# DATA DRIVEN TOOLS FOR DYNAMIC ANALYSIS OF BUILDING FRAMES

**Ph. D Thesis**

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Mr.S.G.Joshi

# CERTIFICATE

Certified that the work presented in the thesis titled, **"DATA DRIVEN TOOLS FOR DYNAMIC ANALYSIS OF BUILDING FRAMES"** which is being submitted by **Mr. Shardul G. Joshi, Regd. No 950902005**, in fulfilment of the requirement for the award of the degree of 'Doctor of Philosophy' in the Department of Civil Engineering, Thapar University, Patiala, is an authentic record of the candidate's own work carried out from October-2010 to October- 2014 in this university under our supervision. The matter presented in this thesis has not been submitted for the award of any other degree in any other university.

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# Declaration

This is to certify that the work which is presented in this thesis report entitled “Data Driven Tools for Dynamic Analysis of Building Frames” being submitted by Shardul G. Joshi, Registration No. 950902005 in partial fulfilment of requirements for the award of degree of Doctor of Philosophy in Civil Engineering at Civil Engineering Department, Thapar University, Patiala, is a bonafied work carried out by him under the supervision of Dr. Naveen Kwatra, HOD, Civil Engineering, Thapar University, Patiala and Dr. Shreenivas N. Londhe, Professor, Vishwakarma Institute of Information Technology, Pune.

The matter embodied in this report has not been submitted in part or full to any other University or Institute for the award of any degree.

Date: 9/10/2015 Mr.Shardul G. Joshi

## ABSTARCT

The determination of the fundamental period of vibration of a structure is essential for earthquake design. Current BIS code equations (IS 1893 (Part1): 2002) provide formulae for the approximate period of earthquake-resistant building systems, which are dependent only on the height and base dimensions of the building. Such a formulation may be overly conservative and unable to account for structures with geometric irregularities. This study estimatesthe fundamental period of three different types of reinforced concrete (RCC) earthquake-resistant building structures: symmetric special moment resisting frames (MRF), shear wall dominant symmetric RCC buildings and shear wall dominant unsymmetrical RCC buildings.The data driven techniques: Artificial Neural Networks (ANN), Genetic Programming (GP) and Wavelet Neural Network (WNN) are explored to estimate the period of vibration, base shear force and top floor displacement of buildings. Data-driven modeling can be considered as an approach to modeling that focuses on using the Machine Learning methods in building models that would complement or replace the "knowledge-driven" models describing physical behavior (Solomatine and Ostfeld, 2008). These techniques require the data in the form of input and output parameters. ANN and WNN techniques give the results in the form of values of parameters of interest whereas the GP technique yields equation as a result.

In order to check the adequacy of the employed techniques, these techniques are applied for performing the dynamic analysis of 206 symmetric MRF buildings. The statistical measures used to assess the accuracy of the developed models are Root Mean Squared Error (RMSE), Correlation Coefficient (r) and Coefficient of Efficiency (CE).Once the applicability of the techniques is ascertained for MRF buildings, these are applied to other types of buildings. Total 52moment resisting frames, 70 shear wall dominant symmetric buildings and 55 shear wall dominant unsymmetrical buildings are analyzed with ETABS v.9.7.2. The fundamental period based on vibration theory for each case is compared with estimated value by data driven tools including current code equations as well as equations proposed in recent literature. Based on the results obtained from the ANN, GP and WNN techniquesempirical equations for the approximate fundamental periods are suggested for aforementioned buildings. The proposed equations of period of vibration are validated with measured period of vibrations cited in the literature. The design base shear force obtained from the response spectrum recommended by IS 1893 (Part1):2002 is found to be much higher than the actual base shear force in case of shear wall dominant unsymmetrical buildings. The safety margin

so presumed is reduced in some cases by proposed modification in the response spectrum recommended by IS 1893 (part1):2002. The same is also validated using the response spectrum suggested for Mumbai city by Desai and Chaudhary, 2014. A linear relationship between the top floor displacement of the building and shorter period of vibration. This relation is applicable for peak ground acceleration (PGA) values between 0.10g and 0.16g.

It can be said that the data driven tools of ANN, WNN and GP can be applied for dynamic analysis of buildings. Additionally the period equation for the buildings proposed in the present study by these tools can be used in practice as evident from closeness of the results with measured period values.

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# CHAPTER 1

# INTRODUCTION

## 1.1. Overview and Problem Statement

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 demand irregularities in mass, strength, stiffness, or structural form. Through the study of their 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. (Kelly, 2011).

The distribution of seismic lateral loads and their magnitude depend on the fundamental period of structure. Structural stiffness and mass govern these seismic lateral loads. Therefore, accurate determination of fundamental period of vibration is necessary for estimation of earthquake forces. However, accurate estimation of period is not an easy task at the design stage. Building code provides some empirical equations which can be used to estimate the period of vibration, based on the geometric dimensions of the buildings. These equations are applicable to buildings with different lateral load resisting systems. These equations were calibrated and verified using data obtained from instrumented buildings and have been revised and improved with availability of more and more data. Further improvements are needed based on the new data that have been recorded during recent earthquakes (Morales, 2000).

Provisions for the linear static and dynamic design of reinforced concrete buildings are included in almost all seismic design codes around the world. Although the names of these procedures vary from code to code, the basic principles are the same. The linear static (or lateral force) method allows engineers to predict the fundamental period of vibration in a simplified manner and calculate the design base shear force from the response spectrum (see Figure 1.1 for example IS 1893 (Part1): 2002 spectrum).

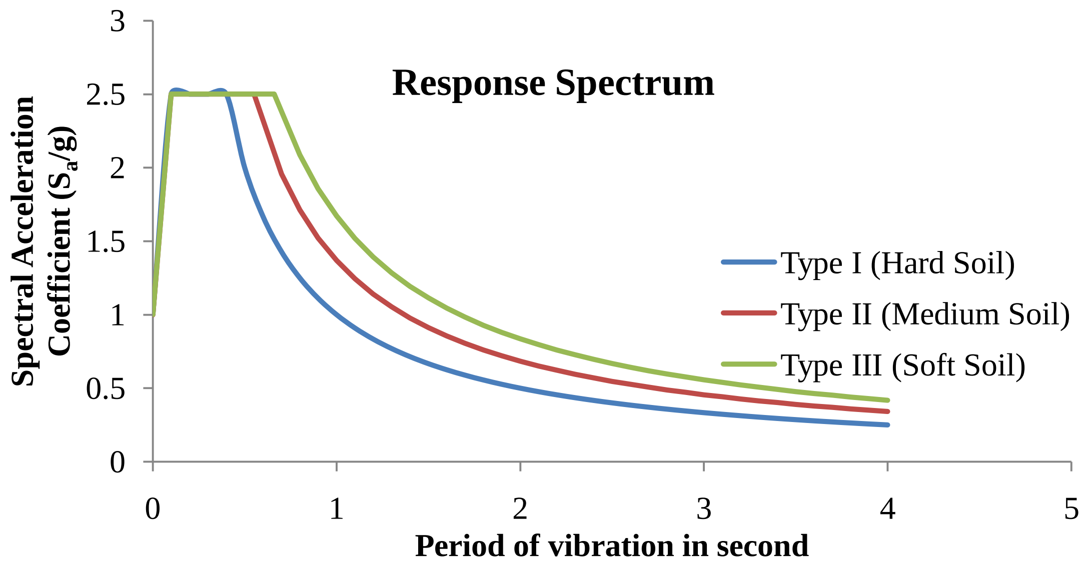


Figure 1.1 Response spectra for Rock and soil sites for 5% damping

This base shear is then distributed along the height of the building in a linear or parabolic manner (Crowley and Pinho, 2009).

The present study assumes the location of buildings in Peninsular India. The following paragraph gives overview of the studies on probabilistic seismic hazard analysis for Peninsular India.

The Peninsular India is one of the oldest Archaean shield regions in the world, whose continental interiors are generallyconsidered as seismically stable. A recent study by Kumar, et al. (2007), indicates a lithospheric thickness of 80–100 kmfor Indian plate. This lithospheric depth is very small whencompared to the depth of lithosphere below other continentalmasses like Africa, Antarctica and Australia. At present Indianplate is moving with a high velocity (Jade, 2004), whichis attributed to the low lithospeheric depth as one of the reasons(Kumar, et al. (2007)). Gangrade and Arora (2000) havereported that a slow and steady accumulation of seismicenergy is occurring in this region which may lead to earthquakesof moderate to significantly high magnitudes. Someof the major earthquakes reported in Peninsular India since18th Century include Mahabaleshwar (1764), Kutch (1819),Damooh hill (near Jabalpur, 1846), Mount Abu (1848),Coimbatore (1900), Son-Valley (1927), Satpura (1938), Anjar(1956), Koyna (1967), Killari (1993), Jabalpur (1997)and the recent Bhuj earthquake (2001). Mandal, et al. (2000)highlighted that during the last four decades stable continentalshield region (SCR) of India has experienced moderateseismic activity.The maximum Peak Horizotal Acceleration (PHA) value of 0.37 g was estimated at the Koyna region. A PHA value of 0.37 g corresponds to zone V as per the current seismic hazard map of India (BIS-1893, 2002). However, the Koyna region is placed in the seismic zone IV, where the PHA value varies for 0.16 g to 0.24 g. The PHA values in the central region of South India, around Bangalore, are in the range of 0.11 g to 0.16 g. This region also shows higher seismic hazard than the code (BIS-1893, 2002) specification. The PHA value for the Bangalore region reported by Sitharam and Anbazhagan (2007) is 0.146 g. Similar results were obtained in the studies by Jaiswal and Sinha (2007) for Koyna region and Anbazhagan, et al. (2009) for Bangalore region (Vipin, et al. 2009). Design response spectrum for Mumbai is suggested based on IS 1893 (Part1): 2002 provisions and Eurocode 8 provisions by Vipin, et al. (2009).

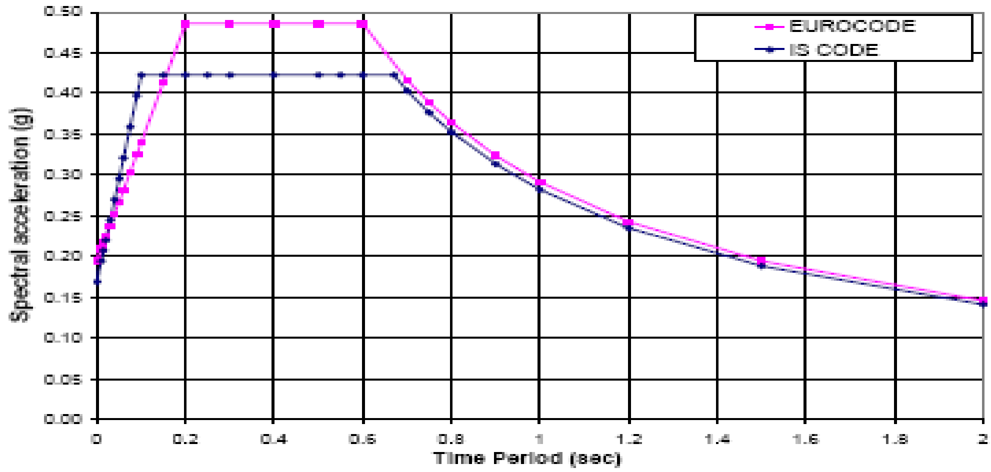


Figure 1.2 Design Response Spectrum for Mumbai for site class D with 10% of probability of exceedance in 50 years. (Vipin, et al. 2009)

Desai and Chaudhari (2014) also showed an underestimation of potential seismic hazard in the entire study region by non-probabilistic zoning prescribed by IS 1893(Part1):2002 with significantly higher seismic hazard values in the southern part of Navi Mumbai.These authors have compared spectral accelerations of important locations of Mumbai city with that recommended by IS 1893 (Part1): 2002. Figure 1.3 and 1.4 shows the results obtained by the authors.

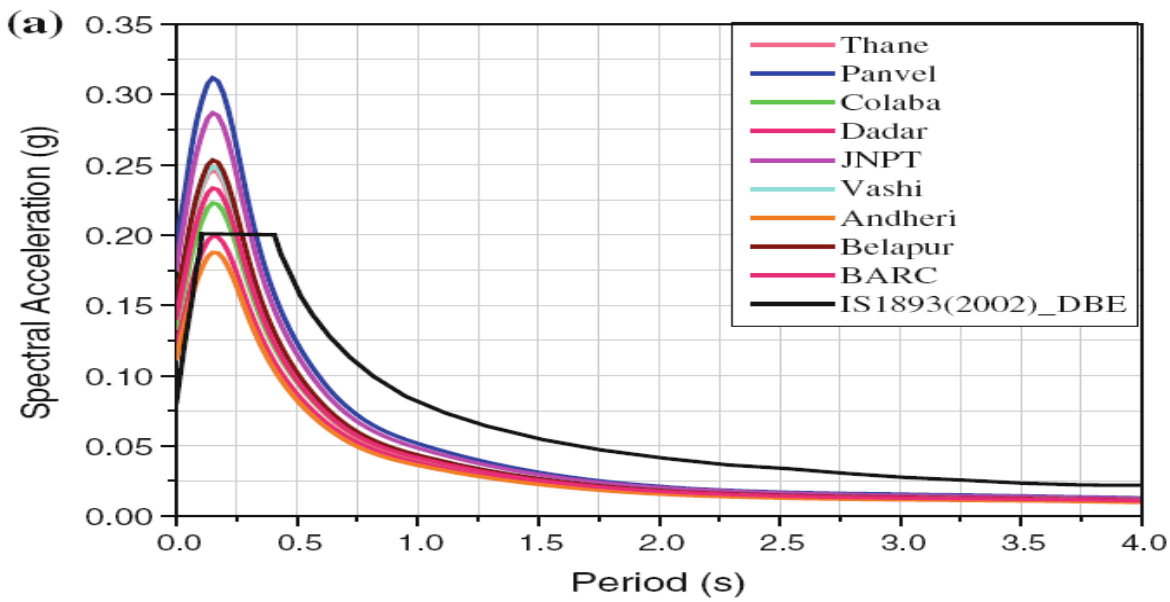


Figure 1.3 Uniform Hazard responses Spectrum for important locations in Mumbai region for 475 years return period. (Desai and Chaudhari, 2014)

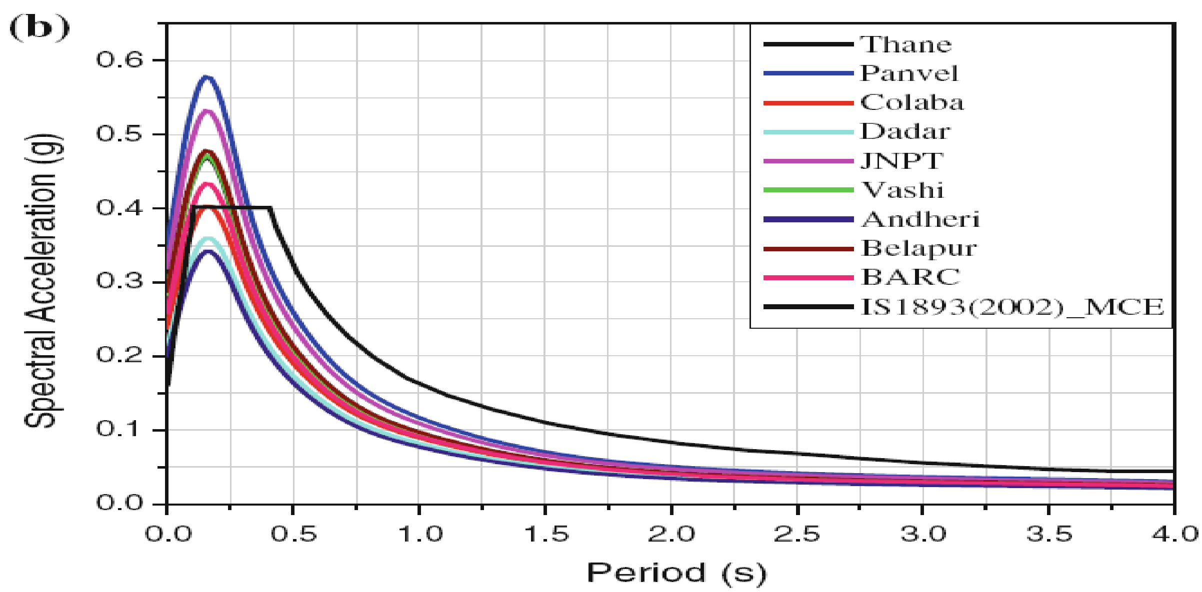


Figure 1.4 Uniform Hazard Response Spectrum for important Locations in Mumbai region for 2475 years return period (Desai and Chaudhari, 2014)

## 1.2 Fundamental Period of Vibration

The period of vibration is a fundamental parameter in the force-based design of structures as this parameter defines the spectral acceleration and thus the base shear force to which the building should be designed. For the usual range of structural periods, higher periods of vibration lead to lower design forces. Fundamental period of vibration is dependent on the mass, strength and stiffness of the structure and is thus affected by many factors such as structural regularity, number of storeys and bays, section dimensions, infill panel properties, axial load level, reinforcement ratio and extent of concrete cracking (Crowley and Pinho, 2006). Period-height relationships which have been obtained for different building typologies from the measured periods of vibration during earthquake ground shaking are generally used, though Rayleigh analysis is also often allowed. The linear dynamic (or modal response spectrum) method requires a simple analytical model of the structure to be produced often using structural sections of reduced stiffness and the periods of vibration and modal shapes of a number of significant modes. The forces resulting from each mode are applied to the building using the appropriate modal shape and the seismic actions resulting from these forces are combined using specified combination rules. (Pinho and Cowley, 2009).

Most of the building codes provide the empirical equations to estimate period of vibration from height or number of floors of the building. Many researchers have attempted to revise these code specified formulae. These formulae were evaluated using available periods measured during past earthquakes. The empirical equations were obtained from the regression analysis. Generally, the code formulae were calibrated to give shorter periods than that measured to produce conservative design seismic forces. However, some times the degree of conservatism may be excessive, while at the other times the period may be overestimated due to the omission of non structural elements in period calculations, leading to non-conservative design forces. Although some improvements have been introduced over the years, these equations still need to be verified and improved, as new data become available after earthquakes. This is especially true for shear wall buildings for which the period is poorly estimated by code expressions (Morales, 2000). Therefore a simple and better method is necessary to arrive at reasonably fair estimate of period of vibration, at least for a preliminary design because computer run at this stage of design is neither feasible nor economical as even the structural member itself might be changed in the further studies.

This approximate approach of estimating period of vibration appears to be quite simple because the fundamentalperiod can be computed even by hand, taking into account characteristics of buildings such as thetotal building height or the number of stories. Because of their simplicity, empirical methods for thecomputation of fundamental period seem to be preferable (Hatzigeorgiou and Kanapitsas, 2013). Most of the codes follows elastic force based approach in which the equations necessarily predict the low valued period (ATC 3-06, UBC 97, Eurocode8

,Masi and Vona (2010), Mehanny (2013)). Many researchers have suggested following displacement approach (Crowley and Pinho (2006), Masi and Vona (2010)). Such upper ceiling to the period value thus admits the fairly noticeable marginof uncertainty and variance expected in the period of vibration even if this period is theoreticallycalculated. (Mehanny, 2013) Additionally, shear-wall dominantsystems have been examined by Goel and Chopra (1998), Lee et al. (2000), Balkaya andKalkan (2003) and Ghrib and Mamedov (2004).The reader may refer Kwonand Kim, 2010 for an extended review for empirical expressions for the fundamental periodsof various structural types. Kwon and Kim (2010), suggested a revision of constant factor from 0.048 to 0.0365 in the equation suggested by ASCE 7-02. Hatzigeorgiou and Kanapitsas (2013) suggested an empirical equation for the evaluation of fundamental period of 3-D RC buildings both for bare and infill frames, where the flexibility of soil, the presence of infill panels and concrete shear walls, the total height, and the width along the seismic direction had been taken into account. It is however shown that the code formulae provide periods that are generally shorter than measured periods (Goel and Chopra, 1997) and current code formulae for estimating fundamental period of vibration of concrete shear wall buildings are grossly inadequate (Goel and Chopra, 1998).

To facilitate development of empirical equation of the fundamental period of vibration, data driven technique in the form of ANN, GP and WNN are employed in the present studies. These data driven techniques extract the information from the data presented to them.

The objectives of the study are summarized below:

**1.3 Objectives and Scope of Research**

As such, the goal of this research is to study the accuracy of existing code-based equations for estimation of the fundamental period of irregular building structures and provide suggestions to improve their accuracy. The present study aims to employ three data driven tools viz. Artificial Neural Networks (ANN), Genetic Programming (GP) and Wavelet Neural Networks (WNN) for estimating periods of vibration, base shear force and top floor displacement of RCC buildings. The objectives are outlines as mentioned below:

1) To carry out experimental investigation on building frames using Uni-axial shake table.

2) Dynamic Analysis using ANN, Genetic Programming and Wavelet Neural Network techniques for symmetric and un-symmetric 3 Dimensional buildings frames.

3) Comparing the results of ANN, GP and Neuro-wavelet techniques to suggest the most suitable method.

After studying the literature pertaining to the use of data driven techniques in dynamic analysis of buildings, it is observed that ANN is the most commonly used tool for such applications. Applications of GP in dynamic analysis is not found in the literature perhaps this study may be its first ever application. WNN is applied in the study to generate the modified response spectrum for unsymmetrical buildings where ANN and GP tools did not give satisfactory results. Hence WNN is also used as the tool for developing other models as well. Potentially wavelet transform is applied to decompose the acceleration time history of any earthquake record. The higher frequency values are removed from the time history and analysis of buildings is performed. This results in reducing the time of computation in case of response history method. Response Spectrum method is used for dynamic analysis here in the study and hence reducing the time of analysis is not the matter of concern.

The scope is limited to reinforced concrete buildings and includes moment resisting frames and buildings with dual lateral load resisting system, both symmetric and unsymmetrical in plan. The following outlines the scope:

1) Review of state of the art and previous research.

2) Generation of the data in terms of the geometry of the building, stiffness and mass of the buildings, periods of vibration, base shear force and top floor displacement using either MATLAB code or software ETABS v 9.7.2.

3) Developing the models of three data driven tools for aforementioned types of buildings based on the generated data.

4) Evaluation of current code formula.

5) Study of effect of parameters that affect the period of buildings.

6) Development of improved expressions for the computation of fundamental period of vibration of the buildings. The estimate predicted by the data driven tools will be corrected with the factor obtained from the experimental observations.

### 1.4 Significance of Proposed Research

This study takes a look at the way in which seismic design codes around the world have allowed the designers to estimate the period of vibration for use in both linear static and dynamic analysis. The influence of the period of vibration on the design will be discussed and empirical equations to estimate shorter period of vibration for linear analysis in IS 1893 (Part1):2002 will be proposed for aforementioned buildings.

This research is expected to have impact on 1) seismic design and analysis of reinforced concrete structures 2) optimization of structural system in terms of anticipation of base shear force and maximum top floor displacement of the structure as close to the reality.

1.4.1 Seismic design/analysis of reinforced concrete structures

The present study suggests empirical equations for estimating shorter period of vibration of reinforced concrete building. It is observed that these equations estimated the period values close to the measured period values. Hence the base shear force determined from code specified response acceleration coefficients will be closer to the actual values.

1.4.2 Optimization of structural system

Structural design of buildings for seismic loading is primarily concerned with structural safety during major earthquakes, but serviceability and the potential for economic loss are also of concern.

The base shear force acting on the building is determined using code specified shorter period of vibration as well as code specified response acceleration coefficients as discussed in chapter 2. It is observed that the base shear so estimated may be over conservative. Hence an attempt is made to suggest modification in code specified response acceleration coefficients using data driven tool of wavelet neural network. Desai and Chaudhari, 2014 have suggested modified response spectrum for Mumbai city based on seismic hazard studies.

The base shear force is found out using modified response spectrum for Mumbai city and also with the modified response acceleration coefficients proposed in the study. It is seen that in many of the cases, these base shear force values computed from the modified response acceleration coefficients are closer to the values obtained from the response spectrum suggested by Desai and Chaudhary, 2014. Thus the modification proposed in the response acceleration coefficients estimate the base shear close to its actual value.

## 1.5 Organization of Thesis

The thesis studies the application of data driven tools for dynamic analysis of building frames. The following chapter 2 discusses in brief dynamic analysis of buildings along with the provisions in IS 1893 (Part1):2002. Chapter 3 introduces three data driven tools viz. ANN, GP and WNN with their applications in dynamic analysis of buildings. Chapter 4 describes in detail the application of these three techniques for the dynamic analysis of symmetric moment resisting frames. Chapter 5 depicts the applications of these tools for dynamic analysis of shear wall dominant symmetric and unsymmetrical buildings. The findings of the current work in the form of conclusions and future work of the study are presented in chapter 6.

# CHAPTER 2
# DYNAMIC ANALYSIS OF BUILDINGS

## 2.1 Introduction

Earthquake response analysis is an art to simulate the behavior of a structure subjected to an earthquake ground motion based on dynamic analysis and mathematical modeling. The correct analysis will depend upon the proper modeling of the behavior of materials, elements, connection andstructures. The study of structural dynamics involves developing an insight into the dynamic behavior of the structures under the influence of dynamic loads. The models used in these investigations can be either small scale laboratory models for experimental studies or mathematical models for analytical studies. The development of an appropriate mathematical model for a specific study requires an understanding of the basic phenomenon and the basic mechanics. (Agarwal, et al. 2008)

The seismic response of a structural building system depends on several factors including its configuration and dynamic characteristics and the characteristics of the applied ground motion. It is imperative to simulate these factors as close to reality as possible in order to correctly predict seismic performance or vulnerability of a given structural system using experimental and/or analytical techniques. (Annan, et al. 2009)

## 2.1 Methods of Analysis

Two broad approaches of earthquake analysis of multistoried structures in present day use are:

1) Equivalent Static Method.

2) Dynamic Method of Analysis.

The methods are discussed in brief in the subsequent paragraphs.

1) Equivalent Static Method

This method is adopted in most of the building codes for moderately high buildings due to its simplicity and due to thefact that many structures designed on the basis of code coefficients have withstood satisfactorily during the past earthquakes. The static horizontal forces are applied based on the values of seismic coefficients to simulate the effect of the earthquake. An earthquake is translated into an equivalent static loading acting horizontally on the building. Equivalent Static method is the simplest method of analysis and requires less computational efforts because the forces depend upon the code based fundamental period of structures. The design base shear shall be first computed as a whole, and then be distributed along the height of the buildings based on simple formulas appropriate for the buildings. The details of this method can be referred from IS 1893 (Part 1):2002.

2) Dynamic Method of Analysis

In this method, the lateral forces that develop at each floor level during a particular earthquake are calculated. Depending upon the intensity of earthquake, a structure may remain elastic for moderate earthquake and may show inelastic behavior for severe earthquake. Consequently the methods of Dynamic Analysis may be classified as follows:

| | |
|---|---|
| 1) Elastic Dynamic Analysis – | a) Response History Method |
| | b) Response Spectrum Method |
| 2) Inelastic Dynamic Analysis - | a) Response History Method |
| | b) Response Spectrum Method |

**2.1.1 Response History Method**

This method consists of a step by step direct integration of differential equation of motion. The time domain is descretised into a number of small time intervals DT and for each time interval the equations of motion are solved with displacements and velocities of previous step serving as the initial values. Details of this method may be referred from (Agarwal, et al. 2008).

