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APPROXIMATE ESTIMATIONS OF NATURAL PERIODS FOR APARTMENTBUILDINGS WITH SHEAR-WALL DOMINANT SYSTEMS

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SUMMARY

This study focused on evaluating the reliability of the code formula, The Korean Building Code of 1988, to estimate the fundamental period of RC apartment buildings with shear-wall dominant system, representative of the residential building construction in domestic areas, and proposing the improved empirical formula. To this end, full-scale measurements were carried out on fifty RC apartment buildings having wall-slab configurations in Korea and its results are compared with those obtained by the current code formula and also by dynamic analysis. It is observed that the stiffness of the tested buildings is so different from that code would tend to imply, and comparatively large errors are likely to be occur using this code formula. Also, any codes such as UBC 1997, NBCC 1995, BSLJ 1994, can not identify the dynamic characteristics for these buildings in Korea. The proposal is for the serviceability condition, but can also be applied to determine the base shear for the seismic design for the apartment buildings with shear-wall dominant system to be constructed in moderate or less seismic zone similar to in Korea.

INTRODUCTION

Most of semi-empirical building codes including the Korean Building Code(KBC 1988, [6]) use the building period to directly proportion the magnitude of force which should be sustained by buildings at specific stress level and provide the empirical formulas to determine the lower bound fundamental period in order to establish the minimum lateral load requirements. However, such codes have not settled on a uniform method to determine the periods, because the required design force level and characteristics of buildings constructed in each regions are different. To determine the design base-shear for seismic design, the formulas of the period specified in the current KBC are derived from those of the 1988 Uniform Building Code [10], which were based on the measured period of buildings from strong motion records during 1971 San Fernando earthquake. Therefore, in case of the apartment buildings which consists of walls and flat slabs without columns and beams, it has long been realized that comparatively large errors are likely to be occur using this formula, and several studies of these buildings also showed that these structures have quite different dynamic characteristics than building codes would tend to imply[1,2,5]. But, there has not been a comprehensive research on the dynamic characteristics of these buildings as yet, which is available to correct the current code formula for apartment buildings. Therefore, more research need to be done in this field. Futhermore, since the present trend of these buildings more slender and lightweight structures has resulted in problems associated with their dynamic behaviour becoming more apparent, accurate asessment of the fundamental period of vibration is also important for serviceability condition as well as for seismic condition.

To this end, full-scale measurements were carried out on fifty RC apartment buildings having wall-slab configurations in Korea. Although building period varies with the amplitude of structural deflection or strain level, ambient surveys should provide an effective tool for experimentally verifying the design period with completed building. The objective of this study is to provide the updated information on the period of such buildings and to evaluate the reliability of the code formula, and finally to propose the improved

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empiricalformula to estimate the fundamental period of RC apartment buildings with shear-wall dominant system.

DESCRIPTION OF THE BUILDINGS

Apartment buildings with shear-wall dominant system are representative of residential buildings constructed in domestic areas. These buildings are almost reinforced concrete structures consisting of walls and regular shaped flat plate slabs without columns and beams, and a centrally located rectangular core or cores spaced by 2 housing units. In general, the thickness of walls and slabs are almost equal(about 200mm), and the walls in units and cores, which are the primary lateral force resisting elements, are continuous throughout the height of the building. Fig. 1 shows typical floor plan of the building.

