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VIBRATION PROPERTIES OF STEEL-FRAMED BUILDINGS DETERMINED FROM AMBIENT VIBRATION TESTS

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SUMMARY

The results of ambient vibration tests on 32 steel-framed buildings, conducted to determine their vibration periods are presented. One aim was to compare the measured periods with the period formulas suggested by Iranian Seismic Code (Standard 2800). These formulas are obtained from US codes and their suitability for buildings in Iran cannot be taken for granted, because of differences in construction materials and processes. Tested buildings, in most of the cases, are regular buildings and have different structural systems with numbers of stories between 5 and 27, and were designed according to the provisions in the Code 2800. First and second translational and torsional periods were identified from AVS records. In nearly all of the cases, the measured translational periods fall below the code curve. Although the formula in the 1st edition of the code, which is of the form $\alpha H / \sqrt{D}$, gives period values closer to the measured periods in comparison with formulas of the form αH^{β} in the 2nd edition, it was concluded that based on statistical analysis, from the point of view of 'form' it doesn't seem to have considerable and clear privilege over the equation of the form αH^{β}. A comparison with vibration periods of buildings in Japan, obtained from dynamic tests, is also made. The first to second and translational to torsional period ratios were also calculated and discussed.

INTRODUCTION

Along with analytical methods, most building codes also suggest empirical formulas for estimation of fundamental vibration period of buildings. The period value is of primary importance in static-equivalent force method because the amount of earthquake force is proportional to this value. The period value is dependant on many factors, like type of lateral-force resisting system, members' characteristics, non-structural elements, underlying soil and even amplitude of vibration and ignoring these factors in the estimation of period value, as well as in the analysis process, will inevitably introduce errors.

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However, if we are to find an easy and practical method for estimation of period value, which is to be used by practicing engineers, there has to be some way for this value to be estimated from initial characteristics of structure rather than sectional properties that will be known after the design. The use of experimentally measured periods to develop empirical formulas is so justified.

Available earthquake records of buildings shaken by earthquakes are valuable sources to evaluate the buildings' periods, vibrating with high amplitudes. However, because in case of Iran, earthquake records are not available, ambient and forced vibration tests seem to be the only practical way in an effort to create a database of experimental data on full-scale buildings. While, in this regard, the issue of dependence of apparent period of soil-building system to vibration amplitude (level of excitation) should be addressed (Çelebi[1]; Trifunac[2],[3],[4]), although it is not the purpose of this paper. However, due to the fact that the proper judgment on the range of these changes doesn't seem possible with the available knowledge, it seems more reasonable, in our case, not to rely much on this effect when attempting to use the results of ambient vibration records to develop empirical period formulas. Let it be noted that the apparent period value can vary even from one earthquake to another and the need for incorporating these changes in future codes has been acknowledged (Trifunac[3],[4]).

The prepared database of ambient vibration records can also be used as pre-earthquake records of tested buildings, after any possible earthquakes, to be compared with the post-earthquake ambient vibration records to investigate any possible variations in structural properties, in future researches. Having all these in mind, the authors have conducted a project to gather ambient vibration records of various types of buildings in Tabriz and Tehran areas, in Iran. From this database, which includes various steel and concrete buildings' data, the results of 32 steel buildings are presented here.

BUILDINGS IN IRAN

Low-rise Steel-framed buildings in Iran, are built using different kinds of columns than those typical for steel structure buildings, in handbooks and other codes. Because of the unavailability of hot-rolled H sections, MRF(moment resisting frames) are built using welded columns. The interior partition walls are built using hollow clay bricks. The exterior walls are often comprised of a layer of hollow clay bricks inside and facade bricks or stone outside. Regular clay bricks are also used in exterior walls but rarely in interior walls. Usually, there isn't any specific detailing used in wall-frame interface deliberately, either to prevent them from interacting or to assure full contact and to prevent walls from falling because of out-of-plane earthquake forces. Therefore it is expected that partition walls have increasing effect on the overall stiffness of such buildings and also in the earthquake induced force of their adjacent columns. However, their permanent presence throughout all the earthquake time is suspicious. The usual flooring system for concrete buildings is concrete joists and blocks covered by a layer of light-weight concrete, intended to embed and hide the pipes that are passing through. Briefly, buildings in Iran can be characterized as possessing relatively heavy dead load and stiff infill walls.

