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Evaluation of the Fundamental Period of Vibration of Irregular Steel Structures

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Abstract

The determination of the fundamental period of vibration of a structure is essential to earthquake design. Current codes equations (ASCE, 2010 and other codes) provide formulas for the approximate period of earthquake-resistant building systems, which are dependent only on the height of the structure or number of stories. Such a formulation is overly conservative and unable to account for structures with geometric irregularities. This paper investigated the fundamental periods of three different types of steel earthquake-resistant building structures: moment resisting frames (MRF), concentrically braced frames (CBF) with varying geometric irregularities. A total of 5, 10, 15 story building designed and analyzed with ETABS. The fundamental periods based on vibration theory for each example were compared with empirical equations, including current code equations as well as equations proposed in recent literature. Based on the results obtained from vibration theory (Rayleigh equation), equations for the approximate fundamental periods are put forth for MRFs and CBFs which take into account vertical and horizontal irregularities. These proposed equations will allow design engineers to quickly and accurately estimate the fundamental period of MRF and CBF structures by taking into account irregularities.

Keywords: Steel frames; Fundamental period; Irregular.

Introduction

A large portion of modern urban infrastructure is made up of buildings with structural irregularities. While often desired by owners for their unique attributes, these irregular structures have architectural and aesthetic considerations which often require irregularities in mass, strength, stiffness, or structural form. Through the study of these structures' performance during earthquakes, it has also been found that irregular structures exhibit significantly different behavior than their regular counterparts during seismic activity. The determination of the fundamental period of vibration of structures is essential to earthquake design and assessment. A reasonably accurate estimation of the fundamental period in such irregular structures is necessary in both response-spectrum and static earthquake analysis of structures [2]. An accurate estimation would allow for an improved estimation of the global seismic demands on an irregular structure. As such, the goal of this research is to investigate the accuracy of existing code-based equations for estimation of the fundamental period of irregular building structures and provide suggestions to improve their accuracy. More specifically, the objectives of this research are: To perform a parametric study of the fundamental period of two different types of steel structures: moment resisting frames (MRF) and concentrically braced frames (CBF) in terms of number of stories, number of bays, configuration, and types of irregularity. Three types of irregular structures are examined in this study: a) structures with varying setbacks (vertical irregularity) also structures with reentrant corner irregularity (horizontal irregularity). Each structure is designed using the ETABS [5] and for effect of masonry infills analyzed using SeismoStruct. Masonry infilled frames built before the development of new seismic regulations are more susceptible to collapse given an earthquake event. A number of studies have been performed on the fundamental period of building structures. As more buildings are instrumented and recorded seismic response data have become available, a number of recent studies have compared results obtained from empirical code equations for the fundamental period with actual measured data of structures during seismic events. Seismic design codes specify empirical formulas to estimate the fundamental period which are based on data from instrumented buildings subjected to ambient vibrations or small to moderate earthquakes. Up until 2002, the fundamental period estimated by ASCE 7-02 (ASCE, 2002) [1] code for all structures was in the form:

$T=C_tH^{3/4}$ (1)

Where H is the height of the structure in feet and C_t is a parameter based on structure type. This equation was present in design codes for nearly 30 years. Equation (1) is still in use in the building codes of many countries, including Eurocode 8, which limits its use to buildings less than 40m (131 feet) (CEN, 2004). Also present in certain design codes for many years, the fundamental period of braced steel frames and concrete shear walls was estimated as:

$$T = 0.05\frac{H}{\sqrt{D}} \qquad (2)$$

Parameter D corresponds to the dimension of the braced frame in a direction parallel to the applied force, called the depth of the structure in this paper. In Eq. (2) H and D are in feet. This equation was first introduced in California building codes for reinforced concrete shear wall structures, and was more recently present in the 1995 National Building Code of Canada. ASCE 7-10 (ASCE, 2010) defines two equations for the approximate fundamental period in seconds:

$$T_a = C_t H^x \qquad (3)$$

$$T_a = 0.1N \qquad (4)$$

Where the values of the parameters C_t and x in Eq. (3) for steel structures are given in Table 1, and N in Eq. (4) is the total number of stories.

