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Fundamental period of irregular eccentrically braced tall steel frame structures

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ABSTRACT

This paper presents the results of investigation on the fundamental periods of eccentrically braced frame (EBF) structures with varying geometric irregularities. A total of 12 EBFs are designed and analyzed. Based on the results obtained from vibration theory, equations for the approximate fundamental periods are put forth for EBFs which take into account vertical and horizontal irregularities. Through statistical comparison, it was found that a 3-variable power model which is able to account for irregularities resulted in a better fit to the Rayleigh data than equations which were dependent on height only. The proposed equations were validated through a comparison of available measured period data for EBFs. These proposed equations will allow design engineers to quickly and accurately estimate the fundamental period of EBF structures by taking into account their irregularities.

1. Introduction

Reasonably accurate estimation of the fundamental period of vibrations of a structure is needed in design of earthquake-resistant structures. Recently, Young and Adeli [14] investigated the fundamental periods of moment resisting frames (MRF) with varying geometric irregularities. Based on the results obtained from the vibration theory (Rayleigh equation), equations for the approximate fundamental periods were proposed for MRFs which take into account vertical and horizontal irregularities. The proposed equations were validated through a comparison of available measured period data for MRFs. Subsequently, Young and Adeli [15] investigated the fundamental periods of concentrically braced frame (CBF) structures with varying geometric irregularities. A total of 12 CBFs were designed and analyzed. Equations for the approximate fundamental periods were proposed for CBFs which take into account vertical and horizontal irregularities. The proposed equations were validated through a comparison of available measured period data for CBFs. The proposed equations will allow design engineers to quickly and accurately estimate the fundamental period of CBF structures by taking into account irregularities.

In this paper, the accuracy of existing code-based equations for estimation of the fundamental period of eccentrically braced frames (EBFs) is investigated. A parametric study is performed in terms of number of stories, number of bays, configuration, and types of irregularity. Three types of irregular EBF structures are examined in this study: a) structures with varying setbacks (vertical irregularity), b) structures with reentrant corner irregularity (horizontal irregularity), and c) structures with a combination of vertical and horizontal irregularity. Also examined is the regular counterpart of each irregular structure. Each structure is designed and analyzed using the nonlinear analysis and design software ETABS v.9.7.2 [5]. The fundamental period of each structure is obtained using a) Rayleigh method, b) Adeli method [1], c) ASCE 7-10 equations [3], and d) ETABS generated based on a normal mode analysis. All calculations are carried out using MATLAB R2009 and Excel 2010. Next, improved equations are developed for estimating the fundamental period of steel EBF structures by nonlinear regression analysis and performing statistical tests taking into account plan and elevation irregularities.

2. Review of relevant literature

2.1. Empirical equation for fundamental period of eccentrically braced steel frames

ASCE 7-10 [3] defines the following equation for the approximate fundamental period of eccentrically braced steel frames in seconds:

$$T_a = C_t H^x \quad (1)$$

where H is the height of the structure in feet (1 ft = 0.3048 m) and the values of the parameters are $C_t = 0.03$ and $x = 0.75$.

Despite more buildings being equipped with instrumentation, there is still a gap in data collection for certain types of structures, such as braced steel frames. Recognizing this, Tremblay [11] performed analytical modeling on an array of braced steel frame configurations published in the literature. Included in the database are 220 braced steel frames: 195 CBFs and 25 EBFs. Fundamental periods were calculated for this

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sample using Eq. (1), and compared to other code equations which represent fundamental period as a function of both height and depth. Tremblay concluded that expressing the period as a function of both height and depth does not yield a benefit when compared to a function of height only.

The code formulations have been calibrated and revised over the past 30 years. Kwon and Kim [9] conducted a quantitative comparison of measured fundamental period and estimated fundamental periods calculated from the code equations. Included in their database are 8 EBF buildings, with a few exhibiting geometric irregularities. All buildings were instrumented by the California Strong Motion Instrumentation Program (CSMIP). The authors identified the apparent periods of the buildings by the transfer function method. When considering EBFs, the authors compared measured periods with the estimated period from ASCE 7-10 (Eq. (1)). The measured data of the 8 EBFs only reflected structures under 100 ft (30.48 m) and over 250 ft (76.20 m), making a conclusion regarding the relationship between measured data and the code equation difficult. For the given number of data points, it appeared that Eq. (1) yields reasonably accurate results for structures under 100 ft (30.48 m), and generally underestimates the period for structures over 250 ft (76.20 m).

2.2. Fundamental period based on vibration theory

ASCE 7-10 code specifies that the fundamental period may be determined through an alternative substantiated analysis such as normal mode analysis or Rayleigh equation:

$$T = 2\pi\sqrt{\sum_{i=1}^{N} w_i\delta_i^2 / g\sum_{i=1}^{N} f_i\delta_i} \tag{2}$$

where w_i is the portion of the total weight of the structure assigned to level i, f_i is the lateral force at level i, δ_i is the deflection at level i relative to the base due to lateral forces, g is acceleration due to gravity, and N is the total number of stories in the building.