**2.1.2 Response Spectrum Method**

Response Spectrum is the most common way to characterize strong ground motion from engineering application point of view. A response Spectrum is a plot of maximum response (maximum displacement, velocity, acceleration) to a specified load function for all possible single degree of freedom systems. The abscissa of the spectrum is the natural frequency (or period) of the structural system and the ordinate is the maximum response. Thus to determine the response from an available spectral chart for a specified excitation, we need to know only the natural frequency of the system. The various Response Spectra are:

a) Deformation response Spectra
b) Pseudo - Velocity Response Spectra
c) Pseudo - Acceleration response Spectra

The following articles discuss the procedure for dynamic analysis as prescribed in IS 1893 (Part1):2002.

**2.2 Seismic Design Philosophy** (Agarwal, et al. 2008).

Earthquake and its occurrence and measurements, its vibration effects and structural response have been studied continuously for many years in earthquake history and thoroughly documented in the literature. Since then the structural engineers have tried hard to examine the procedure with an aim to counter the complex dynamic effect of seismically induced forces in structures for designing of earthquake resistant structures in a refined and easy manner. This reexamination and continuous efforts has resulted in several revisions of Indian Standard: IS 1893: (1962, 1966, 1970, 1975, 1984 and 2002) code of practice on the "Criteria for Earthquake Resistant Design of Structures" by the bureau of Indian Standards (BIS) New Delhi.

The philosophy of seismic design can be summarized as:

a) The design philosophy adopted in the code is to ensure that structures possess at least a minimum strength to

   i) resist minor earthquake (<DBE), which may occur frequently, without damage:

   ii) Resist moderate earthquake (DBE) without significant structural damage though some non structural damage.

   iii) resist major earthquake (MCE) without collapse.

   "Design Basis Earthquake (DBE) is defined as the maximum earthquake that reasonably can be expected to experience at the site once during the life time of the structure. The earthquake corresponding to the ultimate safety requirements is often called as Maximum Considered Earthquake (MCE). Generally the DBE is half of the MCE".

b) Actual forces that appear on the structures during earthquakes are much higher than the design forces specified in the code.

c) The design forces specified in the code shall be considered in each of the two orthogonal directions of the structure.

   The response of a structure to ground vibrations is a function of the nature of the foundation soil; materials, form, size and mode of construction of structures; and the duration and characteristics of the ground motion.

### 2.3 Determination of Design Lateral Loads

#### 2.3.1 Equivalent Lateral Force Procedure

The design lateral load shall first be computed for the building as a whole. The design lateral force shall then be distributed to the various floor levels. The overall design seismic force thus obtained at each floor level shall then be distributed to individual lateral load resisting elements.

The design seismic base shear is given by

$V_B = A_h W$ Eq. (2.1)

Where $A_h$= Horizontal seismic coefficient.

W- Seismic Weight.

##### 2.3.1.1 Seismic Weight of Building (W)

The seismic weight of each floor is its full dead load plus appropriate amount of imposed load. The fraction of live load up to 3 $KN/m^2$ of distributed floor load is 25 percent of imposed load and above 3 $KN/m^2$ is 50 percent of imposed load. While computing seismic weight of each floor the weight of columns and walls in any storey shall be equally distributed to the floors above and below the storey. The seismic weight of the whole building is the sum of seismic weight of all the floors.

##### 2.3.1.2 Horizontal Seismic Coefficient ($A_h$)

The value of horizontal Seismic Coefficient is given by

$A_h = (Z/2)\ (Sa/g)/(R/I)$ Eq. (2.2)

Where

Z= Zone Factor

Sa/g = Average Response Acceleration Coefficient

R=Response reduction Factor

I= Importance factor.

Zone factor Z refers to the zero period acceleration value for the maximum credible earthquake (MCE) in a zone. In determining base seismic coefficient a factor 2 in the denominator is used so as to reduce the Maximum Credible Earthquake (MCE) to a Design Basis Earthquake (DBE). Zone factor Z is given by IS 1893 (Part1):2002 for maximum credible earthquake in the Table 2.1.

Table 2.1 Values of Seismic zone factor (IS 1893 (Part1):2002)

| Serial No. | Zone No. | Z |
|---|---|---|
| 1 | V | 0.36 |
| 2 | IV | 0.24 |
| 3 | III | 0.16 |
| 4 | II | 0.10 |
| 5 | I | 0.10 |

Average Response Acceleration Coefficient (Sa/g) is obtained from the plot (Sa/g) (Fig.1.1) versus T (Time period of vibration) for different soil types.

Fundamental Natural period of vibration (T) may either be established by experimental observations on similar buildings or calculated by any rational method of analysis. In the absence of such data the approximate fundamental natural period of vibration in seconds is calculated as follows:

For moment resisting frame building without masonry infill panels

$T_a = 0.075\ h^{0.75}$- For RCC building Eq. (2.3)

$T_a = 0.085\ h^{0.75}$- For Steel building Eq. (2.4)

Where h is the height of the building in meter.

Importance factor I is taken as 1.5 for all important service and community structures and 1 for all other buildings.

Response Reduction Factor R depends upon the perceived seismic damage performance of the structure characterized by ductile or brittle deformations. This characteristic represents the structure’s ductility, damping as well as the past seismic performance of structure with various structural systems. Experiments and performance of structures during the past earthquakes have shown that the structures designed for those reduced force level perform adequately, if properly detailed. Table 2.3 gives the values of R for various structural systems.

Table 2.3 Response Reduction Factor [1]Rfor Building Systems (IS 1893 (Part1):2002)

| Sr. No | **Lateral Load Resisting System** | R |
|---|---|---|
| | ***Building Frame Systems*** | |
| i) | Ordinary RC moment-resisting frame ( OMRF )[2] | 3.0 |
| ii) | Special RC moment-resisting frame ( SMRF )[3] | 5.0 |
| iii) | Steel frame with<br>a) Concentric braces<br>b) Eccentric braces | <br>4.0<br>5.0 |
| iv) | Steel moment resisting frame designed as per SP 6 ( 6 )***Building with Shear Walls***[4] | 5.0 |
| v) | Load bearing masonry wall buildings[5]<br>a) Unreinforced<br>b) Reinforced with horizontal RC bands<br>c) Reinforced with horizontal RC bands and vertical bars at ***corners*** of rooms and jambs of openings | <br>1.5<br>2.5<br>3.0 |
| vi) | Ordinary reinforced concrete shear walls[6] | 3.0 |
| vii) | Ductile shear walls[7]<br>***Buildings with Dual Systems***[8] | 4.0 |
| viii) | Ordinary shear wall with OMRF | 3.0 |
| ix) | Ordinary shear wall with SMRF | 4.0 |
| x) | Ductile shear wall with OMRF | 4.5 |

1) The values of response reduction factors are to be used for buildings with lateral load resisting elements, and not just for the lateral load resisting elements built in isolation.

2) OMRF are those designed and detailed as per IS 456 or IS 800 but not meeting ductile detailing requirement as per IS 13920 or SP 6 (6) respectively.

3) SMRF defined in 2.15.2.

4) Buildings with shear walls also include buildings having shear walls and frames, but where:

a) frames are not designed to carry lateral loads, or

b) frames are designed to carry lateral loads but do not fulfill the requirements of ‘dual systems’.

5) Reinforcement should be as per IS 4326.

6) Prohibited in zones IV and V.

7) Ductile shear walls are those designed and detailed as per IS 13920.

8) Buildings with dual systems consist of shear walls (or braced frames) and moment resisting frames such that:

a) the two systems are designed to resist the total design force in proportion to their lateral stiffness considering the interaction of the dual system at all floor levels; and

b) the moment resisting frames are designed to independently resist at least 25 percent of the design seismic base shear.

**2.3.1.3 Distribution of Design Force**

The base shear shall be distributed to different floor levels of the building as per the following expression:

$$Q_i = V_B \frac{W_i {h_i}^2}{\sum_{i=1}^{i=n} W_i {h_i}^2} \qquad \text{Eq. (2.5)}$$

Where $Q_i$= Design lateral force at Floor i, $W_i$ = Seismic weight of the floor i, $h_i$=height of the floor i measured from the base, n= number of storeys of the building.

**2.3.2 Dynamic Analysis**

Dynamic Analysis shall be performed to obtain the design seismic force, and its distribution to different levels along the height of the building and to the various lateral load resisting elements for the following buildings:

Regular Buildings:- Those greater than 40 m in height in zone IV and V and those greater than 90 m in height in zone II and III.

Irregular Buildings: - All framed buildings higher than 12 m in height in zone IV and V and those greater than 40 m in height in zone II and III.

Dynamic analysis may be performed either by Time History or by Response Spectrum method. However in either method the design base shear ($V_B$) shall be compared with a base shear $\overline{V_B}$calculated using fundamental period $T_a$ where $V_B$ is less than $\overline{V_B}$ all the response quantities shall be multiplied by $\overline{V_B}$/ $V_B$. (IS 1893 (Part1): 2002)

Time History Method when used shall be based on appropriate ground motion and shall be performed using accepted principles of Dynamics.

Response Spectrum method of analysis shall be performed using the design spectrum or by site specific design spectrum.

**2.3.2.1 Free Vibration Analysis**

Un damped free vibration analysis of the entire building shall be performed as per the established methods of mechanics using the appropriate masses and elastic stiffness of the structural system to obtain the natural periods (T) and the mode shapes of those of its modes of vibration that need to be considered.

**Determination of mode shape coefficient** ($\phi_i^r$)

A popular method for determination of the fundamental mode is the iterative Stodola Method. The equation of motion for a free vibrating motion of a multistoreyed lumped mass can be written as:

$$[M][\ddot{x}] + [K][x]=0 \qquad \text{Eq. (2.6)}$$

In which [M] is diagonal matrix, [K] is the stiffness matrix in relation to the lateral displacements and [x] and [$\ddot{x}$] are the displacement vector corresponding to storey displacement and acceleration vector corresponding to storey acceleration matrices respectively. Assuming the free vibration is simple harmonic,

$$[x] = [\phi] \sin \omega t \qquad \text{Eq. (2.7)}$$

$\phi$ represents the shape of the vibrating system, which does not change with the time but varies with the amplitude,ω represents the circular frequency of the system. Equation 2.6 can be written as

$$-\omega^2 [M][\phi]+ [K][ \phi]=0 \qquad \text{Eq.(2.8)}$$

which can be solved to

$$[G] [M][\phi]=\frac{1}{\omega^2}[ \phi]=0, \text{ where } [G]=[K]^{-1} \qquad \text{Eq. (2.9)}$$

This equation is of the form

$$[A][x]= \lambda[x] \qquad \text{Eq. (2.10)}$$

which represents an Eigen value problem whose solution leads to evaluation of natural frequency and corresponding mode shapes. Knowing ω the fundamental period of mode can be computed as:

$$T=\frac{2\pi}{\omega} \qquad \text{Eq. (2.11)}$$

**Modes to be considered**

Thenumber of modes to be used in the analysis should be such that the sum total of modal masses of all modes considered is at least 90 percent of total seismic mass.

**Modal Mass (**IS 1893 (Part1):2002)

The modal mass ($M_k$) is given by:

$$M_k = \frac{\left[\sum_{i=1}^{n} W_i \phi_{ik}\right]^2}{g \sum_{i=1}^{n} W_i (\phi_{ik})^2} \qquad \text{Eq. (2.12)}$$

Where g = Acceleration due to gravity; $\phi_{ik}$ =Mode shape coefficient of mode i in mode k and Wi = Seismic weight of floor i.

**2.3.2.2 Modal Analysis (**IS 1893 (Part1):2002)

This method of analysis is based on the dynamic response of the building idealized as having the lumped mass and stiffness in various storeys with each mass having one degree of freedom that of the lateral displacement in the direction under consideration. Response in each mode is determined using following relationship.

Design lateral force at each floor is obtained using:

$$Q_{ik}=A_k \phi_{ik} P_k W_i \qquad \text{Eq. (2.13)}$$

Where $A_k$= Design horizontal spectrum value corresponding to natural period of vibration of mode k and $P_k$ is the modal participation factor of mode k.

**Modal Participation factors (**IS 1893 (Part1):2002)

The modal participation factor ($P_k$) in mode k is given by

$$P_k=\frac{\left[\sum_{i=1}^{n} W_i \phi_{ik}\right]}{\sum_{i=1}^{n} W_i (\phi_{ik})^2} \qquad \text{Eq. (2.14)}$$

**Storey Shear Forces in each mode**

The peak shear force ($V_{ik}$) acting in storey i in mode k is given by

$$V_{ik}= \sum_{i=1}^{n} Q_{ik} \qquad \text{Eq. (2.15)}$$

**Storey Shear Forces due to all modes considered**

The peak storey shear force (Vi) in storey I due to all modes considered is obtained by combining those due to each mode.

**Lateral force at each storey due to all modes considered**

The design lateral forces are worked out as under:

$F_{roof}=V_{roof}$ and

$F_i=V_i-V_{i+1}$ Eq. (2.16)

**Modal combination (**IS 1893 (Part1):2002)

The peak storey shear force ($V_i$) in storey I due to all modes considered is obtained by combining those due to each mode in accordance with modal combination i.e. SRSS (Square root of sum of squares) or CQC (Complete Quadratic Combination) methods.

**Square Root of Sum of Squares (SRSS)**

If the building does not have closely spaced modes, the response quantity (λ) due to all modes considered shall be obtained as: (Agarwal, et al. 2008).

$$\lambda = \sqrt{\sum_{k=1}^{r}(\lambda_k)^2} \quad \text{Eq. (2.17)}$$

**Complete Quadratic Combination (CQC)**

$$\lambda = \sqrt{\sum_{i=1}^{r}\sum_{j=1}^{r}\lambda_{ib}\,\rho_{ij}\lambda_j} \quad \text{Eq. (2.18)}$$

Where

r= number of modes to be considered.

$\rho_{ij}$= Cross modal coefficient

$\lambda_i$ = Response Quantity in mode I including sign

$\lambda_i$= Response Quantity in mode j including sign

$$\rho_{ij} = \frac{8\zeta^2\,(1+\beta_{ij})\beta^{1.5}}{(1+\beta_{ij})^2+4\zeta^2\,\beta_{ij}(1+\beta_{ij})^2} \quad \text{Eq. (2.19)}$$

Where

ζ = Modal Damping Ratio.

$\beta_{ij}$ = Frequency Ratio = $\omega_j/\omega_i$ .

$\omega_i$= Circular Frequncy in $i^{th}$ mode.

$\omega_j$ = Circular frequency in $j^{th}$ mode.

# CHAPTER NO. 3

# LITERATURE REVIEW

This chapter covers the details of data driven tools employed for the dynamic analysis along with applications of these techniques for the dynamic analysis.

## 3.1 DATA DRIVEN TOOLS

Data-driven modeling can be considered as an approach to modeling that focuses on using the Machine Learning methods in building models that would complement the "knowledge-driven" models describing physical behavior (Solomatine and Ostfeld, 2008). Three data driven tools are employed for the present study. This chapter gives some of the details of these techniques in subsequent headings. Artificial Neural Networks offer a powerful and distributed computing architecture equipped with significant learning abilities. Fuzzy sets form a key methodology for representing and processing linguistic or in general nonnumeric information. Genetic programming (GP) is an evolutionary algorithm-based methodology inspired by biological evolution to find computer programs that perform a user-defined task. Support Vector Machines are a set of related supervised learning methods used for classification and regression. Support vector machine constructs a hyper plane or set of hyper planes in a high or infinite dimensional space, which can be used for classification, regression or other tasks.A decision tree is a decision support tool that uses a tree-like graph or model of decisions and their possible consequences, including chance event outcomes, resource costs, and utility. Decision trees are commonly used in operations research, specifically in decision analysis, to help identify a strategy most likely to reach a goal.

### 3.1.1 Artificial Neural Networks (ANN)

Since last two decades or so Artificial Neural Networks (or ANNs) are employed effectively for simplification of complex problems with large number of computations in the field of Civil and Structural Engineering (Flood and Kartam, 1994a and b). ANN is also an alternative method and a tool for modeling complex phenomena in different areas of research and engineering practice (Caglar, et al. 2008).

Considered as a subset of Artificial Intelligence, ANN basically constitutes a computer program designed to learn in a manner similar to the human brain. Axons which have an electrical signal and found only on output cells, terminate at synapses that connect it to the dendrite of another neuron. NN, throughout the overall part of the analysis, pertains to ANN and not biological NN.

NN take after the human brain on the following two grounds, first, they acquire knowledge via the network through a learning process and secondly, interneuron connection strengths are used to store the acquired knowledge. Perhaps, the best agreed upon definition of ANN is that they constitute nonparametric regression models which do not require a priori assumptions about the problem with the date being enabled to speak for itself. Ironically, the origin of ANN is not directly linked to any estimation or forecasting exercise since the persons that pioneered research in this field was basically attempting to have an insight of the learning abilities of human brain. However, as ANN displayed interesting learning capacity, this led towards interests in other fields, let alone science such as in finance, economics and econometrics. In a nutshell, ANN tries to sieve out patterns present in the past data and to extrapolate them into the future. Prior to gaining an insight of ANN, it is important to understand the basic components of ANN. Figure 3.1 gives an insight to working of artificial neural Networks.

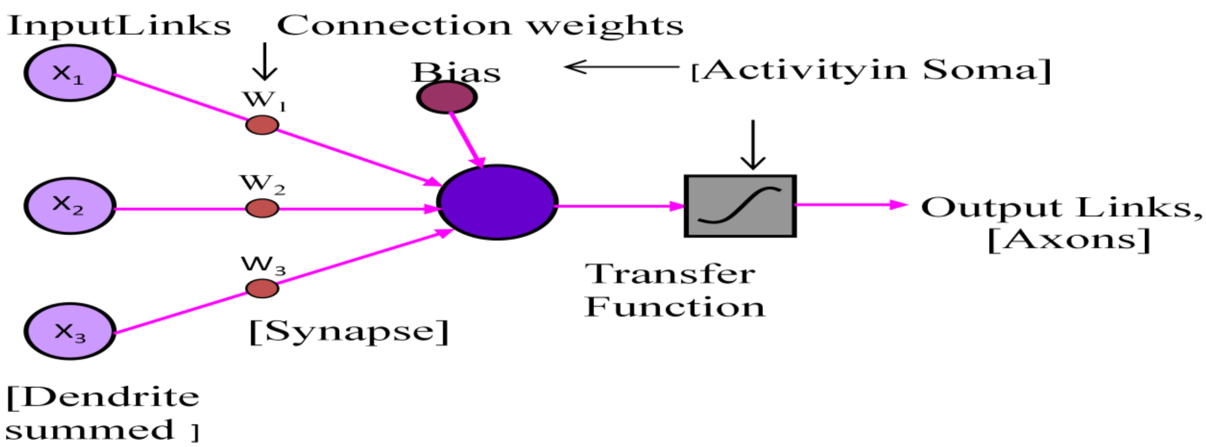


Figure 3.1 Artificial neural networks

Prior to gaining insight of ANN, it becomes proper to have recourse towards the basic components of the brain, labeled as neurons. A neuron signifies a minute processor that receives, processes and sends data to the next layer of the model. The brain is composed of about 100 billions neurons of many distinct types. Neurons are grouped together into an intricate network and they work by transmitting electrical impulses. The reaction of a neuron following receipt of an impulse, will hinge on the intensity of the impulses received together with the neuron's degree of sensitivity towards the neurons that dispatched the neurons. There are two operations being performed inside a neuron, the first being the computation of the weighted sum of all of the inputs while the second one converts the output of the summation in terms of certain threshold.

A neuron has basically four main parts: the cell body which constitutes the spot for processing and generating impulses, the dendrites which are synonymous with signal receivers, that basically accept signal from outside or other neurons, the axon which represents the avenue that sends the message triggered by the neuron to the next neurons and the synaptic terminals that entail excitatory or inhibitory reactions of receiving neuron. Brain power, at the end, is simply a function of this intricately complex network of connections subsisting between the neurons. A perceptron constitutes a model of simple learning, developed in 1962 by Rosenblatt. The perceptron constitutes an element that weighs and sums up the inputs and compares the result with a predefined threshold value. The perceptron emits or releases one if the weighted sum of inputs is greater than the threshold value, otherwise 0. Bishop (1995), points out that a perceptron may work as a linear discriminant in classifying elements that belong to different sets. The higher the number of neurons in a single hidden layer, the higher the complexity of the represented function. Unfortunately, when it comes to solving classification problems that are not linearly separable, the perceptron algorithm developed by Rosenblatt is not able to terminate (Ramlall, 2010).

**3.1.1.2 Network Architecture**

The simplest form of ANN consists of only two layers, the input and output layer (no hidden layer is present). This is sometimes referred to as the skip layer, which basically constitutes a conventional linear regression modeling in a ANN design whereby the input layer is directly connected to the output layer, hence bypassing the hidden layer. Like any other network, this simplest form of ANN relies on weight as the connection between an input and the output; the weight representing the relative significance of a specific input in the computation of the output. It is important to bear in mind that the output generated will heavily depend on the type of activation function used. However, based on the fact that the hidden layer confers strong learning ability to the ANN, in practical applications, a three and above three ANN architecture is used. This is shown in Figure 3.1. It is vital to distinguish between two classes of weights in ANN; first there are those weights that aim to connect the inputs to the hidden layer and then those weights that connect the hidden layer to the output layer. In a parallel manner, there are two classes of activation functions, one found in the hidden layer and one in the output layer. An infinite number of ways prevail as to the construction of a ANN; neurodynamics (basically spells out the properties of an individual neuron such as its transfer function and how the inputs are combined) and architecture (defines the structure of ANN including the number of neurons in each layer and the number of types of interconnections) are two terms used to describe the way in which a ANN is organized. Any network designer must factor in the following elements when building up a network:

1. Best starting values (weight initialisation)
2. Number of hidden layers
3. Number of neurons in each hidden layer
4. Number of input variables or combination of input variables (usually emanating from regression analysis)
5. Learning rate
6. Momentum rate
7. Training time or amount of training(i.e., the number of iterations to employ)
8. Type of activation function to use in the hidden and output layers
9. Data partitioning and evaluation metrics

Ideally, a ANN for a particular task has to be optimized over the entire parameter space of the learning rate, momentum rate, number of hidden layers and nodes, combination of input variables and activation functions. Attaining such an objective is computationally burdensome. There is widespread consensus in the empirical literature that the final artifact of ANN model rests purely on a process of trial and error as there is poor theoretical guidance in creating a ANN network. In that respect, the design of a network is considered an art rather than a science. This is why the design of a network is a time consuming process. Nevertheless, the main criterion used for the design of ANN is to end up with the specification that minimizes the errors; or the optimal network topology (Ramlall, 2010).

**3.1.1.3 Data Processing**

Rescaling the data is considered beneficial to enhance the forecasting accuracy because the estimation algorithms tend to perform better when the input values are small and centeredaround zero. An important step in building up a ANN is to select the proper data pre and postprocessing. This is of major significance by virtue of the impact of curse of dimensionality. An avenue to represent the training data is basically to specify intervals for the input variables and then to classify the data records by stating in which interval the values of a record lie. Contrary to the intuitive assumption that additional data should improve the performance of ANN, it is not necessary the case. As a matter of fact,, the reduction of dimensionality of the training data is vital for a proper functioning of ANN. It makes more sense to preprocess the picture to extract the features vital for recognition of the shape and then apply ANN on these features. As a matter of fact, quality and quantity of data are widely recognized as important issues in the development of neural network models. It is imperative that the input data is free from noise to ensure that the network is given the best possible training for it to be able to generalize better results later. Meade (1995), states that ANN are data-dependent so that the learning algorithms are only as good as the data shown to them. Usually, data are transformed prior to submission to the ANN model. To accomplish a good prediction performance when applying ANN; at the very least, the raw data must be scaled between the upper and lower bounds of the transfer function (usually between zero and one or minus one). First differencing (to remove a linear trend from the data) and taking log (useful for data that can take both small and large values) constitute the two widely used data transformation in NN. Another technique is to use ratios. Sampling or filtering the data refers to removing observations from the training and testing sets to generate a more uniform distribution. Benefit of filtering is a fall in the number of training facts which enables testing of more input variables, random starting weights or hidden neurons rather than training large data sets. In practice, data preprocessing involves much trial and error (Ramlall, 2010).

#### 3.1.1.4 Strengths of ANN

The following are deemed as the strengths of ANN:

1. The greatest power of Neural Networks is that it is endowed with a finite number of hidden units, can yet approximate any continuous function to any desired degree of accuracy. This has been commonly referred to as the property of universal approximator. A universal approximator signifies that, given an ample number of hidden layer units, the NN model can approximate any functional form to any degree of accuracy. In fact, many authors have shown that a three-layer ANN equipped with a logistic activation function in the hidden units, constitutes a universal approximator. But, this is a mere sufficient condition as the necessary condition requires that there be ample number of hidden units being included to ensure that the network can approximate nearly any linear or nonlinear function to a desired level of precision.

2. No prior knowledge of the data generating process is needed for implementing ANN, i.e., ANN are free from statistical assumptions. ANN is more robust to missing and inaccurate data. ANN should, in theory, be able to detect and duplicate any complex nonlinear pattern in the data.

In a parallel manner, ANN is not rigid and hence it can be customised to any architecture as per the fancy of the forecaster. More specifically, ANN can encompass many models such as linear regression, binary probit model and others by simply tweaking with the activation functions and the network architecture.

3. Since under regression analysis, there is need to state the functional form of the model, model misspecification may manifest. However, such problem of model mis-specifcation does not occur in case of ANN since no specifications are used as the network merely learns the hidden relationship in the data. Though, nonlinear functions can be linearised by using specific mathematical transformations in economics and finance, nevertheless, the problem lies in knowing the proper transformation to be applied and this may not be easy in practice. But, when it comes to using ANN, there is no real need to know about the functional form to be applied. Because the universal approximator property under ANN ensures that ANN can mimic almost any functional form.

4. One problem related to Neural Network could yet be considered not as a real strength but as something common among other optimization techniques. Indeed, many studies admit the fact that their estimation may suffer from bias emanating from coefficients which are local rather than being global. But, such a feature is also present among many nonlinear optimization tasks and there is no "silver bullet" to obviate such a problem.

**3.1.1.5 Drawbacks of ANN**

Assessing the other side of the coin, the following drawbacks were noted for ANN:

1. The chief pitfall related to the application of ANN has been coined as the black box problem. One avenue employed has been to generate rules from ANN that are easy for a human user to understand; these rules must be sufficiently simple yet accurate. The conditions of the rules describe a sub region of the input space. Based on the fact that a single rule is not powerful enough to approximate the nonlinear mapping of the network well, the remedy is basically to split the input space of the data into distinct sub regions. Nevertheless, there is still a ray of hope looming on the NN horizon following the proposition made by Refenes, et al. (1994), namely that the black box problem can be alleviated by resorting towards sensitivity analysis. Such a technique involves plotting the value of the output for a range of values of a given input, with all other inputs remaining fixed at their sample mean. Consequently, if the value of the output stays stable for distinct values of the input under inspection, then, the researcher can presume that this

input does not entail much say in the predictive power of the NN model. Such a process is successively applied to all inputs until the researcher ends up with all the relevant inputs in the model. Hence, the ANN model is said to be pruned via the elimination of superfluous inputs.

