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EVALUATION OF BUILDING PERIOD FORMULAS FOR STEEL MOMENT RESISTING FRAMES BASED ON APPARENT BUILDING PERIODS

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ABSTRACT

The fundamental period of a building is an essential parameter for the seismic design of a building structure using equivalent lateral force procedures. In most design practice, the empirical building period formulas are used to initiate the seismic design process. In this study, the empirical building period formulas for steel moment resisting frames in NEHRP 2003 are evaluated with periods from 65 buildings. The apparent periods of 34 buildings are identified utilizing the transfer function method. And periods of 31 buildings are collected from literature. Qualitative comparison of the apparent periods with the periods from the empirical formulas shows that the formula for steel moment resisting frames generally predicts the apparent periods in all height ranges. But in the low to medium rise buildings, the formulas tend to overestimate apparent building periods. The period formula which is a function of number of stories is more conservative than those from the formula as a function of building height. And the buildings in seismic use group III, such as hospitals and emergency support facilities, exhibit shorter periods than the buildings in other seismic use group due to higher importance factor and more stringent drift limits employed in the design process.

Introduction

The fundamental period of a building is a key parameter for the seismic design of a building structure using the equivalent lateral force procedure. As the building period cannot be calculated before the building is designed, the empirical period formulas or finite element analysis with assumed mass and stiffness are used in the preliminary design stage. In most building design projects, empirical building period formulas are used to initiate the design process. The period from the empirical period formula also serves as a basis to limit the period from a finite element model by applying the upper bound factor, C_u, suggested in the 2003 NEHRP Recommended Provisions for Seismic Regulations for New Buildings (BSSC 2003, referred to as NEHRP 2003 hereafter).

In the 1970s design codes, such as UBC-70 (ICBO 1970) and BOCA-75 (BOCA 1975), two formulas were used to estimate building periods: one for moment-resisting frames (MRFs

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hereafter) and the other one for all other structural types as presented in Table 1. These formulas remained in the code until UBC-82 (ICBO 1982). From the ATC 3-06 project (ATC 1978), the period formulas for reinforced concrete and steel moment resisting frames (RC MRFs and steel MRFs hereafter) were calibrated based on identified building periods from the 1971 San Fernando Earthquake. 17 steel MRFs and 14 RC MRFs were used for this calibration. The calibrated building formulas in ATC 3-06 were reflected in BOCA-87 and UBC-88 with minor refinement. The same form of the formula is also applied to other structural types in UBC-88. Most recently, Goel and Chopra (1997a and 1998) calibrated the formula for moment resisting frames and developed a new formula for shear wall buildings with measured (or apparent) building periods from several earthquake events. In their study, 42 steel MRFs, 27 RC MRFs, and 9 shear wall buildings were used. The suggested period formula and calibrated parameters in Goel and Chopra (1997a and 1998) were reflected in NEHRP 2000 and 2003 which is the basis of the current minimum design load for buildings and other structures (ASCE 7-05). Table 1 summarizes the revision history of approximate building period formulas in design specifications (UBC, BOCA, NEHRP, ASCE 7, Euro Code, and ATC 3-06) since 1970s.