SUGGESTED CODE FORMULAS

The suggested formula by the first edition of the Iranian Seismic Code was based on height and plan dimension of building(BHRC[5]):

$$T = 0.09\frac{H}{\sqrt{D}} \qquad (1)$$

This is usable, according to the code, for all except MRF(Moment Resisting Frames) buildings in which no lateral-restricting element is present. The latter is not the case in nearly all of buildings being built in Iran. Therefore, it will be used in both Dual and MRF cases. *H* and *D* are building height from base level and building dimension in the considered direction in meters, respectively.

The second edition of code, however, has omitted the base dimension factor and based the estimation on building height only. According to the 2nd edition of the code, for all building structures except MRF buildings fundamental period can be estimated by(BHRC[6]):

$$T = 0.05\, H^{3/4} \qquad (2)$$

Suggested formula for Steel-MRF buildings with presence of infill panels is:

$$T = (0.08\, H^{3/4})*\%80 \qquad (3)$$

Reduction factor %80 in (3) is included in case of presence of any elements resisting free lateral vibration of frames, most notably the infill panels, in order to taking into account their stiffening effects.

The first formula is the same formula specified by ATC3-06, and the formulas (2) and (3) are the same as the formulas specified by UBC-97, converted to [SI] units. These equations are developed from information on vibration periods of buildings in the California area, shaken during strong earthquakes(Goel[7]).

METHODOLOGY

Vibration properties of structures can be reliably identified from their response to environmental excitations which are known as ambient vibrations because of their various sources. The method which is known as Ambient Vibration Test, has gained variety of usages and many applications during the past three decades(Ivanović[8]). This method was utilized to extract dynamic characteristics of selected buildings. A 3-directional CR4.5-TB sensor, developed by Buttan Service, was used to measure vibrations, along with an amplifier and a portable computer. Data were digitized and recorded using Wave Shot software.

Vibrations in at least two points were recorded for at least 163 seconds at each point and at a sampling rate of 100 points/sec. Since measurements at two points were not simultaneous, it was important to choose one of the points as close to the center of rigidity, as possible, in order to be able to distinguish between the torsional and translational modes by comparing the extracted spectra from the two points.

Natural frequencies were identified from Power Spectral Density and Fourier Spectrum representation of records. Base-line correction for every record was done through least square algorithm. The signals were low-pass filtered using ButterWorth filter and windowed using Hanning window. The spectrum for every record was extracted from the windowed and filtered signal. All of the mathematical operations were done using MATLAB Software.

Because the majority of cases were regular buildings, three distinguished frequencies were usually identifiable easily from spectra, as three uncoupled natural frequencies of building namely two for translational and one for torsional modes. In the case of non-regular buildings where eccentricities caused modal coupling, the three identified frequencies cannot be related to any particular direction and the smallest frequency is the only data point which is added to the graphs in such cases.

GATHERED DATABASE

The database consists of 32 steel buildings' data. The buildings are laterally supported either by dual system (moment resisting frames + wind bracings) or moment resisting frames alone, or simple frames with wind bracings(WB). Low-rise steel buildings(6-story or less) mostly have flooring system consisting of joists and blocks. But higher buildings usually are built of composite floors. The buildings have number of stories ranging from 5 to 27, with an average height of 30.5 meters and are mostly regular or nearly regular in plan and height and are all designed according to the Iranian Code for Steel Buildings along with the instructions of Iranian Seismic Code.

Eight buildings have moment resisting frames(MRFs) as their lateral force resisting system, in both directions; fifteen buildings are supported by dual system(MRF+WB) in one or both directions and sixteen buildings are supported by wind bracings, without moment resisting frames. The required information on buildings such as structure type, presence of surrounding concrete wall at foundation and dimensional characteristics, were obtained from different sources which were not always quite reliable. In cases when drawings or technical documents were not available, we relied upon information which the buildings' owner or structural engineer could deliver. However, all details are well documented and the database can further be refined.

For buildings which were on construction stage, attention was paid to make sure that the elements with considerable contribution to ultimate dead load and the infill panels, which are believed to have significant increasing effect on lateral stiffness, were in place at the time of the test. In the present database, three of the buildings are not in complete agreement with the above criteria.

Also, it was required for the buildings to be able to vibrate freely and not to be constrained by the adjacent buildings. Most of the buildings in the database, satisfy this criterion completely, and were free from all sides or were separated by minimum gap from adjacent buildings.

Table 1 summarizes the acquired information and results. General information about every building such as location, address, usage, occupancy, flooring system, date of test, condition at the time of testing and photos -in some cases- are also included in the database.