2. The addition of too many hidden units incites the problem of over fitting the data; meaning that the network learns too well in the training data session but generates inferior results in case of out of sample session. The effect of over fitting in case of a forecasting exercise, manifests in form of poor output of sample forecasts. Alternatively stated, over fitting signifies that rather than learning the fundamental structure of the training set that would enable a satisfactory and sufficient generalization, the network learns insignificant details of individual cases. Over fitting can be caused either by a shorter sample size in use or a too complex ANN model so that the ANN tends to memorize rather than generalize from the data. In that specific case, to avoid over fitting, ANN model should be kept small or parsimonious. There are two ways to deal with the over fitting problem, the first is to train the network model on the training set and then to analyse the performance on the test set. This technique is usually referred to as early stopping criteria, whereby the data is split into three parts; the training set, the test set and the validation set. In that context, the training set is used by the algorithm to estimate the network weights; basically the training sets represents the in sample period of the regression model while the test set is dedicated for out of sample analysis. The early stopping strategy is, however, not without any caveat. The reason is that in case of small samples, the three-pronged decomposition of the data set becomes somewhat problematic. Results can also be sensitive to the observations contained in each of the three specific data sets. To curb the over fitting problem, Refenes (1995), recommends cross-validation to be implemented during learning. The second approach is to have recourse towards one of the distinct network pruning algorithms.

3. ANN depends so much on the quality of the data that the algorithms employed are only as good as the data used to apply them. This is why ANN is often called weakly deterministic systems. Similarly, ANN needs large samples to work. For instance, if a simple ANN model is equipped with a large number of weights, then, it s most likely that this leads towards a limited number of degrees of freedom.

4. The construction of the ANN model can be a time-consuming process since building up the ANN architecture is synonymous to a strenuous activity involving trial and error. For instance, subjectivity in the construction of ANN has led towards researchers to consider the results being

doubtful. Learning results in ANN may not be stable on the back of random initialization of weights coupled with complexity of the error surface. So, while building up the ANN, it becomes imperative to keep such subjectivity to a low level as far as possible. In the same vein, the early stopping strategy used to fight against the over fitting problem may be subject to arbitrary judgments made by the researcher. For instance, the researcher must make judgment about dividing the sample into the training, validation and testing sets. Usually, researchers cling to some rule of thumb for dividing the data sets. However, such a shortcoming does not pose a major issue of concern, bearing the out of sample forecasting feature whereby 30% of the sample tends to represent the holdout sample.

5. ANN should never be viewed as a panacea. For instance, in case of extreme cases such as major crisis that could substantially alter the movement in prices, ANN prediction is unlikely to be satisfactory. Consequently, expert judgments should always be present. ANN models are prone to problems of local optima, a conspicuous feature noted in case of non-linear optimization.

**3.1.1.6 Applications of ANN in structural Engineering**

Van and Roufei (1990), applied neural network to arrive at the location and magnitude of the maximumbending moment of a simple supported rectangular plate.Hajela and Berke (1991), obtained optimum design of trusses using neural networks. Flood and Kartam (1994a ; 1994b) presented the concept and application of neuralnetworks to structural engineering in two parts. In the first part (1994a), concepts pertaining to neural networks havebeen discussed clearly by solving a simple structural analysis problem using the most popular form of neuralnetworking system – a feed forward network trained using a supervised scheme. In second part (1994b), a range ofdifferent types of civil engineering problems have been considered and approaches to their solutions using differentneural-network algorithms has been discussed. Rogers (1994), applied neural network for carrying out structural analysis of structure with large degrees of freedom. Mukherjee (1997), developed a self-organizing neuralnetwork for identification of natural modes of multi-story buildings. Waszczyszyn and Ziemianski (2001), developed neural networks for various applications in structural engineering. In one of the application, the bending analysis of elastoplastic beams was carried out by using hybrid neural network. Maru, et al. (2004), presented feasibility analysis of a neural network for the evaluation of creep and shrinkage effects in tall buildings. Pendarkar et al. (2007) developed a neural network model for continuous composite beams to predict the inelastic moments, due to creep and shrinkage in concrete, from the elastic moments. Mukherjee and Despande (1995) presented the suitability ofneural network for modeling an initial design process. The preliminary design model is of vital importance in thesynthesis of a finally acceptable solution in a design problem. Tashakori and Adeli (2002) developed a neural network for optimum design of cold-formed steel space frames. Hadi (2003) developed two neural networks for thedesign of steel fibreous reinforced concrete beams in accordance with Australian standard for concrete structures(AS 3600:1994). Cladera and Mari (2004a; 2004b), developed neural networks to formulate simple expressions for the design of high strength and normal strength reinforced concrete beams from the large amount of information available in the literature.

### 3.1.2 Genetic programming (GP)

The concept of genetic programming is borrowed from theprocess of evolution occurring in nature, where the speciessurvive according to the principle of ‘survival of the fittest’. TheGP is similar to genetic algorithms (GA) but unlike the latter itssolution is a computer program or an equation as against a set ofnumbers in the GA. (Gaur and Deo, 2008).Although research on GP techniques dates back to the 1960s and1970s, GP emerged as a distinct discipline presented by Koza.(Johariet al.2006). Koza developed a special genetic algorithm known as “genetic programming (GP)” which its population is represented by the “parse tree” (computer programs). A population memberin GP is a structured computer program consisting of functions and terminals. The functions and terminals are picked out from a set of functions and a set of terminals. A function set could contain functions such as basic mathematical operators (+, -, *, /, etc.), Boolean logic functions (AND, OR, NOT, etc.), or any other user defined function. The terminal set contains the arguments for the function and can consist of numerical constants, etc.The functions and terminals are selected randomly and put together to form a computermodel in a tree-like structure with a root point with branches extending from each function and ending in a terminal. An example of a simple tree representation of a GP model is shown in Figure 2.2. (Kermani, et al. 2009)

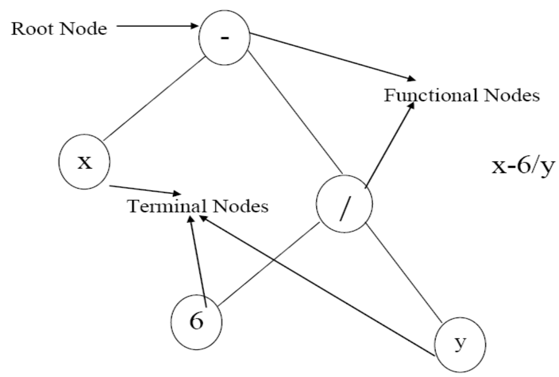


Figure 3.2 Typical GP Tree Representations

**3.1.2.1 The primitives of genetic programming.**

Every solution evolved by GP is assembled from two sets of primitives nodes; terminals and functions. The terminal setcontains nodes that provide an input to the GP system while the unction set contains nodes that process valuesalready in the system. Constants can be used in GP by including them in the terminal set. Once the evolutionaryprocess is started, the GP system randomly selects nodes from either set and thus may not utilize all of the availablenodes. However increasing the size of each node set enlarges the search space. Therefore only a relatively simple nodeset is initially provided and nodes are usually added only if required. (Shaw et al.2004)

**3.1.2.2 Tree based genetic programming.**

The primitives of GP, the function and terminal nodes, must be assembled into a structure before they may be executed.Three main types of structure exist: tree, linear and graph. Within this work, the input (the structure to be optimised ordesigned) actually forms a graph network. However by the duplication of joint data i.e. the same ‘joint node’ can existin the same tree on more than one occasion, this graph network is converted into a tree structure. (Shaw, et al. 2004)

**3.1.2.3 Algorithm of Genetic Programming**

Genetic programming starts with an initial population of randomly generated computer programs composed of functions and terminals appropriate to the problem domain. The functions may be standard arithmetic operations, standard programming operations, standard mathematical functions, logical functions, or domain-specific functions. Depending on the particular problem, the computer program may be Boolean-valued, integer-valued, real-valued, complex-valued, vector-valued, symbolic-valued, or multiple-valued. The creation of this initial random population is, in effect, a blind random search of the search space of the problem. Each individual computer program in the population is measured in terms of how well it performs in the particular problem environment. This measure is called the fitness measure. The nature of the fitness measure varies with the problem. Typically, each computer program in the population is run over a number of different fitness casesso that its fitness is measured as a sum or an average over a variety of representative different situations.

The Darwinian principle of reproduction and survival of the fittest and the genetic operation of sexual recombination (crossover) are used to create a new offspring population of individual computer programs from the current population of programs. The reproduction operation involves selecting, in proportion to fitness, a computer program from the current population of programs, and allowing it to survive by copying it into the new population. The genetic process of sexual reproduction between two parental computer programs is used to create new offspring computer programs from two parental programs selected in proportion to fitness. The parental programs are typically of different sizes and shapes. The offspring programs are composed of sub expressions (sub trees, subprograms, subroutines, building blocks) from their parents. These offspring programs are typically of different sizes and shapes than their parents. Intuitively, if two computer programs are somewhat effective in solving a problem, then some of their parts probably have some merit. By recombining randomly chosen parts of somewhat effective programs, we may produce new computer programs that are even fitter in solving the problem. After the operations of reproduction and crossover are performed on the current population, the population of offspring (i.e., the new generation) replaces the old population (i.e., the old generation). Each individual in the new population of computer programs is then measured for fitness, and the process is repeated over many generations.At each stage of this highly parallel, locally controlled, decentralized process, the state of the process will consist only of the current population of individuals. Typically, the best individual that appeared in any generation of a run (i.e., the best-so-far individual) is designated as the result produced by genetic programming. In summary, the genetic programming paradigm breeds computer programs to solve problems by executing the following three steps:

(1) Generate an initial population of random compositions of the functions and terminals of the problem (computer programs).

(2) Iteratively perform the following sub steps until the termination criterion has been satisfied:

(a) Execute each program in the population and assign it a fitness value according to how well it solves the problem.

(b) Create a new population of computer programs by applying the following two primary operations. The operations are applied to computer program(s) in the population chosen with a probability based on fitness.

(i) Copy existing computer programs to the new population.

(ii) Create new computer programs by genetically recombining randomly chosen parts of two existing programs.

(3) The best computer program that appeared in any generation (i.e., the best-so-far individual) is designated as the result of genetic programming. This result may be a solution (or an approximate solution) to the problem. (Koza, 1992)

Figure 3.3 is a flowchart for the genetic programming paradigm. (Koza, 1992)

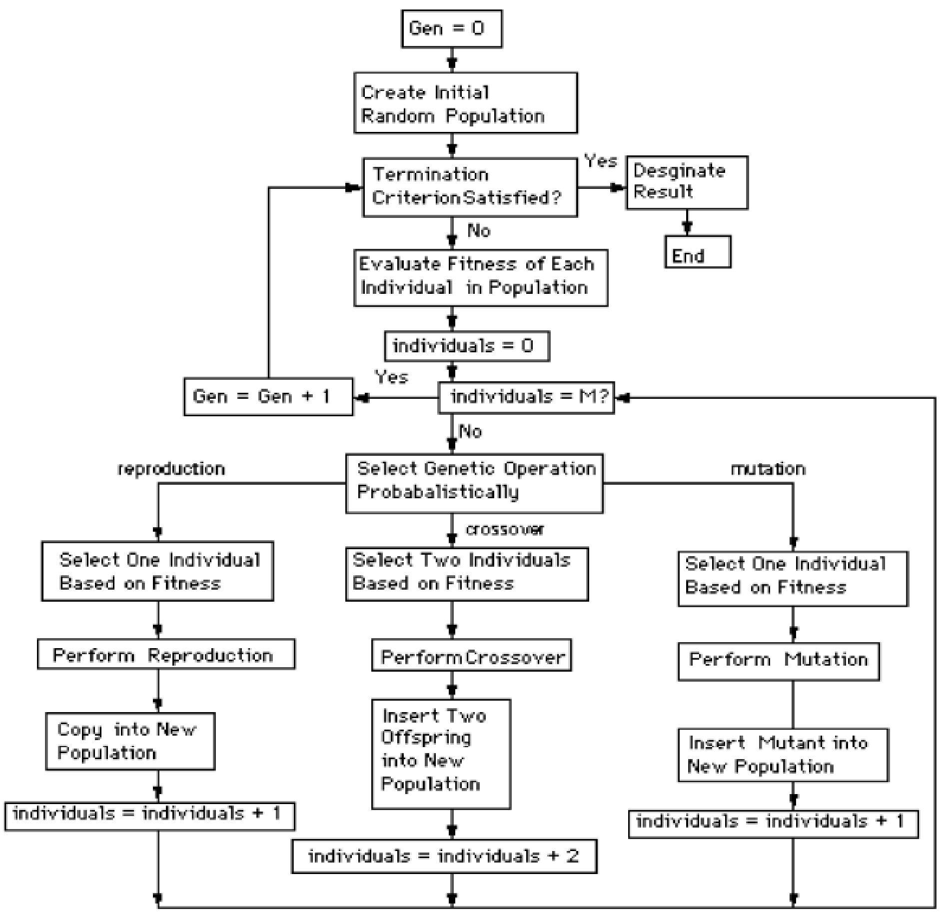


Figure 3.3 Flow Chart of Genetic Programming

#### 3.1.2.4Genetic Operators

Model structures evolve through the action of three basic genetic operators: reproduction, crossover and mutation.

**Reproduction**: In the reproductionstage, a strategy must be adopted as to which programs should die. In this implementation, a small percentage of trees with worst fitness are killed. The population is then filled with the surviving trees according to a binary tournament selection.The best program is copied as it is as per the fitness criterion and included in the new population. Individuals areincreased by 1.

Reproduction rate= 100 - mutation rate-(crossover rate * [1-mutation rate]). (Londhe, 2008)

**Cross Over**: The crossover operator is responsible for combining good information from two strings and for testing new points in the search space. The two off springs are composed entirely of the genetic material from their two parents. By recombining randomly certain effective parts of a character string, there is a good chance of obtaining an even more fit string and making progress towards solving the optimization problem. Several ways of performing crossover can be used. The simplest but very effective is the one-point crossover. Two individual strings are selected at random from the population. Next, a crossover point is selected at random along the string length, and two new strings are generated by exchanging the substrings that come after the crossover point in both parents. Cross-over operator produces two new individuals for new generation by choosing two individuals of current population and randomly changing one's branch with another.(Kermani et al. 2009)The mechanism is illustrated in Figure 2.4

**Mutation**: Mutation prevents the population from premature convergence or from having multiple copies of the same string. This feature refers to the phenomenon in which the algorithm loses population diversity because an individual that does not represent the global optimum becomes dominant. In such cases the algorithm would be unable to explore the possibility of a better solution. Mutation operator produces one new individual for new generation by randomly changing a node of one of the trees in current population. (Figure 2.5). (Kermani et al.2009) .

An additional operator, *elite transfer*, is used to allow a relatively small number of the fittest programs, called the elite, to be transferred unchanged to a next generation, in order to keep the best solutions found so far. As a result, a new population of trees of the same size as the original one is created, but it has a higher average fitness value.

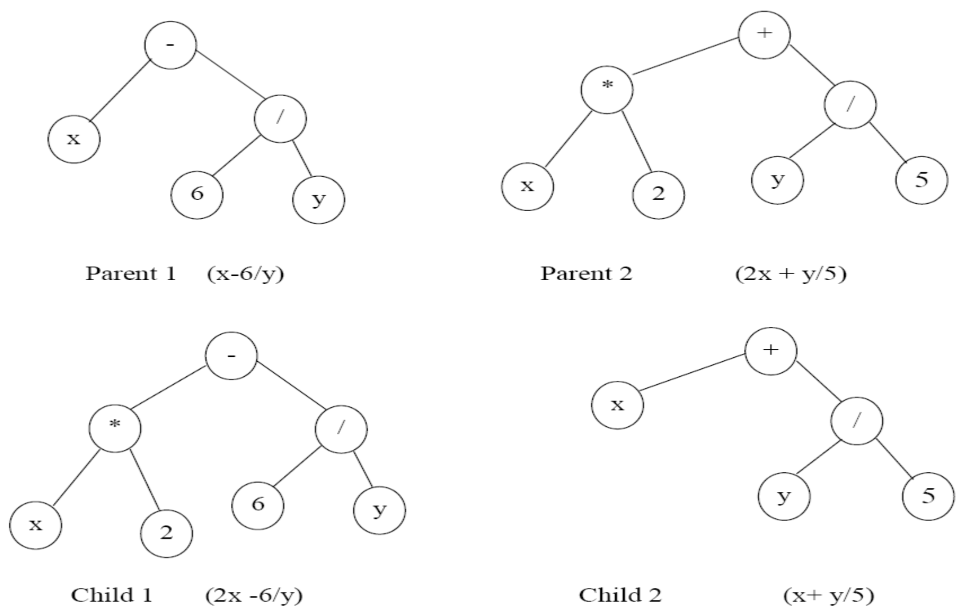


Figure 3.4 Typical cross over operation in GP

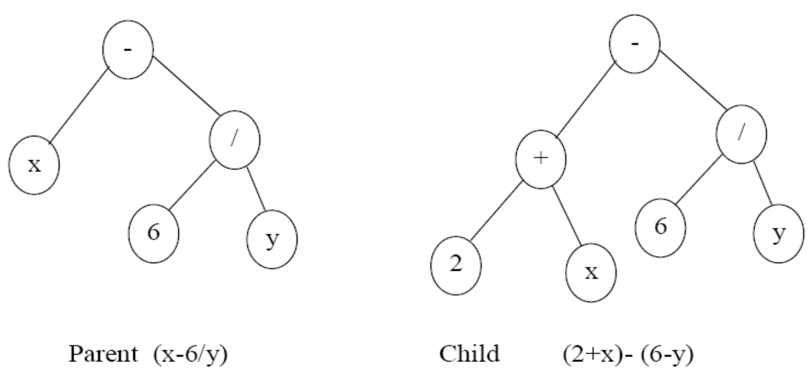


Figure 3.5 Typical Mutation operation in GP

### 3.1.2.5 Advantages of Genetic Programming

A key advantage of GP as compared to traditionalmodelling approaches is that it does not assumeany a priorifunctional form of the solution. Forinstance, in a typical regression method, the model structure is specified in advance (which is ingeneral difficult to do) and the model coefficientsare determined. For neural networks, the timeconsuming task of initially defining the networkstructure has to be undertaken and then thecoefficients (weights) are found by the learningalgorithm. On the other hand, in GP, the buildingblocks (the input and target variables and thefunction set) are defined initially, and the learningmethod subsequently finds both the optimalstructure of the model and its coefficients.Moreover, since GP evolves an equation orformula relating the input and output variables, amajor advantage of the GP approach is itsautomatic ability to select input variables thatcontribute beneficially to the model and disregardthose that do not. GP can thus reduce substantiallythe dimensionality of the input variables. However common drawback of GP is the difficulty to handle constants.

In GP, as in any data-driven prediction model, theselection of appropriate model inputs is extremelyimportant. This is especially so when lagged inputvariables are also used. Inclusion of irrelevantinputs leads to poor model accuracy and creationof complex models, which are more difficult tointerpret as compared to simpler ones.

#### 3.1.2.6 Applications of Genetic Programming in Civil Engineering

Applications of Genetic Programming in Civil Engineering are sparse and few. Majority of them can be found in Hydraulic Engineering including wave hydrodynamics, Hydrology and Hydraulics. Londhe and Dixit (2012) have taken a comprehensive review of these applications along with theory of GP. Amongst other applications in Civil Engineering,Heshmati, et al. (2008), proposed new formulations for soil classification by means of linear genetic programming (LGP). It was observed that LGP models were able to predict the target values to high degree of accuracy and the equations obtained through GP models were quite short, more simple and more practical as compared with then existing models found in the literature. Johari, et al. (2006) employed GP to predict the soil water characteristic curve (SWCC) of soils. GP simulations were compared with the experimental results as well as the models proposed by other investigators. This comparison indicated superior performance of the proposed model for predicting the SWCC. Shaw, et al. (2004) has discussed some basics of genetic programming and its applications in civil engineering and structural engineering. As mentioned in introduction there are no applications of GP were found particularly in the field of Earthquake Engineering by the authors. Perhaps the present work is a first ever application of GP to predict natural periods of vibration.

### 3.1.3 Wavelet Neural Networks (WNN)

The combination of wavelet theory and neural networks has led to the development of wavelet networks. Wavelet networks have been used in classification and identification problems with some success. The strength of wavelet networks lies in their capabilities of catching essential features in "frequency-rich" signals. In wavelet networks, both the position and the dilation of the wavelets are optimized besides the weights. Wavenet is another term to describe wavelet networks. In wavenets, the position and dilation of the wavelets are fixed and the weights are optimized by the network.

Wavelet analysis is a new mathematical technique and in the recent years enormous interest in application of engineering has been observed. This new technique is particularly suitable for non-stationary processes as in contrast to the Fourier transform. The wavelet transform allows exceptional localization, both in time and frequency domains. The application of the wavelet transform to earthquake engineering is rare (Heideri and Salajegheh, 2006).

The term wavelet as it implies means a little wave. This little wave must have at least a minimum oscillation and a fast decay to zero, in both the positive and negative directions, of its amplitude(Ahamadi et al. 2008). It allows an adjustable trade-off between time and frequency resolutions in the transformed signal and provides a powerful tool for the analysis of transient and non-stationary data. It is particularly useful in picking out characteristic variations at different resolutions or scales; it is similar to Fourier transform but with more advantages. The time scale wavelet transform of a continuous time signal, x (t), is defined as

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} g^* \frac{(t-b)}{a} \, x(t)dt \qquad \text{(Mallat, 1998)} \qquad \text{Eq. (3.1)}$$

Where '*' corresponds to the complex conjugate and g(t) is called the wavelet function or mother wavelet. The parameter 'a' acts as a dilation factor, while 'b' corresponds to a temporal translation of the function g (t), which allows the study of the signal around b. The wavelet transform searches for correlations between the signal and wavelet function. This calculation is done at different scales of 'a' and locally around the time of 'b'. The wavelet decomposition consists of calculating a "resemblance index" between the signal and the Wavelet located in position 'b' and of scale 'a'. If the index is large, the resemblance is strong; otherwise, it is slight. A discretization of Eq. (3.1) based on the trapezoidal rule is perhaps the simplest discretization of the continuous wavelet transform. This transform produces $N^2$ coefficients from a data set of length N; hence, redundant information is locked up within the coefficients, which may or may not be a desirable property. To overcome this redundancy, logarithmic uniform spacing can be used for the ‘a’ scale discretization with correspondingly coarser resolution of the b locations, which allows for N transform coefficients to completely describe a signal of length N. Such a discrete wavelet function at the decomposition level of m (scale, a $=a_o^m$) can be written as

$$g_{m,n} = \frac{1}{\sqrt{{a_0}^m}} g\left(\left(\frac{t - nb_0\, {a_0}^m}{{a_0}^m}\right)\right) \qquad \text{Eq.(3.2)}$$

where m and n are integers that control the wavelet dilation and translation, respectively; $a_0$ = specified fined dilation step greater than 1;and $b_0$ = location parameter and must be greater than zero. The most common and simplest choice for parameters are $a_0 = 2$ and $b_0 = 1$. (Dixit, et al. 2015).Daubechies’ wavelets are a special class of wavelets that are good at filtering one dimension dimensional signals. An example of a typical Daubechies wavelet is shown in Figure 3.6.

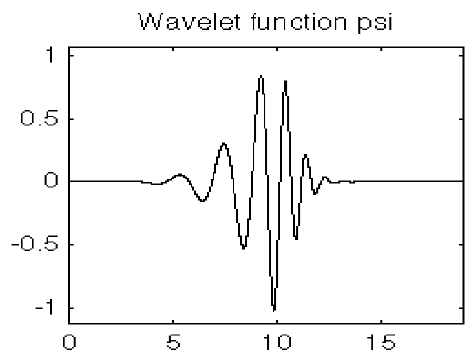


Figure 3.6A typical db10 wavelet

Inwavelet analysis, the “*APPROXIMATIONS”* are high scale, low frequency components of the signal. The “*DETAILS”* are the low scale, high frequency components of the signal. The original signal, S, passes through two complementary filters and emerges as two signals.

In the present work, the database is passed through these two filters and approximate and detail coefficients are obtained using Daubechies’ wavelet. db18 wavelet is found to be suitable to train all the models except for obtaining acceleration response spectrum coefficients. db30 wavelet is found to be suitable for obtaining the acceleration response spectrum coefficients.  A single level decomposition is carried out for the data.A separate artificial neural network model is developed each for approximate coefficients and detail coefficients. The results obtained through these developed models are assembled back to the original database using *wavelet reconstruction*.

### 3.2 Statistical Measures of Assessment of Models

The statistic measures used to assess the accuracy of the developed models are Root Mean Squared Error (RMSE), Correlation Coefficient (r) and Coefficient of Efficiency (CE). Levenberg-Marquardt algorithm is used to train the model. CE and r are the correlation measures that measure the "goodness of the fit" of modeled data with respect to the observed data. The CE statistic provides a measure of the ability of a model to predict values which are different from the mean. CE ranges from $-\infty$ at the worst case to +1 for a perfect correlation; r ranges from -1(perfect negative correlation), through 0 (no correlation), to +1 (perfect positive correlation). CE of 0.9 and above is very satisfactory, 0.8 to 0.9 represents a fairlygood model, and below 0.8 is deemed unsatisfactory. RMSE is an absolute error measure. Goodness of fit and absolute error measures is to be used in combination to assess model performance. Scatter plots also provide a useful visual aid to assess a model's accuracy (Dawson and Wilby, 2001).

# CHAPTER 4

# DYNAMIC ANALYSIS OF MOMENT RESISTING FRAMES

In this chapter, ANN, GP and WNNtechniques are used to predict the structural response of symmetric reinforced concrete frames in terms of natural periods of vibration, base shear force, base bending moment and top floor displacement. ANN, GP and WNN models are developed with input parameters chosen to represent mass, stiffness and geometry of the building. Total numbers of 206 buildings have been analyzed out of which, data set of 142 buildings has been used to train the model and that of remaining buildings has been used to test the model. Various statistic measures are used to assess performance of the developed models. Dynamic analysis has been performed using Indian Standard Code IS 1893 (Part1):2002. The basic objective of the exercise is to check adequacy of these data driven techniques in performing dynamic analysis of buildings.

## 4.1 Literature Review

Following paragraphs describe the empirical equation of period of vibration recommended by various building codes and researchers as well as the use of ANN and WNN in the dynamic analysis of buildings.

### 4.1.1 Equation of Period of Vibration

The fundamental period of vibration required for the simplified design of reinforced concrete structures has been calculated for many years using a simplified formula relating the period to the height of the building. IS 1893 (Part1): 2002 has given following equation in determining fundamental period of vibration.

$$T=0.075H^{0.75} \qquad \text{Eq. (4.1)}$$

Where T is fundamental period of vibration in seconds and H is the height of building in meter.