Table 1. Approximate fundamental period formulas

	RC MRF	Steel MRF	EBF	RC/Masonry Shear Wall	Other
UBC-70, 82(i) BOCA-75	$T_a = 0.10N$		$T_a = 0.05h_n / \sqrt{D}$		
ATC 3-06 (1978)	$T_a = C_t h_n^{3/4}$		$T_a = 0.05h_n / \sqrt{D}$		
	$C_t = 0.025$	$C_t = 0.035$			
BOCA 87 (i)	$T_a = C_t h_n^{3/4}$		$T_a = 0.05h_n / \sqrt{D}$ (ii)		See note (i)
	$C_t = 0.030$	$C_t = 0.035$			
UBC-88, 94, 97(i) Eurocode 8 (2004)(vi)	$T_a = C_t h_n^{3/4}$				
	$C_t = 0.030$	$C_t = 0.035$	$C_t = 0.030$	$C_t = 0.02$ or, $C_t = 0.1 / \sqrt{A_C}$ (v)	$C_t = 0.020$
ASCE 7-97 BOCA-96 NEHRP 94, 97	$T_a = C_t h_n^{3/4}$				
	$C_t = 0.030$	$C_t = 0.035$	$C_t = 0.030$(vii)	$C_t = 0.020$	$C_t = 0.020$
	or, $T_a = 0.10N$ (iii)		–	–	–
NEHRP 00, 03 ASCE 7-02,05	$T_a = C_r h_n^x$				
	$C_r = 0.016$ $x = 0.9$	$C_r = 0.028$ $x = 0.8$	$C_r = 0.030$ $x = 0.75$	$C_r = 0.020$ $x = 0.75$	$C_r = 0.020$ $x = 0.75$
	or, $T_a = 0.10N$ (iii)		–	or, $T_a = 0.0019h_n / \sqrt{C_w}$ (iv)	–

Note: (i) Rayleigh's method is also suggested as a period formula for all structural types in BOCA-87, UBC-82-97. As the equation is not a function of geometry and needs a structural model *a priori*, the equation is not included in this table.

(ii) For shear walls or exterior concrete frames utilizing deep beams or wide piers, or both, D is the dimension of the building in ft in a direction parallel to the applied force. For isolated shear walls not interconnected by frames or for braced frames, D is the dimension is the shear wall or braced frame in a direction parallel to the applied force.

(iii) Applicable to structures not exceeding 12 stories in height and having a minimum story height of not less than 10 ft.

(iv) Refer to NEHRP 2003 for the definition of C_w.

(v) Refer to UBC-94 for the definition of A_c.

(vi) Eurocode 8 also suggests using $T_a=2\sqrt{(d)}$, where d is the lateral elastic displacement of top of the building in m due to the gravity l oads applied in the horizontal direction. Since the equation is not a function of geometry and needs a structural model *a priori*, the equation is not included in this table.

(vii) BOCA-96 allows the use of $C_t = 0.03$ for both EBF systems and dual systems using EBF.

While the code formulas suggest that the building period are mainly a function of structural types, previous studies showed that the apparent periods are also affected by other parameters such as importance factors (Tremblay 2005) and seismic hazard levels (Nakashima et al. 2000). These variables directly affect the design base shear, which governs the size of structural members and consequently the periods of the buildings. In the U.S. the importance factors, I, ranging from 1.25 to 1.5 for essential facilities have been used since 1980s; UBC-82 (I=1.5), BOCA-87 (I=1.5), UBC-88, 94 (I=1.25), and NEHRP 1997-2003 (I=1.5). Hence, it is expected that essential facilities designed and constructed after 1980 were designed with 25 to 50% higher design base shear than buildings in other seismic use group assuming that other design parameters are similar. In addition to the importance factors, essential facilities are subjected to higher drift limit than other buildings. For instance, story drift for the seismic use group III is 1% while that for the seismic use group I and II are 2% and 1.5%, respectively. Consequently, if a design of a building is controlled by drift limit, the periods of essential facilities are expected to be shorter than those of non-essential buildings. The shorter periods in general attract higher seismic demand. The effect of seismic use group to the apparent building period for steel moment resisting frames is discussed in this paper.