Table 1. *Information and Identified Apparent Periods of Selected Buildings*

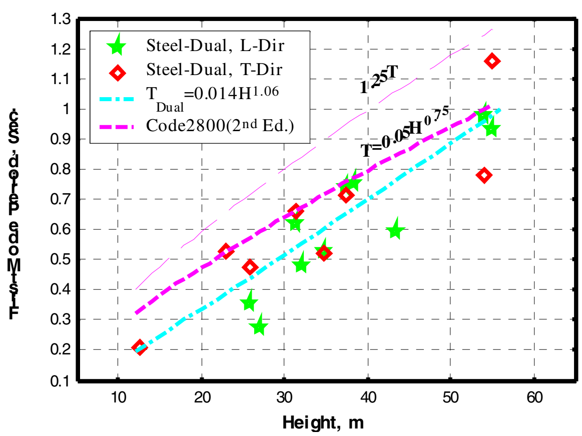
No.	Building ID	No. of Stories (Above G.L. / Below G.L.)	Height (m) (from base level)	Dimensions (m)		Lateral force-resisting system		First Mode Measured Period (Sec.)		Code 2800 First Edition (Sec.)		Code 2800 Second Edition (Sec.)	Second Mode Measured Period (Sec.)	
				L-dir	T-dir	L-dir	T-dir	L-dir	T-dir	L-dir	T-dir		L-dir	T-dir
1	**17**	5 / 0	15.3	14.3	12.6	WB	WB	0.403	0.333	0.34	0.38	0.39	0.139	0.108
2	**18**	5 / 0	15.3	12.5	12.4	WB	WB	0.42	0.31	0.39	0.39	0.39	0.128	0.079
3	**20**	5 / 0	15.3	18.5	13.2	WB	WB	0.33	0.33	0.32	0.38	0.39	0.115	0.109
4	**26**	5 / 0	17.5	18.0	12.0	WB	WB	0.309	0.341	0.37	0.45	0.43	-	-
5	**32**	5 / 0	16.0	15.5	9.2	WB	WB	0.413	0.326	0.37	0.47	0.40	0.136	0.102
6	**36**	6 / 0	21.2	18.0	13.0	WB	WB	0.44	0.56	0.45	0.53	0.49	-	-
7	**52**	7 / 1	32.0	33.0	23.0	Dual	MRF	0.48	0.69	0.50	0.60	0.67,0.65	0.138	0.226
8	**57**	12 / 2	38.4	-	-	Dual	MRF	0.75	0.90	-	-	0.99	0.238	0.272
9	**58**	9 / ?	27.0	27	12	Dual	MRF	0.275	0.52	0.47	0.70	0.96	-	0.167
10	**65**	6 / *var.*	12.6	23.9	12.5	MRF	Dual	0.28	0.21	0.23	0.32	0.43	-	-
11	**66**	14 / 1	42.4	20.8	13.8 ~ 22.0	MRF	MRF	1.12	0.87	0.84	-	1.06	0.357	-
12	**67**	14 / 1	42.4	20.8	17.5	MRF	MRF	1.12	0.81	0.84	0.91	1.06	0.357	0.260
13	**70**	7 / 1	23.0	21.0	11.6	WB	Dual	0.31	0.53	0.45	0.61	0.53	-	0.179
14	**71**	19 / 5	70	40.0	21.3	Dual	Dual	1.59	1.63	1.0	1.37	1.21	0.535	0.515
15	**73**	8 / 1	25.8	18.0	10.0	Dual	Dual	0.36	0.47	0.55	0.69	0.57	-	-
16	**75**	11 / 1	34.7	24.3	21.2	Dual	Dual	0.53	0.52	0.63	0.68	0.71	0.167	0.169
17	**76**	20 / 4	55.0	49.0	16.4	Dual	Dual	0.93	1.16	0.71	1.21	0.83	0.306	0.346
18	**78**	5 / 0	15.3	15.2	8.0	WB	WB	0.30	0.35	0.35	0.46	0.39	-	-
19	**79**	6 / 0	18.4	22.2	17.0	WB	WB	0.32	0.32	0.35	0.40	0.44	-	-
20	**80**	5 / 0	15.0	22.7	20.7	WB	WB	0.28	0.31	0.28	0.30	0.38	-	-
21	**81**	5 / 0	15.2	30.6	12.7	WB	WB	-	0.28	0.25	0.38	0.38	-	-
22	**82**	5 / 0	15.2	12.8	12.5	WB	WB	-	0.30	0.38	0.39	0.38	-	-
23	**84**	6 / *var.*	18.4	20.0	17.2	WB	WB	0.29	0.34	0.37	0.40	0.44	0.106	0.116
24	**85**	5 / *var.*	15.3	20.0	17.2	WB	WB	0.26	0.30	0.31	0.33	0.39	0.097	-
25	**86**	5 / 0	15.3	22.2	17.0	WB	WB	0.29	0.29	0.29	0.33	0.39	-	-
26	**92**	18 / ?	61.0	Non-rectangular		Composite		1.49,1.35,1.27		-	-	1.09	0.46,0.40, -	
27	**94**	14 / 1	43.4	23.4	19.8	Dual	MRF	0.59	0.84	0.81	0.88	0.85,1.08	-	-
28	**95**	15 / 1	54.0	18.0	17.2	Dual	Dual	0.98	0.78	1.15	1.17	1.0	0.314	0.226
29	**96**	27/ var.	81.4	46.0	34.0	Composite		1.47	1.91	1.08	1.26	1.36	0.467	0.595
30	**99**	11 / -	35.7	27.0	9.8	WB	MRF	0.44	0.57	0.62	0.88	0.83,0.93	-	-
31	**100**	12 / 0	37.4	26.3	26.3	Dual	Dual	0.74	0.71	0.66	0.66	0.76	0.234	0.236
32	**101**	10 / 0	31.3	26.3	15.9	Dual	Dual	0.62	0.66	0.55	0.71	0.66	0.198	0.208