The particular form of Eq. (4.1) was theoretically derived by assuming that the equivalent static lateral forces are linearly distributed over the height of the building and the distribution of stiffness with height produces a uniform storey drift under the linearly distributed lateral forces. Furthermore in ATC3-06 [ATC, 1978] the base shear force was assumed to be inversely proportional to $T^{2/3}$and thus these two assumptions led to Eq. (4.1), as quoted above. The period of vibration (T) of a single degree of freedom oscillator can be obtained from Eq. (4.2) where *m* is the mass of the oscillator and *k* is the stiffness:

$T=2\pi\sqrt{\frac{m}{k}}$ Eq. (4.2)

The stiffness of the oscillator can be obtained from the base shear (*V*) divided by the lateral displacement (Δ). From the response spectrum in early design codes, the base shear for theusual range of periods of structures was taken as inversely proportional to the period to the power of two-thirds, with the coefficient of proportionality defined as $C_t$herein. If one assumes that the distribution of stiffness with height produces a uniform storey drift under the linearly distributed lateral forces, then the lateral displacement, $\Delta$ is given by the inter storey drift, ϑ, multiplied by the height, H:

$k=\frac{V}{\Delta}=\frac{C_t}{T^{2/3}\,\Delta}=\frac{C_t}{T^{2/3}\vartheta H}$ Eq.(4.3)

By replacing Eq. (4.3) in Eq. (4.2) and simplifying, the relationship shown in Eq. (4.1) between period and height can be obtained,

$T^{4/3}=C_tH$ (Pinho and Crowley, 2009) Eq.(4.4)

In ATC3-06 [ATC, 1978], the coefficient $C_t$in Eq. (4.4) was given equal to 0.060 for reinforced concrete moment resisting frames. This coefficient was identified from a study by Gates and Foth (1978), based on the measured periods of vibration of reinforced concrete frames during the 1971 San Fernando earthquake. A subsequent re-evaluation by SEAOC-88 [SEAOC, 1988] found that a value of $C_t$=0.075 was more appropriate for reinforced concrete buildings (Pinho and Crowley, 2009). For a lower bound estimate of the period, Berteroet al. (1988), recommend the use of $C_t$ = 0.085. The use of the form of period-height equation shown in Eq. (4.1), along with the SEAOC-88recommended 0.075 coefficient, has been adopted in many design codes since 1978, forexample in UBC-97 (UBC, 1997), in SEAOC-96 (SEAOC, 1996) , in NEHRP-94 (FEMA,1994) and in Eurocode 8 (CEN 1994; 2004) (Pinho and Crowley, (2009)). Goel and Chopra (1997), performed analysis on buildings that were strongly shaken but did not reach the yield point. The authors found that the lower bound of measured period was about 1.2 times the code value. Therefore it was suggested to use a coefficient of 0.086 instead of 0.075.They proposed an equation that provided the best fit to the available data. The proposed equation is given below:

$T= 0.0466\ H^{0.9}$ Eq. (4.5)

Where, T is period of vibration in seconds and H is the height of building in meters. Based on the linear regression, it was proposed that the period from the rational analysis should not exceed a value of 1.4 times the period calculated from the Eq. (4.5). Figure 4.1 shows the comparison between the measured period values and period values obtained from Eq. (4.5). A similar study was carried out by Hong e Hwang (2000) for 21 RC seismic buildings inTaiwan subjected to 4 events claimed to not yield the structures. The coefficients proposed inthat study lead to the following expression:

$T = 0.029H^{0.804}$ Eq. (4.6)

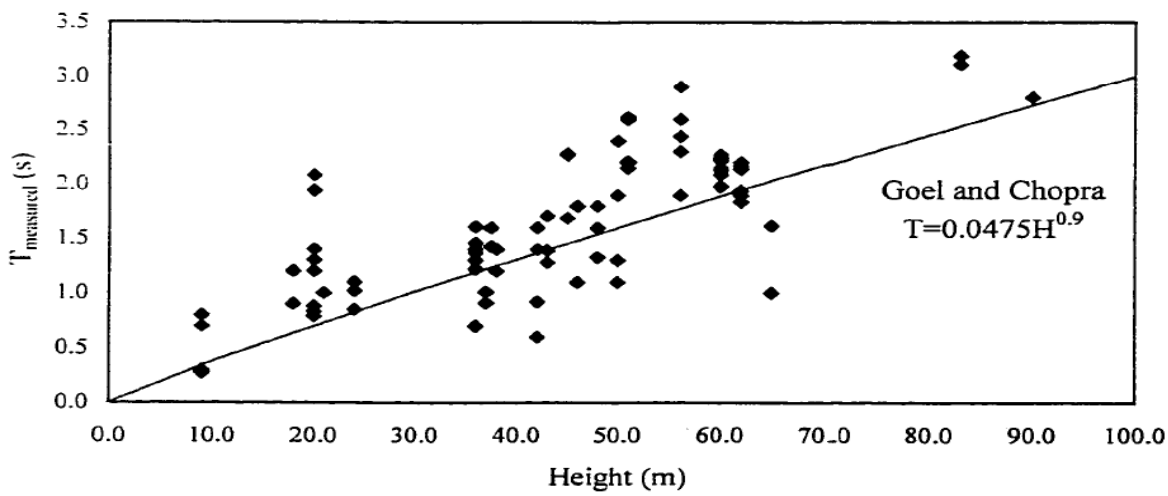


Figure 4.1 Comparison of measured periods and the periods obtained from Eq. (4.5) (Morales, 2000)

Crowley and Pinho (2004), proposed a period-height formula from theresults of eigenvalue, push-over and nonlinear dynamic analyses carried out on 17 RC framesrepresentative of the European building stock.Avery simple relationshipwas obtainedwhichwas valid for RC buildings without masonry infill:

$T = 0.1\ H$ Eq.(4.7)where

*T* is fundamental period of vibration in seconds and *H* is the height of building in meters.Crowley and Pinho (2006) calculated elastic and yield period values of existing European RCbuildings of varying height using eigenvalue analysis. Such studies led to asimplified period-height (T-H) expression for use in the assessment of existing RC buildings wherethe presence of masonry infills was also taken into account:

$T = 0.055\ H$. Eq. (4.8)

Guler, et al. (2008) computed the fundamental periods of some RC buildings, considering theeffects of infill walls, using ambient vibration tests and elastic numericalanalyses. A period-height (T - H) relationship relevant to Turkish RC moment-resisting frames wasderived for a fully elastic condition:

$T = 0.026\ H^{0.90}$. Eq. (4.9)

Furthermore, results showed that a75% increased value of the elastic period could be used to estimate period elongation duringmoderate intensity earthquakes.

NZSEE recommended the period height relationship in a modified form of Eq. (4.1) as follows:

$T=0.094H^{0.75}$ Eq. (4.10)

Masi and Vona(2008), recommended period-height relationships for bare frames considering uncracked ($T_e$) and cracked ($T_y$) concrete sections in frame elements. These formulae have the following form:

$T_e=0.085H$ Eq. (4.11)

$T_y=0.110H$ Eq. (4.12)

Applying nonlinear regression analysis for the experimental results provided by Saatcioglu and Humar(2003), a new period-height relationship has been obtained with the form:

$T=0.125H^{0.684}$ Eq. (4.13)

Kwon and Kim (2010) have also verified and recommended Eq. (4.5) based on the dataset of 58 RC M.R.F. buildings.Gallipoli, et al. (2008) showed that ambient vibration data for RC buildings provides very similar results in different countries. The fundamental period-height formula for all the considered buildings is provided in the form:

$T = 0.016\ H$ Eq. (4.14)

Hamdy and Majed (2013), has proposed following simple period (T)- height (H) relation from eigen value analysis results by applying regression analysis:

$T=0.068H$ Eq. (4.15)

Verderame, et al. (2010), determined relationships of elastic period of sub-standard reinforced concrete moment resisting frame buildings for the three populations (with seismic coefficient 0.05g, 0.07g and 0.1g.) of seismic building.The authors have analyzed 700 structures to investigate the elastic period in two principal directions of the building. The variation in the length and width of the buildings is considered between 15 m to 30 m and 8 m to 12 m respectively. The height of the building is considered between 6 m to 24 m. The result of the study has suggested that height of the building seem inadequate to predict period variability and a global parameter such as plan area should be added in simplified relationship for rapid period evaluation.The proposed equations for period of vibration along transverse direction ($T_{et}$) and along longitudinal direction ($T_{el}$) in terms of height of the building (H) and Plan area of the building (S) are shown below:

Design acceleration 0.05g

$T_{et}=0.029H^{0.79} S^{0.21}$ $\quad\quad$ $T_{el}= 0.059H^{0.69}S^{0.14}$ $\quad\quad$ Eq. (4.16)

Design acceleration 0.07g

$T_{et}=0.033H^{0.75}S^{0.20}$ $\quad\quad$ $T_{el}= 0.062H^{0.66}S^{0.12}$ $\quad\quad$ Eq. (4.17)

Design acceleration 0.1g

$T_{et}=0.039H^{0.70}S^{0.19}$ $\quad\quad$ $T_{el}= 0.068H^{0.65}S^{0.10}$ $\quad\quad$ Eq. (4.18)

Hatzigeorgiou and Kanapitsas(2013) have proposed the following equation considering presence of infill panels and concrete shear walls, flexibility of soil, height of the building and dimension of the building along the seismic direction:

$T= H^{0.745}L^{0.24}(0.073-0.021W) / (1-e-^{0.706KS0.6}) (1+0.043\rho)^{1/2}$ $\quad\quad$ Eq. (4.19)

Table 4.1 shows the empirical equations suggested by different codes:

Table 4.1 Empirical equation of period of vibration by building codes

| Source of Equation | Reinforced concrete M.R.F. buildings |
|---|---|
| IS 1893 (Part1):2002 | $T = 0.075H^{0.75}$ |
| UBC 88,94,97 and Euro code 8 | $T = 0.075H^{0.75}$ |
| ASCE 7-05 (2005) | $T = 0.0466H^{0.90}$ |
| NZSEE (2006) | $T = 0.094H^{0.75}$ |
| ATC 3-06 | $T = 0.0609H^{0.75}$ |

### 4.1.2 Application of ANN and WNN in Dynamic Analysis

In recent years, ANN was successfully applied in many structural engineering applications including seismic analysis (Adeli and Hojjat 2001). Ghaboussi and Lin (1998), proposed a method based on neural networks for generating artificial earthquake accelerograms. Lee and Han (2002), developed five artificial neural network-based models for the generation of artificial earthquake and response spectra. Caglar,et al. (2008), proposed two ANN models to estimate the fundamental period of vibration, base shear forces, base bending moments and top floor displacement. In all eleven Input parameters were chosen for developing the models which were easy to obtain from the drawings except Moment of Inertia values. Chakraverty,et al. (2006) developed ANN based models to compute response of structural system subject to Indian Earthquakes for Chamoli and Uttarkashi ground motion data. Ahmadi,et al. (2008) employed Generalized Regression (GR) Neural Network and Back Propagation wavelet Neural Network (BPW) for approximating the dynamic time history responses of eight storey steel frame structure. Results of BPW were compared with those of GR which indicated that the accuracy of BPW was better than that of GR. Kamyab and Gholizadeh (2008) introduced a parallel wavelet back propagation neural network model. Heidari,et al. (2006) used Fast Wavelet Transform (FWT) and Discrete Wavelet Neural Network (DWN) to approximate the dynamic responses of the structures. The numerical results showed that the time of dynamic analyses is reduced to about 0.1 of the time required for the time history dynamic analysis using the original earthquake. Arslan (2009)developed ANN based models for estimating the failure load and failure displacement of R.C. structures. Seven input parameters were chosen to predict the failure load and failure displacement. It has been demonstrated that all these input parameters directly affected the seismic performance of the building. Alireza and Kimia (2012)investigated the adequacy of Artificial Neural Networks to determine the three dimensional dynamic response of FRP strengthened RC buildings under the near-fault ground motions. For this purpose, one ANN model was proposed to estimate the base shear force, base bending moments and roof displacement of buildings in two directions. It was demonstrated that the neural network based approach is highly successful in determining the response. Joghataie and Farrokh (2008) developed a new type of activation function based on the use of the Prandtl–Ishlinskii operator and used in the feed forward neural networks in order to improve capabilities in learning to identify and analyze nonlinear structures subject to dynamic loading. Lagaros and Papadrakakis (2012) proposed a new adaptive scheme in order to predict the structural non-linear behavior when earthquake actions of increased severity are considered. The predicted structural response by ANNs can be used in the performance based design framework when dynamic analyses are performed, aiming at reducing the excessive computational cost.

The literature review cited above reveals that ANN and WNN have been applied for the dynamic analysis of buildings. The present study mainly focuses on obtaining empirical equation for period of vibration and maximum lateral displacement of the buildings.

**4.2 Geometry and Material Properties**

A typical floor plan of symmetric building is taken in the present study. The dataset of 206 buildings is generated by varying the dimensions of the buildings. Length of the building is varied from 9.75 m to 36 m whereas width of the building is varied from 8 m to 32 m. Height of the building is assumed between 12 m to 52.5 m with height of the storey as either 3 m or 3.5 m. ANN, GP and WNN techniques are then employed to estimate the structural response in terms of period of vibration, base shear force and top floor displacement. The details are covered in subsequent articles. These models are developed under different categories so as to check adequacy of the technique for performing dynamic analysis of building frames.

The buildings are assumed to be fixed at the base without soil structure interaction and the floors as rigid diaphragm. The sections of the structural elements are rectangular and square for the beams as well as the columns. The thickness of slab is 150 mm and the height of the floor as 3m or 3.5m. The beam sections are considered in the size range of 230 mm x 450 mm to 450 mm x 750 mm. The column sections for square shapes are assumed in the size range of 300 mm x 300 mm to 750 mm x 750 mm and that for rectangular shapes are considered in the range of 230 mm x 300 mm to 230 mm x 600 mm. The modulus of elasticity is considered as 5000 $\sqrt{f_{ck}}$where $f_{ck}$ is the characteristics compressive strength of concrete and the mass density as 25 $KN/m^3$. Three grades of concrete assumed in the analysis are M20, M25 and M30. Live load intensity is considered as either 2 $KN/m^2$ or $3KN/m^2$. A typical floor plan of building is shown in Figure4.2

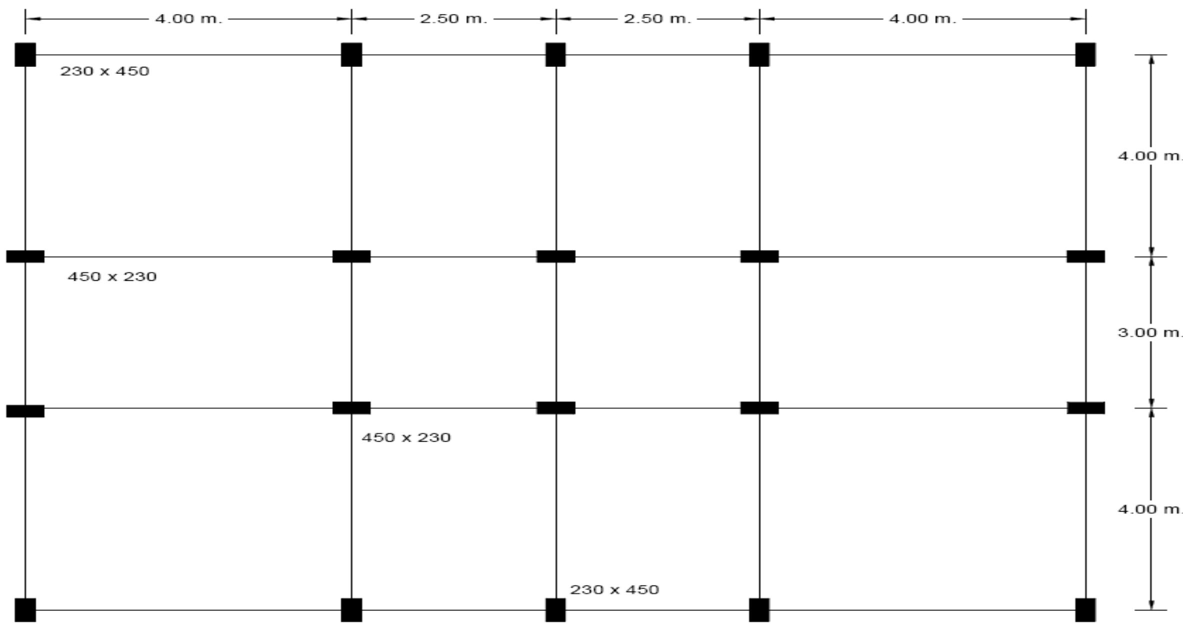


Figure 4.2 Typical Floor Plan of the Building

### 4.3 Generation of data

Total numbers of 206 buildings with height range between 4 storeys to 15 storeys are analyzed for natural periods of vibration along X as well as Y directions. The structures are assumed to be located in the seismic zone number III on the medium soil. Importance Factor (I) as 1 and Response Reduction factor (R) as 5 are considered for all buildings. Base shear force and top floor displacement are also obtained through this analysis. Author has developed MATLAB codes to perform the analysis. Effect of first three modes is considered for the dynamic analysis. The data so derived in presented in Appendix A. As the objective of the exercise is to check the adequacy of these tools for performing dynamic analysis, it is thought that sufficiently large data set may be used to develop the models. As a trial, data set of 206 buildings is generated to develop the models.

### 4.4 Application of ANN in Dynamic Analysis

#### 4.4.1 Methodology

Out of the data for 206 buildings, the data set of 142 buildings is used to train the model and that of remaining 64 buildings is used to test the model. This division of the data is arrived at after the several trials. In order to avoid over fitting of the data, validation check is applied. So the division of the data is approximately 70 % for training, approximately 15% for validation and remaining about 15% for testing the model. The statistical measures used to assess the accuracy of the developed models are Root Mean Squared Error (RMSE), Correlation Coefficient (r) and Coefficient of Efficiency (CE). Levenberg-Marquardt algorithm is used to train the model. The training algorithms are classified as local methods and global methods. Further the local schemes could be first or second order. First order local methods are based on the method of steepest gradient descent, in which the weight change is made proportional to the negative derivation of error function. This involves the standard backpropagation. In another scheme based on search technique called conjugate gradient, a search is performed along conjugate (orthogonal) directions, which produces generally faster convergence than the steepest descent directions.Second order local methods are based on Newton's methods which require computation of inverse of Hessian matrix restricting its applications to networks with a limited number of weights ( <100), ( Maier and Dandy, 2000). Though their convergence rate is faster as compared to the first order methods, they can stuck up in local minima as well as the algorithm may move uphill as inverse of Hessian matrix is not guaranteed to be positive definite. Levenberg- Marquardt modification of Newton's method guarantees that the Hessian is positive definite.

### 4.4.2 Model formulation

In the present study, ANN models are developed under three categories, namely category A, category B and category C as shown in Table 4.2. Each category mentioned here consists of four subcategories as mentioned in Table 4.3. The basic aim of arriving at the optimum ANN architecture is to decide the significant parameters of the building required for dynamic analysis of the buildings. Category A comprises all ANN models developed with 9 input parameters. These input parameters are chosen considering the effect of geometry, mass distribution and the stiffnesscharacteristics of the building frames in the dynamic analysis. Effect of geometry is incorporated in terms of L, W and H whereas the effect of the mass of the building is incorporated in terms of $N_c$, $N_B$, $W_{cmin}$, $W_{cmax}$, $D_{cmin}$, $D_{cmax}$ and n. The stiffness characteristic of the building frames is assumed in terms of $W_{cmin}$, $W_{cmax}$, $D_{cmin}$, $D_{cmax}$ and h.

Table 4.2 Details of categories of ANN models

| Category of ANN model | Number of input parameters | Sub- categories |
|---|---|---|
| A | 9 | 4 |
| B | 8 | 4 |
| C | 5 | 4 |

Table 4.3 Output Parameters of subcategories of ANN models

| Model | Direction of Analysis | Output parameters | | |
|---|---|---|---|---|
| | | Output 1 | Output 2 | Output 3 |
| ANN 1 | X | Natural Period of Vibration for first mode ($T_1$) | Natural Period of Vibration for second mode ($T_2$) | Natural Period of Vibration for third mode ($T_3$) |
| ANN 2 | Y | Natural Period of Vibration for first mode in seconds($T_1$) | Natural Period of Vibration for second mode in seconds ($T_2$) | Natural Period of Vibration for third mode in seconds ($T_3$) |
| ANN 3-1 | X | Base shear force in KN | ------ | ------ |
| ANN 3-2 | Y | Base shear force in KN | ------ | ------ |
| ANN 4-1 | X | Top floor displacement in mm | ------- | ------- |
| ANN 4-2 | Y | Top floor displacement in mm | ------ | ------ |

Category B comprises ofANN models developed with eight input parameters. The perimeter of the building (P) is introduced as a substitute for two input parameters viz. Length and Width of building. New set of ANN models are developed using eight input parameters instead of nine.

Category C comprisesof ANN models developed with five input parameters with an aim to minimize the number of input parameters to avoid duplication of information to the model. Perimeter (P) and height of the building (H) can represent the geometry to the model, sizes of the columns and height of the storey ($W_{cmin}$, $W_{cmax}$, $D_{cmin}$, $D_{cmax}$ and h) can be referred for the stiffness calculations and the effect of the other input parameters like number of beams and columns per floor and number of floors ($N_c$, $N_B$ and n) may be taken indirectly into account through the perimeter of the building, height of the building and other input parameters chosen. So five input parameters becomes: Perimeter of the building (P), Minimum Width of the Column ($W_{cmin}$), maximum width of Column ($W_{cmax}$), Height of the building (H) and Height of the storey (h) along X direction and Perimeter of the building (P), Minimum depth of the column ($D_{cmin}$), and maximum depth of column ($D_{cmax}$), Height of the building (H) and height of the storey (h) along Y direction.

All these input parameters are easy to obtain from the structural and architectural drawings. Table 4.4 and 4.5 given below shows the input parameters used along X and Y directions respectively for category A models.

Table 4.4 Input parameters for X direction

| Sr. No. | Parameter | Notation Used |
|---|---|---|
| 1 | Length of building | L |
| 2 | Width of Building | W |
| 3 | Number of Columns per floor | $N_c$ |
| 4 | Number of Beams per floor | $N_B$ |
| 5 | Minimum dimension of column along X direction | $W_{cmin}$ |
| 6 | Maximum dimension of column along X direction | $W_{cmax}$ |
| 7 | Height of the Building | H |
| 8 | Height of the storey | H |
| 9 | Number of Floors | N |

The mechanics behind choosing the input parameters is explained earlier paragraph.

Table 4.5 Input parameters for Y direction

| Sr. No. | Parameter | Notation Used |
|---|---|---|
| 1 | Length of building | L |
| 2 | Width of Building | W |
| 3 | Number of Columns per floor | Nc |
| 4 | Number of Beams per floor | NB |
| 5 | Minimum dimension of column along Y direction | $D_{cmin}$ |
| 6 | Maximum dimension of column along Y direction | $D_{cmax}$ |
| 7 | Height of the Building | H |
| 8 | Height of the storey | H |
| 9 | Number of Floors | N |

### 4.4.3 Results and Discussions

Results of developed ANN models are presented in subsequent paragraphs. All models were tested with trained weights and biases and results of testing are presented here only. The accuracy is judged by calculating 'r', 'rmse' and 'CE' between the analytical and predicted values as mentioned earlier. Architecture of ANN model describes number of neurons in input layer, hidden layer and output layer sequentially. Epochs is number of iterations at the end of which error between predicted and target values are reduced as low as possible.

#### 4.4.3.1 Results of Category A models

ANN models are developed and the results are shown in table 4.6 and table 4.7.

Table 4.6 Results of ANN model (Category A)

| Model | Architecture | Performance Parameters | $T_1$ | $T_2$ | $T_3$ | Epochs |
|---|---|---|---|---|---|---|
| ANN1 | 9:9:3 | R | 0.97 | 0.97 | 0.97 | 12 |
| | | RMSE | 0.100 | 0.039 | 0.022 | |
| | | CE | 0.92 | 0.93 | 0.92 | |
| ANN2 | 9:8:3 | R | 0.98 | 0.98 | 0.98 | 21 |
| | | RMSE | 0.056 | 0.016 | 0.0088 | |
| | | CE | 0.95 | 0.96 | 0.98 | |

Table 4.7: Results of ANN Models (Category A)

| Model | Architecture | Performance Parameters | Base Shear | Epochs |
|---|---|---|---|---|
| ANN3-1 | 9:30:1 | r | 0.99 | 43 |
| | | RMSE | 107.21 | |
| | | CE | 0.975 | |
| ANN3-2 | 9:25:1 | r | 0.98 | 25 |
| | | RMSE | 150.24 | |
| | | CE | 0.953 | |
| Model | Architecture | Performance Parameters | Top Floor Displacement | Epochs |
| ANN4-1 | 9:12:1 | r | 0.967 | 42 |
| | | RMSE | 0.000367 | |
| | | CE | 0.94 | |
| ANN4-2 | 9:25:1 | r | 0.987 | 33 |
| | | RMSE | 0.00516 | |
| | | CE | 0.964 | |

Table Nos. 4.6 and 4.7 shows that ‘r’ values are more than 0.95 and ‘CE’ values are more than 0.9. These indicate that the models are performing fairly well. The hidden neurons for ANN 3-1 model are 30. As per some guidelines number of weights should not exceed number of training samples. However large number of neurons may be attributed to the highly non linear problem. They give high degrees of freedom to the model. In absence of any formal rules for design of ANN, such training should be accepted.

#### 4.4.3.2 Results of Category B models

The results of these models are shown in Table 4.8 and Table 4.9. Also are shown the scatter plots of first output parameter of each ANN model of category B in Figure nos. 4.3, 4.4, 4.5 and 4.6.

Table 4.8: Results of ANN Models (Category B)

| Model | Architecture | Performance Parameters | $T_1$ | $T_2$ | $T_3$ | Epochs |
|---|---|---|---|---|---|---|
| ANN1 | 8:8:3 | r | 0.97 | 0.97 | 0.97 | 12 |
| | | RMSE | 0.099 | 0.033 | 0.0022 | |
| | | CE | 0.93 | 0.93 | 0.92 | |
| ANN2 | 8:5:3 | r | 0.98 | 0.98 | 0.98 | 20 |
| | | RMSE | 0.059 | 0.017 | 0.010 | |
| | | CE | 0.95 | 0.96 | 0.97 | |

Table 4.9 Results of ANN Models (Category B)

| Model | Architecture | Performance Parameters | Base Shear | Epochs |
|---|---|---|---|---|
| ANN3-1 | 8:30:1 | r | 0.98 | 14 |
| | | RMSE | 106.53 | |
| | | CE | 0.975 | |
| ANN3-2 | 8:40:1 | r | 0.98 | 62 |
| | | RMSE | 136.60 | |
| | | CE | 0.961 | |
| Model | Architecture | Performance Parameters | Top Floor Displacement | Epochs |
| ANN4-1 | 8:27:1 | r | 0.96 | 24 |
| | | RMSE | 0.000458 | |
| | | CE | 0.90 | |
| ANN4-2 | 8:22:1 | r | 0.98 | 31 |
| | | RMSE | 0.000518 | |
| | | CE | 0.964 | |

Table Nos.4.8 and 4.9also shows that ‘r’ values are more than 0.95 and ‘CE’ values are more than 0.9.