The California Strong Motion Instrumentation Program developed by the California Geological Survey (CGS) has instrumented over 170 buildings in California since its establishment in 1972. Among the instrumented buildings, around 40 buildings were instrumented after the 1994 Northridge Earthquake. These instrumented buildings have recorded many minor to moderate seismic events in the U.S for the past several decades. The objective of this study is to evaluate the current building period formulas for steel moment resisting frames with measured (or apparent) building periods from the instrumented buildings. To achieve this objective, 34 steel MRF buildings are selected from the CGS stations and apparent periods of the buildings are identified utilizing the transfer function method. In addition, periods of 31 buildings from previous studies (ATC 3-06 1978; Goel and Chopra 1997a) are compiled to build a period database of 65 steel moment resisting frames buildings. These apparent periods are used to evaluate the building period formulas for steel moment resisting frames in the current seismic design provision, NEHRP 2003 (BSSC 2003). The effects of seismic use group, building height, and number of stories to the fundamental periods of the buildings are evaluated. As part of this study, the building period formulas for several other building types, such as concrete moment resisting frames, braced frames, shear walls, and other types of structures, are also evaluated. Due to the page limitation, however, the focus of this article is only on the evaluation of period formula for steel MRFs. The evaluation results for the other building types will be available elsewhere (Kwon and Kim, 2009).

Selected Buildings and Recorded Earthquake Events

To evaluate the approximate period formulas in the current seismic design code, a period database of 65 steel MRF buildings is developed. Among the buildings, 34 buildings are CGS stations while others are buildings from literature (ATC 3-06 1978; Goel and Chopra 1997a, 1997b). The non-CGS stations are from ATC 3-06 (16 buildings), National Oceanic and Atmospheric Administration (NOAA, 11 buildings), and United States Geological Survey (USGS, 4 buildings). Except ATC 3-06, the original references of the periods are not available. Thus the periods of these buildings are excerpted from the study by Goel and Chopra (1997a, 1997b). Table 2 shows the list of the selected building stations in this study. The periods of the stations with plus (+) are identified in this study while the periods of other stations were reported in the previous study by Goel and Chopra (1997a).

Heights of the selected buildings are defined as the height from the lowest level without lateral support from surrounding soil. For instance, if a building has underground structures but laterally supported by surrounding soil, the height of the building is measured from the 1st floor (ground level) to the roof level. If there is a gap between building and surrounding soil which allows the building to vibrate without lateral constraint, then the height is measured from the support. If a building has a penthouse with a relatively large footage area, then the height of the penthouse is included in the building height. Otherwise, the penthouse is neglected when calculating the height of the building. The number of stories is also determined by the same procedure used for determining building height.

The selected buildings are also classified into two seismic use groups, namely essential facilities (Seismic Use Group III) and non-essential facilities (Seismic Use Group I and II). Among the 65 steel MRF stations, 11 buildings belong to Seismic Use Group III, such as hospitals and buildings for post-earthquake emergency responses and communications. The buildings in this group are highlighted in Table 2. Since buildings in Seismic Use Group III are designed with higher design base shear than the buildings in other seismic use groups, the investigation on the periods of these buildings can provide insight on the effects of seismic design level on structural periods.