Recognizing the shortcomings of empirical equations which depend only on a structure's height and sometimes depth, Adeli [1] proposed approximate explicit formulae for the estimation of the fundamental period of several building systems including moment-resisting frames, braced frames, and frames with shear walls based on vibration theory, which take into account many structural parameters. The formulae were derived from the differential equations of free vibrations of a cantilever column, taking into account both bending and shear deformation while making a number of simplifying assumptions. The equation for the fundamental period of shear mode of vibration in seconds for EBFs is represented by:

$$T_S = \frac{2.83}{\cos\alpha_b}\sqrt{\frac{W\text{H}}{\text{g}\text{E}\text{A}_\text{b}\sin\alpha_\text{b}}} \tag{3}$$

where H = height of structure in feet, W = total weight, A_b = cross-sectional area of bracing, and α_b is the horizontal angle of inclination of the bracing, g = acceleration due to gravity, and E = modulus of elasticity of steel. The equation for the fundamental period of bending mode of vibration in seconds is:

$$T_B = 6.2\frac{\text{H}}{\text{D}}\sqrt{\frac{\text{WH}(\text{N}_\text{C}-1)}{\text{gEA}_\text{C}\text{N}_\text{C}(\text{N}_\text{C}+1)}} \tag{4}$$

where D = dimension of the structure in feet in the direction parallel to the applied forces, N_C = number of columns, and A_C = the average cross sectional area of columns. Eq. (4) is based on the assumption that lateral deflection of the bending mode of vibrations is produced by elongation or shortening of columns. The fundamental periods for shear and bending modes of vibration are then combined using Dunkerley's equation:

$$T = \sqrt{\text{T}_\text{S}^2 + \text{T}_\text{B}^2}. \tag{5}$$

In this research, the geometric and property data used in the Adeli equation are all based on weighted averages for the earthquake resisting frames in the direction under consideration.

ETABS, the software used for simulation in this research, calculates the fundamental period of the structure based on a vibration modal analysis using the stiffness and mass properties of the structure. The fundamental period is taken as the period of the mode calculated to have the largest participation factor in the direction the lateral earthquake loads are applied.

3. Methodology

The first step of this research is the design of each structure according to the prevalent design codes: The American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) [2], and ASCE 7-10. Seismic design is based on the equivalent lateral force procedure of ASCE 7-10. The methodology for design is similar to that for CBFs presented in Young and Adeli [15] and will not be repeated here for brevity.

4. Building design models

All EBF structures are modeled with either 30 stories, 20 stories, or 10 stories (N) and 5 bays (N_b). All structures have a uniform story height of 10 ft (3.408 m), with the exception of the first story which is 12 ft (3.66 ft), and a uniform bay spacing of 25 ft (7.62 m). An eccentricity (e) of 5 ft (1.524 m) is used in all examples. A total of 12 EBF structures are evaluated: 3 vertically irregular structures, 3 horizontally irregular structures, 3 vertically and horizontally irregular structures, and 3 regular reference structures. Three-dimensional models of 5-bay EBFs are

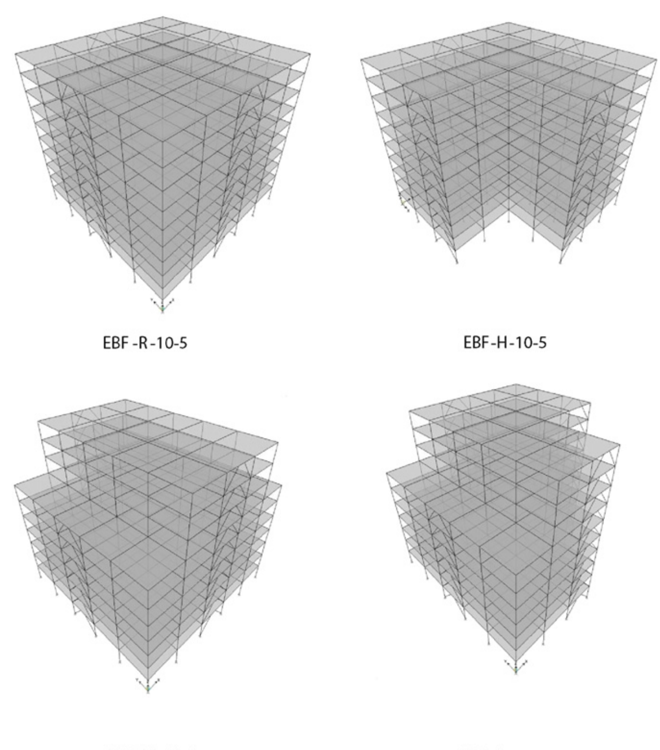

Fig. 1. 10 Story, 5 Bay EBF Views.