In which, "MRF" stands for "Moment-Resisting Frames", "Dual" indicates lateral force resisting system consisting of moment-resisting + wind bracings frames, and "WB" is abbreviation for "Wind Bracings". "L-Dir" and "T-Dir" refer to Longitudinal and Transverse Directions, respectively.

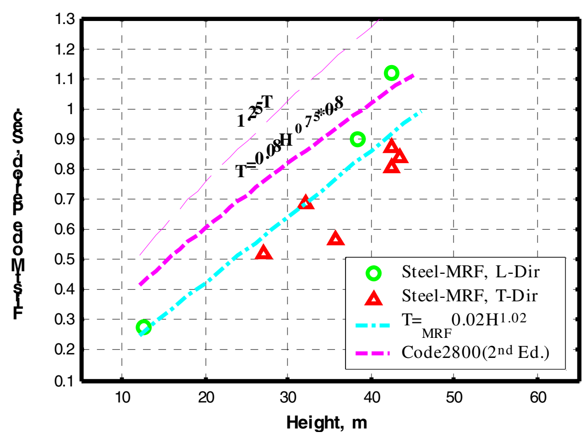
A COMPARISON WITH CODE PERIOD FORMULAS

Formulas in the Second Edition of Code 2800

Measured periods are plotted in Fig. 1 against building height, measured from base level. In cases of buildings with surrounding concrete walls at foundation with small or no openings, the base level is considered above the wall level. Three of the cases(ID.71,92,96) which were either very different from others in height or period or had composite elements or other special detailing in their structures were excluded from the graphs. Longitudinal and transverse periods for each building are plotted using different symbols. Predicted values by specified formulas in the second editions of Code 2800 are added to the graphs. Results for Dual, MRF and WB systems are presented in different diagrams. Due to the fact that natural period of buildings can depend on many factors and we are trying to predict it only from height of building, some scatter is expected. Certainly, more scatter results in less accurate period formulas, which are obtained by statistical analysis on experimental data. It should also be noted that applying the described procedure of testing and data analysis, the obtained period values will be in fact the values of "apparent period" belonging to the system of soil-foundation-structure and not only to the structure itself.



(a)



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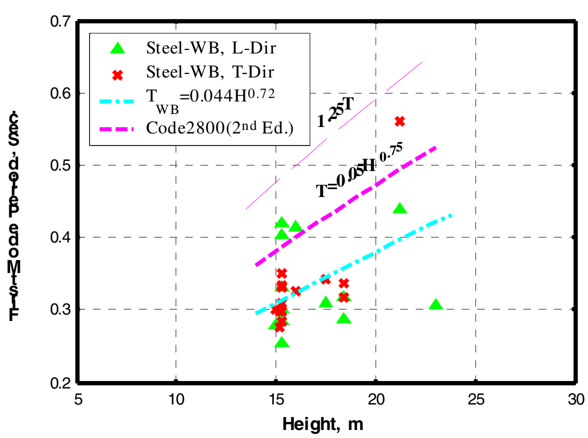