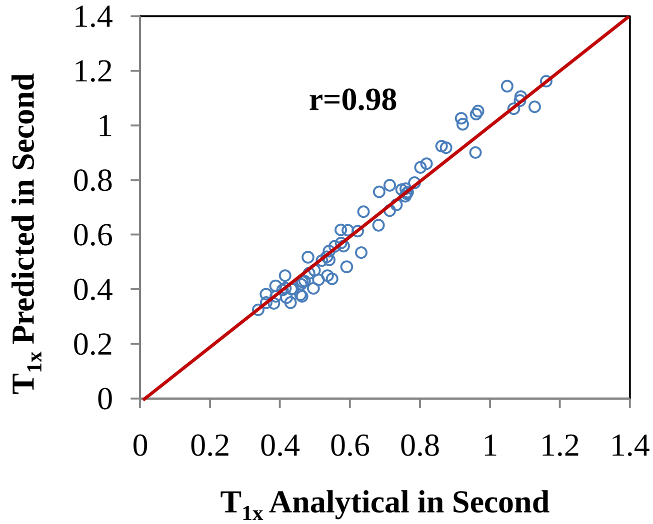


Figure4.3 Scatter plot of fundamental period of vibration along X direction. (ANN1 Model)

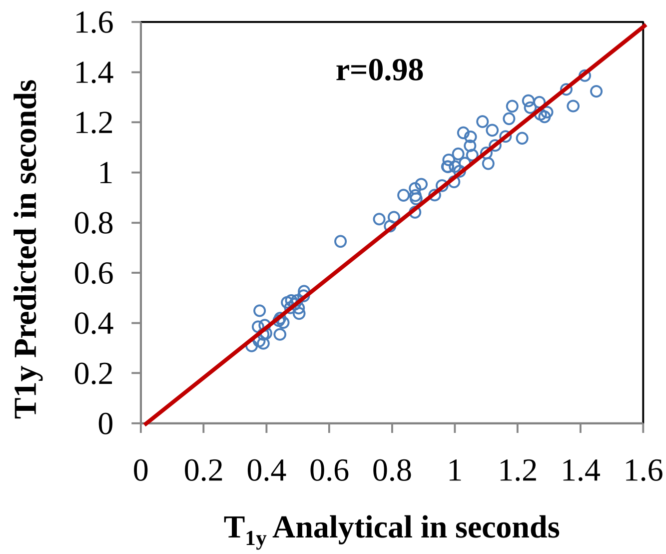


Figure 4.4 Scatter plot of fundamental period of vibration along Y direction (ANN2 Model)

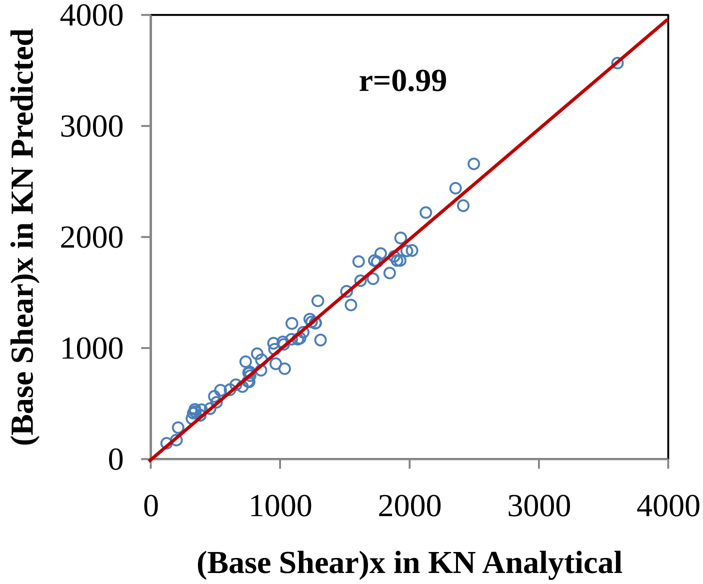


Figure 4.5 Scatter plot of Base Shear Force along X direction (ANN3 Model)

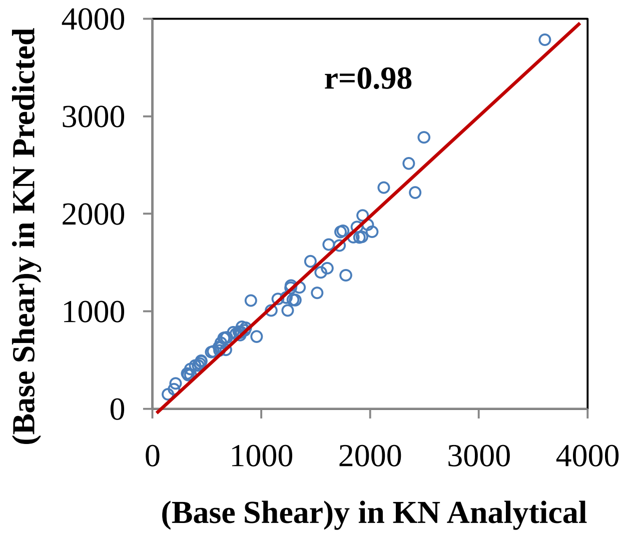


Figure 4.6 Scatter plot of Base Shear Force along Y direction (ANN3 Model)

The above scatter plots show that all the predicted values are close to the analytical values and a balance scatter is given by the ANN models.

**4.4.3.3 Results of Category C models**

The results of these models are shown in Table 4.10 and Table 4.11.

Table 4.10 Results of ANN Models (Category C)

| Model | Architecture | Performance Parameters | $T_1$ | $T_2$ | $T_3$ | Epochs |
|---|---|---|---|---|---|---|
| ANN1 | 5:4:3 | r | 0.96 | 0.96 | 0.97 | 19 |
| | | RMSE | 0.105 | 0.0354 | 0.0218 | |
| | | CE | 0.90 | 0.91 | 0.93 | |
| ANN2 | 5:6:3 | r | 0.97 | 0.97 | 0.98 | 23 |
| | | RMSE | 0.061 | 0.019 | 0.012 | |
| | | CE | 0.94 | 0.95 | 0.96 | |

Table 4.11 Results of ANN Models (Category C)

| Model | Architecture | Performance Parameters | Base Shear | Epochs |
|---|---|---|---|---|
| ANN3-1 | 5:12:1 | r | 0.97 | 39 |
| | | RMSE | 177.288 | |
| | | CE | 0.930 | |
| ANN3-2 | 5:30:1 | r | 0.98 | 21 |
| | | RMSE | 133 | |
| | | CE | 0.963 | |
| Model | Architecture | Performance Parameters | Top Floor Displacement | Epochs |
| ANN4-1 | 5:3:1 | r | 0.95 | 11 |
| | | RMSE | 0.000508 | |
| | | CE | 0.885 | |
| ANN4-2 | 5:4:1 | r | 0.98 | 25 |
| | | RMSE | 0.000582 | |
| | | CE | 0.955 | |

Here also Table 4.10 and 4.11 shows that ANN models performs well as it is seen from ‘r’ and ‘CE’ values.

**4.4.3.4 Hinton Diagram and its significance in the study**

The concept of Hinton diagram is used to understand the influence of each input over the output parameter. The Hinton diagram provides a qualitative display of the values in a data matrix (normally a weight matrix). Each value is represented by a square whose size is associated with the magnitude and whose color indicates the sign. Hinton Diagram used here represent weight matrix between the Input layer and Hidden layer of ANN model graphically.

A typical Hinton Diagram is shown in Figure 4.7 for ANN 2 model developed under category B. The Hinton Diagram for ANN1and ANN2 models in category A and Category B has shown more influence from $N_c$, $N_B$and $W_{cmin}$, $W_{cmax}$(along X direction) or $D_{cmin}$, $D_{cmax}$ (along Y direction) and n. Hinton Diagram thus indirectly shows the influence of mass and stiffness over the natural periods of vibrations.

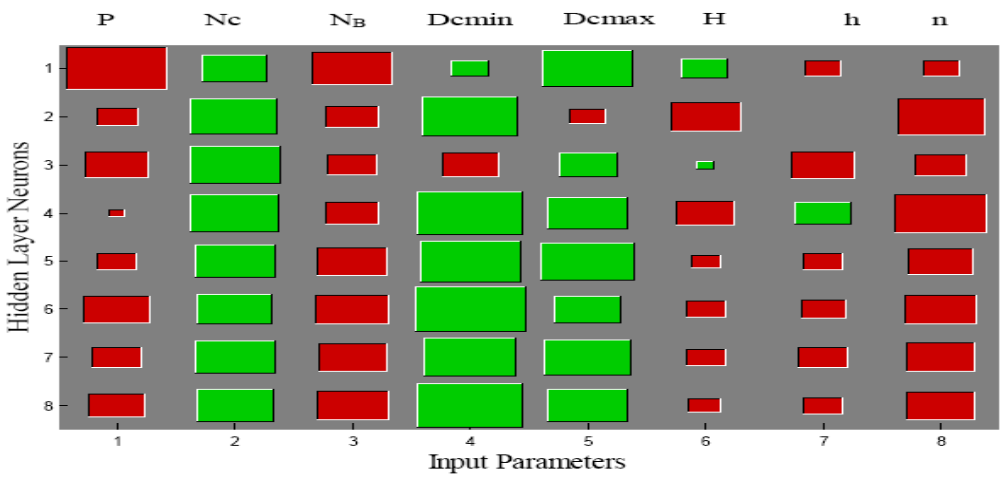


Figure 4.7 Hinton Diagram of ANN 2 model (category B)

Figure 4.8 shows the Hinton Diagram for ANN 2 model developed under category C. In case of ANN1 and ANN2 models developed under category C, the influence of $W_{cmin}$, $W_{cmax}$(along X direction) or $D_{cmin}$, $D_{cmax}$ (along Y direction) and H is seen in the Hinton Diagram. Here also the effect of stiffness of the building is well understood by the model indirectly through $D_{cmin}$ and $D_{cmax}$ and h.

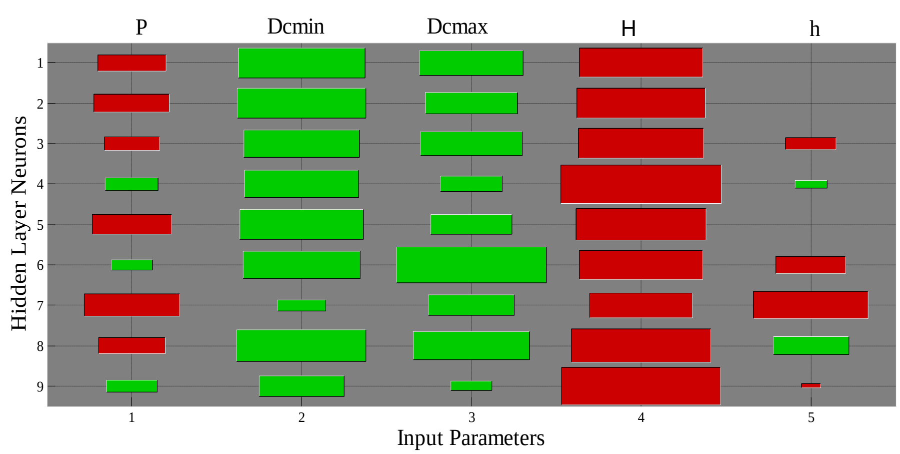


Figure4.8 Hinton Diagram of ANN 2 model (category C)

It is evident from Figure 4.7 that the input parameters $D_{cmin}$, $D_{cmax}$ and $N_c$ have opposite influence ( as seen by different colors) on the values of T when compared with the influence of other input parameters like perimeter (P), height of the building (H), height of storey (h), and number of floors (n). This may be explained from the equation of T as discussed below.

From the theory of structural dynamics, for single degree of freedom systems fundamental period of vibration (T) is found out as,

$T = 2\pi\,(m/k)^{1/2}$ Eq. (4.20)

$k = N_c\,(12\,E\,I / h^3)$ Eq. (4.21)

$k = N_c\,[12\,E\,(w\,D^3/12) / h^3]$ Eq. (4.22)

where w= width of column, D is the depth of column, E is Modulus of Elasticity, I is moment of Inertia, $N_c$is number of columns and h is height of storey.

$T = 2\pi\,(mh^3/N_c\,E\,wD^3)^{1/2}$ Eq. (4.23)

Further mass (m) of the system may be found out using perimeter (P) and height of the building (H). This influence can be seen in the Hinton diagram shown in Figure no. 4.7 and Figure no. 4.8. It indicates that ANN assigns weight values to every input parameter considering its positive or negative influence on the output parameters. This article has shown that ANN technique understand the theory of structural dynamics reasonably well and may be used to derive the empirical equation of fundamental period of vibration ($T_1$) as discussed in the next article.

**4.4.3.5 Comparison of ANN results with the other equations**

Thedeveloped models are used to obtain the relationship between the height of the building and fundamental period of vibration along X and Y directions. Table 4.12 shows the comparison of the equations suggested by different researchers or building code and those obtained through developed ANN models. The empirical equations are derived from the developed models under category B. These equations are obtained for the buildings up to 40 m in height. While developing these equations, the form of the equation suggested by codes or researchers is kept intact. The regression was fitted to the values of ANN models obtained in testing. Though it will reduce the accuracy owing to inherent limitation of regression. Still it gives some idea.

Table 4.12 Comparison of ANN equations and other recommended equations

| Source of the equation | Suggested Equation | ANN equation along X direction | ANN equation along Y direction |
|---|---|---|---|
| IS 1893(Part1): 2002 | $T= 0.075\ H^{0.75}$ | $T= 0.0703\ H^{0.75}$ | $T= 0.0811\ H^{0.75}$ |
| Goel and Chopra (1997) | | $T=0.0457\ H^{0.9}$ | $T=0.053\ H^{0.9}$ |
| Lower bound | $T= 0.0466\ H^{0.9}$ | | |
| Best Fit | $T= 0.052\ H^{0.9}$ | | |

| | | | |
|---|---|---|---|
| Upper bound | T= 0.065 $H^{0.9}$ | | |
| Crowley and Pinho (2006) | | | |
| Bare Frames | T= 0.054 H | | |
| In filled frames with openings | T= 0.034 H | T=0.0344 H | T=0.040 H |
| Fully infilled frames | T= 0.025 H | | |

Table 4.12 shows that the equations derived from ANN technique along X direction are close to the recommended equations by IS 1893 (Part1): 2002, lower bound of Goel and Chopra (1997) and in filled frames with openings by Crowley and Pinho (2006). ANN equation along Y direction is close to the equation recommended as best fit by Goel and Chopra (1997).

The equation of $T_1$ along X and Y directions are obtained as below for the buildings up to the height 20 m.

$T_{1X}$=0.127 $H^{0.75}$ Eq.(4.24)

$T_{1Y}$=0.143 $H^{0.75}$ Eq.(4.25)

### 4.5 Application of GP in Dynamic Analysis

#### 4.5.1 Methodology

The data division and model assessment is same as that for ANN models. The only difference is one more category of models is developed using seismic weight, stiffness of the floor directly as an inputs. A tree based GP has been employed to develop these models using GPKernel Software developed by Babovic and Keijzer (2000).

#### 4.5.2 Model Formulation

In the present study, Genetic Programming models are developed under four categories i.e. GP A, GP B, GP C and GP D. Each of these categories comprises of four subcategories as GP1, GP2, GP3 and GP4. GP1 category models estimates the natural period of vibrations for first three modes along X direction. GP2 category models estimates the natural period of vibrations for first three modes along Y direction. GP3 category models estimates base shear force along X and Y direction. GP4 category models estimates top floor displacement along X and Y direction.

Like ANN models, Category A, Category B and Category C models are developed using nine, eight and five input parameters respectively. Category D comprises all GP models developed with six input parameters. An attempt is made to develop GP models using six input parameters viz. seismic weight of the building (m), stiffness of the building per floor (K) , number of floors (n), length (L), width (W) and height (H) of the building. Geometry of the building is given in terms of the length, width and height of the building.

### 4.5.3 Results and Discussions

As per the discussions in previous paragraphs, four categories of GP models are developed and comparison of the results is discussed here in this article.

#### 4.5.3.1 Results of Category A model

The results are shown in Table 4.13 and Table 4.14.

Table 4.13 Results of GP Models (Category A)

| Model | Performance Parameters | $T_1$ | $T_2$ | $T_3$ |
|---|---|---|---|---|
| GP1 | r | 0.97 | 0.97 | 0.97 |
| | RMSE | 0.059 | 0.022 | 0.013 |
| | CE | 0.93 | 0.93 | 0.94 |
| GP2 | r | 0.98 | 0.97 | 0.98 |
| | RMSE | 0.075 | 0.029 | 0.013 |
| | CE | 0.95 | 0.94 | 0.97 |

Table 4.14 Results of GP model (Category A)

| Model | Performance Parameters | Base Shear |
|---|---|---|
| GP3-1 | r | 0.99 |
| | RMSE | 102.137 |
| | CE | 0.98 |
| GP3-2 | r | 0.98 |
| | RMSE | 129.69 |
| | CE | 0.97 |
| Model | Performance Parameters | Top Floor Displacement |
| GP4-1 | r | 0.96 |
| | RMSE | 0.00058 |
| | CE | 0.85 |
| GP4-2 | r | 0.96 |
| | RMSE | 0.00669 |
| | CE | 0.80 |

Here also the 'r' and 'CE' values are more than 0.9 and 0.8 respectively and hence GP models are also performing fairly well. Although drop in 'CE' values are observed than those for ANN models.

#### 4.5.3.2 Results of Category B model

The results of these models are shown in Tables 3.15 and Table 3.16.

Table 4.15 Results of GP Models (Category B)

| Model | Performance Parameters | $T_1$ | $T_2$ | $T_3$ |
|---|---|---|---|---|
| GP1 | r | 0.96 | 0.97 | 0.97 |
| | RMSE | 0.064 | 0.024 | 0.014 |
| | CE | 0.91 | 0.90 | 0.93 |
| GP2 | r | 0.97 | 0.97 | 0.97 |
| | RMSE | 0.079 | 0.028 | 0.026 |
| | CE | 0.94 | 0.94 | 0.88 |

Table 4.16 Results of GP Models (Category B)

| Model | Performance Parameters | Base Shear |
|---|---|---|
| GP3-1 | r | 0.99 |
| | RMSE | 104.74 |
| | CE | 0.976 |
| GP3-2 | r | 0.98 |
| | RMSE | 145.64 |
| | CE | 0.955 |
| Model | Performance Parameters | Top Floor Displacement |
| GP4-1 | r | 0.96 |
| | RMSE | 0.000669 |
| | CE | 0.85 |
| GP4-2 | r | 0.98 |
| | RMSE | 0.000564 |
| | CE | 0.958 |

Tables 4.15 and 4.16 showsfailrly good GP models. ‘r’ and ‘CE’ values are more than 0.9 and 0.85 respectively.

#### 4.5.3.3 Results of Category C model

The results of these models are shown in Table 4.17 and Table 4.18.

Table 4.17 Results of GP Models (Category C)

| Model | Performance Parameters | $T_1$ | $T_2$ | $T_3$ |
|---|---|---|---|---|
| GP1 | r | 0.96 | 0.97 | 0.97 |
| | RMSE | 0.065 | 0.023 | 0.014 |
| | CE | 0.91 | 0.91 | 0.93 |
| GP2 | r | 0.97 | 0.97 | 0.96 |
| | RMSE | 0.072 | 0.028 | 0.021 |
| | CE | 0.94 | 0.94 | 0.91 |

Table 4.18Results of GP Models (Category C)

| Model | Performance Parameters | Base Shear |
|---|---|---|
| GP3-1 | r | 0.98 |
| | RMSE | 132.37 |
| | CE | 0.96 |
| GP3-2 | r | 0.98 |
| | RMSE | 138.056 |
| | CE | 0.96 |
| Model | Performance Parameters | Top Floor Displacement |
| GP4-1 | r | 0.95 |
| | RMSE | 0.000528 |
| | CE | 0.88 |
| GP4-2 | r | 0.98 |
| | RMSE | 0.000573 |
| | CE | 0.96 |

Table Nos. 4.17 and 4.18 also shows fairly good performance of GP models.

**4.5.3.4 Results of Category D model**

The results of these models are given in Table 4.19 and 4.20.

Table 4.19 Results of GP Models (Category D)

| Model | Performance Parameters | $T_1$ | $T_2$ | $T_3$ |
|---|---|---|---|---|
| GP1 | r | 0.99 | 0.99 | 0.99 |
| | RMSE | 0.010 | 0.010 | 0.012 |
| | CE | 0.99 | 0.98 | 0.95 |
| GP2 | r | 0.99 | 0.99 | 0.99 |
| | RMSE | 0.010 | 0.018 | 0.014 |
| | CE | 0.99 | 0.97 | 0.96 |

Table 4.20 Results of GP Models (Category D)

| Model | Performance Parameters | Base Shear |
|---|---|---|
| GP3-1 | r | 0.99 |
| | RMSE | 126.77 |
| | CE | 0.965 |
| GP3-2 | r | 0.99 |
| | RMSE | 109.12 |
| | CE | 0.98 |
| Model | Performance Parameters | Top Floor Displacement |
| GP4-1 | r | 0.99 |
| | RMSE | 0.286 |
| | CE | 0.98 |
| GP4-2 | r | 0.99 |
| | RMSE | 0.409 |
| | CE | 0.98 |

Tables 4.19 and 4.20 shows the better results than that for category A, B and C models. All 'r' and 'CE' values are more than 0.95.

Table 4.21 shows the hypothesis, obtained from the developed GP models in all the four categories, for the fundamental period of vibration.

Table 4.21 Hypothesis of GP models

| Category | Model | Hypothesis |
|---|---|---|
| A | GP1 | $T_{1x} = 0.00602\ h\ H^{3/4}/(W_{cmin}^{0.5} W_{cmax})$ |
| A | GP2 | $T_{1y} = W^{0.25}\ h\ H\ /(1268.54\ D_{cmin} D_{cmax})$ |
| B | GP1 | $T_{1x} = 0.00188\ h\ H/\ (W_{cmin}^{0.5}\ W_{cmax}^{1.5})$ |
| B | GP2 | $T_{1y} = 0.00164\ h\ H/\ (D_{cmin} D_{cmax})$ |
| C | GP1 | $T_{1x} = 0.00188\ h\ H/\ (W_{cmin}^{0.5}\ W_{cmax}^{1.5})$ |
| C | GP2 | $T_{1y} = 0.00164\ h\ H/\ (D_{cmin} D_{cmax})$ |
| D | GP1 | $T_{1x} = n\ \sqrt{1.7\ m/K_x}$ |
| D | GP2 | $T_{1y} = n\ \sqrt{1.7\ m/K_y}$ |

However these equations are obtained for the range of input parameters as shown in the table 4.22. These results are discussed in detail in the next article.

Table 4.22 Range of the values of input parameters

| Input Parameter | Range of the values |
|---|---|
| Length of the building | 9.75 m – 36 m |
| Width of the building | 8 m – 32 m |
| Dimensions of the column | 0.23 m – 0.75 m |
| Height of the building | 12 m -52.5 m |
| Height of the storey | 3 m – 3.5 m |
| Number of floors | 4 - 15 |

**4.5.3.5 Discussions**

It is clear from the above tables, that is, Table nos. 4.13, 4.14,4.15,4.16,4.17,4.18,4.19 and 4.20 that the GP models developed under category GP-D gives better results as compared with GP models under category GP-A, GP-B and GP-C. The reason may be due tothe direct values of seismic weight and stiffness of the building are used as input parameters in developing these models. The equations obtained from the categoryD are of the same form.

As the details of mass of the building, stiffness of the building and geometry of the building are given to the models in all above cases, the values of r are obtained more than 0.95 in every case.

GP models developed under Category GP-A gives fairly good results when compared with GP models developed under Category GP-B and GP-C. In all these models the seismic weight and the stiffness values are given indirectly as input parameters.

In models developed under all the four categories, the GP1 hypothesis do not show effect of the length and width of building or the perimeter of the building on fundamental period of vibration. It seems that effect of stiffness of the building has been shown in terms of h, $W_{cmin}$ and $W_{cmax}$.

GP2 model developed under category GP-A, show the effect of width of the building on fundamental period of vibration. However the effect is not much dominant as it is seen from one forth power of width of the building in the expression for fundamental period of vibration. In all other categories of the GP2 model effect of perimeter or width of the building has not been shown.

In category GP-D wherein seismic weight and stiffness are used as input parameters, effect of geometry of the buildings is not seen over the values of fundamental period. However GP technique has given the hypothesis which is very similar to one used for single degree of freedom (SDOF) system. Thus it can be observed that GP technique understands the basic theory of vibration analysis. This may be further supported by the exactly similar equations obtained under category GP-B and GP-C.

The equation obtained under category GP-B and GP-C for GP2 models is used to derive relation between height of the building and the fundamental period of vibration. The equation is reduced to the form recommended by Goel and Chopra (1997). The GP technique has given following equation:

$T_{1y} = 0.0459\ H^{0.9}$ Eq. (4.33)

Whereas the equation (lower bound) suggested by Goel and Chopra (1997) is

$T = 0.0466\ H^{0.9}$ Eq. (4.34)

In category GP-A, GP-B and GP-C, all the models are showing influence of height of the storey (h) and height of the building (H) over the fundamental period of vibration along X and Y directions.

From the database used to develop the models and the GP equations stated above, following equations are suggested for the fundamental period of vibration along X direction.

| | | |
|---|---|---|
| $T_{1X} = 0.013hH$ | Up to 20 m height of the building | Eq. (4.35) |
| $T_{1X} = 0.0114hH$ | More than 20 m and up to 25 m height | Eq. (4.36) |
| $T_{1X} = 0.0109hH$ | More than 25 m and up to 30 m height | Eq. (4.37) |
| $T_{1X} = 0.00922hH$ | More than 30 m and up to 35 m height | Eq. (4.38) |
| $T_{1X} = 0.008hH$ | More than 35 m and up to 50 m height | Eq. (4.39) |

The height of the floor is assumed as 3.25 m and when multiplied with average coefficient of the above equations, the following equation is obtained:

$T_{1x} = 0.0105x3.25H = 0.0341\ H$ Eq. (4.40)

GP technique has also given the equation as same as ANN technique.

**4.6 Application of WNN in Dynamic Analysis**

**4.6.1 Methodology**

The data division and model assessment is same as that for ANN and GP techniques. Figure 4.9 shows flow chart for the WNN model. ANN and GP techniques have given better results for category B models. Hence it is decided to develop WNN models using eight input parameters.

### 4.6.2 Model Formulation

WNN models consist of four subcategories as mentioned in Table 4.3. WNN models are developed using 8 input parameters (category B models).

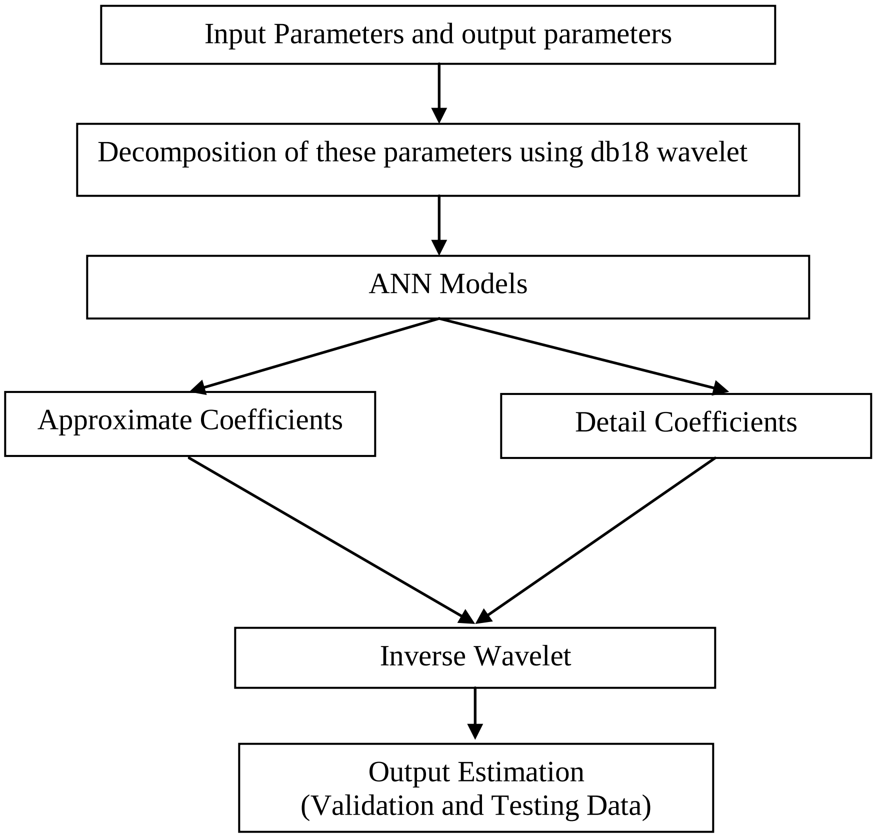


Figure 4.9 Flow Chart of WNN Model

### 4.6.3 Results and Discussions

The results of these models are shown in Table 4.23 and Table 4.24. The scatter plots are shown in Figure nos. 4.10, 4.11, 4.12 and 4.13.

