SEISMIC PERFORMANCE OF SUPER TALL BUILDINGS

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Abstract:
With the rapid population growth and dynamic economic developments, the demand for residential, mixed use and commercial buildings has been increasing significantly all around the world. Due to the excessive increase in height of buildings in this era, there is a significant impact on the methods used to analyze and design of tall buildings. There is a clear acceptance within the engineering community that the specifications given in codes of practice are not suitable for very tall buildings.
General concepts, current methods of analysis and seismic performance of super tall buildings are reviewed in this paper. Further the effect of higher modes on the performance of super tall buildings is also discussed.

Key Words: *Super tall buildings, Seismic loads, Higher mode effects*

1. Introduction

During the last few decades, the application of new techniques and of new mechanical means was witnessed in virtually every human activity. It became clear in time that the innovation in architecture would come from those who grasps the possibilities of the new materials and techniques. The present day, construction of super tall buildings have become a trend and the impetus behind the surge of these tall buildings has been the need to satisfy the growing demand for office and apartment space. The convenience of having all of the services one needs in a single building is now becoming a reality with mixed-use buildings; some of these buildings may also bring the prospect of being able to live and work without leaving the building. Further the value of time and the high cost of gasoline may be part of the economic drivers that have sparked renewed interest in urban living and a return to the central city or downtown areas of many cities, which is a reverse trend from living in the suburbs as in the past. Due to this new technology towards super tall buildings, engineering judgment has to be made carefully.

As buildings are built to greater heights, the aspect ratio becomes larger, leading to excessive deflection problems due to the lateral load acting on the building. To meet the challenge for limiting deflections due to wind or seismic loads, innovative structural schemes are being continuously developed. Various wind bracing concepts have been developed and outrigger braced structural system is one of the most popular systems among them. There are well recognized analytical methods available for the analysis of buildings under wind or seismic loads. But due to these extreme heights in the super tall buildings, some general methods of analysis had to be reviewed and modified accordingly. In this paper, the behavior of super tall buildings under seismic loads will be addressed.

2. Earthquake ground motions for the design of tall buildings in high-seismic areas

In general, tall buildings respond to seismic motion differently compared to low rise buildings. A tall building tends to be more flexible than a low rise building, and in general would experience accelerations much less than a low rise building. On the other hand, a very flexible tall structure subjected to motion for a prolonged time may experience much larger forces if its natural period is near that of the ground waves. During the first few seconds of the earthquake, the acceleration of the ground reaches a peak value and is associated with relatively short period components, which have little influence on the fundamental response of the building. On the other hand the long period components that occur at the tail end of the earthquakes, and have periods closer to the fundamental period of the building have a profound influence on its behavior. Further tall buildings tend to experience greater structural damage when they are located on soils having a long period of motion because of the resonance effect that develops between the structure and the under laying soils.

It is very apparent that the specification of the earthquake ground motions is important in the process of designing a tall building. The development of the design criteria for performance-based seismic design may include provisions to ensure that a tall building will not collapse under a very rare event such as the maximum credible earthquake ground motion (usually defined as those ground motions having a 2% probability of being exceeded in 50 years, or having a return period of about 2400 years). This ground motion is usually represented in the form of response spectra that considers all of the seismic sources in the surrounding region of the site, given the estimated activity of the sources and the site characteristics for that given level of risk. (Lew 2007)