Table 1: ASCE 7-10 values of approximate period parameters

Structure Type	C_t	**X**
Steel moment-resisting frame	0.028	0.8
Eccentrically braced steel frame	0.03	0.75
Concentrically braced steel frame	0.02	0.75

The parameters of Eq. (3) for moment resisting structures is based on a study by Goel and Chopra [4] (1997) in which they performed regression analysis on the fundamental periods of 42 steel buildings located in southern California measured during eight California earthquakes occurring between 1971 and 1994 including the 1971 San Fernando earthquake (M=6.6) and 1994 Northridge earthquake (M=6.7). The buildings ranged from 3 stories to up to 60 stories [7,8]. Equation (3) has not been calibrated for CBFs or EBFs since the late 1980s when the equation was first introduced in UBC-88. The same old Ct and x values are used in ASCE 7-10. Equation (4) has been present in the code since the 1970s. ASCE 7-10 limits its use for buildings of 12 stories or fewer, with story heights of at least 10 feet [1]. 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 were 220 braced steel frames: 195 CBFs and 25 EBFs. Of these, only three structures of each type represented frames that had actually been built; the remaining cases were textbook examples or hypothetical frames. Tremblay found that Eq. (3) results in more conservative period estimates than Eq. (2) for all CBF and EBF examples. When the ratio of analytically computed period to code predicted period (Eq. 2 and Eq. 3) was evaluated for each example, it was found that Eq. (3) resulted in a smaller scatter of the data compared with Eq. (2), leading to the conclusion 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.

Masonry Infilled

Most of the past research focuses on the behavior of the masonry panel and, more recently, on the improvement of the modeling techniques to capture the physical behavior of the relationship between the infill and frame. Due to the large number of structures and the potential fatalities and losses involved in high seismic regions, there is a need to develop the tools needed to assess the performance of these buildings more generally in a performance-based probabilistic framework. The Pacific Earthquake Engineering Research (PEER) Center has developed a rigorous probabilistic framework for performance-based earthquake engineering (PBEE), which integrates seismic hazard and structural modeling with loss modeling to generate probabilistic predictions of building response, considering the inherent uncertainty in modeling and loading The value in PBEE methods is in its ability to produce metrics that can be used to address the seismic assessment of existing buildings to permit more informed decision making on the seismic performance, vulnerability, and safety of the buildings considering various hazard levels. The study of masonry infilled frames in the PBEE framework can help decision makers to improve their understanding of the risk posed by these types of buildings, which in turn could help them to prioritize mitigation of the most dangerous structures. Moreover, this paper studies the effect of several other building and modeling aspects that can significantly affect the assessed collapse performance of steel buildings with masonry infill in the PBEE framework.

Structural Irregularities

Along with studies into the fundamental period of structures, another topic which has attracted attention of researchers is the seismic performance of buildings with irregularities in mass, stiffness, strength, and structural form. Modern design codes lay out guidelines for each type of vertical and horizontal irregularity. ASCE 7-10 provides the following definitions for the two types of irregularities studied in this paper: 1-Vertical geometric irregularity: Exists when the horizontal dimension of the seismic force resisting system in any story is more than 130% of any adjacent story. 2-Reentrant corner irregularity: Exists when both plan projections of the structure beyond a reentrant corner are greater than 15% of the plan dimension of the structure in the given direction.

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), and ASCE 7-10. Seismic design is based on the equivalent lateral force procedure of 2800 iranian code. All other loads and load combinations are in accordance with subject 6 iranian code. The static loads considered for the design of each structure include dead, live earthquake, and wind loading. The load combinations considered for steel frame design are followed in accordance with the guidelines in 2800 iranian code. Uniform live and dead loads are assigned to each floor. A 200 kg/m^2 live load is assigned at each level. The uniform dead load consists of the self-weight of the building structure, plus an additional 75 kg/m^2 to account for partitions, ceilings, ductwork, and any additional structural items. Included in the self-weight are all steel members and a 15 cm thick concrete slab. Steel members are designed with a minimum specified yield stress of 2400 kg/cm^2 and a minimum tensile strength of 3700 kg/cm^2. For design of beam and column sections, a wide flange (W) shape is selected from the Euro profiles. It is assumed that there are no architectural restrictions on member geometry. This cycle of analysis and design is repeated until all members pass the stress/capacity check and all deflection criteria are satisfied. A rigid diaphragm is assumed for each floor. All MRFs and CBFs structures are modeled with either 15 stories, 10 stories, or 5 stories and 5 bays.All structures with 5 bays have a uniform story height of 3 m. The bays have a uniform spacing of 5 m. Three-dimensional models of 5-bay MRFs are shown in Figure 1 and 2 (for 5-story structures), Figure 3 and 4 (for 10-story structures), and Figure 5 and 6 (for 15-story structures).