(c)

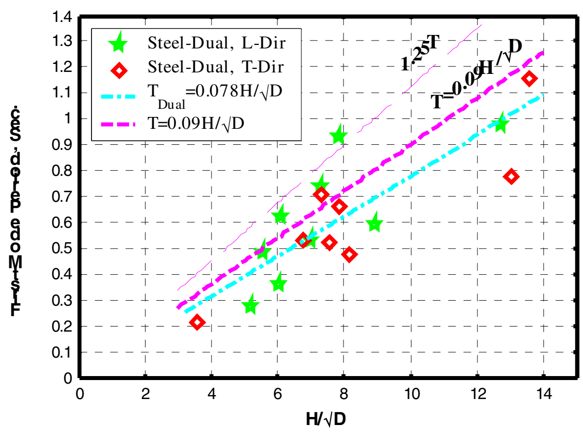
Figure 1. Measured and Code 2800(2nd Edition)-predicted periods vs. Height: (a) Buildings with Dual(MRF+WB) lateral-force resisting system; (b) MRFs as lateral-force resisting systems; (c) Buildings with Wind Bracings, as lateral-force resisting system.

The estimated values by the formulas in second edition of Code 2800 are predominantly located above the upper limits of measured values. Due to the fact that these period formulas are developed from earthquake-time periods which are longer than the low-amplitude vibration periods, this difference cannot directly be interpreted to inaccuracy of these period formulas and any judgment on this issue should be done with the acknowledgement of this fact.

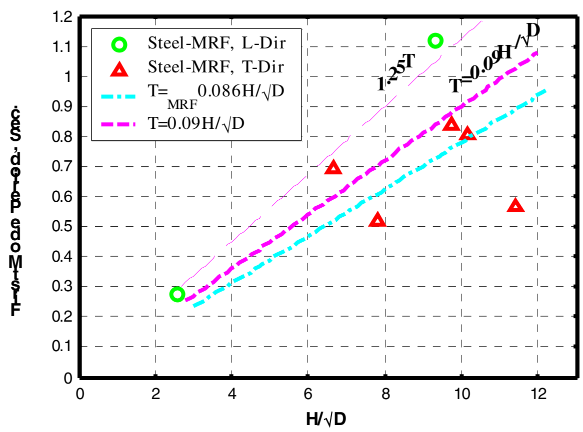
As in other seismic codes, using analytical methods such as Rayleigh's Method or eigenvalue analysis for estimating building period is permitted by Code 2800. However an upper limit is set on the obtained values to safeguard against any over-estimation of period value which is often the result of incomplete mathematical models, where infill panels and other effective non-structural elements usually are not involved. According to Code 2800, the calculated period values using analytical methods shouldn't exceed the values given by empirical formulas by factor 1.25. Therefore, the structural engineer is allowed to reduce earthquake forces by assuming period values as high as 1.25*T*, if the analytical methods give higher values, which is usually the case. Reminding the fact that sometimes practicing engineers resort to such an approach, to reduce the estimated amount of earthquake force, the importance of setting an appropriate limit for calculated period values is more realized. The allowed upper limit by the code for period value is also plotted in figures, by offsetting the code's curve. There is a considerable difference between the allowed limit and the measured values.

Formulas in the First Edition of Code 2800

In order to compare results with the formula in first-edition of Code 2800(equation (1)), the horizontal axis in diagrams in Fig.2 is chosen to indicate $H/\sqrt{D}$ ratio. The code curve, the fitted curve and the



(a)



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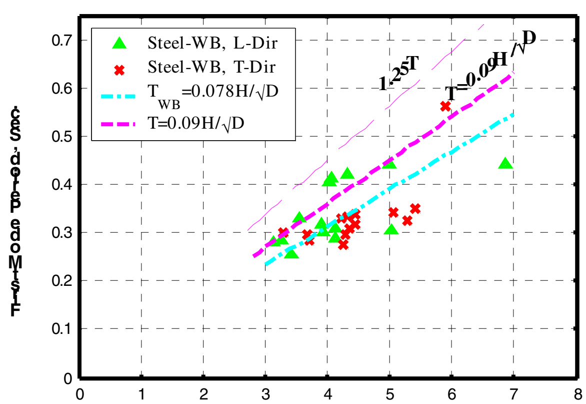


(c)

Figure 2. Measured and Code2800(1st Edition)-predicted periods vs. parameter $H/\sqrt{D}$: (a) Buildings with Dual(MRF+WB) lateral-force resisting system; (b) MRFs as lateral-force resisting systems; (c) Buildings with Wind Bracings as lateral-force resisting system.