Table 2. Steel MRF building stations for apparent period identification

Build. Code	City	Story	Hgt., ft	Long.	Trans.
C12299	Palm Springs	4	51.5	MRF (Steel)	MRF (Steel)
C14323	Long Beach	7	91.0	MRF (Steel)	MRF (Steel)
C23516	San Bernardino	3	41.3	MRF (Steel)	MRF (Steel)
C24370	Burbank	6	82.5	MRF (Steel)	MRF (Steel)
C24643	Los Angeles	19	283.0	MRF (Steel)	Brace (CBF)
C57357	San Jose	13	173.1	MRF (Steel)	MRF (Steel)
C57562	San Jose	3	49.5	MRF (Steel)	MRF (Steel)
C58506	Richmond	3	46.2	MRF (Steel)	MRF (Steel)
C58532	San Francisco	47	564.0	MRF (Steel)	other
C03233 +	La Jolla	2	56.3	MRF (Steel)	MRF (Steel)
C13213 +	Moreno Valley	3	45.0	MRF (Steel)	MRF (Steel)
C13291 +	Newport Beach	7	135.0	MRF (Steel)	MRF (Steel)
C14533 +	Long Beach	15	288.0	MRF (Steel)	MRF (Steel)
C14766 +	Los Angeles	4	45.0	MRF (Steel)	MRF (Steel)
C23481 +	Redlands	7	80.0	MRF (Steel)	MRF (Steel)
C23515 +	San Bernardino	9	117.6	MRF (Steel)	MRF (Steel)
C23634 +	San Bernardino	5	69.0	MRF (Steel)	MRF (Steel)
C24104 +	Simi Valley	2	28.5	MRF (Steel)	MRF (Steel)
C24198 +	Cahtsworth	2	34.0	MRF (Steel)	MRF (Steel)
C24288 +	Los Angeles	32	337.0	MRF (Steel)	MRF (Steel)
C24546 +	Pasadena	12	178.8	MRF (Steel)	MRF (Steel)
C24566 +	Pasadena	12	168.0	MRF (Steel)	MRF (Steel)
C24569 +	Los Angeles	15	236.0	MRF (Steel)	MRF (Steel)
C24609 +	Lancaster	5	78.5	MRF (Steel)	MRF (Steel)
C24629 +	Los Angeles	54	715.5	MRF (Steel)	MRF (Steel)
C54388 +	Bishop	2	26.0	Brace (CBF)	MRF (Steel)
C57783 +	Fremont	3	45.0	MRF (Steel)	MRF (Steel)
C58199 +	Walnut Creek	3	45.0	MRF (Steel)	MRF (Steel)
C58261 +	San Francisco	4	52.5	MRF (Steel)	MRF (Steel)
C58480 +	San Francisco	18	229.3	MRF (Steel)	MRF (Steel)
C58615 +	Redwood City	16	222.4	MRF (Steel)	other
C58661 +	Castro Valley	2	29.0	MRF (Steel)	MRF (Steel)
C58776 +	San Francisco	14	181.7	MRF (Steel)	MRF (Steel)
C68669 +	Santa Rosa	4	57.4	MRF (Steel)	MRF (Steel)
ATC.ST01	Los Angeles	19	208.5	MRF (Steel)	MRF (Steel)
ATC.ST02	Pasadena	9	128.5	MRF (Steel)	MRF (Steel)
ATC.ST03	Los Angeles	N/A	120.0	MRF (Steel)	MRF (Steel)
ATC.ST04	Los Angeles	27	368.5	MRF (Steel)	MRF (Steel)
ATC.ST05	Los Angeles	19	267.0	MRF (Steel)	MRF (Steel)
ATC.ST06	Los Angeles	17	207.0	MRF (Steel)	MRF (Steel)
ATC.ST07	Los Angeles	N/A	250.0	MRF (Steel)	MRF (Steel)
ATC.ST08	Los Angeles	32	428.5	MRF (Steel)	MRF (Steel)
ATC.ST09	Los Angeles	N/A	208.5	MRF (Steel)	MRF (Steel)
ATC.ST10	Los Angeles	39	494.0	MRF (Steel)	MRF (Steel)
ATC.ST11	Los Angeles	15	202.0	MRF (Steel)	MRF (Steel)
ATC.ST12	Los Angeles	31	336.5	MRF (Steel)	MRF (Steel)
ATC.ST13	Los Angeles	N/A	102.0	MRF (Steel)	MRF (Steel)
ATC.ST14	Los Angeles	N/A	158.5	MRF (Steel)	MRF (Steel)
ATC.ST15	Los Angeles	41	599.0	MRF (Steel)	MRF (Steel)
ATC.ST17	Los Angeles	N/A	81.5	MRF (Steel)	MRF (Steel)
N151-3	Los Angeles	15	202.0	MRF (Steel)	MRF (Steel)
N157-9	Los Angeles	39	469.0	other	MRF (Steel)
N163-5	Los Angeles	41	599.0	MRF (Steel)	MRF (Steel)
N172-4	Los Angeles	31	336.5	MRF (Steel)	MRF (Steel)
N184-6	Los Angeles	27	398.0	MRF (Steel)	MRF (Steel)
N187-9	Los Angeles	19	270.0	MRF (Steel)	MRF (Steel)
N267-8	Pasadena	9	130.0	MRF (Steel)	MRF (Steel)
N428-30	Los Angeles	32	443.5	MRF (Steel)	MRF (Steel)
N440-2	Los Angeles	17	207.0	MRF (Steel)	MRF (Steel)
N461-3	Los Angeles	19	231.7	MRF (Steel)	MRF (Steel)
NA01_STMRF	San Francisco	60	843.2	MRF (Steel)	MRF (Steel)
U482	Alhambra	13	198.0	MRF (Steel)	MRF (Steel)
U5208	Los Angeles	6	104.0	MRF (Steel)	MRF (Steel)
U5233	Los Angeles	32	430.0	MRF (Steel)	MRF (Steel)
U5239	Norwalk	7	96.0	MRF (Steel)	MRF (Steel)