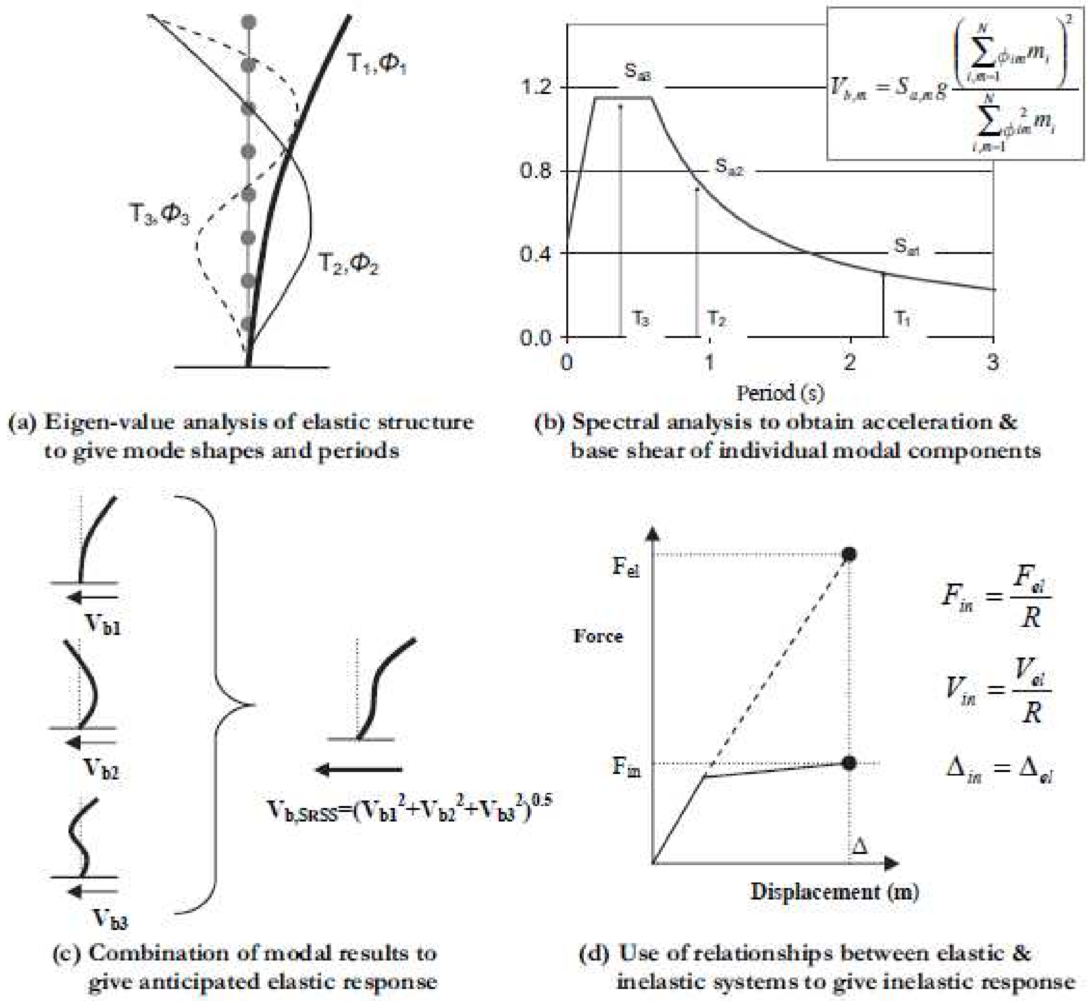
As this design spectra are estimated for a very long return period, the uncertainty included in the analysis is large. There is an uncertainty coming from the reality that there are very few recorded ground motions at close distances for large-magnitude events; thus, there is little guidance to constrain ground motion attenuation relations that attempt to model ground motions at these distances and magnitudes. Further, the long return period results in more uncertainty in the events, and the dispersion of the results increases the ground motion estimates. In addition to the above, most current ground motion attenuation relations do not extend to more than 2–5 s. As many of the new proposed tall buildings are well over 70 storeys, the fundamental period may be as high as 8–10 s. Thus, there is even a greater uncertainty as to the characteristics of the spectral ordinates of the ground motion spectra at these long periods.

3. Analysis and design of tall buildings for seismic loads

With the advent of computers and greater understanding of the earthquake phenomenon, the structural engineering profession has gradually moved towards more exact approaches in the seismic design of tall building. Relatively simple methods based on equivalent static loads are no longer satisfactory. The current design practice often requires more precise determination of local seismicity and critical ground motion characteristics and application of advanced dynamic analysis techniques using sophisticated computer programs. For most buildings, an inelastic response can be expected to occur during a major earthquake. Performance based design is one of the most popular design methods put into practice to incorporate inelastic behaviour. Some well recognized methods available in the design of building for earthquake forces are discussed in detail in the following sections.