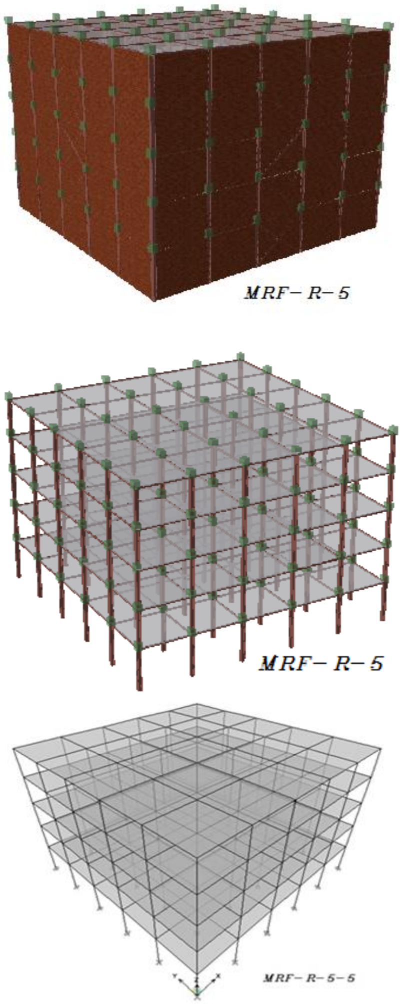
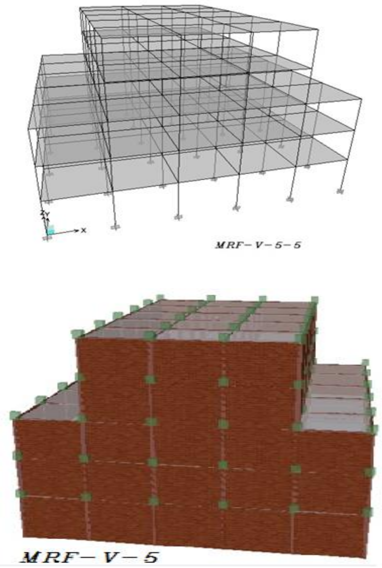


Fig.1: 5 story, 5 bay MRF views, with and without infills (regular)



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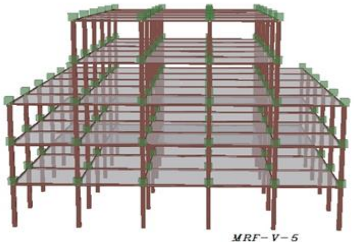
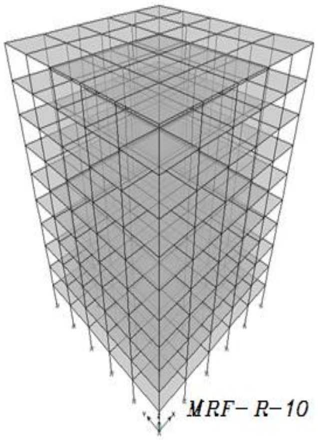
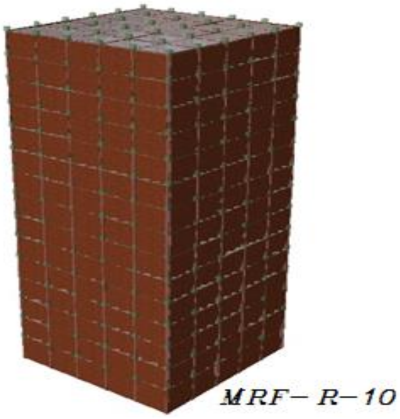


Fig.2: 5 story, 5 bay MRF views, with and without infills (irregular)