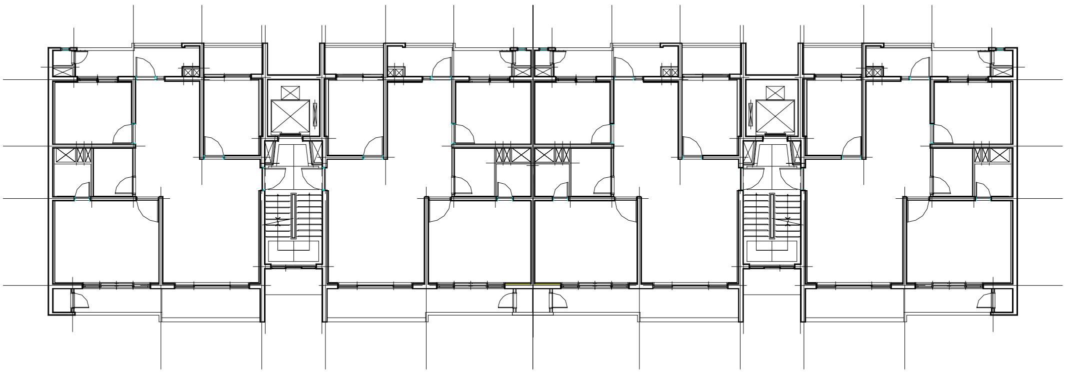


Figure 1 : typical floor plan of the apartment buildings

The measured buildings are fifty apartment ones of 10 to 25 stories having various size of plan shape (3.0-7.0). The story height is about 2.6m in all stories. Each building has a mat or a pile foundation. Details regarding the building plan dimension, the number of story and height, and the ratio of the sum of the length of walls aligned in the direction the period was measured to the plan area of a typical floor are presented in Table 1.

INSTRUMENTATION AND RESPONSE MEASUREMENTS

The acceleration data for fifty apartment buildings were recorded from the March 1996 to the April 1997. Buildings were completed and unoccupied during the measurements. The dynamic responses were measured using two couples of accelerometers perpendicular to each other which were set on the highest floor of the buildings. Some references give details of the measurement procedures [1,12]. The accelerometers selected are Dytran Model 3191A with 5.0 V/g sensitivity and 0.1Hz to 1.0 kHz frequency range. Because the range of acceleration is within a few milli-g, some degree of signal amplification is required to be applied to the basic output from the accelerometer. Also, in order to obtain a clean signal, whereby background noise is eliminated, it is necessary to filter off the higher frequency background component. The amplification and filtering functions are carried out by a purpose-built unit containing a sixth order 12.5Hz low-pass filter. Conditioned signals could be stored on tape via a Sony PC204A DAT tape recorder (4-channels 16-bit resolution, 80 dB or more dynamic range, 78dB or more S/N ratio, 0.02% or less distortion within the band width) and digitized using data transfer system PCIF200A (16-bit resolution, programmable global gains 20V, 192 Kwords/second conversion rate).

IDENTIFICATON OF NATURAL FREQUENCIES

In order to identify natural frequencies, the averaged normalized power spectrum(ANPS) was computed using the NPS program which was developed at the Korea National Housing Corporation. NPS employs Maximum Entropy Method(MEM) which gives a very high resolution for short time series in the low frequency domain. ANPS was obtained by first normalizing the power spectral density amplitudes of each record with respect to the sum of all the amplitudes within the frequency range of interest of the record, and then averaging all the normalized spectral densities of selected sets of records. NPS sampled each record at a sampling frequency of 46.7Hz in conjunction with the earlier low-pass filtering at 12.5Hz and filtered by the high-pass filter at 0.1Hz in order to remove any DC offset from record. The peaks in the averaged normalized spectrum represented the natural frequencies for various modes of vibration. Since there were pairs of sensors oriented in both the longitudinal and transverse directions, translational and torsional motions could be enhanced, respectively, by adding and subtracting the signals from each pair of sensors in time domain. But, in this study, only lateral behavior of building is of interest. The fundamental frequencies of vibration for tested buildings are summaried in Table 1.