4. Modal Analysis

One of the most commonly adopted means of designing structures for earthquakes in line with code legislation is to use response-spectrum analysis, also referred to as multi-modal analysis, in order to obtain estimates of structural response both in terms of design forces and displacements. The basis of the multi-modal analysis procedure is illustrated in Fig. 1.



$$V_{b,m} = S_{a,m} g \frac{\left(\sum_{i,m=1}^{N} \phi_{im} m_i\right)^2}{\sum_{i,m=1}^{N} \phi_{im}^2 m_i}$$

$$F_{in} = \frac{F_{el}}{R} \qquad V_{in} = \frac{V_{el}}{R} \qquad \Delta_{in} = \Delta_{el}$$

Fig 1 Modal analysis -Source: (Sullivan 2008)

The first step of the procedure, shown in Fig. 1(a), is to perform Eigen-value analysis of the structure with a given mass and elastic stiffness in order to identify its modal characteristics. The characteristics of particular importance are the modal periods and modal shapes. The modal periods are used together with the design acceleration spectrum to read off acceleration coefficients for each mode, as shown in Fig. 1(b). The mode shapes furnish the mass excited by each mode, which is then multiplied by the acceleration coefficient to give individual modal base shears. By distributing the base shear for each mode up the height of the structure as a set of equivalent lateral forces (proportional to the mode shape and mass distribution), the elastic-response is obtained for each mode. These components are then combined in accordance with established modal combination rules, such as SRSS or CQC (Chopra 2000) to provide design forces and displacements associated with elastic response, as indicated in Fig. 1(c). Finally, given that the actual response of the structure will be inelastic, a set of behavior factors, R, are then used to scale the building's elastic response to provide inelastic design actions. The assumed relationship between the elastic and inelastic response shown in Fig. 1(d) is representative of the equal-displacement rule.

5. Capacity Spectrum method

The capacity spectrum method was developed by Freeman (2004). By means of a graphical procedure, it compares the capacity of a structure with the demands of earthquake ground motion on the structure (Figure 2). The graphical presentation makes possible a visual evaluation of how the structure will perform when subjected to earthquake ground motion. This method is easy to understand. The capacity of the structure is represented by a force displacement curve, obtained by non-linear static (pushover) analysis. The base shear forces and roof displacements are converted to the spectral accelerations and spectral displacements of an equivalent Single-Degree-Of-Freedom (SDOF) system, respectively. These spectral values define the capacity spectrum. The demands of the earthquake ground motion are defined by highly damped elastic spectra. The Acceleration Displacement Response Spectrum (ADRS) format is used, in which spectral accelerations are plotted against spectral displacements, with the periods represented by radial lines. The intersection of the capacity spectrum and the demand spectrum provides an estimate of the inelastic acceleration (strength) and displacement demand.

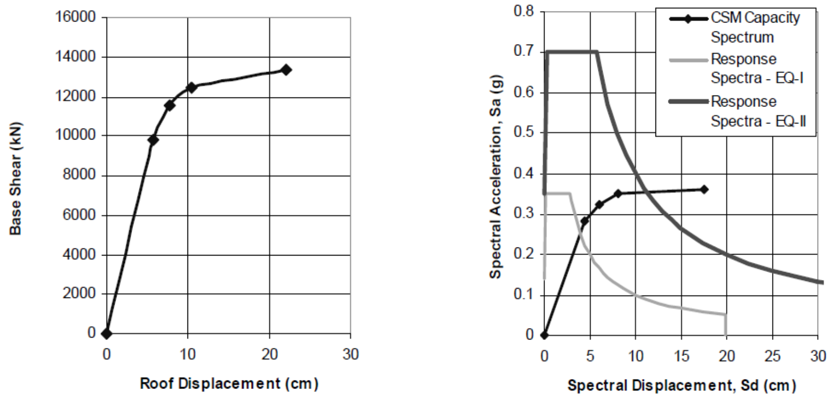


Fig 2: Demand and capacity spectra

6. N2 method

The N2 method is, in fact, a variant of the capacity spectrum method based on inelastic spectra. Inelastic demand spectra are determined from a typical smooth elastic design spectrum. Reduction factors, that relate inelastic spectra to the basic elastic spectrum, are consistent with the elastic spectrum. A simple transformation from a Multi-Degree-Of-Freedom (MDOF) to an equivalent SDOF system is used. Therefore the some deficiencies of the original version of capacity spectrum were overcome by introduction of the N2 method. The graphical representation of N2 method is shown in Fig 3.(Fajfar 1999)