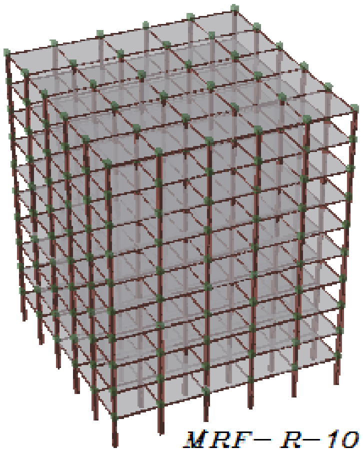
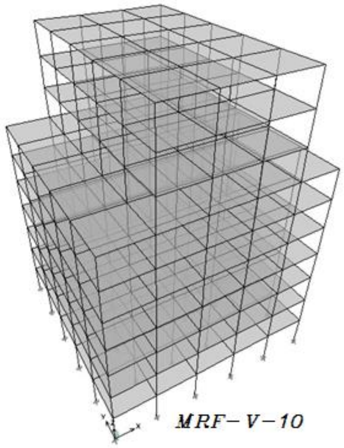
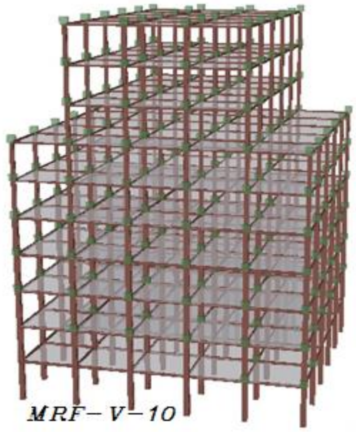


Fig.3: 10 story, 5 bay MRF views, with and without infills (regular)





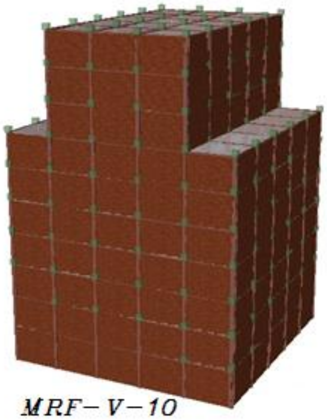
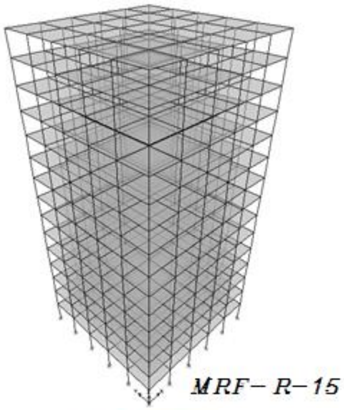


Fig.4: 10 story, 5 bay MRF views, with and without infills (irregular)



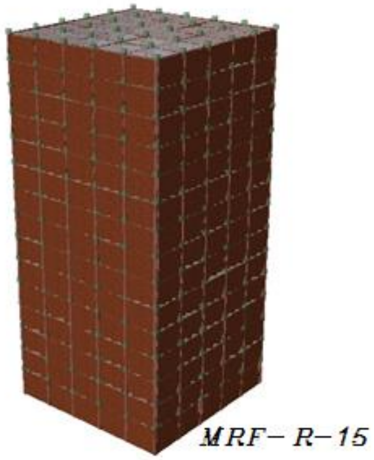
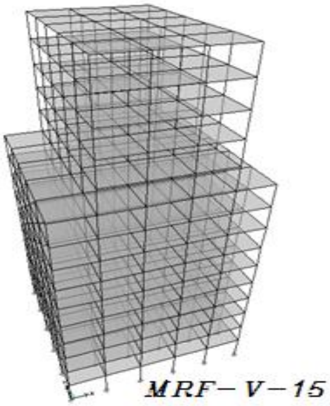
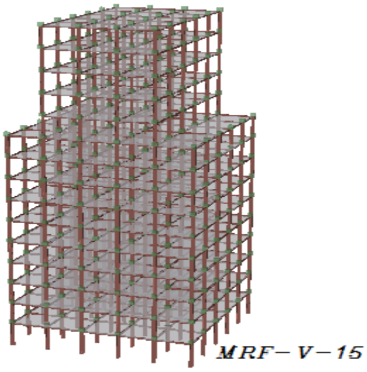


Fig.5: 15 story, 5 bay MRF views, with and without infills (regular)





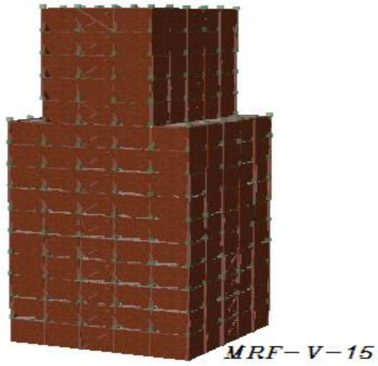


Fig.6: 15 story, 5 bay MRF views, with and without infills (irregular)

Results

For each story the column section, beam section, lateral deflection of each story, assigned weight, and seismic force assigned to each story are given. Figures 7-18 shows the fundamental period plotted against regular or irregular for each structure type (combination irregularity, horizontal irregularity, vertical irregularity, and no irregularity.) with and without infills. The ASCE Eq. (4) yields the most conservative estimate of the fundamental period for all 5 and 10 story MRFs, followed by ASCE Eq. (3). In general, the periods obtained by ETABS modal analysis yield close values and the longest fundamental period. In general, structures without irregularities tend to have a longer period compared with those with irregularities.