Table 1. Period data for apartment buildings

Building	Number	Dimesion, m			L_w	Measured period, sec.		Predicted period, sec.	
		Height	Length	Width		Longitudinal	Transverse	Longitudinal	Transverse
1	15	40.0	38.98	11.26	0.15 / 0.28	1.92	0.71	0.58 (2.42)	1.07 (0.81)
2	15	40.0	27.22	12.83	0.15 / 0.26	N.A	1.08	0.69	1.01
3	20	53.5	30.94	12.38	0.13 / 0.23	1.89	1.19	0.87 (2.16)	1.37 (1.29)
4	20	53.5	31.66	12.02	0.14 / 0.21	1.90	1.44	0.86 (2.36)	1.39 (1.59)
5	20	53.5	30.94	10.88	0.14 / 0.27	1.93	N.A	0.87	1.46
6	15	40.0	49.22	11.61	0.07 / 0.20	N.A	1.27	0.51	1.06
7	15	40.0	27.22	12.83	0.12 / 0.26	2.22	N.A	0.69	1.01
8	15	40.0	56.28	12.47	0.13 / 0.25	1.86	1.16	0.48	1.02
9	15	40.0	28.14	12.47	0.13 / 0.27	1.66	1.09	0.68	1.02
10	15	40.0	34.46	12.47	0.13 / 0.26	1.93	N.A	0.61 (2.06)	1.02 (0.90)
11	20	53.5	42.20	12.14	0.13 / 0.24	2.11	N.A	0.74 (3.09)	1.38 (1.35)
12	15	40.0	38.98	11.28	0.15 / 0.25	1.63	N.A	0.58	1.07
13	15	40.0	27.22	12.83	0.12 / 0.28	2.05	0.91	0.69 (2.58)	1.01 (1.09)
14	20	53.5	41.80	11.18	0.16 / 0.23	1.82	1.16	0.74 (2.06)	1.44 (1.21)
15	20	53.5	37.20	12.36	0.16 / 0.21	1.95	N.A	0.79 (2.66)	1.37 (1.05)
16	20	53.5	45.40	11.94	0.16 / 0.21	1.88	N.A	0.71 (2.28)	1.39 (1.15)
17	20	53.5	45.40	11.94	0.17 / 0.21	1.82	1.50	0.71	1.39
18	20	53.5	32.00	11.94	0.17 / 0.22	1.76	N.A	0.85 (2.60)	1.39 (1.14)
19	15	40.0	51.90	10.36	0.15 / 0.29	1.91	0.90	0.50 (2.36)	1.12 (1.10)
20	15	40.0	34.60	10.36	0.15 / 0.30	N.A	0.86	0.61 (1.89)	1.12 (0.91)
21	15	40.0	61.80	11.80	0.15 / 0.25	1.89	1.28	0.46	1.05
22	15	40.0	41.60	11.80	0.14 / 0.26	N.A	0.99	0.56	1.05
23	15	40.0	53.40	10.80	0.13 / 0.28	N.A	1.16	0.49	1.10
24	15	40.0	36.60	11.90	0.15 / 0.27	1.92	1.27	0.60	1.04
25	15	40.0	35.60	10.80	0.17 / 0.29	1.79	N.A	0.60	1.10
26	15	40.0	42.90	11.00	0.17 / 0.24	1.65	N.A	0.55	1.09
27	18	48.1	43.40	11.62	0.11 / 0.24	1.81	N.A	0.66 (2.74)	1.27 (1.05)
28	20	53.5	34.64	10.73	0.16 / 0.28	1.85	1.17	0.82	1.47
29	18	48.1	34.60	12.50	0.15 / 0.23	1.88	1.23	0.74	1.22
30	20	53.0	53.60	11.40	0.14 / 0.19	1.88	1.12	0.65 (2.85)	1.41 (1.22)
31	20	53.5	29.44	11.40	0.14 / 0.20	1.83	N.A	0.89 (2.75)	1.43 (1.53)
32	20	53.5	35.48	11.40	0.15 / 0.20	1.92	1.31	0.81 (2.96)	1.43 (1.44)
33	20	53.5	52.50	10.92	0.16 / 0.28	1.79	1.06	0.66 (2.88)	1.46 (1.32)
34	22	58.9	52.50	10.92	0.16 / 0.29	1.89	1.04	0.73	1.60
35	25	67.0	43.40	12.12	0.12 / 0.23	2.33	1.79	0.92 (3.23)	1.73 (1.93)
36	25	67.0	35.00	10.92	0.15 / 0.30	N.A	1.33	1.02	1.82
37	25	67.9	38.10	12.30	0.12 / 0.24	2.56	1.39	0.99 (3.65)	1.74 (1.41)
38	25	67.9	20.80	11.50	0.16 / 0.28	2.04	1.59	1.34 (2.67)	1.80 (1.73)
39	25	67.9	27.30	12.00	0.11 / 0.25	2.17	1.61	1.17 (3.06)	1.76 (1.87)
40	25	68.0	63.90	11.50	0.10 / 0.23	2.50	N.A	0.77 (3.66)	1.80 (2.20)
41	25	68.0	51.84	12.60	0.13 / 0.21	2.13	1.69	0.85 (2.68)	1.72 (1.90)
42	19	51.1	36.80	11.20	0.16 / 0.28	1.89	N.A	0.76 (2.09)	1.37 (1.20)
43	20	53.9	36.80	11.20	0.16 / 0.26	1.79	1.25	0.80 (2.12)	1.45 (1.42)
44	15	40.0	18.30	10.70	0.11 / 0.30	1.69	0.90	0.84 (1.88)	1.10 (0.92)
45	20	55.6	35.60	11.40	0.19 / 0.17	1.79	N.A	0.84 (2.65)	1.48 (1.18)
46	20	55.6	53.40	11.40	0.16 / 0.17	1.72	1.25	0.68 (2.32)	1.48 (1.29)
47	20	55.6	41.60	12.00	0.14 / 0.25	1.82	1.27	0.78 (2.63)	1.44 (1.29)
48	20	54.0	31.80	10.00	0.13 / 0.28	N.A	1.25	0.86 (2.06)	1.54 (1.30)
49	20	54.0	51.20	11.60	0.11 / 0.22	1.96	1.39	0.68 (3.61)	1.43 (1.68)
50	20	54.0	50.40	12.30	0.09 / 0.27	2.13	1.20	0.68 (3.70)	1.39 (1.53)