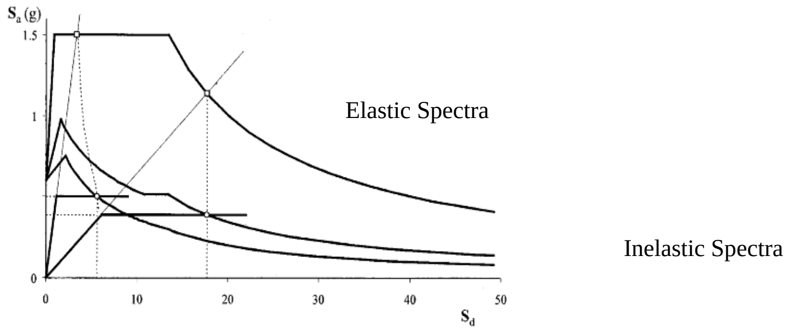


Fig 3: Demand and capacity spectra for inelastic analysis -Source: (Fajfar 1999)

7. Direct displacement-based design (DDBD)

The aim of the direct displacement-based design (DDBD) procedure is to develop an equivalent SDOF representation of the MDOF structure. This is achieved by assigning strength proportions and subsequently using the moment profile in the walls to set a design displaced shape before any analysis has taken place. Knowledge of the displacement profile and recommendations for the combination of frame and wall damping components enable representation of the structure as an equivalent single-degree of freedom system. Then the required effective period and the stiffness are determined using the substitute structure approach. The design base shear is obtained through multiplication of the necessary effective stiffness by the design displacement and the strength of individual structural elements is set taking care to ensure that initial strength assignments are maintained. A flow chart, which explains the procedure briefly, is presented in Fig 4 (Sullivan 2005; Priestley 2007).

