEM} is shown in Fig. 10. These discrete spots are fitted by a lognormal cumulative distribution function. The fitted mean value and the fitted standard deviation (SD) are 1.0 and 0.06, respectively.

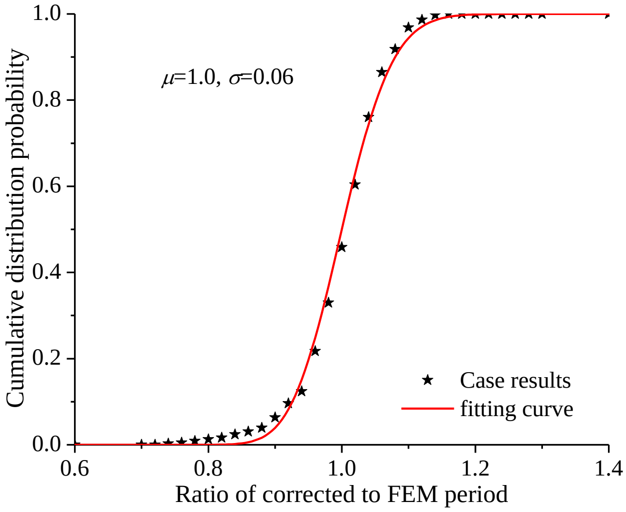


Fig. 10 Lognormal cumulative distribution fitting based on the 792 buildings

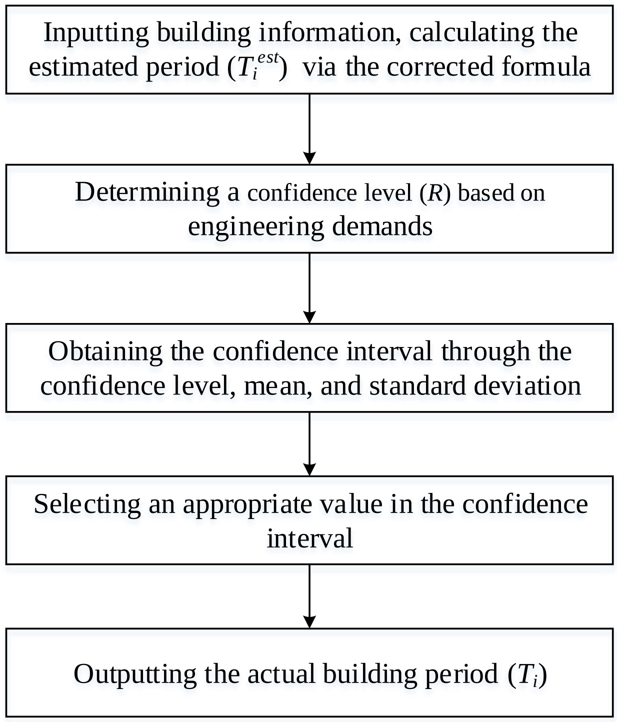


Fig. 11 Flow chart of the proposed method to determine the probability-based fundamental period

For example, an estimated period of a masonry wall infilled RC building is calculated by the corrected formula, and the ratio between the estimated period and the final designing period is considered. The engineers acquire an confidence interval for this ratio with a confidence demand R (e.g. R=95%), then the interval can be calculated as [μ – 1.96σ, μ + 1.96σ], and it is expressed as:

$$P\{\mu - 1.96\sigma \le T_i^{est}/T_i \le \mu + 1.96\sigma\} = 95\% \tag{25}$$

where $P\{*\}$ is the exceedance probability; μ is the mean value; σ is the SD; T_i^{est} is the estimated period; T_i is the final designing period.

The process is concluded in Fig. 11, including the following steps: (1) inputting the building information to the proposed correction formula to calculate the estimated period (T_i^{est}); (2) determining a confidence level (R) of the confidence interval based on the engineering demands; (3) obtaining the confidence interval through the confidence level R, the mean value μ and the SD σ; (4) selecting an appropriate value of the ratio (T_i^{est} / T_i) in the confidence interval, (5) outputting the final designing period of the building (T_i).

5. Conclusions

In this paper, a simplified theoretical method for estimating the fundamental periods of the masonry infilled RC frames is proposed. The method considers the mechanical characteristics of the infilled masonry walls, and the single diagonal strut model is used to simplify the behavior of the masonry walls and it is included in the proposed theoretical method. The effects of the building height, the section properties, the number of span, the span length and the stiffness of the the RC frame as well as the masonry walls are considered in the proposed method, which are contained by some calculation parameters in the corrected formula of the fundamental period. The main advantages of the proposed method are: (1) it considers the configurations of the RC frame as well as the masonry walls, thus it is more accurate and reasonable than the empirical method in the standards or codes. (2) the method is easily-understood and can be hand-calculated, thus it is much more simple than the finite element method (FEM). It is perhaps a more suitable method for engineering practice than the exiting methods.

The FEM results on fundamental periods of 792 cases in the FP4026 Research Database are used to validate the proposed theoretical method. These case buidings have various types of parameters on the total height H, the ratio of the columns stiffness to the beams stiffness λ_f and the wall-frame relative stiffness parameter λ_h. A correction coefficient for these parameters is proposed to correct the predicted results of the theoretical method, and the corrected results show better precision. The correction formula is also validated by two shaking table test models, and the errors between the estimated and test period are 2.3% and 23.2%.

Finally, a probability-based method is proposed to the structural engineers, thus they could select an appropriate fundamental period in a certain safety redundancy. A statistical analysis is conducted for the ratio (T_i^{est} / T_i) of the estimated periods to the FEM periods of the 792 case buildings, and the results are fitted by a lognormal cumulative distribution function. The structural engineers could determine a confidence level (R) based on the engineering demands, and the confidence interval of the ratio (T_i^{est} / T_i) can be obtained. Thus a more flexible result on the fundamental period could be used for engineering practice, and it also provides an insight for probability-based fundamental period estimation of building structures, which is important for the reliability-based structural design of building structures.

The theoretical model proposed in this study is derived from the basic theory of engineering mechanics. Compared with the mathematical regression analysis of existing methods, the results are more convincing. The shear deformation of RC frame and the axial deformation of the single diagonal strut are considered in this model. Thus, different configurations of RC frame and masonry wall can obtain different period results, which are easy for engineers to distinguish. Compared with a determined period value given by the existing method, the probability-based method gives a reasonable interval. The engineer chooses a period value with a certain of guarantee, which is more practical and flexible. In the future, the influence of the openings in the infill panels might be conducted for fundamental period estimation of masonry infilled reinforced concrete frames.

Acknowledgments

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