Note : L_w implies the wall length, in meters, per unit plan area, in square meters, in the longitudinal/ transverse direction ; N.A indicates data not available ; Predicted period implies the period given by the code formula, $0.09H/\sqrt{B}$, and () indicates the period obtained from computer based analysis.

COMPARISON WITH CODE-PRESCRIBED PERIODS

The current Korean code specified that the fundamental period of a multistory apartment building with shear-wall dominant system to determine the design base shear for earthquake resistant design can be estimated by

$$T = 0.09\,H/\sqrt{B} \tag{1}$$

where, H=the height of the building in meter, B=the full plan dimension of the building, in meter, in the direction parallel to the applied forces without regard to shear wall dimensions. This formula derived from that in U.S. building code, the 1988 version of Uniform Building Code [10], because Korea has insufficient experience for earthquake. To show its relative accuracy, the measured periods are compared with the periods obtained from the code formula in Fig. 2. It is observed for a majority of buildings that code formula gives a period much shorter in the longitudinal direction and longer in the transverse direction than that measured in this study. In general, the period measured from earthquake is longer than that measured from ambient vibration because of stiffness degradation. But, considering the fact that the code formula is really not meant to provide the real period but to determine the lower bound fundamental period for finding the proper design force level and Korea is located in the regions of low seismicity, the periods from code formula, to be conservative, should be less than the periods measured under ambient conditions. In this respect, the longer period from the code formula in transverse direction underestimates the seismic coefficient ; otherwise, the shorter period from the code formula in longitudinal direction overestimates the seismic coefficient. In addition, the major problem in this formula is that the difference of stiffness due to shear-wall layouts in both directions is ignored. Fig. 2 always shows a period much longer in longitudinal direction than in transverse direction. It means that the stiffness of tested buildings is so different from that code would tend to imply. This observations clearly indicate that this formula is grossly inadequate and that it is difficult to estimate the period of apartment building with shear-wall dominant system only with simple variables such as the height or dimension of the building which can not incorporate the stiffness of building. Analogous result can be found in Fig. 3 which shows the relationship between the measured periods and the values given by various code empirical formulas such as those of the Building Standard Law in Japan of 1994 [3], the Australian Wind Loading Code AS 1170.2 of 1989 [3] and the Uniform Building Code of 1997 [11] The Canadian building code NBCC 1995 [7]and the U.S. building codes UBC 1997 [11] and SEAOC 1996 [8] permit an alternative formulas including the amounts of wall to estimate the fundamental period for the shear-wall buildings. The alternative formula of NBCC 1995 is of the form