Table 4.23 Results of WNN Models

| Model | Architecture | Performance Parameters | $T_1$ | $T_2$ | $T_3$ | Epochs |
|---|---|---|---|---|---|---|
| WNN1 | 8:3:3<br>8:7:3 | r | 0.97 | 0.97 | 0.97 | 14<br>12 |
| | | RMSE | 0.100 | 0.0339 | 0.0228 | |
| | | CE | 0.92 | 0.93 | 0.92 | |
| WNN2 | 8:6:3<br>8:6:3 | r | 0.98 | 0.98 | 0.98 | 24<br>28 |
| | | RMSE | 0.133 | 0.044 | 0.027 | |
| | | CE | 0.94 | 0.95 | 0.95 | |

Table 4.24 Results of WNN Models

| Model | Architecture | Performance Parameters | Base Shear | Epochs |
|---|---|---|---|---|
| WNN3-1 | 8:9:1<br>8:12:1 | r | 0.95 | 12<br>08 |
| | | RMSE | 231.69 | |
| | | CE | 0.88 | |
| WNN3-2 | 8:3:1<br>8:15:1 | r | 0.93 | 12<br>8 |
| | | RMSE | 259.94 | |
| | | CE | 0.86 | |
| **Model** | **Architecture** | **Performance Parameters** | **Top Floor Displacement** | **Epochs** |
| WNN4-1 | 8:10:1<br>8:14:1 | r | 0.95 | 11<br>15 |
| | | RMSE | 0.000480 | |
| | | CE | 0.897 | |
| WNN4-2 | 8:12:1<br>8:15:1 | r | 0.98 | 20<br>26 |
| | | RMSE | 0.000586 | |
| | | CE | 0.954 | |

As it is seen from ‘r’ and ‘CE’ values, these WNN models are also performing fairly well.

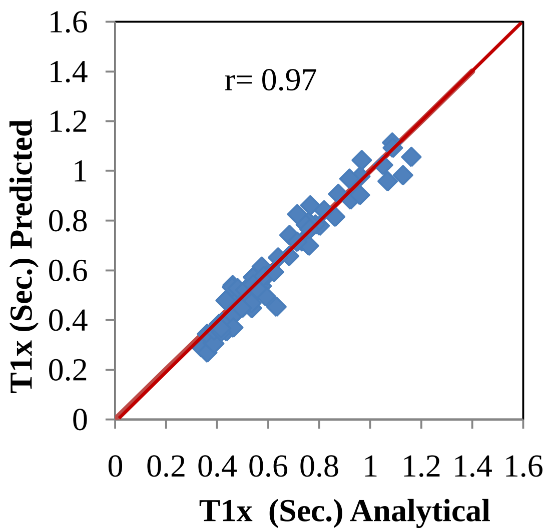


Figure 4.10 Scatter plot of fundamental period of vibration along X direction. (WNN Model)

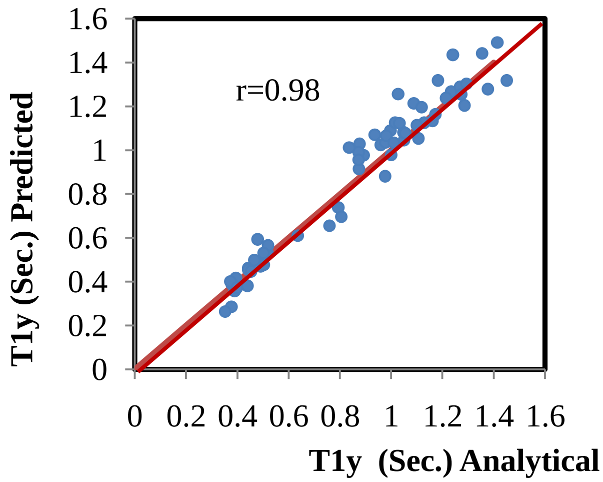


Figure 4.11 Scatter plot of fundamental period of vibration along Y direction (WNN Model)

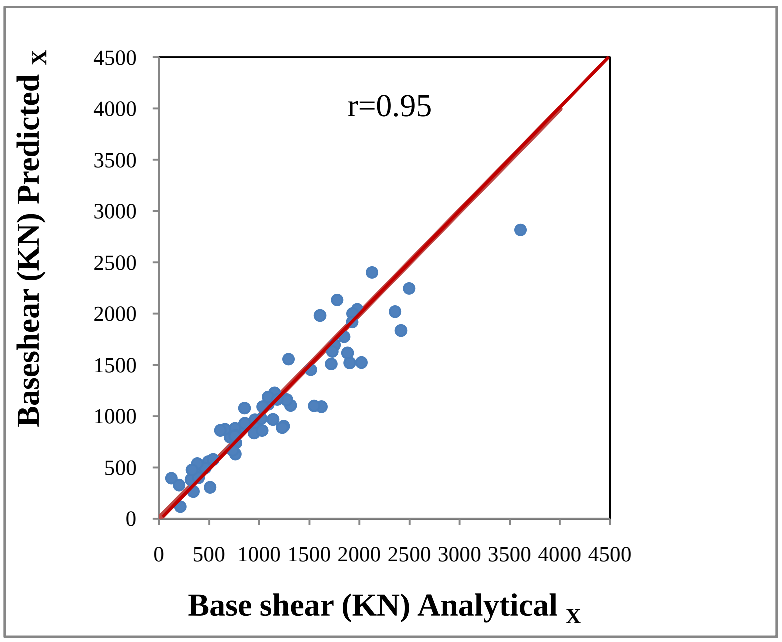


Figure4.12 Scatter plot of Base Shear Force along X direction (WNN Model)

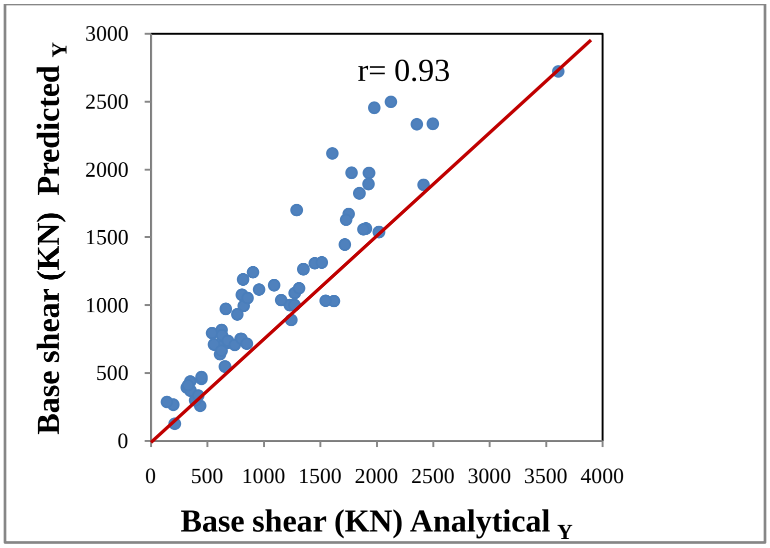


Fig. 4.13 Scatter plot of Base Shear Force along Y direction (WNN Model)

The scatter plots obtained above shows that the predicted values and analytical values are in good agreement with each other.

**4.6.3.1 Discussions**

It is clear that ANN models are performing equally well with WNN models in case of ANN2, ANN4-1 and ANN4-2. In case of the other models performance of ANN models is better than the WNN models.

**4.6.3.2 Comparison of WNN results with the other equations**

The empirical equations are obtained from the testing dataset of the WNN models as discussed in following paragraph.

**4.6.3.2.1 Fundamental period of vibration ($T_1$)**

Thedeveloped models are used to obtain the relationship between the height of the buildingand fundamental period of vibration along X and Y directions. Table 4.25 shows the comparison of the equations suggested by different researchers or building code and those obtained through developed WNN models. These equations are obtained for the buildings up to 40 m in height.

Table 4.25 Comparison of WNN equations and other recommended equations

| Source of the equation | Suggested Equation | WNN equation along X direction | WNN equation along Y direction |
|---|---|---|---|
| IS 1893(Part1): 2002 | $T= 0.075\ H^{0.75}$ | $T= 0.071H^{0.75}$ | $T= 0.098\ H^{0.75}$ |
| Goel and Chopra (1997) | | $T=0.0465H^{0.9}$ | $T=0.0634H^{0.9}$ |

| | | | |
|---|---|---|---|
| Lower bound | T= 0.0466 $H^{0.9}$ | | |
| Best Fit | T= 0.052 $H^{0.9}$ | | |
| Upper bound | T= 0.065 $H^{0.9}$ | | |
| Crowley and Pinho (2006) | | T=0.0344H | T=0.0475H |
| Bare Frames | T= 0.054 H | | |
| In filled frames with openings | T= 0.034 H | | |
| Fully in filled frames | T= 0.025 H | | |

Here also WNN technique has given the same equation as that by ANN and GP techniques. Hence Eq.(4.41) is used for calculating the period values and comparing it with measured period values.

T= 0.0344H Eq. (4.41)

Table 4.25 shows that the equations derived from WNN technique along X direction agrees good with the recommended equations by IS 1893 (Part1): 2002, lower bound of Goel and Chopra (1997) and in filled frames with openings by Crowley and Pinho (2006). Thus WNN technique is able to closely map, the findings of Goel and Chopra, (1997).

In the exercise above, the data was obtained for 206 buildings which is quite a high number. An attempt is made in the next exercise to check the accuracy of these techniques when these techniques are applied for smaller data set. This exercise is undertaken to decide the size of dataset.

**4.7 Application of ANN,GP and WNN for dynamic analysis using smaller data set**

**4.7.1Generation of data**

Totalnumbers of 52 buildings with height range between 4 storeys to 20 storeys areanalyzedfor naturalperiodsofvibrationalongXaswellasY directions as well as base shear force and top floor displacement.ThestructuresareassumedtobelocatedintheseismiczonenumberIIIonthemediumsoil.ImportanceFactor(I)as1and ResponseReductionfactor(R)as5areconsidered forallbuildings.Length of the building is varied from 16 m to 48 m whereas width of the building is assumed between 12 m to 31.5 m. Height of the building is taken between 12 m to 60 m.

### 4.7.2 Methodology

Outofthedatafor 52buildings,thedatasetof 34buildingsisusedtotrainthemodeland thatofremaining 18buildingsisusedtotestthemodel.Thisdivisionofthedataisarrivedatafter theseveral trials. Sothe division ofthe data isapproximately70 % fortrainingand remaining30% fortestingthemodel.

### 4.7.3 ModelFormulation

In the present study, ANN, GP and WNN models are developed in three categories to estimate fundamental period of vibration, maximum base shear and maximum top floor displacement. Seven input parameters are used to develop these models. Length, width and height of the buildings are used as inputs to present geometry of the buildings to the model. Dimensions of the column along with height of the storey are given to the model to represent the stiffness of the floor whereas all these input parameters represent mass of the building to the model. Table 4.26 shows the details of the models developed and Table 4.27 shows the input parameters used for the development of the models. The data is presented in Appendix B.

Table 4.26 Details of the WNN models

| Model | Output Parameter |
|---|---|
| 1 | Fundamental Period of vibration in Seconds |
| 2 | Base Shear Force in KN |
| 3 | Top Floor Displacement in mm |

Table 4.27 Input parameters

| Sr. No. | Input Parameters | Notation used |
|---|---|---|
| 1 | Length of the building in m. | $L$ |
| 2 | Width of the building in m. | $W$ |
| 3 | Height of the building in m. | $H$ |
| 4 | Minimum dimension of the column in m | $D_{cmin}$ |
| 5 | Maximum dimension of the column in m | $D_{cmax}$ |
| 6 | Height of the storey in m | $H$ |
| 7 | Number of floors | $n$ |

### 4.7.4 Results and Discussions

ANN, GP and WNN models are developed and the results are shown in the following paragraph.Table 4.28 shows the results of the ANN models developed using eight input parameters. Similarly Tables 4.29 and 4.30 indicates the results of GP models and WNN models respectively.

Table 4.28 Results of ANN Models

| Models | r | RMSE | CE |
|---|---|---|---|
| ANN1 | 0.99 | 0.0080 | 0.99 |
| ANN2 | 0.99 | 109 | 0.99 |
| ANN3 | 0.99 | 0.51 | 0.99 |

Table 4.29 Results of GP Models

| Models | r | RMSE | CE |
|---|---|---|---|
| GP 1 | 0.99 | 0.010 | 0.99 |
| GP 2 | 0.99 | 297 | 0.95 |
| GP 3 | 0.99 | 2.46 | 0.84 |

Table 4.30 Results of WNN Models

| Models | r | RMSE | CE |
|---|---|---|---|
| WNN1 | 0.99 | 0.037 | 0.97 |
| WNN2 | 0.98 | 410 | 0.91 |
| WNN3 | 0.96 | 1.73 | 0.92 |

Thus it can be observed that even if the data set is reduced these data driven techniques performs the dynamic analysis with the same accuracy as seen from ‘r’ and ‘CE’ values.

**4.8 Experimental Program**

Uni axial shake table of size 0.6 m X 0.8 m with a design pay load capacity of 100 Kg. is used to determine the natural periods of vibration ($T_1$). Its working frequency ranges from 5 Hz to 2000 Hz. A sinusoidal signal is used to excite the test frames with base acceleration of 1g. m/s$^2$. Three storied mild steel frames are tested and acceleration- frequency graph is drawn from these observations. Table 4.31 shows the details of the frames tested and the experimental results.

Table 4.31Experimental Results on Mild Steel Frames

| Frame No. | Column size in mm | Beam size in mm | Floor size in mm | $T_1$(sec) (experimental) | T1 Sec. (Analytical) | Error in percentage |
|---|---|---|---|---|---|---|
| 1 | 25X12X250 | 25X12X200 | 200 X 200 X 8 | 0.0293 | 0.0262 | 10.51 |
| 2 | 25X12X350 | 25X12X200 | 200 X 200 X 8 | 0.0497 | 0.0445 | 10.51 |
| 3 | 12X12X250 | 25X12X200 | 200 X 200 X 8 | 0.0397 | 0.0333 | 16.00 |
| 4 | 12X12X300 | 25X12X200 | 200 X 200 X 8 | 0.0469 | 0.0441 | 6.05 |
| Average Error | | | | | | 10.75 |

Table 4.31 shows that the experimental value of (T) is found to be higher than analytical value by around 10.75%. Analytical values of T are found out using the procedure discussed in chapter 2. However Lee et al. (2000) observed that the ratio of measured periods of vibration to those obtained from computer methods is 0.75 along longitudinal direction and about 0.9 along the transverse direction for shear wall dominant buildings. This may be because of the additional stiffness due to masonry infill and non structural members. Hence as the experimental values of period of vibration are obtained on higher side, its effect is considered in the subsequent analysis of the building types. Table 4.32 shown below shows the error observed in the floor accelerations.

Table 4.32 Error in the floor accelerations of Mild Steel Frames

| Frame No. | Column size in mm | Beam size in mm | Floor size in mm | Acceleration ($m/s^2$) experimental | Acceleration ($m/s^2$) Analytical | Error in percentage |
|---|---|---|---|---|---|---|
| 1 | 25X12X250 | 25X12X200 | 200 X 200 X 8 | 20.68 | 14.125 | 46.4 |
| 2 | 25X12X350 | 25X12X200 | 200 X 200 X 8 | 16 | 17.13 | 6.6 |
| 3 | 12X12X250 | 25X12X200 | 200 X 200 X 8 | 24.92 | 15.64 | 59.24 |
| 4 | 12X12X300 | 25X12X200 | 200 X 200 X 8 | 22.58 | 16.71 | 35.05 |
| Average Error | | | | | | 33 |

However it may be noted that the experimental floor accelerations are closer to the values obtained from the response spectrum suggested by Jain and Murty in their commentary on Indian Seismic code IS 1893 (Part1): 2002. As per the suggested spectrum coefficients, the floor accelerations work out to be 24.52 $m/s^2$. Figure 4.14 shows the photograph taken during the experiment and Figure 4.15 shows the results of frame no. 3 of the M.S. frames. CH referes to the channels connected to the floors and base of the frame.

Figure 4.14 Photograph of the frame

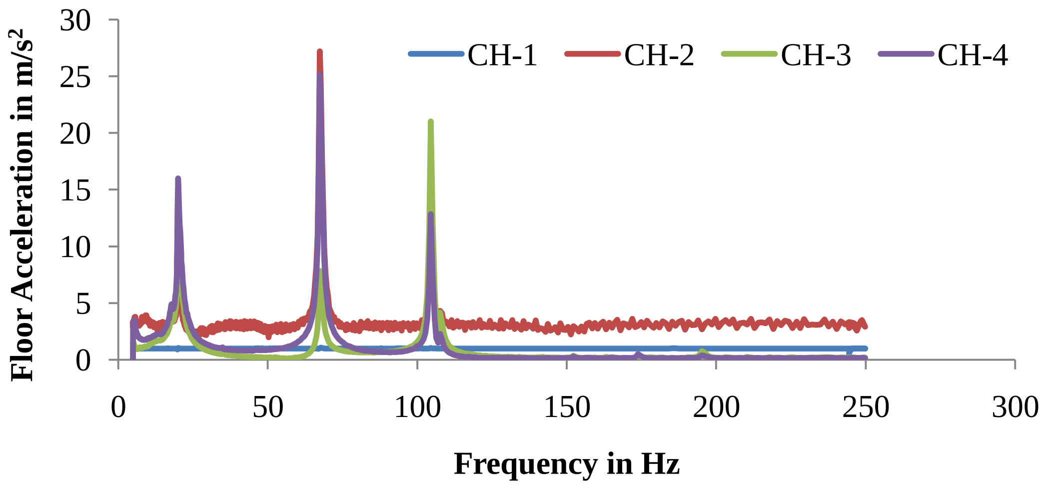


Figure 4.15 Test results for frame no. 3 of the M.S. Frames

The Table 4.33 shows the comparison between the period of vibration (T in second) obtained from the different equations and measured values of T. These values are referred from Morales, (2000).

Table 4.33 Comparison of Period of Vibration obtained through different equations

| Sr. No. | H in m. | T Observed in second | T by Eq.(4.41) in second | T by experimental correction in second | T Eq. (4.1) in second | T by Eq. (4.5) in second |
|---|---|---|---|---|---|---|
| 1 | 18 | 0.9 | 0.62 | 0.69 | 0.65 | 0.64 |
| 2 | 20 | 0.79 | 0.69 | 0.76 | 0.70 | 0.70 |
| 3 | 20 | 0.83 | 0.69 | 0.76 | 0.70 | 0.70 |
| 4 | 20 | 1.2 | 0.69 | 0.76 | 0.70 | 0.70 |
| 5 | 20 | 1.3 | 0.69 | 0.76 | 0.70 | 0.70 |
| 6 | 20 | 1.94 | 0.69 | 0.76 | 0.70 | 0.70 |
| 7 | 21 | 1 | 0.72 | 0.80 | 0.73 | 0.74 |
| 8 | 24 | 0.85 | 0.83 | 0.91 | 0.81 | 0.83 |
| 9 | 24 | 0.85 | 0.83 | 0.91 | 0.81 | 0.83 |
| 10 | 36 | 1.3 | 1.24 | 1.37 | 1.10 | 1.19 |
| 11 | 36 | 1.37 | 1.24 | 1.37 | 1.10 | 1.19 |
| 12 | 36 | 1.46 | 1.24 | 1.37 | 1.10 | 1.19 |
| 13 | 36 | 1.3 | 1.24 | 1.37 | 1.10 | 1.19 |
| 14 | 37.5 | 1.43 | 1.29 | 1.43 | 1.14 | 1.24 |
| 15 | 38 | 1.2 | 1.30 | 1.44 | 1.15 | 1.25 |
| 16 | 42 | 1.4 | 1.44 | 1.60 | 1.24 | 1.37 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 17 | 43 | 1.28 | 1.48 | 1.64 | 1.26 | 1.40 |
| 18 | 43 | 1.28 | 1.48 | 1.64 | 1.26 | 1.40 |
| 19 | 45 | 1.69 | 1.54 | 1.71 | 1.30 | 1.46 |
| 20 | 46 | 1.1 | 1.58 | 1.75 | 1.32 | 1.49 |
| 21 | 48 | 1.6 | 1.65 | 1.83 | 1.37 | 1.55 |
| 22 | 50 | 1.9 | 1.72 | 1.90 | 1.41 | 1.61 |
| 23 | 51 | 2.2 | 1.75 | 1.94 | 1.43 | 1.64 |
| 24 | 51 | 2.6 | 1.75 | 1.94 | 1.43 | 1.64 |
| 25 | 51 | 2.15 | 1.75 | 1.94 | 1.43 | 1.64 |
| 26 | 56 | 1.9 | 1.92 | 2.13 | 1.54 | 1.78 |
| 27 | 56 | 2.9 | 1.92 | 2.13 | 1.54 | 1.78 |
| 28 | 60 | 1.98 | 2.06 | 2.28 | 1.62 | 1.89 |
| 29 | 60 | 2.09 | 2.06 | 2.28 | 1.62 | 1.89 |
| 30 | 60 | 2.15 | 2.06 | 2.28 | 1.62 | 1.89 |
| 31 | 60 | 2.13 | 2.06 | 2.28 | 1.62 | 1.89 |
| 32 | 62 | 1.84 | 2.13 | 2.36 | 1.66 | 1.95 |
| 33 | 62 | 1.94 | 2.13 | 2.36 | 1.66 | 1.95 |
| 34 | 62 | 1.9 | 2.13 | 2.36 | 1.66 | 1.95 |
| 35 | 83 | 3.11 | 2.85 | 3.16 | 2.062 | 2.53 |
| 36 | 90 | 2.8 | 3.09 | 3.42 | 2.19 | 2.72 |

Equation 4.41 is employed to find out the value of T. These values are corrected further by an error observed in the experimental results. In some of the cases the corrected values of T are closer to the observed values than that obtained through the other equations. The correction is applied to Eq. (4.41) and eq. (4.42) is suggested for period of vibration.

$T=0.038\,H$ Eq.(4.42)

**4.9Application of ANN, GP and WNN techniques for predicting measured period values for Moment Resisting Frames**

An attempt is made to apply these tools for measured values of period of vibration as given in (Goel and Chopra, 1997) and (Goel and Chopra, 1998). The details of the buildings and measured period values for moment resisting frames are shown in Table 4.34.

Table 4.34 Measured Period values for Moment Resisting Frames

| Building No. | Height of Building in meter H | Height of floor in meter h | Period of Vibration along X direction in seconds $T_x$ | Period of Vibration along Y direction in seconds $T_y$ |
|---|---|---|---|---|
| 1 | 90.0901 | 3.003 | 2.8 | 2.8 |
| 2 | 36.036 | 4.004 | 1.4 | 1.3 |
| 3 | 48.048 | 3.432 | 1.8 | 1.6 |
| 4 | 49.8498 | 3.8346 | 1.9 | 2.4 |
| 5 | 41.2913 | 4.12913 | 1.4 | 1.6 |
| 6 | 18.3183 | 2.6169 | 0.9 | 1.2 |
| 7 | 20.4204 | 2.9172 | 1 | 1 |
| 8 | 59.0991 | 3.11048 | 2.15 | 2.22 |
| 9 | 37.2372 | 3.3852 | 1.43 | 1.6 |
| 10 | 61.3514 | 2.7887 | 1.9 | 2.2 |
| 11 | 45.6456 | 2.85285 | 1.1 | 1.8 |
| 12 | 35.7357 | 7.14715 | 1.46 | 1.61 |
| 13 | 35.7357 | 7.14715 | 1.4 | 1.3 |
| 14 | 82.2823 | 5.48549 | 3.11 | 3.19 |
| 15 | 42.3423 | 4.7047 | 1.39 | 1.28 |
| 16 | 59.0991 | 2.95495 | 2.27 | 2.09 |
| 17 | 59.0991 | 2.95495 | 2.27 | 2.13 |
| 18 | 59.0991 | 2.95495 | 2.24 | 1.98 |
| 19 | 61.3514 | 2.7887 | 1.94 | 2.14 |
| 20 | 61.3514 | 2.7887 | 1.84 | 2.17 |
| 21 | 50.7508 | 2.53754 | 2.6 | 2.62 |
| 22 | 50.7508 | 2.53754 | 2.15 | 2.21 |
| 23 | 9.00901 | 4.5045 | 0.28 | 0.3 |
| 24 | 9.00901 | 4.5045 | 0.27 | 0.29 |
| 25 | 23.4234 | 3.9039 | 0.85 | 1.1 |
| 26 | 23.4234 | 3.9039 | 0.85 | 1.02 |
| 27 | 19.5195 | 3.9039 | 0.83 | 0.83 |
| 28 | 37.2372 | 2.8644 | 1.2 | 1.4 |
| 29 | 55.4054 | 4.26195 | 1.9 | 2.3 |
| 30 | 19.7297 | 2.81853 | 0.79 | 0.88 |
| 31 | 19.7297 | 2.81853 | 1.4 | 1.2 |

The models are developed in two categories. Category A models predict period of vibration along X direction and Category B models predict period of vibration along Y direction. Table

4.35 indicate the input and output parameters. Sticking to 70% training and 30% testing data values, 22 data values are used for training and remaining values are used for testing the models.

Table 4.35 Input and Output Parameters

| Model Category | Input Parameters | Output Parameter |
|---|---|---|
| A | H, h | Tx |
| B | H, h | Ty |

### 4.9.1 Results of the models

Table 4.36 shows the performance of the models.

Table 4.36 Assessment of Models

| Model Category | r | RMSE | CE |
|---|---|---|---|
| ANN- A | 0.94 | 0.12 | 0.82 |
| GP- A | 0.95 | 0.24 | 0.33 |
| WNN- A | 0.97 | 0.13 | 0.83 |
| ANN- B | 0.70 | 0.15 | 0.35 |
| GP- B | 0.61 | 0.16 | 0.47 |
| WNN- B | 0.68 | 0.16 | 0.54 |

Table 4.36 shows consolidated performance of these models. The reason may be in the small data set with less number of input parameters used to develop the models. However GP models have given following two equations:

$Tx = 0.0973\ H^{0.75}$ Eq.(4.43)

$Ty = 0.0375H$ Eq.(4.44)

It may be noted that Eq. (4.44) is very close to the Eq. (4.42) which is recommended by the study. Though the results are not very consistent they are fair enough to say that the equations generated using GP are similar to the equations obtained by using experimental values.