1.25T limit-curve are also plotted. In comparison with previous diagrams, the code and fitted curves seems to be closer to each other. As a quantitative measure of comparison, we calculated the value of square root of mean squared relative difference between code and measured periods, in order to compare degree of closeness of formulas (1),(2) and (3) to the measured periods. Based on this index, the formula (1) is as close to the measured points as the formula (3) but closer to than formula (2). However, this relative closeness cannot necessarily be an indication that formula (1) is superior in 'from'. We shall compare the two forms with each other, by comparing values of correlation coefficient and *R*-square, separately for each type of structural systems. Correlation coefficient is an indication of degree of linear dependence between two values, and the R-square is the ratio of sum of square of difference between fitted curve and mean value to the difference between data points and the mean value. This parameter is a measure of degree of success of the fitted curve in explaining the variation of the data around the mean, and values closer to unity indicate a better fit(The MathWorks[9]).

As it is seen from the tables, for dual systems, both indexes are close for the two forms of equations, however, values closer to unity in case of formula of the form (αH^{β} ;Table 2), indicate that this form is slightly more successful, on the other hand, in case of WB systems, the first form($\alpha \frac{H}{\sqrt{D}}$; Table 1) proves to be better than the other. For MRF systems, the number of data points seems to be too small to allow a reliable judgment.

Table 2. *Summery of results of regression; equation of the form* $\alpha \frac{H}{\sqrt{D}}$.

Lateral-force Resisting System	Number of data points	Correlation Coefficient	*R*-square	Results of regression (α)
Dual	17	0.82	0.67	0.078
MRFs	8	0.59	0.31	0.086
WBs	27	0.60	0.37	0.078

Table 3. *Summery of results of regression; equation of the form* αH^{β}.

Lateral-force Resisting System	Number of data points	Correlation Coefficient	*R*-square	Results of regression	
				α	β
Dual	18	0.89	0.80	0.014	1.06
MRFs	10	0.87	0.86	0.020	1.02
WBs	27	0.42	0.23	0.044	0.72

Variations in Seismic Coefficient:

The estimated amount of seismic force, in the code-recommended equivalent static force method, is taken directly proportional to seismic coefficient, as well as weight of the building. Seismic coefficient is calculated based on formula $C = ABI/R$. In which, $B = 2.5(T_0/T)^{2/3}$ is the response factor, with maximum allowable value of 2.5. Response factor is dependant upon the natural period of vibration of the building(T) and soil(T_0). Values of seismic coefficient, calculated based on measured periods, normalized to the values obtained using code-specified period formulas are shown in diagrams in Fig. 3. Two kinds of soils-profiles are considered, called type I and Type IV by the Code 2800, for which T_0 = 0.4, 1.0 respectively. These diagrams are meant to give an assessment on the variation of amount of seismic force, if the measured period values were used to calculate the seismic coefficient. As it is seen from diagrams, for the range of heights we are investigating, overestimation of fundamental vibration period of buildings will have greater effects for buildings located on stiffer soils than more flexible soils, because values greater than 2.5 will be obtained for B in both cases, and the 2.5 upper limit will be dominant.