$$T = 0.09\ H/\sqrt{D_S} \tag{2}$$

where D_S =length of wall or braced frame, in meters, which constitutes the main lateral load resisting system in the direction parallel to the applied forces. The alternative formula of UBC 1997 and SEAOC 1996 is of the form

$$T = 0.1/\sqrt{A_c}\ h^{3/4} \tag{3}$$

where A_c = the combined effective area, in square feet, of shear walls is defined as

$$T = \sum A_e\,[0.2 + (D_e/h_n)^2] \tag{4}$$

in which A_e =the minimum cross-sectional shear area, in square feet, of a shear wall; D_e =the length, in feet, of a shear wall in the direction parallel to the applied forces; h_n =the height of the building, in feet, above the base. The value of D_e / h_n in (4) should not exceed 0.9. The relationship between the periods obtained from these two formulas and the measured periods are plotted against the each of predictors in Fig. 4 and Fig. 5 respectively. From the observation of figures, for all the buildings, these two formulas give a period much shorter by two or three times than the measured period and a seismic coefficient much larger than the value based on the measured period. Since the poor correlation between the predictor and the measured period is also apparent, it is clear that these formulas can not incorporate the stiffness of the tested apartment buildings. It is therefore inappropriate to use these formulas to estimate the fundamental period of apartment buildings as well.

SIMPLE EMPIRICAL FORMULA FOR APARTMENT BUILDINGS

To obtain simple but more reliable formula for the fundamental period of concrete apartment buildings with