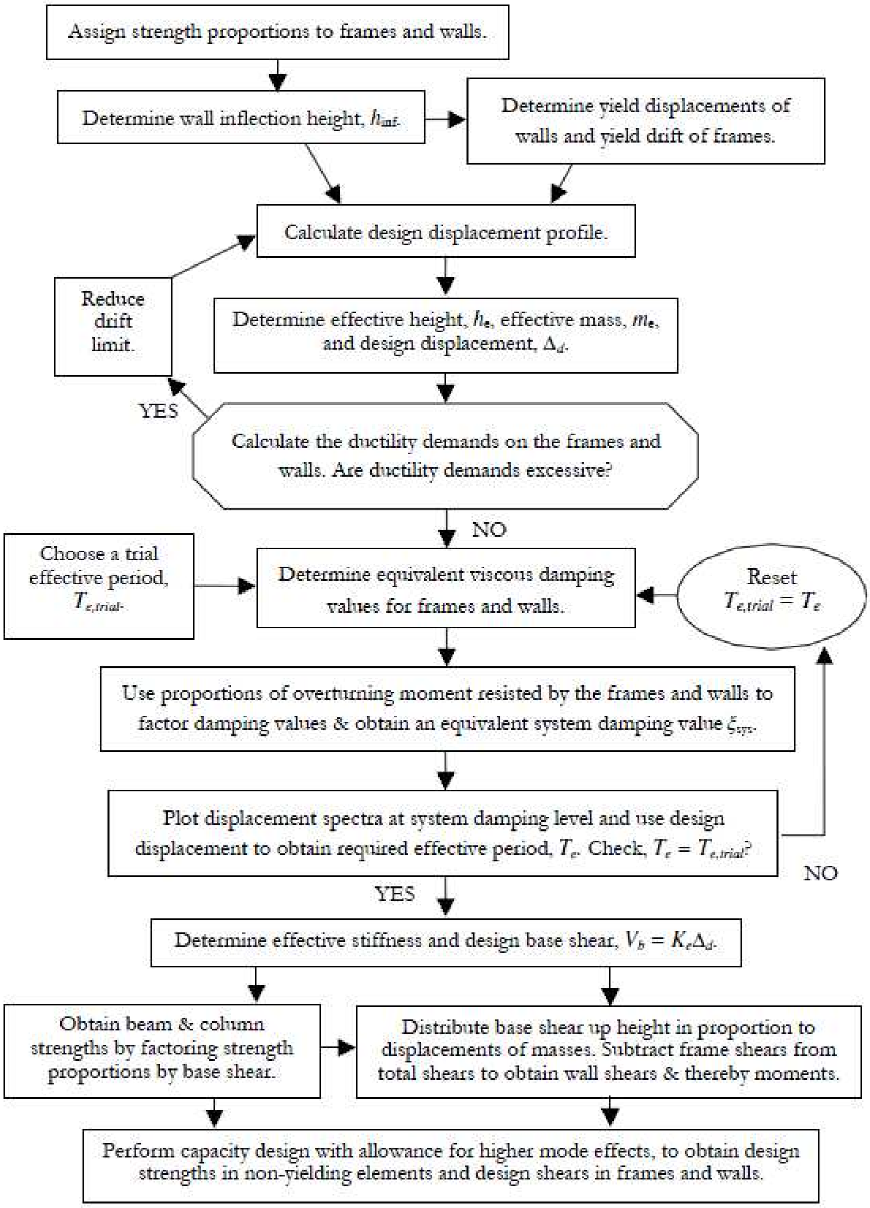


Fig 4 : Flow chart of Design methodology. Source :(Sullivan 2008)

8. Higher mode response of super tall buildings

As mentioned earlier, there is a clear acceptance within the engineering community that higher modes of vibration play an important role in the seismic response of structures. The fundamental period of super tall buildings may be high as 8-10s and the second mode period may be 2-3s. Therefore the second mode period also lies within the constant displacement portion of the response spectrum and this is different to the medium or low rise buildings. As it is already known that the higher modes play an important role in the analysis of super tall buildings, it is uneconomical to analyze these types of buildings always assuming the first mode governs the behavior of the structure. Most of the analysis methods derived so far to analyze the buildings for seismic loads apply the characteristics of the first mode. But when it comes to super tall buildings, as the higher mode participation is important, the methods derived so far has to be modified accordingly (Sullivan et al. 2008).

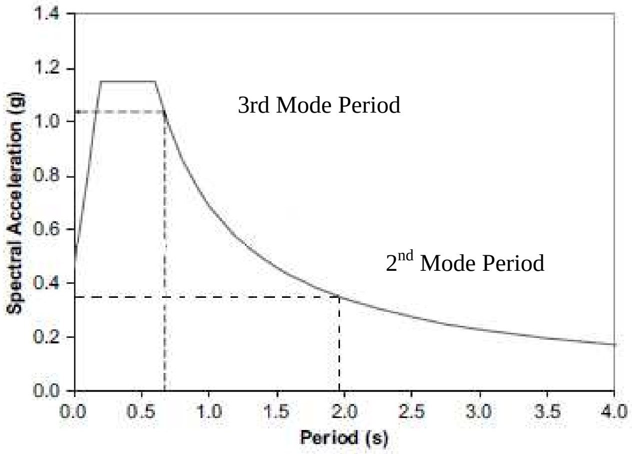


Fig 5 General Response Spectrum

Sullivan et al. (2008) have introduced a new concept of transitory inelastic modes and it has been shown that the characteristics of transitory inelastic modes for RC frame-wall structures may be approximated in a simple manner by performing Eigen-value analysis of a structure in which plastic hinge locations are assigned a low post-yield tangent stiffness. A new modal superposition approach that utilizes these transitory inelastic modes of vibration has been shown to provide much improved prediction of peak base shears than traditional modal superposition methods. The results of this work suggest that there may be real benefits in using transitory inelastic modal characteristics instead of elastic modal characteristics for the capacity design of structures. But this study was conducted only for low to medium rise buildings and this concept is explored for super tall buildings at the University of Melbourne.