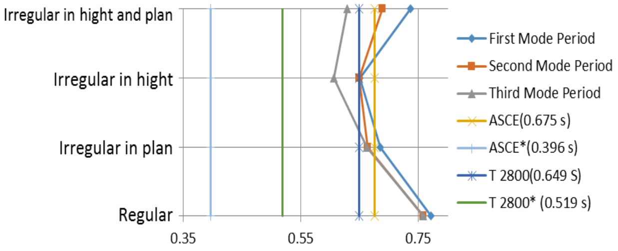


Fig.7: Fundamental periods of MRFs, 5 story, without infill

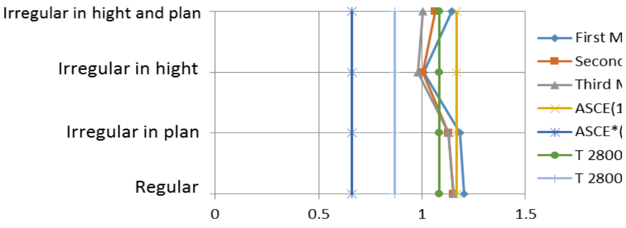


Fig.8: Fundamental periods of MRFs, 10 story, without infill

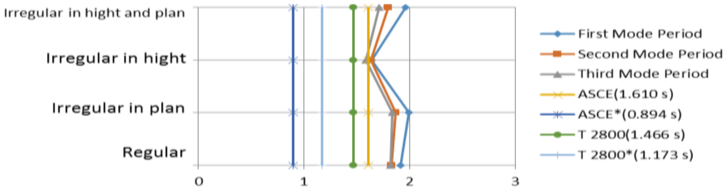


Fig.9: Fundamental periods of MRFs, 15 story, without infill

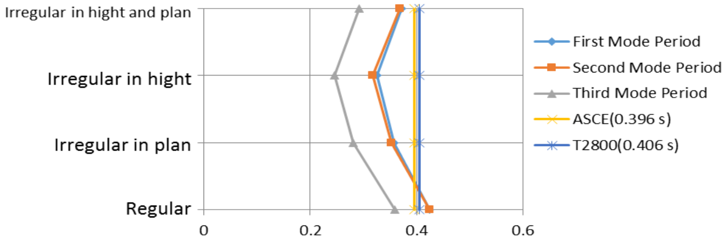


Fig.10: Fundamental periods of CBFs, 5 story, without infill

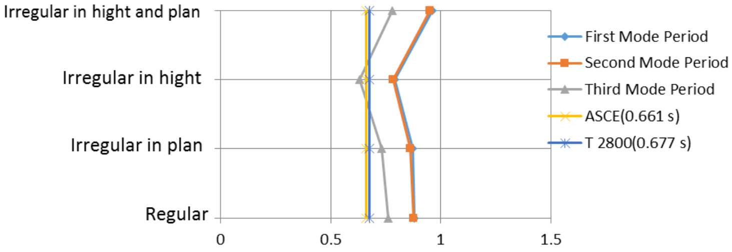


Fig.11: Fundamental periods of CBFs, 10 story, without infill

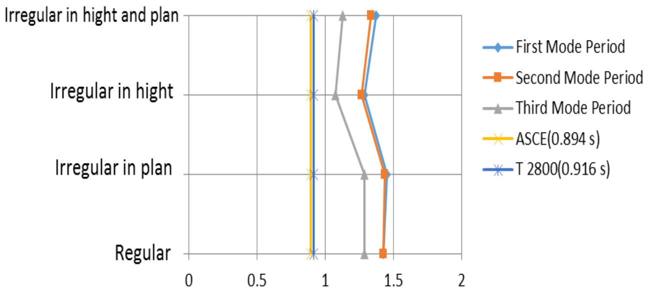


Fig.12: Fundamental periods of CBFs, 15 story, without infill

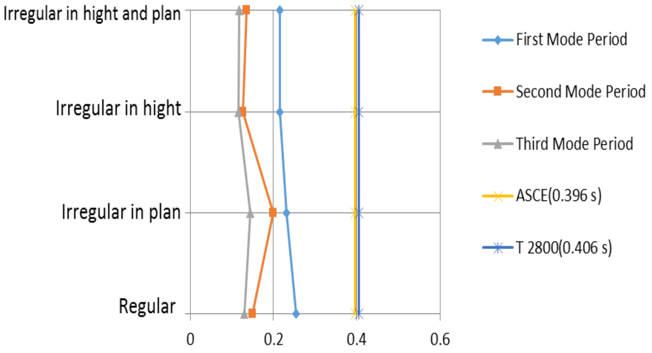