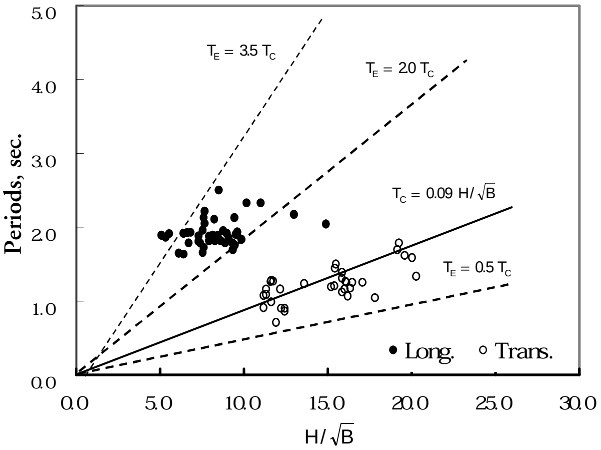


Figure 2 : Comparison of Measured and Code Periods

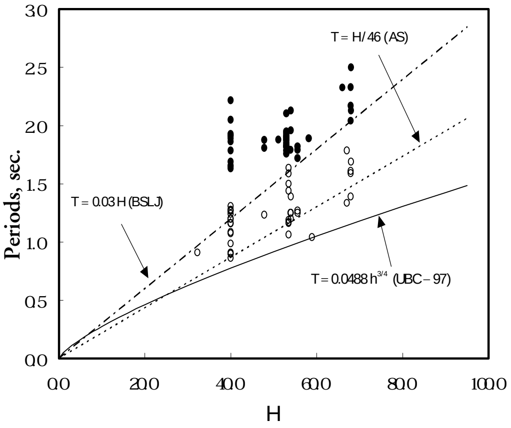


Figure 3 : Comparison of Measured and Various Code Periods

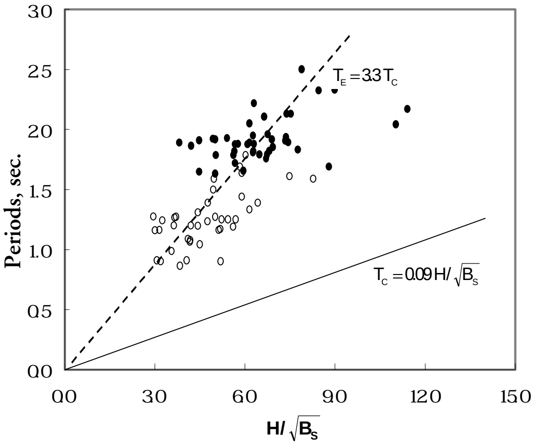


Figure 4 : Comparison of Measured and NBCC(1995) Code Periods

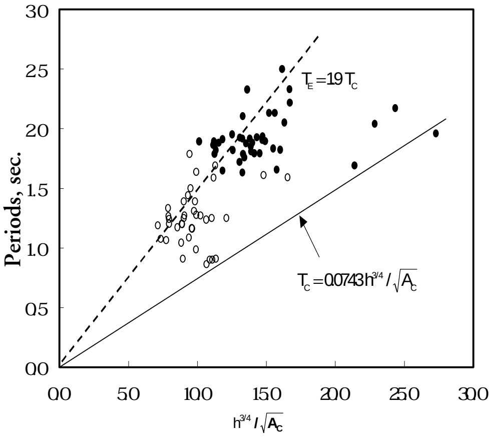
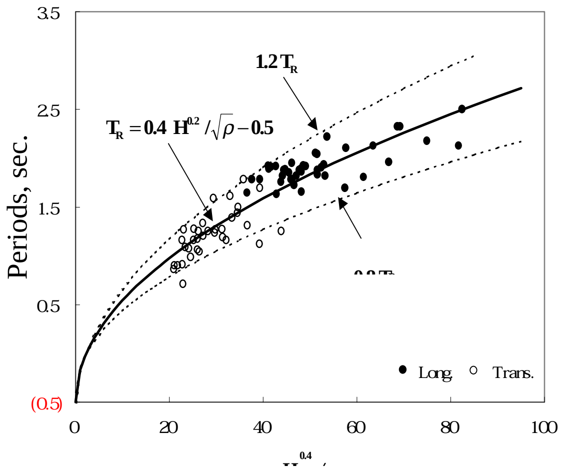


Figure 5 : Comparison of Measured and UBC(1997) Code Periods



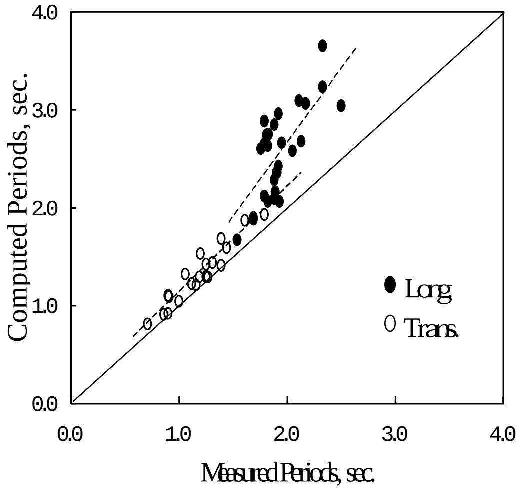


Figure 6 : Proposed Period Formula

Figure 7 : Comparison of Measured and Computed Periods

shear-wall dominant system, regression analysis was carried out on the basis of the measured period data for 50 buildings(78 data points) listed in Table 1. The following regression model was used for this correlations :

