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# Ambient vibration testing of low and medium rise infilled RC frame buildings in Jordan

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A B S T R A C T

This study aims at investigating the fundamental period of vibration of infilled RC frame buildings using measurements of ambient vibrations and numerical analyses. Ambient vibrations were measured at the roof level of 29 selected buildings with heights of one to six stories. Using Nakamura technique, the horizontal-to-vertical spectral ratio curves were obtained in the two orthogonal building directions. The estimated period values ranged between 44% and 91% of elastic periods suggested by the local code. Preliminary period–height relations were proposed using regression analysis of the measured periods. Limited by the availability of structural details, the periods of vibration of 15 buildings only were evaluated using linear modal analysis of three dimensional computer models including the effect of stone–concrete infills. Considering cracking of the structural concrete elements increased the period of vibration by 40–50% compared to the elastic value. Analytical period values showed large differences with both the measured and code values.

## 1. Introduction

The fundamental period of vibration, *T*, of a structure is an essential parameter in the seismic design and assessment procedures. The period value has a significant role in computing the seismic design base shear and is also needed to estimate the seismic demand for assessment purposes.

The fundamental period of a structure is a function of its mass and stiffness. In 1963, Housner and Brady [1] derived equations for the natural periods of vibration of buildings and proposed that the degree of earthquake deformations of the building is related to the induced change in its natural period. Based on observations of the dynamic behavior of two buildings over a period of 10 years during which the buildings experienced three strong earthquakes and numerous tests, Udwadia and Trifunac [2] demonstrated that the period value is affected by the excitation amplitude. Bertero et al. [3] correlated the increase in the period of vibration of moment-resisting frame (MRF) structures to both structural and no-structural damage. Using a comprehensive database of measured periods of buildings recorded during actual earthquakes, Goel and Chopra [4] established that the fundamental periods of buildings tend to elongate as the level of shaking increases as a result of the reduced stiffness associated with increased concrete cracking during strong shaking. Calvi et al. [5] provided experimental evidence for significant period elongation of a number of instrumented buildings during strong ground shaking. Masi and Vona [6] also examined the relationship between damage level and period elongation (stiffness reduction) of reinforced concrete frame buildings.

## 2. Period of vibration of reinforced concrete frame buildings

At the design stage, the code value for the period of vibration plays a key role in identifying the level of design forces. The fundamental period of a building is estimated using code empirical formulas that are typically based on field observations related to building behavior during real earthquakes of different intensities. In general, the approximate code values for the elastic period of vibration are associated with the building height above its base or number of stories and the structural typology as identified by the lateral force resisting system and materials used.

In 1978 a semi-empirical period–height expression, given by Eq. (2-1), was adopted by ATC3-06 [7] for reinforced concrete (RC) moment-resisting frames.

$$T = C_t \ H^{3/4} \qquad (2-1)$$

where *T* is the fundamental period of vibration, *H* is the building height and $C_t$ is a numerical coefficient.

The mathematical form for this expression was theoretically derived, using Rayleigh′s method, by assuming that the horizontal forces are linearly distributed over the height of the building (*H*), the mass distribution is constant, the mode shape is linear and the

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base shear is inversely proportional to $T^{2/3}$. The coefficient $C_t$ in this expression was obtained through regression analysis of measured periods for a number of RC frame buildings during the 1971 San Fernando earthquake and was later revised by SEAOC-88 [8]. A similar expression was adopted by the Uniform Building Code [9] and Eurocode 8 [10], among others.

In 1997, Goel and Chopra [11] investigated the period of vibration for 27 concrete MRF buildings that were monitored during 8 small- to medium-sized Californian earthquakes, including the 1971 San Fernando earthquake, and obtained comparable results to those proposed by the period–height relation of the Uniform Building Code [9]. Yet, based on the lower bound of the data, Goel and Chopra [11] proposed the empirical expression of Eq. (2-2) for RC frames.

$$T = 0.0466\ H^{0.9}\ (H \text{ in meters}) \qquad (2-2)$$

Using the lower bound periods estimated through Eq. (2-2), which was later adopted by ASCE 7–10 [12], provides a conservative estimate of the base shear.

