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Investigations of elastic vibration periods of reinforced concrete moment-resisting frame systems with various infill walls

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ABSTRACT

The fundamental period of vibration is a crucial characteristic in assessing the dynamic performance of reinforced concrete (RC) buildings because it is not only directly related to the mass and stiffness of the structure, but also to the lateral actions applied, e.g. earthquakes and winds. In this study, the RC moment-resisting frame (MRF) systems designed under gravity and wind loading have been evaluated by utilising 3D FE modelling incorporating eigen-analysis to obtain the elastic periods of vibration. The parameters considered include the number of storeys, the number and length of bays, plan configurations, mechanical properties of infill walls, and the presence of openings in the uncracked and cracked infill walls. These analyses provide a sound basis for further investigating the effects of these parameters and exploring the possibility of proposing new formulas for predicting the fundamental vibration period by utilising regression analyses on the obtained results. The proposed numerically based formula for vibration periods of bare RC frame models reasonably agrees with some cited formulas for vibration period from design codes and standards due to disregarding contributions of infills' stiffness towards the structural systems. Meanwhile, the proposed formulas for RC MRF buildings with uncracked infills agree well with most cited experimentally based formulas and some numerically based ones. However, the proposed formulas for RC MRF buildings with cracked infills only reasonably agree with some cited numerically based formulas.

1. Introduction

The period of vibration has been widely evaluated with regard to the effect of seismic forces on reinforced concrete (RC) buildings by using the equivalent lateral load analysis. However, evaluating such dynamic characteristics of these buildings under wind loading has attracted less attention than earthquake loading due to the life threating situations caused under the latter. In conventional structural analysis, the bare frame is only taken into account with all other structural elements, while the effect of non-structural elements such as infill walls is neglected due to uncertainty on the behaviour of these non-structural elements [1–4]. However, the inclusion of the infills in assessing the behaviour of RC buildings with infills has become of interest due to their significant contributions to the enhancement of the lateral stiffness of bare frame buildings under seismic loading, and then to the alternations of the dynamic properties of these buildings by the added mass and stiffness of the infills [5–7].

The behaviour of RC buildings with infills, i.e. linear or nonlinear, is related to the intensity of the applied lateral loads where there are two distinguished phases, namely local and global behaviours, depending on the interactions between the infill panels and the surrounding frame elements. In the past few decades, these two phases have been evaluated using experimental investigations and analytical simulations, and the latter approach has been calibrated with the former in many studies to evaluate different behaviours of RC framed buildings with infills. Much attention has been paid to analytical methods to simulate the behaviour of RC frame structures with infills, including two common techniques, namely macro-modelling and micro-modelling. The former technique simulates the infills as equivalent diagonal struts, while the latter technique models the infill materials individually using the finite element method [8]. Thus, the macro-modelling approach is widely used to simulate the global behaviour of RC framed buildings with infills, e.g. in determining the period of vibration due to the simplicity of the model. The micro-modelling technique is used to simulate the local behaviour of these buildings, such as

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local forces and failure modes, and is made possible by the accurate and intensive simulation of the interactions of the infilled panels with the surrounded frame elements in the numerical analysis [3,9,10].

In general, the evaluation of seismic forces on RC buildings relies on the period of vibration of the structures. In the event of moderate to high intensity earthquakes, the pre-existing cracking in RC concrete members can be more influential, resulting in larger periods of vibration and lower levels of stiffness of buildings. Therefore, the use of either numerically or experimentally based formulae for predicting the periods of vibration of RC buildings under moderate to high intensity earthquakes may significantly overestimates the periods of vibration under other types of low amplitude motion, e.g. wind [11]. Thus, the design of buildings according to their behaviour under earthquakes will be very conservative due to the assumption of cracking and degraded stiffness. However, the design of buildings under wind loading is more economical than earthquake design due to the linear elastic assumptions of structural members. In particular, the design of tall buildings is governed by wind loading with respect to lateral drift and human comfort. In regions with low seismic events, therefore, the design of mid-rise to high-rise buildings is dominated by wind loading as the leading variable action. Some numerical studies [5,12–15] have simulated low-rise to mid-rise infilled RC buildings by evaluating the period of vibration based on their popularity and easiness, and some experimental investigations have been conducted on these types of buildings for comparison. Most studies so far have been conducted on the design of RC buildings under gravity loads only, or by considering seismic forces.