9. Study conducted on the proposed method

An outrigger braced reinforced concrete residential building with a total height 300m and horizontal floor dimensions of 36mx36m was considered for the study. The core was assumed to be 12mx12m in square with 500mm thick walls on average. Floor to floor height was considered to be 3.5m and the depth of outriggers was 7m. Two outrigger locations were considered and one outrigger was placed at 58th level and the other outrigger was placed at 27th level. The optimum outrigger positions for wind was found by Chung (2009) and the same outrigger positions were considered for this study.
In order to investigate the behavior of the structure, the core, outrigger and outrigger braced columns were transformed to an equivalent frame with an equivalent stiffness and the analytical model was subjected to nonlinear time-history analyses in ANSYS 12 using the earthquake records listed in Table 2. These records were selected to be compatible with the code design spectrum. In modeling the structure in ANSYS 12, elastic properties were assigned to elements that were not intended to yield and Beam 4 elements were used for such elements. All structural components (beams and columns) are considered to have rigid connections and floors were modeled as rigid. A constant 5% damping was considered for the structure.

Record Name	Earthquake Name	Year	Record length (s)	Time Step (s)	Station	Unscaled GPA	Scale Factor
EQ 1	Parkfield	1966	43.8	0.02	Cholame - Shandon Array #13	0.50	1.8
EQ2	Tabas	1978	49.9	0.04	Tabas	0.81	1.5
EQ3	San Fernando	1971	41.7	0.02	Pacoima Dam	1.16	1.0
EQ4	Chile	1985	116.4	0.01	LLOLLEO, D.I.C	0.72	2.0
EQ5	Northridge	1994	60.0	0.02	New Hall	0.20	2.0

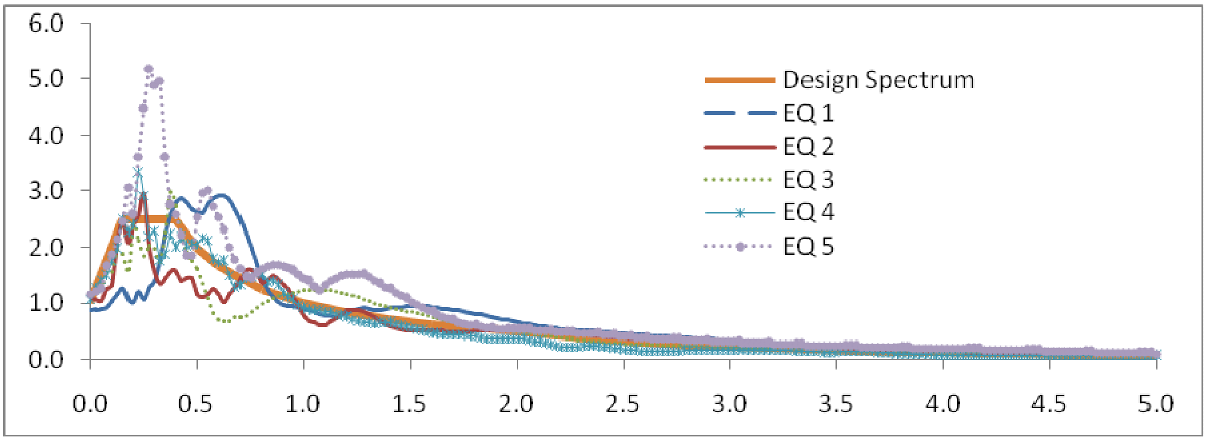


Fig 6 Acceleration response spectra at 5% damping for the five spectrum-compatible earthquake records