Notes: (i) The fist characters of building codes, C, ATC, U, and N, denote the sources of stations, CGS, ATC3-06 report, United States Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA), respectively.

(ii) The highlighted buildings are essential buildings (Seismic Use Group III). The buildings without shades are either non-essential buildings or buildings whose usage cannot be identified.

(iii) The building code with '+' indicates newly added buildings in this study. Note that there are several essential buildings in the list.

Adopted System Identification Method

The fundamental period in this study refers to the apparent first mode period identified from transfer functions of recorded accelerations. It is termed 'apparent' as the true fundamental period of a building is very difficult to identify due to several factors including the variation of the periods due to inelastic response of soil and structure, soil-structure-interaction, inadequate distribution or insufficient number of accelerometers, and noise in the measurement system. The approximate period formula in the code provides a conservative period to initiate the seismic design process. As the nonlinearities of structures are considered through the response modification factor (R) and deflection amplification factor (C_d), and as the soil-structure-interaction is considered by applying a modification factor in the structural periods (Equation 5.6-3 in NEHRP 2003), the apparent periods measured from low intensity earthquake vibration with a PGA of 0.15g or less are used to evaluate the approximate period formulas.

Numerous studies have been conducted on the identification of dynamic systems from measured responses. For identification of fundamental periods of structures, the modal minimization method (Beck 1978; Li and Mau 1991), autoregressive modeling method (Safak 1988, 1991), principal component analysis method (Aschheim et al. 2002), and transfer function method are often used. The transfer function method is a nonparametric system identification method where the transfer function, $H(i\omega)$, is derived from input ground motions and output responses. The method usually works well for a system with limited noise under ambient vibration. When a structure is subjected to earthquake ground motion, the structural properties vary with time and the identified periods show large variability. The smoothing of the transfer function can reduce the variability and thus make the resonant peaks more apparent, but lead to a loss of information that can result in the damping ratios being overestimated (Goel and Chopra 1997b). Past work suggests that the only vibration properties that can be reliably estimated from the transfer function are the frequencies of the first few modes and possibly the damping ratio in the fundamental vibration mode (Goel and Chopra 1997b). As the objective of this study is to evaluate only the first fundamental period of a structural system, the transfer function method is adopted in this study.

Transfer functions of each building for each direction (transverse and longitudinal direction) are identified with one input channel (typically base acceleration) and several output channels along the height of the building. Input and output channels of all CGS stations are carefully selected after inspection of the sensor locations. Output channels at a specific location of the buildings, which may independently vibrate or which may not capture the global vibration of the building, such as at a penthouse or at one of the peculiar wings of the building, are not included in the system identification. When output channels show distinctively different fundamental periods depending on the location in the building, the fundamental periods are defined as either average of the periods or as the periods of channels at the geometric center of the building based on engineering judgment. Welch's method (1967) is used to average transfer functions. The window size in the averaging is selected considering expected periods of the structure. The average of periods from multiple channels is defined as the apparent period of the building. For instance, the transfer functions of CGS station C23481 in Figure 1 show slightly different periods depending on output channels. The average of these periods is used as the period of the building in the considered direction.