Fig.13: Fundamental periods of MRFs, 5 story, with infill

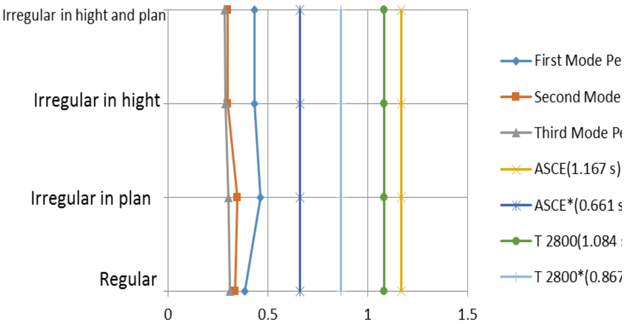


Fig.14: Fundamental periods of MRFs, 10 story, with infill

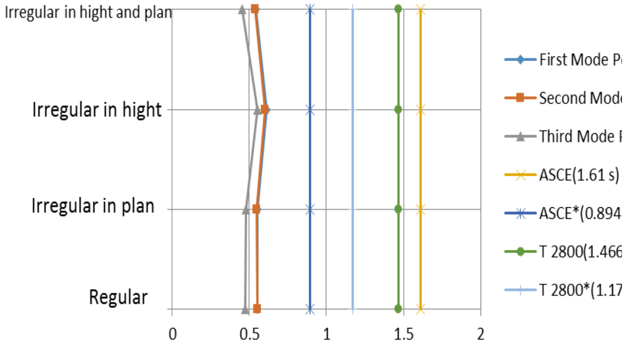


Fig.15: Fundamental periods of MRFs, 15 story, with infill

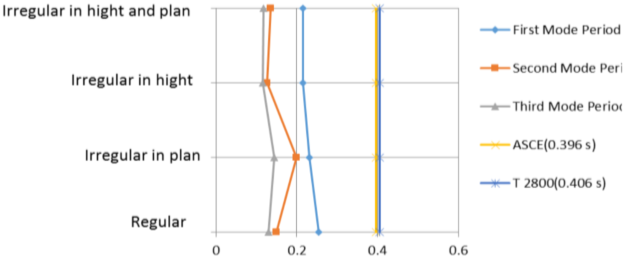


Fig.16: Fundamental periods of CBFs, 5 story, with infill

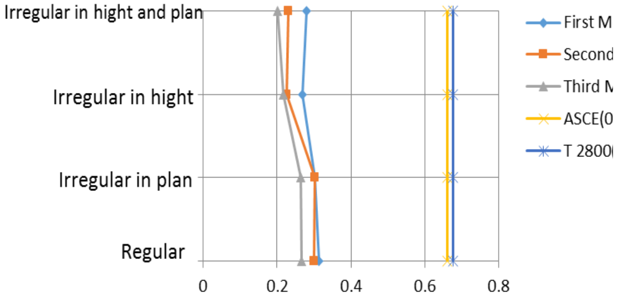


Fig.17: Fundamental periods of CBFs, 10 story, with infill

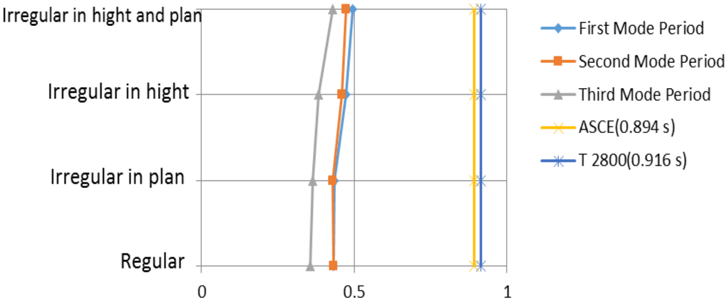


Fig.18: Fundamental periods of CBFs, 15 story, with infill

Equation (3) yields an average overall underestimate of 41% for all examples compared with Seismostruct.

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