$$T = \underline{C_1} \frac{1}{\sqrt{L_w}} H^{\beta} + \underline{C_2} \tag{5}$$

where $\underline{C_i}$ =the constants determined by regression analysis; L_w =the values defined as the wall length per unit plan area; H=the height of the building in meters. This model was derived from the fundamental period of a uniform cantilever beams, considering flexural and shear deformations. Details of how this model was obtained are found in many books and papers [5,9,13], except that L_w is substituted only the wall length for the shear area of the wall, considering the thickness of the walls are almost equal and not determined accurately in the preliminary design stage. For regression with ease, the above relation (5) was transformed to as follows :

$$\log T = \log \underline{C_1} + \beta \log H - \frac{1}{2} \log L_w + \log \underline{C_2} \tag{6}$$

Using the regression method, the following best-fit line was determined :

$$T = b_1 \frac{1}{\sqrt{L_w}} H^{\beta_1} + b_2 \tag{7}$$

in which b_1, b_2, β_1 are unbiased estimaters of $\underline{C_1}, \underline{C_2}, \beta$ respectively. For regression curve fits, error was assessed using the standard error and correlation coefficient. These tools are not perfect, but they do give helpful evaluation of the performance of the curve fit. After relation (7) has been determined, constrained regression analysis was executed in order to simplify the relation (7) with b1 fixed at 0.2, to which b1 in (7) is rounded off and this formula is proposed for apartment buildings because it is simpler, although it has a slightly larger standard error. the formula obtained from the second regression analysis is presented in Fig. 6 together with the measured periods shown in circles. Although the proposal is for serviceability stress level, it can be applied for seismic code in the regions of low seismicity, considering the fact that the code formula must be consulted to determine the lower bound fundamental period in order to establish the proper design force level. it is verified in the following clause that this proposal is not so much over-conservative in the low seismicity region as in Korea.

COMPARISON WITH COMPUTER BASED PREDICTIONS

If a dynamic analysis is used in the design process, building periods are normally computed from a mathematical model rather than from the code formulas. Unless care is exercised on the part of the designer to include all the effective stiffness and mass of the structural and non-structural elements, the computed period could result in a less conservative design. It is this theoretical idealization which is generally responsible for the major errors in this final result. Therefore, to obtain more accurate predictions, a better understanding of the overall behaviour of buildings is necessary, and this will be achieved only by comparing theoretical predictions with experimental measurements. The natural frequencies are often used as one of the basic criteria for more accurate structural idealization.

Fig. 7 illustrates the difference of the real period of the building from the period obtained from the computer based analysis, using ETABS v6.13. It is shown by comparison that the ratio of measured periods to those obtained from the computer based method is about 0.75 for the longitudinal direction and about 0.9 for the transverse direction, which means that the elements providing additional stiffness were much more in the longitudinal direction than in the transverse direction. It is generally realized that the earthquake period is longer than the ambient period because of cracks and a loss of bond between the structural members and non-structural members, and the period of the building during an earthquake approaches the natural period computed from a theoretical model of the pure structural system, neglecting all non-structural elements [4]. In this respect, the proposed formula is not so much over-consevative, considering the ratio of the periods obtained from the proposed formula to those obtained from the computer based analysis is 0.75 averaged, and can give a period in reasonable agreement with value code would tend to imply.

CONCLUSIONS

In order to provide the updated information on the period for the apartment buildings with shear-wall dominant system, full-scale measurements were carried out on fifty RC apartment buildings in Korea, and the reliability of the current empirical code formula was evaluated. As expected, the measured period in the longitudinal direction was longer than that in the transverse direction, which shows that this type of buildings are very different dynamic characteristics from those the current KBC would tend to imply. Also, any codes examined in this study can not identify the dynamic characteristics for apartment buildings with shear-wall dominant system in Korea, because the poor correlation between the predictors in various building codes and the measured periods is also apparent.

The improved formula was proposed on the basis of the ambient vibration measurements. This formula is for the serviceability condition, but can also be applied to determine the base shear for the seismic design for the apartment buildings with shear-wall dominant system to be constructed in moderate or less seismic zone similar to in Korea.

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