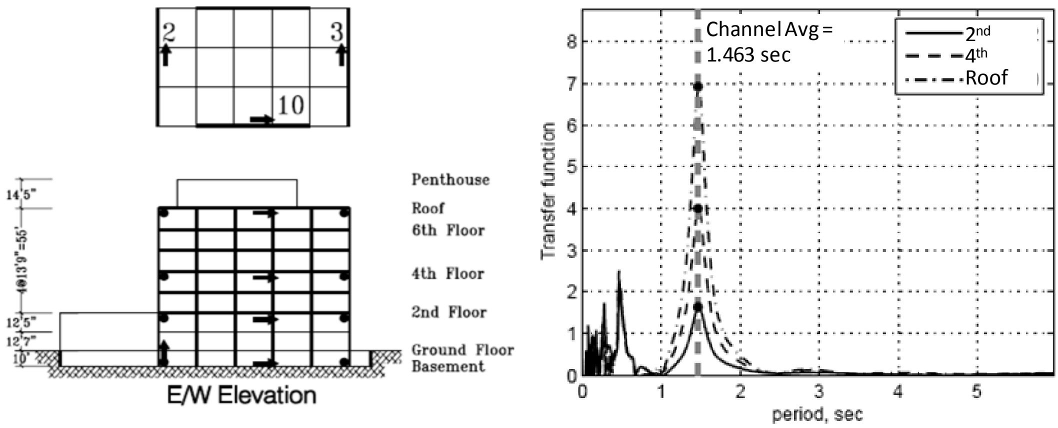


Figure 1. Transfer function in EW direction (C23481 station, 192 Landers Earthquake)

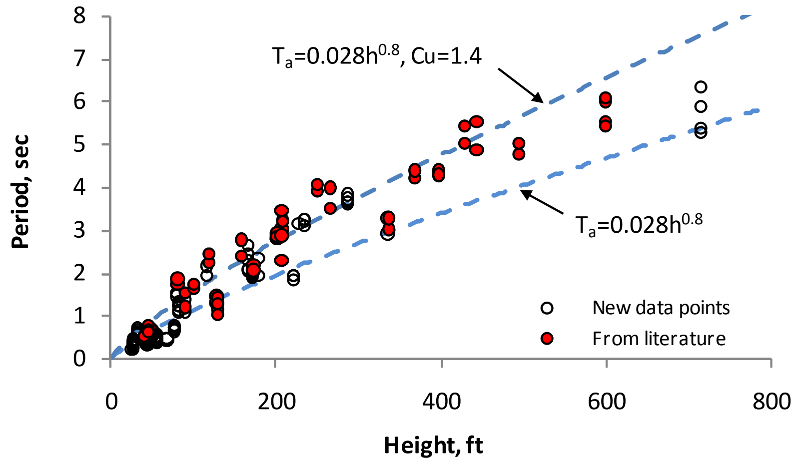
Evaluation of Building Period formulas

There are two approximate period formulas for steel MRFs in the current seismic design provisions. The first period formula, Eq. (1), is based on the study by Goel and Chopra (1997a) where periods from 42 steel buildings (a total of 81 lateral and transverse steel MRF systems) were used for the calibration. The second formula, Eq. (2), has been in the code since the 1970s and is applicable to structures not exceeding 12 stories and with a minimum story height greater than 10ft.

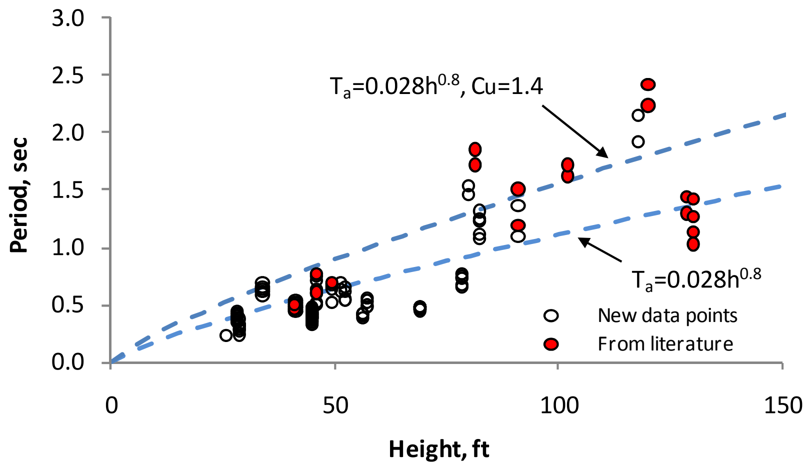
$$T_a = C_r h_n^x, \text{ where } C_r = 0.028, \ x = 0.8 \qquad (1)$$