## 4.10 Application of ANN, GP and WNN techniques for predicting measured period values for Shear Wall Dominant Buildings

These tools are also applied to the data set referred by (Goel and Chopra, 1998). The details of the buildings and measured period values are shown in Table 4.37.

Table 4.37 Measured Period Values for Shear Wall Dominant Buildings

| Length of building in meter L | Width of building in meter W | Height of building in meter H | Height of storeyin meter h | Period of vibration along x direction in second $T_x$ | Period of vibration along y direction in second $T_y$ |
|---|---|---|---|---|---|
| 64.56 | 22.52 | 26.42 | 2.64 | 0.6 | 0.56 |
| 64.56 | 22.52 | 26.42 | 2.64 | 0.57 | 0.51 |
| 61.56 | 24.32 | 21.32 | 4.26 | 0.17 | 0.34 |
| 46.25 | 18.91 | 38.14 | 4.76 | 1.54 | 1.62 |
| 68.17 | 24.024 | 44.95 | 2.64 | 1.18 | 1.05 |
| 68.17 | 24.024 | 44.95 | 2.64 | 1 | 1 |
| 46.85 | 22.82 | 48.49 | 4 | 1.19 | 1.14 |
| 46.85 | 22.82 | 48.49 | 4 | 1.07 | 1.13 |
| 54.05 | 18.01 | 15.07 | 3.75 | 0.5 | 0.6 |
| 22.52 | 20.72 | 42.64 | 4.26 | 0.71 | 0.52 |
| 22.52 | 20.72 | 42.64 | 4.26 | 0.98 | 0.62 |
| 22.52 | 20.72 | 42.64 | 4.26 | 0.97 | 0.62 |
| 39.33 | 23.12 | 12.19 | 4.06 | 0.38 | 0.46 |
| 57.65 | 25.22 | 31.23 | 3.47 | 1.2 | 1.3 |
| 57.65 | 25.22 | 31.23 | 3.47 | 1 | 1.45 |
| 63.06 | 19.22 | 28.82 | 2.88 | 0.73 | 0.43 |
| 63.06 | 19.22 | 28.82 | 2.88 | 0.7 | 0.42 |
| 63.06 | 19.22 | 28.83 | 2.88 | 0.65 | 0.43 |
| 63.06 | 19.22 | 28.83 | 2.88 | 0.63 | 0.41 |
| 22.52 | 21.32 | 19.91 | 4.97 | 0.24 | 0.35 |

Here also the models are developed in two categories. Category A models predict period of vibration along X direction and Category B models predict period of vibration along Y direction. Table 4.35 indicate the input and output parameters. Sticking to 70% training and 30% testing data values, 14 data values are used for training and remaining 6 data values are used for testing the models.

Table 4.38 Input and Output Parameters

| Model Category | Input Parameters | Output Parameter |
|---|---|---|
| A | L, W, H, h | $T_x$ |
| B | L, W, H, h | $T_y$ |

### 4.10.1 Results of the models

Table 4.39 shows the performance of the models.

Table 4.39 Assessment of Models

| Model Category | r | RMSE | CE |
|---|---|---|---|
| ANN- A | 0.65 | 0.11 | 0.35 |
| GP- A | 0.5 | 0.15 | 0.38 |
| WNN- A | 0.78 | 0.061 | 0.69 |
| ANN- B | 0.94 | 0.089 | 0.84 |
| GP- B | 0.96 | 0.15 | 0.84 |
| WNN- B | 0.84 | 0.14 | 0.69 |

Table 4.39 shows consolidated performance of these models. The reason may be in the small data set with less number of input parameters used to develop the models. ANN model has shown relatively better performance and hence the testing and validation data set is used to derive the linear relation between height of the building and period of vibration as given below:

$T=0.023\ H$ Eq. (4.45)

### 4.11 Concluding Remarks

As mentioned earlier, the objective of the exercise was to check the adequacy of these data driven techniques in performing dynamic analysis of the buildings. It can be seen from the results discussed above; these techniques are performing fairly well in performing dynamic analysis of the buildings. The equations obtained through these techniques are close to those recommended by building codes and other researchers. Thus, it may be agreed upon that these techniques may be implemented for carrying out dynamic analysis of moment resisting frames as well as other types of buildings. Even though these models are developed on the basis of analytical values, the equations obtained through these techniques, after incorporating the experimental correction, are close to the experimental equations as shown in the Tables 4.12, Table 4.25, Eq. (4.42), Eq. (4.44) and Eq. (4.45). The study recommends use of Eq. 4.42 for determination of period of vibration.

The last article of the chapter dealt with the application of data driven tools on experimental data set referred by Goel and Chopra, 1997 and Goel and Chopra, 1998. Though the results are not very consistent they are fair enough to say that the equations generated using data driven tools are similar to the equations obtained by using experimental values. It may therefore be inferred that the data driven tools may be applied on the analytical data set and then to be corrected for experimental error.

# CHAPTER 5

# DYNAMIC ANALYSIS OF SHEAR WALL DOMINANT BUILDINGS

In this chapter, ANN, GP and WNNtechniques are applied to predict the structural response of symmetric and unsymmetrical reinforced concrete shear wall dominant buildings in terms of natural periods of vibration, base shear force, base bending moment and top floor displacement. These models are developed with input parameters, chosen to represent mass, stiffness and geometry of the building. Total numbers of 70 symmetrical buildings have been analyzed out of which, data set of 49 buildings have been used to train the model and that of remaining buildings have been used to test the model. Total numbers of 55 unsymmetrical buildings have been analyzed out of which, data set of 39 buildings have been used to train the model and that of remaining buildings have been used to test the model.Statistical measures are used to assess performance of the developed models. Dynamic analysis of shear wall dominant building has been performed as per the clauses recommended by Indian Standard Code IS 1893 (Part1):2002.

## 5.1 Literature Review

Following paragraphs describe the empirical equation of period of vibration recommended by various building codes and researchers.

### 5.1.1 Equation of Period of Vibration for Shear Wall Dominant Building

The fundamental period of vibration required for the simplified design of reinforced concrete structures has been calculated for many years using a simplified formula relating the period to the height of the building and dimension of the building in the direction of seismic force. IS 1893 (Part1): 2002 has given following equation in determining fundamental period of vibration:

$$T=0.09H/\sqrt{d} \quad \text{Eq. (5.1)}$$

Where T is the fundamental period of vibration, H is the height of the building in meter and d is the base dimension of the building in the direction of the analysis. Sindel (1996), concluded that ductile moment-resisting frames may not escape non-structural damage. He recommended the use of ductile shear walls(SW) almost all reinforced concrete (R/C) buildings not only to provide adequate structural safety, but also to protect against non-structural damage. Sezen et al. (2003), found that buildings constructed using SWs as the primary lateral load-resisting system performed quite well in the 1999 Kocaeli, Turkey earthquake, and for the most part, buildings with SWs survived with limited or no damage. Ayala and Charleson(2002) and Sonuvar et al. (2004), have shown that the most effective and economic method of increasing thestiffness and lateral load strength of existing buildings is adding new elements such as a SW to the existing buildingsystem.Table 4.1 shows the summary of the empirical equations suggested by many building codes.

Table 5.1 Empirical Equations of Period of Vibration recommended by different codes (Kwon and Kim, 2010)

| | R.C. MRF | Steel MRF | EBF | RC/Masonry Shear Wall | Other |
|---|---|---|---|---|---|
| UBC -70, 82 BOCA- 75 | $T_a$=0.10$N$ | | $T_a$=0.05$h_n$/sqrt($D$) | | |
| ATC 3-06 | $T_a=C_t h_n^{3/4}$ | | $T_a$=0.05$h_n$/sqrt($D$) | | |
| | $C_t$=0.025 | $C_t$=0.035 | | | |
| BOCA 87 | $T_a=C_t h_n^{3/4}$ | | $T_a$=0.05$h_n$/sqrt($D$) | | |
| | $C_t$=0.030 | $C_t$=0.035 | | | |
| UBC-88,94,97 Eurocode 8 | $T_a=C_t h_n^{3/4}$ | | | | |
| | $C_t$=0.030 | $C_t$=0.035 | $C_t$=0.030 | $C_t$=0.02 *or* $C_t$=0.1/sqrt($A_C$) | $C_t$=0.02 |
| ASCE 7-98 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 | $C_t$=0.020 | $C_t$=0.02 |
| | *Or* $T_a$=0.10$N$ | | - | - | - |
| ASCE 7-98 BOCA-96 NEHRP 94,97 | $T_a=C_r h_n^{x}$ | | | | |
| | $C_r$=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* $T_a$=0.10$N$ | | - | $T_a$=0.0019 $h_n$/sqrt($C_W$) | |

As an alternative for buildings with concrete or masonry SWs, ICC (International Code Council, 1997) provides the following formula to compute $C_t$ which depends on the properties of the SWs as follows:

$$C_t = 0.075/(A_c)^{1/2} \qquad \text{Eq. (5.2)}$$

Where,

$$A_c = \sum_{i=1}^{NW} Ai[0.2 + (\frac{Li}{H})^2] \qquad \text{Eq. (5.3)}$$

where $A_i$ is the horizontal area (in square meters), $L_i$ is the dimension in the direction under consideration (inmeters) of the $i^{th}$ SW in the first floor of the structure, and NW is the total number of SWs. The value of (Li/H)in Equation 4.3 should not exceed 0.9. It should be noted that equations5.2 and 5.3are identical to those reported in theEurocode 8 (CEN 1998) and ECL (HBRC 2003), except that equation 5.3 took the following form:

$$A_c = \sum_{i=1}^{NW} Ai[0.2 + (\frac{Li}{H})]^2 \qquad \text{Eq. (5.4)}$$

Crowley and Pinho (2010) stated that Eq. (5.4)has an error and that Eq.(5.3) is the original one; the differencemay be due to an editing error, and the error should be rectified. Goel and Chopra (1998), calibrated the Dunkerley's equation (Inman, 1996) using the measured periods of vibration of SW buildings and obtained the formula in equation 5.5 which has been included in ASCE (2006) as follows:

$$T=0.0063H/\sqrt{C_W} \qquad \text{Eq. (5.5)}$$

where the equivalent shear area is as follows:

$$C_W = \frac{100}{A_B}\sum_{i=1}^{NW} \frac{H_i}{H}^2 \frac{A_i}{[1+0.83\left(\frac{H_i}{L_i}\right)^2]} \qquad \text{Eq. (5.6)}$$

where $A_B$ is the building plan area, H is the building height in meters, $A_i$,$H_i$, and $L_i$ are the area in square meters and height and length in meters in the direction under consideration of the ith SW, and NW is the number of SWs. They also recommended that the period computed from a rational analysis should not exceed 1.4 times the value obtained from Eq. 5.5. The lowerlimit of fundamental period represents the value measuredunder ambient vibration for the intact buildingwith no cracks. However, the upper limit represents thatobtained from strong motion records of the crackedbuilding (Morales 2000).Morales (2000), found that Eq. 5.5 provided improved results as compared with any of the code suggestedexpressions, e.g., the Canadian code NBCC (National Building Code of Canada, 1996) or the American code, ICC (International Code Council, 1997). Michel et al. (2010), suggested that for French existing buildings, the fundamental period is proportional to building height or floor number. However, for design, they recommended relationships based on the wall lengths by Goel and Chopra (1998). Crowley and Pinho (2010), suggested updating Eq. 5.4 in the Eurocode 8 (CEN 1998) by the equation proposed by Goel and Chopra (1998). It is worth to mention that Eq.5.4 is valid for SW with different heights and takes into account shape factor and shear modulus, as well as both flexural and shear deformations. Gills and Mcclure (2011), performed ambient vibration measurements on 39 multi-storey buildings, ranging in height from 12 to 195 m, in Montréal, Québec (Canada). The dynamic properties of up to six vibration modes were then extracted from the measured ambient responses using the enhanced frequency domain decomposition (EFDD) method.The measured dynamic properties of the 27 RCSW buildings studied are compared to different models proposedin the literature. The empirical equations proposed in several building codes (National Building Code of Canada, 2005, ASCE/SEI 7-05, SEAOC,1999) to estimate the fundamental sway period do not fit the measured data very well. Based on the results of regression analyses, an improved equation is proposed as follows.

T=0.019 H Eq. (5.7)

Where, T is the fundamental period of vibration and H is the height of the building in meter.

Hatzigeorgiouand Kanapitsas, (2013), have proposed following empirical equation where the flexibility of soil, the presence of infill panels andconcrete shear walls, the total height, and the width along the seismic direction have been taken intoaccount.

$$T= \frac{H^{0.745} L^{0.024} (0.073-0.021W)}{\left[1-\exp\left(-0.706 {K_S}^{0.2}\right)\right]\sqrt{(1+0.043\rho)}} \quad \text{Eq. (5.8)}$$

Where,

L is the width of structure in seismic design direction under consideration (in meters)

$\rho$is theratio of the areas of shear wall sections along a seismic action direction to the total area of the walls and columns

H is the height of the building in meters.

$K_s$is the sub grade modulus of soil in mega Newton per cubic meter.

W is identical with the amount of infill panels which is 0 for bare frames and 1 for the buildings which have infill walls in each moment resisting frames.

Lee, et al (2000), proposed improved formula for shear wall dominant buildings based on the full scale measurements on 50 apartment buildings in Koria.

$$T= \frac{0.33}{\sqrt{L_W}} H^{0.35} - 0.5 \quad \text{Eq. (5.9)}$$

Where, $L_w$ implies wall length in meters per unit plan area in square meters,T is the fundamental period of vibration and H is the height of the building in meter.

The difference between the real period of the building and the period obtained from the computerbasedanalysis using ETABS v6_13 is also presented and is shown by comparison that the ratio ofmeasured periods to those obtained from the computer-based method is about 0.75 for the longitudinaldirection and about 0.9 for the transverse direction.

Kwon and Kim (2010), suggested following equation based on the data points of 56 RS shear wall buildings.

T= 0.0365 $H^{0.75}$ Eq. (5.10)

Morales (2000), suggested following equation for determination of period of vibration.

$$T=\frac{2\pi}{3.516}\sqrt{\frac{m}{EI}}H^2 \qquad \text{Eq. (5.11)}$$

Where m is the mass of the building and H is the building height in meters.

### 5.1.2 Application of ANN and WNN for dynamic analysis of shear wall dominant buildings

Caglar,et al. (2008), proposed two ANN models to estimate the fundamental period of vibration, base shear forces, base bending moments and top floor displacement. In all, eleven Input parameters were chosen for developing the models which were easy to obtain from the drawings except Moment of Inertia values.Kameli,et al. (2011), have applied artificial neural network to predict the structural response of reinforced concrete frames with masonry infillwalls.

ANN, GP and WNN techniques are applied for performing dynamic analysis of shear wall dominant building frames. The models are developed using eight input parameters to predict period of vibration, base shear force and top floor displacement along X and Y directions. The details of modeling are described in subsequent paragraphs:

## 5.2 Application of ANN in Dynamic Analysis of Symmetric Buildings

ANN technique is applied for performing dynamic analysis of shear wall dominant symmetric R.C. building frames. The methodology, geometry and results are discussed in following paragraphs.

### 5.2.1 Data generation, methodologyandanalysis

#### 5.2.1.1 Geometry and Material Properties

The buildings are assumed to be fixed at the base without soil structure interaction and the floors as rigid diaphragm. The sections of the structural elements are rectangular for the beams as well as the columns. The thickness of slab is 150 mm and the height of the floor as 3m or 3.5m. The beam sections are considered in the size range of 230 mm x 450 mm to 450 mm x 900 mm. The column sections for rectangular shapes are considered in the range of 230 mm x 450 mm to 1200 mm x 1500 mm. The length of shear wall ranges from 3 m to 5 m and thickness of shear wall ranges from 0.2 m to 0.35 m. The modulus of elasticity is considered as $5000\sqrt{f_{ck}}$ and the mass density as 25 $KN/m^3$. Two grades of concrete assumed in the analysis are M20 and M25. Length of the building is assumed between 25 m to 49 m, width of the building between 20 m to 30 m and height between 18 m to 90 m. Live load intensity is considered as either 2 $KN/m^2$ or $3KN/m^2$. A typical floor plan of building is shown in figure 5.1. Length of the building is varied from 25 m to 49 m. Width of the building is assumed between 20 m to 28 m and height of the building variation is between 18 m to 90 m.

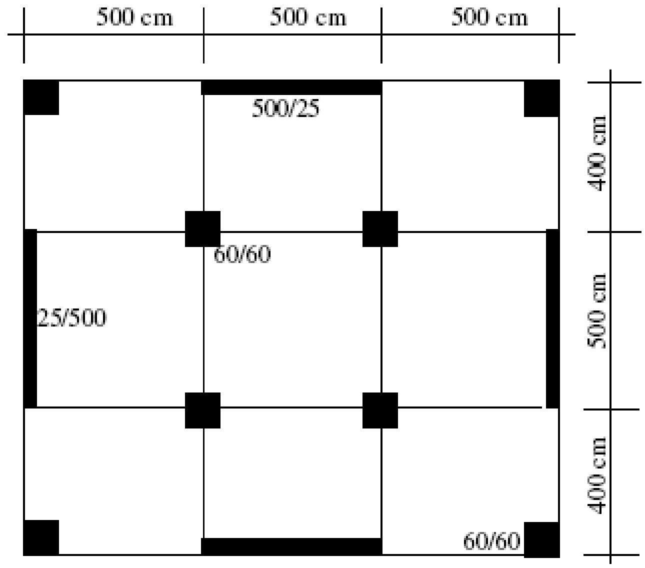


Figure 5.1 Typical Floor Plan of Symmetric Building

**5.2.1.2 Generation of Data**

Total number of 70 buildings with height range between 6 storeys to 30 storeys is analyzed for natural periods of vibration along X as well as Y directions. The structures are assumed to be located in the seismic zone number III on the medium soil. Importance Factor (I) as 1 and Response Reduction factor (R) as 5 are considered for all buildings using ETABS v 9.7.2. Effect of first three modes is considered for the dynamic analysis. The data is presented in Appendix C.

**5.2.1.3 Methodology**

Out of the data for 70 buildings, the data set of 49 buildings is used to train the model and that of remaining 21 buildings is used to test the model.

**5.2.1.4 Model Formulation**

In the present study, ANN models are developed to predict the structural response in terms of natural periods of vibration along X and Y directions, base shear force and top floor displacements.ANN1 category models estimates the natural period of vibrations for first three modes along X direction. ANN2 category models estimates the natural period of vibrations for first three modes along Y direction. ANN 3-1 and ANN 3-2 categories of ANN estimates base shear force along X and Y direction respectively. Similarly ANN 4-1 and ANN 4-2 models of ANN estimates top floor displacement along X and Y direction respectively.All ANN models are developed with 8 input parameters. These input parameters are chosen considering the effect of geometry, mass distribution and the stiffness characteristics of the building frames in the dynamic analysis. Effect of geometry is incorporated in terms of L, W and H whereas the effect of the mass of the building is incorporated in terms of $W_{cmin}$, $W_{cmax}$, $D_{cmin}$, $D_{cmax}$ and n. The stiffness characteristic of the building frames is assumed in terms of $W_{cmin}$, $W_{cmax}$, $D_{cmin}$, $D_{cmax}$ and h.Table 5.2 and 5.3 given below shows the input parameters used along X and Y directions respectively.

Table 5.2 Input parameters for X direction

| Sr. No. | Parameter | Notation Used |
|---|---|---|
| 1 | Length of building | $L$ |
| 2 | Width of Building | $W$ |
| 3 | Height of the Building | $H$ |
| 4 | Plan Area of the building | $A$ |
| 5 | Minimum dimension of column along X direction | $W_{cmin}$ |
| 6 | Maximum dimension of column along X direction | $W_{cmax}$ |
| 7 | Area of shear wall along X direction | $A_{swx}$ |
| 8 | Height of the storey | $H$ |

Table 5.3 Input parameters for Y direction

| Sr. No. | Parameter | Notation Used |
|---|---|---|
| 1 | Length of building | $L$ |
| 2 | Width of Building | $W$ |
| 3 | Height of the Building | $H$ |
| 4 | Plan Area of the building | $A$ |
| 5 | Minimum dimension of column along Y direction | $D_{cmin}$ |
| 6 | Maximum dimension of column along Y direction | $D_{cmax}$ |
| 7 | Area of shear wall along Y direction | $A_{swy}$ |
| 8 | Height of the storey | $H$ |

### 5.2.1.5 Results and Discussions

As per the discussions in previous paragraphs, ANN models are developed and comparison of the results is discussed here in this article. Tables 4.4 and 4.5 show the assessment of the developed ANN models.

Table 5.4 Results of ANN Models (Categories 1 and 2)

| Model | Architecture | Performance Parameters | $T_1$ | Epochs |
|---|---|---|---|---|
| ANN 1 | 8:4:1 | r | 0.99 | 18 |
| | | RMSE | 0.013 | |
| | | CE | 0.99 | |
| ANN 2 | 8:4:1 | r | 0.99 | 15 |
| | | RMSE | 0.0084 | |
| | | CE | 0.99 | |

Table 5.5 Results of ANN Models ( Categories 3 and 4)

| Model | Architecture | Performance Parameters | Base Shear | Epochs |
|---|---|---|---|---|
| ANN3-1 | 8:4:1 | r | 0.99 | 14 |
| | | RMSE | 75.46 | |
| | | CE | 0.99 | |
| ANN3-2 | 8:4:1 | r | 0.99 | 52 |
| | | RMSE | 62.38 | |
| | | CE | 0.99 | |
| Model | Architecture | Performance Parameters | Top Floor Displacement | Epochs |
| ANN4-1 | 8:3:1 | r | 0.99 | 35 |
| | | RMSE | 0.22 | |
| | | CE | 0.99 | |
| ANN4-2 | 8:4:1 | r | 0.99 | 61 |
| | | RMSE | 0.21 | |
| | | CE | 0.99 | |

Table nos. 5.4 and 5.5 shows that ‘r’ and ‘CE’ values are 0.99 in every case which is good indication of very satisfactory performance of developed models.

The stiffness of these buildings along Y direction was more than that along X direction and hence $T_{1y}$ is smaller than $T_{1x}$. The following equations given in Table 5.6 are deduced for the fundamental period of vibration from the validation and testing dataset of ANN models. The forms of the equations are assumed similar to code recommended or recommended by researchers.

Table 5.6 Empirical Equation of T (ANN Modeling)

| Sr. No. | ANN Equation without correction | ANN Equation with correction |
|---|---|---|
| 1 | $T= 0.0244\ H$ | $T= 0.022\ H$ |
| 2 | $T= 0.0698\ H^{0.75}$ | $T= 0.0628\ H^{0.75}$ |
| 3 | $T=0.127\ H/\sqrt{W}$ | $T=0.114\ H/\sqrt{W}$ |

Scatter plots for period of vibration along X direction, base shear force and top floor displacements along Y direction are shown in Figures 5.2, 5.3 and 5.4.

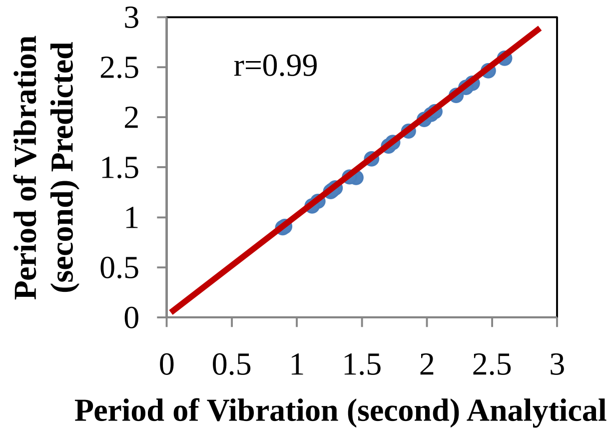


Figure 5.2 Scatter Plot for Period of Vibration along X direction

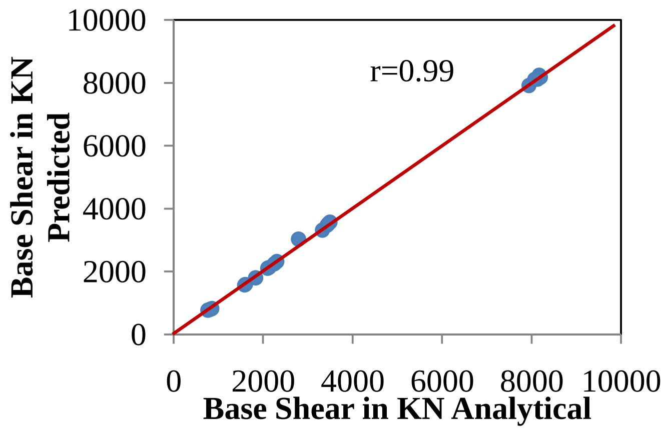


Figure 5.3 Scatter Plot for Base Shear along Y direction

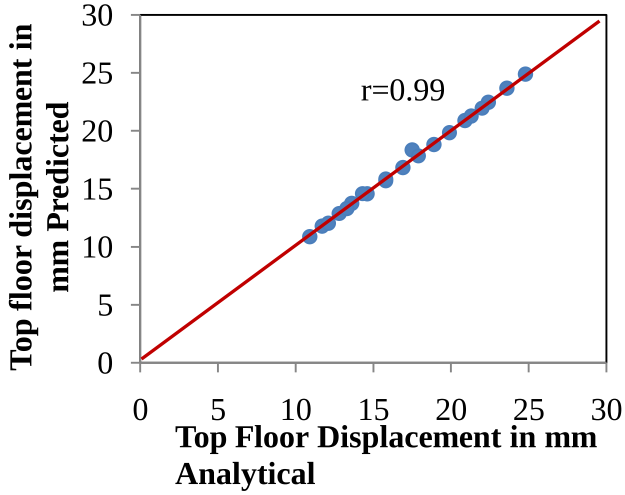


Figure 5.4 Scatter Plot for Top Floor Displacement along Y direction

Again, all these scatter plots also shows very satisfactory performance of developed models.

### 5.3 Application of GP in Dynamic Analysis of Symmetric Buildings

GP technique is applied for performing dynamic analysis of shear wall dominant symmetric R.C. building frames. The methodology, geometry and model formulation remain same as that for ANN modeling. The results are discussed in the following article.

#### 5.3.1 Results and Discussions

GP models are developed four categories as in the case of ANN modeling. The assessment of these models is presented in Table Nos. 5.7 and 5.8.

Table 5.7 Results of GP Models (Categories 1 and 2)

| Model | Performance Parameters | $T_1$ |
|---|---|---|
| GP 1 | r | 0.98 |
| | RMSE | 0.104 |
| | CE | 0.96 |
| GP 2 | r | 0.99 |
| | RMSE | 0.0452 |
| | CE | 0.99 |

Table 5.8 Results of GP Model (Categories 3 and 4)

| Model | Performance Parameters | Base Shear |
|---|---|---|
| GP 3-1 | R | 0.99 |
| | RMSE | 85.63 |
| | CE | 0.99 |
| GP 3-2 | R | 0.99 |
| | RMSE | 106.67 |
| | CE | 0.99 |
| Model | Performance Parameters | Top Floor Displacement |
| GP 4-1 | R | 0.99 |
| | RMSE | 0.35 |
| | CE | 0.98 |
| GP 4-2 | R | 0.99 |
| | RMSE | 0.47 |
| | CE | 0.97 |

Table Nos. 5.7 and 5.8 indicate very satisfactory performance of developed GP models. But ‘rmse’ values obtained are more than that for ANN models in every case.