Although, seismic codes allow the determination of the period value through substantiated analysis using the uncracked structural properties and deformation characteristics of the resisting elements yet, these codes set upper limits on the calculated period e.g. [12]. Researchers have shown that numerical analyses, as permitted by international design codes, usually return period values that are significantly different than those calculated using the code period–height expressions [6,13,14]. The main source for this discrepancy was associated with the presence of infill walls and their connectivity to the bounding frame: whether the infill panels are rigidly connected to or isolated from the bounding beams and columns. Using modal analyses of finite element building models, Amanat and Hoque [13] investigated the fundamental period of vibration of regular RC frame buildings with and without infill walls. Compared to the analytical values, the code equation was found to underestimate the period of RC frames when the infills were neglected, while good agreement was found when the effect of the infills was included in the models.

Using parametric analysis of typical European RC frame buildings, Masi and Vona [14] confirmed that the period of vibration of infilled frames is shorter than that of bare frames. High differences between the period values obtained from code relations and numerical and experimental results have been reported. Masi and Vona [6] investigated the period–height relationship of RC frame buildings without earthquake resistant design. Parametric analysis of the selected building frames was carried out for three cases: totally infilled frames, frames without infill walls and partially infilled frames. The period of vibration of infilled frames was found to be shorter than that of the bare frame. The periods of vibration for infilled and partially infilled frames were found to be practically equal. Again, high differences between the numerical and experimental values were noted.

Taking into account the presence of infill panels, Crowley and Pinho [15] proposed a simplified period–height relation for the use in large scale vulnerability assessment of existing RC buildings. Crowley and Pinho [16] suggested that the period of vibration of RC moment resisting frames with rigid infills can be estimated using the following equation:

$$T = \frac{0.09\,H}{\sqrt{D}} \qquad (2-3)$$

where $D$ is the dimension of the building at its base in the direction under consideration. The use of the period–height relation given in Eurocode 8 [10] for “other structures” was also recommended.

Kose [17] evaluated numerically the fundamental period of vibration of 189 RC frame buildings considering the building height, frame type and the presence of infill walls among other parameters. The fundamental periods of vibration of the infilled frames were found to be shorter (by 5–10%) than that of RC frames without infill walls regardless of the presence of shear walls. Depending on the model parameters, code equations of the Uniform Building Code [9], FEMA 450 [18], Eurocode 8 [10] and NBCC [19] under-estimated the fundamental periods of the models by 2–4%. Nonetheless, the building height was found to be the major parameter affecting its period of vibration.

## 3. Problem statement

The Jordanian Code for earthquake-resistant buildings [20] adopted the period formulae of the 1997 Uniform Building Code [9] given by the general form in the following equation:

$$T = C_t\ h_n^{3/4} \qquad (3-1)$$

where $T$ and $h_n$ represent the period of vibration in seconds and the building height above its base in meters, respectively. The numerical coefficient $C_t$ varies according to the lateral force resisting system.

RC frame buildings, designed for gravity loads only, constitute a majority of the residential building stock in Jordan. The exterior frames, in buildings constructed post 1990, are generally infilled with a multi-layered stone–concrete wall panel with the dimensions shown in Fig. 1(a) while the interior frames are infilled with the typical 100 or 200 mm thick masonry walls using hollow concrete blocks. In fact, this type of residential construction can also be found in countries of the eastern Mediterranean including Syria and Lebanon. Slight variations in the cross-sectional details of the infill wall shown in Fig. 1(a) may be encountered. A $C_t$ value of 1/25 was suggested in the local seismic code, merely based on expert judgment, for this dominant type of infilled RC frame buildings.

The main objective of this study is to investigate the fundamental period of vibration of the typical infilled RC frame buildings in Jordan using measurements of ambient vibrations and numerical (eigenvalue) analyses. In addition, microtremor measurements are carried out in the vicinity of a number of the investigated buildings in order to assess the proximity of the site period to that of the building and establish the potential for resonance in case of strong earthquakes.

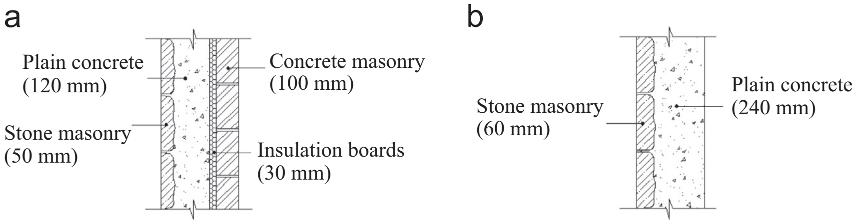

**Fig. 1.** Cross-sectional details of stone–concrete walls. (a) Infill panel and (b) Bearing wall.