$$T_a = 0.10\,N \qquad (2)$$

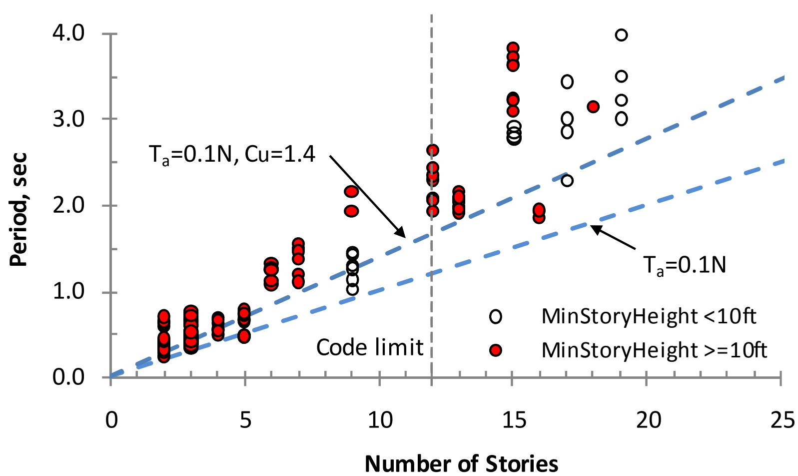
where C_r and x are parameters whose values vary depending on the lateral load resisting system of the building, h_n is height in ft, and N is number of stories. The database in this study includes 65 steel MRF buildings (total 125 longitudinal and transverse steel MRF systems). The newly added building periods in this study include periods from several low-to-medium rise buildings lower than 100ft in height, which were not available in the previous studies. Figure 2 compares the periods of steel MRFs with the approximate period formula in NEHRP 2003. The lower bound period is calculated using Eq. (1) with C_r = 0.028 and x = 0.8. The upper bound period is calculated for a site with $SD_1 \geq 0.4g$. Figure 2(a) shows that the current code formula conservatively predicts the lower bound of structural periods for all building heights. However, Figure 2(b), indicates that the code formula overestimates apparent periods of buildings, especially for buildings with heights less than 100ft, which corresponds to 6~8 story buildings. Considering that the majority of buildings are low- to medium-rise buildings, and Figure 2(b) shows that the code formula overestimate the periods of these buildings, the code formula may need to be refined for different height ranges. Figure 2(c) compares apparent building periods in terms of the number of stories with periods using Eq. (2) which is applicable to buildings with a minimum story height larger than 10 ft and with the number of stories not exceeding 12. For the purpose of evaluation of the formula, all buildings are plotted in Figure 2(c) including buildings with minimum story heights of less than 10 ft. The database of the selected buildings shows that the buildings that have a minimum story height less than 10 ft are mostly residential buildings



(a) Comparison with Eq. (1) for low-to-medium rise buildings



(b) Comparison with Eq. (1) for low-to-medium rise buildings



(c) Comparison with Eq. (2)

Figure 2. Comparison of periods of steel MRFs from records

and hotels. From Figure 2(c), it can be observed that the formula that has been used for over thirty years predicts the lower bound of building periods, especially for buildings with less than 5 stories. For buildings with more than 12 stories, the formula largely underestimates structural periods. Buildings with a minimum story height less than 10 ft tend to have shorter periods than other buildings, but may not need to be restricted from the application of the Eq. (2).