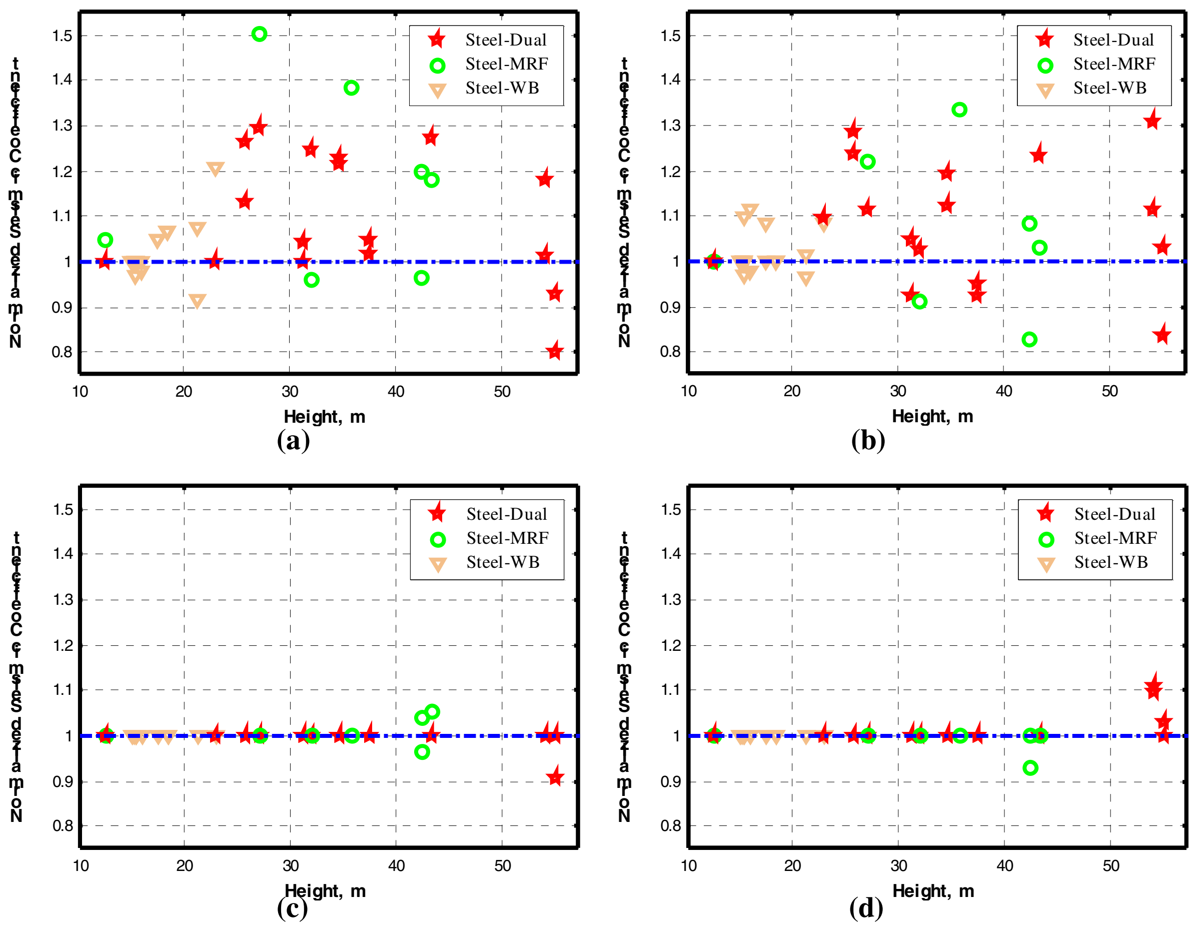


Figure 3. Seismic coefficient values, based on measured periods, normalized to the values calculated using code periods: (a) Soil type I (T_0=0.4), Values are normalized to the Second Edition Code values; (b) Soil Type I, Values are normalized to the First Edition Code values; (c) Soil Type IV (T_0=1.0), Values are normalized to the Second Edition Code values; (d) Soil Type IV, Values are normalized to the First Edition Code values.

A COMPARISON WITH BUILDINGS IN JAPAN

If we are to consider the use of empirical period formulas suggested by other foreign codes which are developed from information on buildings in that countries, it will be useful to compare our results with the period values of buildings in other countries, obtained from low-amplitude vibration tests. Fig.4 contains all measured periods and the fitted curve and plot of an equation adopted from reference[10], which is a fitted line to measured periods of Japanese buildings, identified from low-amplitude vibration tests. The two curves seem to be very close to each other.

Such comparisons can be useful for assessing the suitability of period formulas, suggested by foreign codes, for buildings in Iran. However, closeness of low-amplitude vibration periods doesn't necessarily means that the earthquake-time periods will also be alike, so that we can accept period formulas which are based on earthquake records, and more judgments seem to be necessary.