In this study, RC moment-resisting frame (MRF) systems were strictly designed under the effects of gravity, imposed and wind loads to structural Eurocodes [16–20], and then these systems were modelled in a parametric study to investigate the effects of several design parameters on the dynamic response of the models in terms of the elastic period of vibration. The parameters investigated included the number of storeys, the number and length of bays, plan configurations, mechanical properties of infill walls, and the presence of openings in the infill walls. These parameters are vital in the investigation due to their direct and indirect effects on the dynamic performance of RC buildings. Nowadays, with the availability of powerful computers, numerical analysis using the Finite Element (FE) method becomes a reliable approach of accurately evaluating the dynamic response of this type of buildings due to the involvement of the mass and stiffness of the model. Correspondingly, this can help to establish the formulas for estimating the periods of vibration experienced by the addressed buildings. The deduced formulas will be compared with those cited from the literature and in the design codes and standards to check their accuracy in evaluating this dynamic property.

2. Formulas for determining the vibration period of RC buildings

To evaluate the dynamic characteristics in terms of the fundamental period of vibration and the damping ratio for RC MRF systems, gravity loads are normally considered together with lateral loads, e.g. earthquake. Many design standards and codes recommend assessing the period of vibration solely with respect to the building height. In the presence of infills or shear walls, the wall area and length in the considered directions are normally considered. Therefore, many studies have utilised code approaches by applying different parametric studies on the obtained data experimentally or numerically to establish formulas and evaluate the periods of vibration of RC MRF systems. These studies have investigated MRF systems with different configurations, e.g. bare frames, frames with solid masonry infills of clay bricks and concrete blocks, or with the presence of openings. However, these systems have not been comprehensively analysed under wind loading, and their height limit is narrowed down to low-rise to mid-rise buildings due to the popularity of these structures in the cities around the world. This has attracted much attention onto RC MRF buildings.

The proposed formulas in these studies have created huge scatters in relation to different key issues for comparison with the formulas proposed in the design standards and codes. These issues include the amplitude of motion sources in the experimental studies, the cracking or damage of structural components in the tested buildings, the presence of other structural components, e.g. shear walls, the presence of infills and the variety of their mechanical properties, the height of the building, the assumptions adopted in the numerical modelling, etc. In particular, the classification of excitation sources has expanded from weak to strong amplitudes, which cause variations of the response of the structure. Even under weak motions, nonlinear response can be observed, i.e. a variation of the elastic properties due to nonlinear elastic phenomena as stated in the study by Guéguen et al. [21], or due to atmospheric loading, e.g. temperature or/and wind as stated in the studies by Clinton et al. [22], Herak and Herak [23], and Mikael et al. [24]. They can therefore be used to evaluate the dynamic characteristics of buildings, including their fundamental vibration periods and damping ratios. Thus, this paper focuses on those prior studies which used low intensity sources to carry out ambient microtremor vibration tests to obtain the fundamental vibration period. The formulas presented in the design codes/standards and suggested by other researchers are summarised, and then compared with those proposed in the present study based on the numerical results generated.

2.1. Design codes and standards for buildings

The American Standard ASCE 7-10 [25] states that for wind design, the proposed formulas for predicting the fundamental frequency under earthquakes may lead to non-conservative values for wind. The frequency will be higher than the actual one and yield lower gust effect factor and design wind pressures. Thus, the standard recommends that such formulas are used in predicting the fundamental frequency under wind loading, but some limitations need to be verified with respect to the height and effective width of the buildings with regular plans. Hence, the cited design formulas are presented in terms of the period of vibration, T, rather than the fundamental frequency (the inverse of T), and the International System of Units (SI) is used. Most codes and standards evaluate the vibration periods or frequencies of buildings in terms of the building height H as follows, based on the regression analyses on the prior test results:

$$T = \alpha H^{\beta} \tag{1}$$

where α and β are empirical coefficients. The upper-bound formula provided for concrete moment-resisting frame buildings is based on the study by Goel and Chopra [26]. The standard also provides another upper-bound expression obtained from analytical analyses for wind tunnel tests, which can be applied to all buildings with height below 122 m, regardless of their material types. The empirical coefficients used for Eq. (1) are listed in Table 1.

The Eurocode BS EN 1991-1-4 [20] and the Australian and New Zealand Standard AS/NZS 1170.2 [27] recommend a similar formula for obtaining the fundamental period of vibration for all types of buildings, which was first derived by Ellis [28], with the corresponding empirical coefficients cited in Table 1. Fig. 1 illustrates the recommended formulas in the standards and codes mentioned