Fig. 5 indicates that the periods of the higher modes in outrigger braced building will generate larger spectral accelerations. Fourier analysis was used to study the dynamic response of the building and the frequencies of each mode were compared with the elastic periods of the structure. For this process, base shear variation with time was taken and subjected to a Fourier analysis using the program Seismosignal to identify the frequencies that most influence the base shear response. The peak Fourier amplitude is an indicative of a dominant structural frequency and it can be seen from Fig 7 that, the average peak Fourier amplitude for all the earthquake records is considerably lower than the elastic frequencies for second and third mode frequencies as shown in dotted lines. Therefore it can be concluded that even for tall buildings with outriggers, a period lengthening for the higher modes can be expected. Due to this, there will be a significant effect on the magnitude of the higher mode forces and this change of forces has to be accounted in the Response spectrum analysis. For shorter structures, both the elastic and the lengthened higher-mode periods may lie within the constant acceleration plateau, implying that the spectral accelerations of the higher modes will not be affected by the phenomenon of period lengthening. However, for longer-period structures such as the model structure used in this study, when the development of inelasticity shifts the periods along the descending branch of the acceleration spectrum, significant reductions in higher-mode response could be expected as explained in Fig 5.

From Fig.7, it is clear that the second and third mode periods obtained from Fourier analysis is comparatively less than the elastic mode periods. Therefore the transient inelastic mode method introduced by Sullivan et al. (2008) will be adopted for the calculation of base shear of the building. This study is continuing at the University of Melbourne

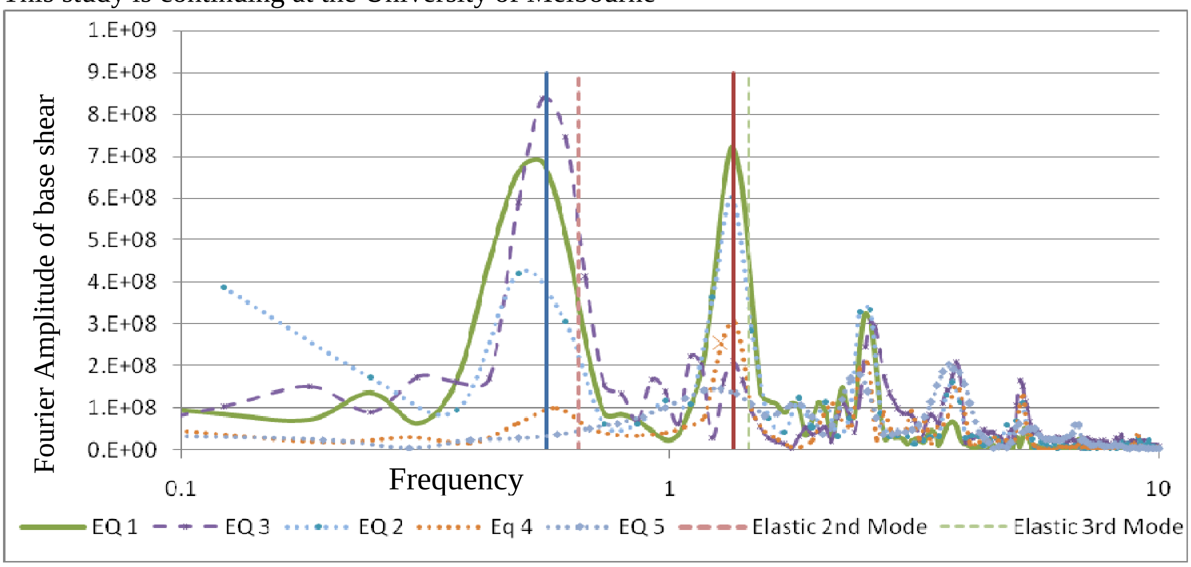


Fig 7: Results of the Fourier analysis of Base shear

10. Concluding Remarks

General concepts and widely used seismic analysis methods (Displacement based method, N2 method, Capacity Spectrum Method) are briefly reviewed in this paper. It is shown that these methods may not be directly applicable to super tall buildings due to the higher mode effects. The phenomenon of higher-mode period lengthening has been illustrated through the non linear dynamic analysis of a 300m tall building. This work is continuing at the University of Melbourne.

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