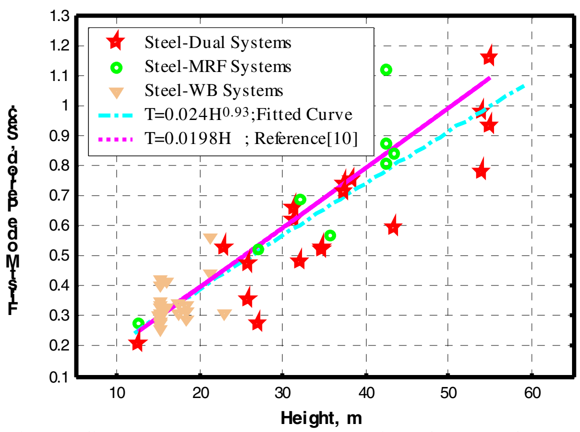
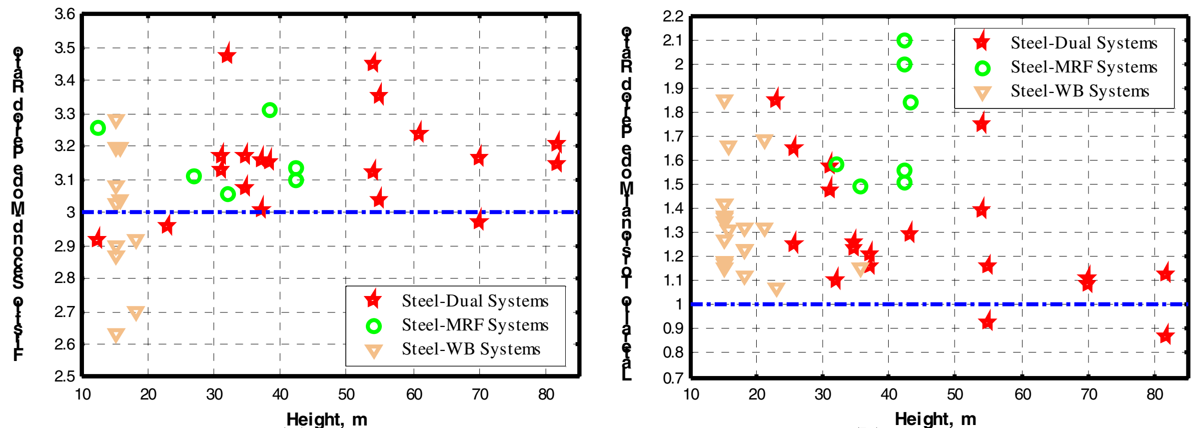


Figure 4. All measured periods, fitted curve and the equation from reference [10], which is the fitted line to vibration periods of buildings in Japan, obtained from low-amplitude vibration tests.

PERIOD RATIOS

The ratio of first to second mode period is usually of interest because it gives an indication of degree of shear or flexural-type behavior of over-all structural system (Li[11]; Chopra[12]). The theoretical value for the ratio of first to second-mode period is 3 for a uniform pure-shear cantilever or a shear building, and 6.3 in case of a pure-flexural cantilever beam. The translational(lateral) to torsional-period ratio is another quantity of interest. It is an indication of distribution of stiffness across the plan of building(Li[11]). The importance of relative values of lateral and torsional-mode periods arises from the fact that it is usually accepted that degree of lateral-torsional motions in buildings is dependant on the closeness of translational and torsional free vibration periods(Yoon[13]).

These two period ratios are plotted in Fig.5. In Fig.(5-a) which shows the first to second-mode period ratio, no particular trend is seen, however, it seems that the ratio usually takes values between 3 and 3.5 for MRF and Dual systems. The translational to torsional-mode period ratios which are plotted in Fig.(5-b) are mostly located above unity. This means that nearly in all of the cases, where torsional period was identified, the torsional-mode period is less than the periods of translational modes.



(a) **(b)**

Figure 5. Period Ratios: (a) First to second-mode period ratio; (b) Ratio of translational to torsional-mode periods.

CONCLUSIONS

Natural period of vibration of 32 steel-framed building, determined from ambient vibration tests, were reported and an evaluation of period formulas, suggested by Iranian Seismic Code was made. The following conclusions can be drawn:

1. Measured periods are mainly located below the formulas suggested by 2nd Edition of Iranian Seismic Code (Standard 2800). The fitted curves show a linear variation vs. height for Dual and MRF systems.

2. However the formula '$0.09H/\sqrt{D}$'(equation(1))gives period values closer to measured periods in comparison with equations(2) and (3), based on statistical analysis, from the point of view of 'form' it doesn't seem to have considerable and clear privilege over the equation of the form αH^{β}.

3. The ratio of first to second-mode period was extracted and was found to lie between 3 and 3.5 for tested steel buildings with Dual and MRF lateral-force resisting systems. The ratio of translational to torsional-mode period was examined and it was found that the first torsional-mode period is shorter than the two first translational-mode periods in most of the cases.

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