Seismic design codes mandate the use of higher design base shear for essential facilities which are required for post-earthquake recovery or which contain substantial quantities of hazardous substances. For the design of the essential facilities, which belong to Seismic Use Group III in the NEHRP 2003, higher occupancy importance factors are applied. The occupancy importance factors were not specified in the design codes in the 1970s. The importance factors, I, from 1.25 to 1.5 for essential facilities have been used since 1980s. Hence, it is expected that essential facilities designed and constructed after 1980 were designed with 25 to 50% higher design base shear than buildings in other seismic use group assuming that other design parameters are similar.

To investigate the effects of higher design load on the fundamental periods of steel MRFs, Figure 2 is re-plotted with two categories of periods for essential facilities, such as hospitals and emergency response agencies, and non-essential facilities. There are total 8 steel MRF buildings that belong to Seismic Use Group III which were designed after 1980. The heights of these buildings are less than 100ft. The periods of the essential facilities and non-essential facilities in this height range are compared in Figure 3 and regression analyses are conducted with the two sets of data points. For the purpose of comparison, Eq. (1) with x=0.8 is used for the regression analysis. Figure 3 shows that the periods of the essential facilities are about 40% shorter than that of the nonessential buildings. The decrease in period with the use of the importance factor is consistent with the findings of Tremblay (2005) where it was found that concentrically braced frame structures may reduce periods by as much as 42% due to application of the importance factor. This finding has two implications: 1) Use of the importance factor tends to shorten the period which in general leads to a larger seismic demand depending on the period. 2) The building period depends on the level of design base shear. Buildings designed for lower seismic regions are expected to have longer periods than buildings in built in higher seismic regions.

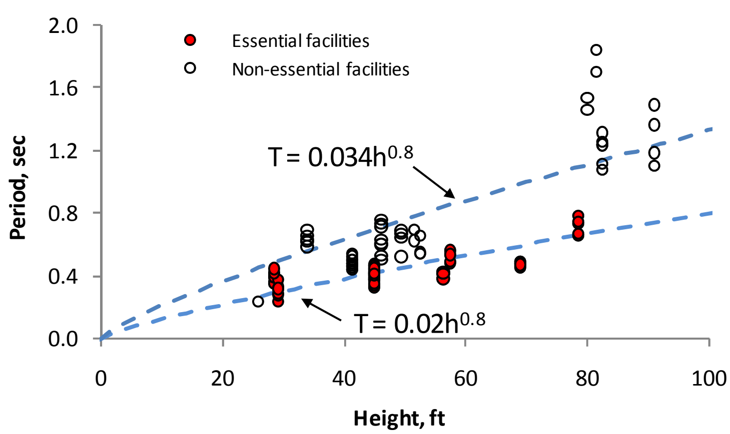


Figure 3. Effects of seismic use groups to steel MRFs

Nakashima et al. (2000) reported similar variations of building period with seismic hazard levels for high-rise steel frames built in Japan between 1968 and 1988. In the current code, the variation of building period is indirectly considered by allowing higher C_u factor (up to $C_u = 1.7$) in regions with low seismic base shear demand. With a lack of period data in low seismic regions in the U.S, however, further data collection is required to calibrate empirical building period formulas for buildings in low seismic regions.

Conclusions

In this paper, the code formulas for steel MRFs are evaluated with the apparent building periods. The longitudinal and transverse periods of 65 buildings with steel MRFs are identified. The building period formulas as a function of building heights and as a function of number of stories are evaluated. The comparison of the building periods from code formulas with the apparent building periods shows that for low to medium rise buildings, the code formula as a function of building height tend to overestimate building periods which may lead to unconservative design. The code formula as a function of number of stories generally underestimates the building period and has less correlation with the apparent building periods than the formula as a function of building heights. The periods of essential buildings are generally shorter than other buildings, which can be attributed to the higher base shear and more stringent drift limit employed in the design process. As the shorter building periods can attract higher seismic demand, the net effect of higher importance factor to the actual seismic performance of essential buildings remains for further study.

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