The hypothesis obtained from the developed GP models is as below:

$T_x = H\ W_{cmax}^{5/8} / W\ A_{swx}^{17/8}$ Eq. (5.12)

$T_y = H^{1.22} W^{0.22} / h^5 A_{swy} D_{cmax}^{1/2}$ Eq.(5.13)

Upon substituting the values of $W_{cmax}$,$A_{swx}$, h and $D_{cmax}$, the equations are reduced to following forms:

$T_x = H/2W$ Up to $H <= 40$m Eq. (5.14)

$T_x = H/2.2W$ For $H > 40$m Eq. (5.15)

$T_y = 0.0055\ H^{1.22} W^{0.22}$ Eq. (5.16)

After substituting an error of 9 % in the period value (Lee, et al. 2000), we obtain following equation.

$T_y = 0.00495\ H^{1.22} W^{0.22}$ Eq. (5.17)

After substituting the values of width of the buildings used in the data set above,

$T_y = 0.0081\ H^{1.22}$ Eq. (5.18)

### 5.4 Application of WNN in Dynamic Analysis of Symmetric Buildings

WNN technique is also applied for performing dynamic analysis of shear wall dominant symmetric R.C. building frames. The methodology, geometry and model formulation remain same as that for ANN modeling. The results are discussed in the following article.

#### 5.4.1 Results and Discussions

WNN models are developed four categories as in case of ANN modeling. The assessment of these models is presented in Table Nos. 5.9 and 5.10.

Table 5.9 Results of WNN Models (Categories 1 and 2)

| Model | Architecture | Performance Parameters | $T_1$ | Epochs |
|---|---|---|---|---|
| WNN 1 | 8:4:1<br>8:6:1 | R | 0.98 | 42<br>19 |
| | | RMSE | 0.12 | |
| | | CE | 0.91 | |
| WNN 2 | 8:2:1<br>8:3:1 | R | 0.98 | 31<br>20 |
| | | RMSE | 0.1 | |
| | | CE | 0.93 | |

Table 5.10 Results of WNN Model (Categories 3 and 4)

| Model | Architecture | Performance Parameters | Base Shear | Epochs |
|---|---|---|---|---|
| WNN3-1 | 8:3:1<br>8:4:1 | R | 0.98 | 12<br>31 |
| | | RMSE | 389.73 | |
| | | CE | 0.98 | |
| WNN3-2 | 8:3:1<br>8:4:1 | R | 0.99 | 7<br>20 |
| | | RMSE | 262 | |
| | | CE | 0.99 | |
| Model | Architecture | Performance Parameters | Top Floor Displacement | Epochs |
| WNN4-1 | 8:13:1<br>8:7:1 | R | 0.94 | 18<br>45 |
| | | RMSE | 1.95 | |
| | | CE | 0.89 | |
| WNN4-2 | 8:16:1<br>8:7:1 | R | 0.99 | 49<br>15 |
| | | RMSE | 0.835 | |
| | | CE | 0.96 | |

Table nos. 5.9 and 5.10 shows very satisfactory performance of developed WNN models. However 'rmse' values when compared with that for ANN and GP techniques, shows overestimation of all the response values.

Similar to ANN modeling, following equations given in Table 5.11 are deduced for the fundamental period of vibration from the validation and testing dataset of WNN models.

Table 5.11 Empirical Equation of T (WNN Modeling)

| Sr. No. | WNN Equation without correction | WNN Equation with correction |
|---|---|---|
| 1 | T= 0.0237 H | T= 0.02133 H |
| 2 | T= 0.067 $H^{0.75}$ | T= 0.0603 $H^{0.75}$ |
| 3 | T=0.123 $H/\sqrt{W}$ | T=0.111 $H/\sqrt{W}$ |

**5.5 Validation of the Proposed Equations of Period of Vibration**

The equations obtained above are validated for the measured values of period of vibration along Y direction. The dataset used in Table 5.12 is referred from Lee, et al. (2000). The equations corresponding to serial number 1 of the Tables 5.6 and 5.11 are used to obtain period of vibration. Further ANN and WNN techniques have given almost same equation (Eq. 5.19) and hence used in Table 5.12.

T=0.022 H Eq. (5.19)

This equation is very close to the equation (Eq. 4.45) obtained for the data set referred by Goel and Chopra, 1998.

Table 5.12 Validation of proposed equations

| Building No. | Length in meter | Width in meter | Height in meter | Measured Period in seconds | Period in second from Eq.(5.18) | Period in second from Eq.(5.19) | Period in second from Eq.(5.1) |
|---|---|---|---|---|---|---|---|
| 1 | 30.94 | 12.38 | 53.50 | 1.19 | 1.04 | 1.18 | 1.37 |
| 2 | 27.22 | 12.83 | 40.00 | 0.91 | 0.73 | 0.88 | 1.00 |
| 3 | 41.80 | 11.18 | 53.50 | 1.16 | 1.04 | 1.18 | 1.44 |
| 4 | 51.90 | 10.36 | 40.00 | 0.90 | 0.73 | 0.88 | 1.12 |
| 5 | 34.60 | 10.36 | 40.00 | 0.86 | 0.73 | 0.88 | 1.12 |
| 6 | 53.60 | 11.40 | 53.00 | 1.12 | 1.03 | 1.16 | 1.41 |
| 7 | 35.48 | 11.40 | 53.50 | 1.31 | 1.04 | 1.18 | 1.43 |
| 8 | 52.5 | 10.92 | 53.50 | 1.06 | 1.04 | 1.18 | 1.46 |
| 9 | 52.50 | 10.92 | 58.90 | 1.04 | 1.17 | 1.29 | 1.60 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 | 35.00 | 10.92 | 67.00 | 1.33 | 1.37 | 1.47 | 1.82 |
| 11 | 38.10 | 12.30 | 67.90 | 1.39 | 1.39 | 1.49 | 1.74 |
| 12 | 20.80 | 11.50 | 67.90 | 1.59 | 1.39 | 1.49 | 1.80 |
| 13 | 27.30 | 12.00 | 67.90 | 1.61 | 1.39 | 1.49 | 1.76 |
| 14 | 51.84 | 12.60 | 68.00 | 1.69 | 1.39 | 1.50 | 1.72 |
| 15 | 36.80 | 11.20 | 53.90 | 1.25 | 1.05 | 1.18 | 1.45 |
| 16 | 18.3 | 10.70 | 40.00 | 0.90 | 0.73 | 0.88 | 1.10 |
| 17 | 53.4 | 11.40 | 55.60 | 1.25 | 1.09 | 1.22 | 1.48 |
| 18 | 41.60 | 12.40 | 55.60 | 1.27 | 1.09 | 1.22 | 1.42 |
| 19 | 31.80 | 10.00 | 54.00 | 1.25 | 1.05 | 1.19 | 1.54 |
| 20 | 50.40 | 12.30 | 54.00 | 1.20 | 1.05 | 1.198 | 1.38 |

Table 5.12 shows that ANN and WNN equation yield the period values relatively closer to the measured period values than those by code recommended equation or GP equation as shown in Figure 5.5. Figure 5.5 also depicts the higher values estimated by code equation as against the measured period values.

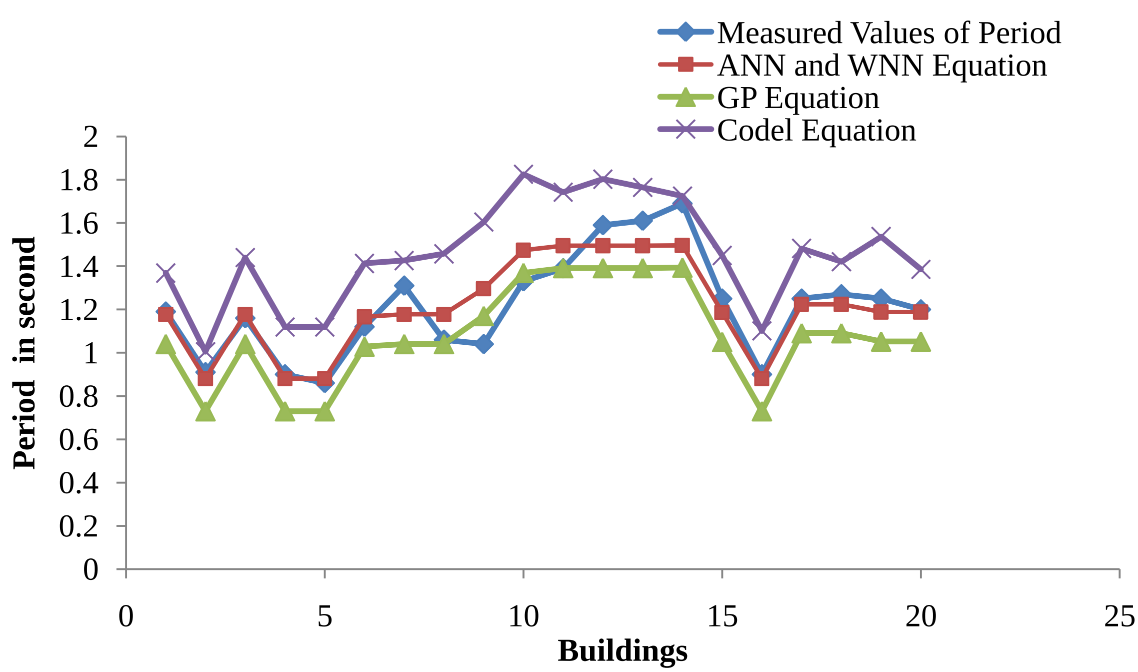


Figure 5.5 Comparison of measured period values (in seconds) with those by different equation

## 5.6 Maximum Lateral Displacement of Symmetric Building

The predicted values of the lateral displacement by WNN and ANN techniques are correlated with the height of the building. The following equation is obtained which is applied to the analytical data set of for validation.

$D_{max} = 0.322H$ Eq. (5.20)

Using Eq. 5.19 and Eq. 5.20, data set is generated in terms of the height of the building, minimum period of the building and maximum displacement of the buildings as shown in Table 5.13.

Table 5.13 Minimum Period of Vibration and maximum Displacement

| H in meter | $T_{min}$ in seconds | $D_{max}$ in mm. | H in Meter | $T_{min}$ in seconds | $D_{max}$ in mm. |
|---|---|---|---|---|---|
| 10 | 0.22 | 3.22 | 110 | 2.42 | 35.42 |
| 20 | 0.44 | 6.44 | 120 | 2.64 | 38.64 |
| 30 | 0.66 | 9.66 | 130 | 2.86 | 41.86 |
| 40 | 0.88 | 12.88 | 140 | 3.08 | 45.08 |
| 50 | 1.1 | 16.1 | 150 | 3.3 | 48.3 |
| 60 | 1.32 | 19.32 | 160 | 3.52 | 51.52 |
| 70 | 1.54 | 22.54 | 170 | 3.74 | 54.74 |
| 80 | 1.76 | 25.76 | 180 | 3.96 | 57.96 |
| 90 | 1.98 | 28.98 | 190 | 4.18 | 61.18 |
| 100 | 2.2 | 32.2 | 200 | 4.4 | 64.4 |

The relation between the minimum period of vibration and maximum displacement of the building is then obtained as shown in Eq. 5.21.

$D_{max}= 13.5\ T_{min}$ Eq. (5.21)

The Eq. (5.21) is validated with the available data set as indicated in Table 5.14.

Table 5.14 Validation of correlation between period and displacement

| Sr. No. | $T_{min}$ in seconds | $D_{max}$ Analytical in mm. | $D_{max}$ Estimated in mm |
|---|---|---|---|
| 1 | 1.9 | 25.2 | 25.65 |
| 2 | 1.82 | 24.1 | 24.57 |
| 3 | 1.74 | 23.1 | 23.49 |
| 4 | 1.66 | 22.1 | 22.41 |
| 5 | 1.581 | 21.1 | 21.3435 |
| 6 | 1.504 | 20.1 | 20.304 |
| 7 | 1.429 | 19.1 | 19.2915 |
| 8 | 1.355 | 18.2 | 18.2925 |
| 9 | 1.282 | 17.3 | 17.307 |
| 10 | 1.211 | 16.3 | 16.3485 |
| 11 | 1.142 | 15.4 | 15.417 |
| 12 | 1.074 | 14.5 | 14.499 |
| 13 | 1.007 | 13.7 | 13.5945 |
| 14 | 0.941 | 12.8 | 12.7035 |
| 15 | 0.877 | 11.9 | 11.8395 |
| 16 | 2.688 | 36.6 | 36.288 |
| 17 | 2.57 | 35.3 | 34.695 |
| 18 | 2.47 | 33.9 | 33.345 |
| 19 | 2.364 | 32.5 | 31.914 |
| 20 | 2.258 | 31.2 | 30.483 |

## 5.7 Concluding Remarks- Symmetric Buildings

Three data driven techniques are applied for the dynamic analysis of shear wall dominant symmetric R.C. building frames. It is seen that ANN and WNN techniques yielded the same equation for fundamental period of vibration which is found to be more realistic as compared to code equations, when validated with measured data. Further it is seen that the fundamental period of vibration is a function of height of the building and not the function of plan dimensions of the building or area of the shear walls of the building. The maximum displacement of the building is further correlated with the fundamental period of vibration and is found to be a linear function of period of vibration.

## 5.8 Application of ANN for Dynamic Analysis of Unsymmetrical Building

ANN technique is applied for performing dynamic analysis of shear wall dominant asymmetric R.C. building frames. The methodology, geometry and results are discussed in following paragraphs.

### 5.8.1 Data generation, methodologyandanalysis

#### 5.8.1.1 Geometry and Material Properties

The buildings are assumed to be fixed at the base without soil structure interaction and the floors as rigid diaphragm. The sections of the structural elements are rectangular for the beams as well as the columns. The thickness of slab is 150 mm and the height of the floor as 3m or 3.5m. The beam section considered is 200 mm x 700 mm with concrete of M 35 grade. The column sections for rectangular shapes are considered in the range of 200 mm x 1000 mm to 300 mm x 1500 mm. The grade of concrete is M 35 to M50. The length of shear wall ranges from 4.3 m to 11.56 m and thickness of shear wall ranges from 0.2 m to 0.3 m. M 50 grade of concrete is assumed for the shear wall. The modulus of elasticity is considered as $5000\sqrt{f_{ck}}$ and the mass density as 25 $KN/m^3$. Length of the building is assumed between 33 m to 49 m, width of the building between 13 m to 27 m and height between 27 m to 87 m. Live load intensity is considered as either 2 $KN/m^2$ or $3KN/m^2$. A typical floor plan of building is shown in Figure 5.6. Variation in the length of the building is considered between 33.75 m to 49 m. Width of the buildings is considered between 13 m to 27 m and variation in the height of the building is between 27 m to 87 m.

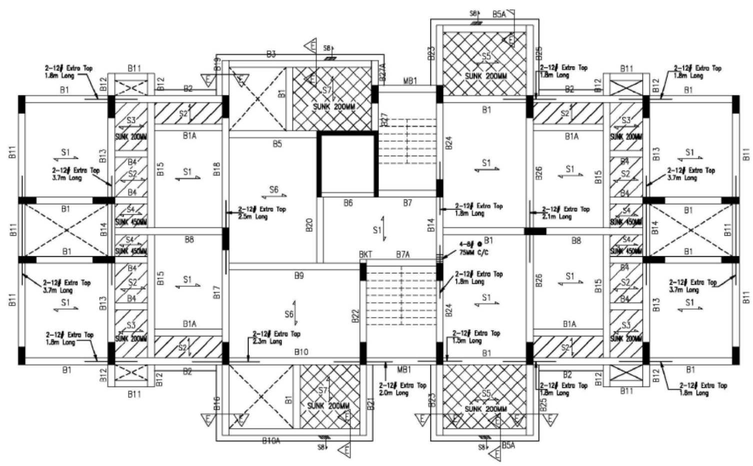

Figure 5.6 Typical Plan of Unsymmetrical Building

#### 5.8.1.2 Generation of Data

Total number of 55 buildings with height range between 9 storeys to 29 storeys is analyzed for natural periods of vibration, base shear force and top floor displacements along X as well as Y directions. The structures are assumed to be located in the seismic zone number III on the medium soil. Importance Factor (I) as 1 and Response Reduction factor (R) as 5 are considered for all buildings using ETABS v 9.7.2. Effect of first twelve modes is considered for the dynamic analysis.The data is presented in Appendix D.

#### 5.8.1.3 Methodology

Out of the data for 55 buildings, the data set of 39 buildings is used to train the model and that of remaining 16 buildings is used to test the model.

#### 5.8.1.4 Model Formulation

In the present study, ANN models are developed to predict the structural response in terms of shorter natural period of vibration, maximum base shear force and maximum top floor displacement.ANN1 category models estimates shorter natural period of vibration. ANN2 category of model estimates maximum base shear force and similarly ANN 3 model of ANN estimate maximum top floor displacement. All ANN models are developed with 8 input parameters. These input parameters are chosen considering the effect of geometry, mass distribution and the stiffness characteristics of the building frames in the dynamic analysis. Effect of geometry is incorporated in terms of L, W and H whereas the effect of the mass of the building is incorporated in terms of $D_{cmin}$, $D_{cmax}$ and total area of shear wall along X and Y directions. The stiffness characteristic of the building frames is assumed in terms of $D_{cmin}$, $D_{cmax}$total area of shear wall along X and Y direction and h.Table 5.15 given below shows the input parameters used to develop these models. Shorter period of vibration is observed along the transverse direction of the building and hence maximum base shear force and top floor displacement are seen along Y direction. The input parameters shown in Table 5.15 uses dimensions of the column along transverse direction but total area of shear wall along both the directions is used as the input parameters.Table 5.16 describes the ANN models developed for the study.

Table 5.15 Input Parameters along Y direction

| Sr. No. | Parameter | Notation Used |
|---|---|---|
| 1 | Length of building | $L$ |
| 2 | Width of Building | $W$ |
| 3 | Height of the Building | $H$ |
| 4 | Minimum dimension of column along Y direction | $D_{cmin}$ |
| 5 | Maximum dimension of column along Y direction | $D_{cmax}$ |
| 6 | Height of the storey | $H$ |
| 7 | Total area of shear wall along X direction | $A_{swx}$ |
| 8 | Total area of shear wall along Y direction | $A_{swy}$ |

Table 5.16 ANN Models Developed

| Model | Output Parameter |
|---|---|
| ANN 1 | Shorter Period of Vibration in seconds |
| ANN 2 | Maximum Base Shear Force in KN |
| ANN 3 | Maximum Top Floor Displacement in mm |

### 5.8.1.5 Results and Discussions

As mentioned in the earlier section, ANN modeling has been applied for the dynamic analysis of the asymmetric shear wall dominant R.C. building frames. The results are presented below in the Table 5.17.

Table 5.17 Results of ANN Models

| Model | Architecture | Performance Parameters | $T_1$ | Epochs |
|---|---|---|---|---|
| ANN 1 | 8:4:1 | r | 0.99 | 34 |
| | | RMSE | 0.018 | |
| | | CE | 0.99 | |
| Model | Architecture | Performance Parameters | Maximum Base Shear | Epochs |
| ANN 2 | 8:16:1 | r | 0.99 | 50 |
| | | RMSE | 24.44 | |
| | | CE | 0.99 | |
| Model | Architecture | Performance Parameters | Maximum Top Floor Displacement | Epochs |
| ANN 3 | 8:16:1 | r | 0.99 | 28 |
| | | RMSE | 1.84 | |
| | | CE | 0.97 | |

Table 5.17 shows that the ANN models fairly estimate the shorter period of vibration, maximum base shear force and maximum top floor displacement as it is seen from statistical parameters r, RMSE and CE. Scatter plots for period of vibration, maximum base shear force and maximum top floor displacement are shown in Figure Nos. 5.7, 5.8 and 5.9.

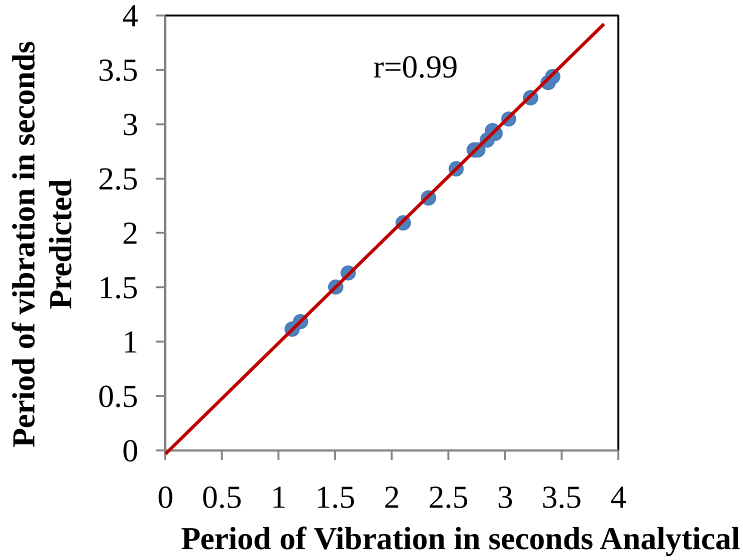


Figure 5.7 Scatter plot for shorter period of vibration

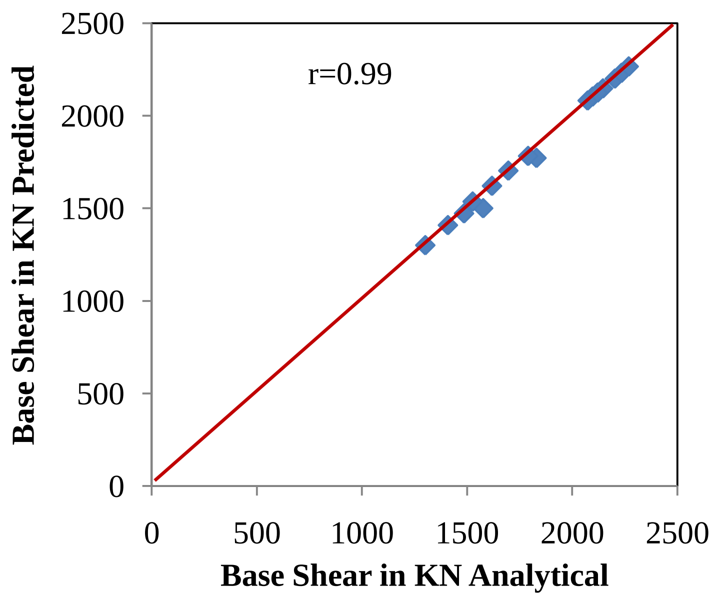


Figure 5.8 Scatter plot for maximum base shear force

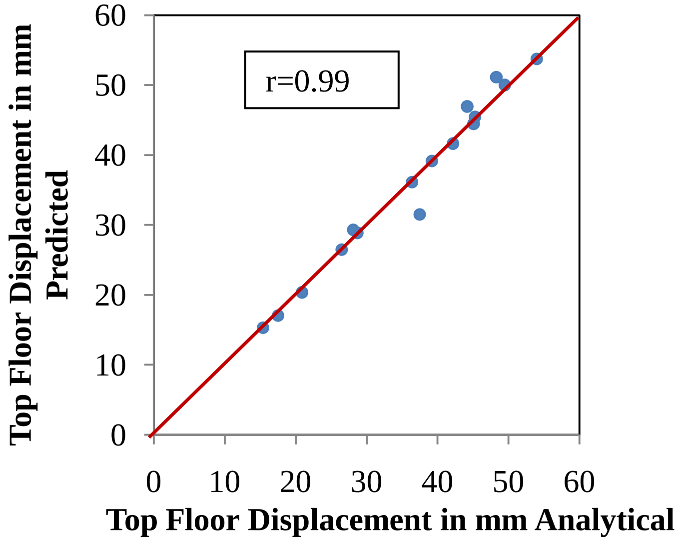


Figure 5.9 Scatter plot for maximum top floor displacement

Here also the scatter plots shown above are a good indication of performance of developed ANN models. All the predicted values are in close comparison of analytical values.

Table 5.18 indicates the empirical equations for determining shorter period of vibration, obtained through validation and testing data set. Here also correction factor of 0.9 has been applied along the transverse direction.

Table 5.18 Empirical equations for shorter period of vibration

| Sr. No. | ANN Equation without correction | ANN Equation with correction |
|---|---|---|
| 1 | T= 0.04 H | T= 0.036 H |
| 2 | T= 0.112 $H^{0.75}$ | T= 0.100 $H^{0.75}$ |
| 3 | T=0.175 $H/\sqrt{W}$ | T=0.157 $H/\sqrt{W}$ |

Following equation is suggested for the estimation of shorter period of vibration.

T= 0.036 H Eq. (5.22)

The predicted values of the lateral displacement by ANN technique are correlated with the height of the building. The following equation is obtained by regression analysis which is applied to the analytical data set of for validation.

$D_{max}$ = 0.642H Eq.(5.23)

Using Eq. 5.22 and Eq. 5.23, data set is generated in terms of the height of the building, minimum period of the building and maximum displacement of the buildings as shown in Table 5.19.

Table 5.19 Shorter period of vibration and Maximum top floor displacement

| H in meter | $T_{min}$ in seconds | $D_{max}$ in mm. | H in meter | $T_{min}$ in seconds | $D_{max}$ in mm. |
|---|---|---|---|---|---|
| 10 | 0.36 | 6.42 | 110 | 3.96 | 70.62 |
| 20 | 0.72 | 12.84 | 120 | 4.32 | 77.04 |
| 30 | 1.08 | 19.26 | 130 | 4.68 | 83.46 |
| 40 | 1.44 | 25.68 | 140 | 5.04 | 89.88 |
| 50 | 1.8 | 32.1 | 150 | 5.4 | 96.3 |
| 60 | 2.16 | 38.52 | 160 | 5.76 | 102.72 |
| 70 | 2.52 | 44.94 | 170 | 6.12 | 109.14 |
| 80 | 2.88 | 51.36 | 180 | 6.48 | 115.56 |
| 90 | 3.24 | 57.78 | 190 | 6.84 | 121.98 |

Based on data set presented in Table 5.19, following equation is obtained by regression analysis:

$D_{max} = 17.85\ T_{min}$ Eq. (5.24)

### 5.9 Application of GP for Dynamic Analysis of Unsymmetric R.C. Building Frames

GP technique is applied for performing dynamic analysis of shear wall dominant asymmetric R.C. building frames. The methodology, geometry and model formulation is already discussed in article 5.8.1. The results are discussed in following paragraphs.

#### 5.9.1 Results and Discussions

As mentioned before, GP modeling has been applied for the dynamic analysis of the un symmetric shear wall dominant R.C. building frames. The results are presented below in the Table 5.20.

Table 5.20 Results of GP Models

| Model | Performance Parameters | $T_1$ |
|---|---|---|
| GP 1 | r | 0.99 |
| | RMSE | 0.38 |
| | CE | 0.75 |
| Model | Performance Parameters | Maximum Base Shear |
| GP 2 | r | 0.96 |
| | RMSE | 116 |
| | CE | 0.8 |

| Model | Performance Parameters | Maximum Top Floor Displacement |
|---|---|---|
| GP 3 | r | 0.98 |
| | RMSE | 2.31 |
| | CE | 0.96 |

Table no. 5.20 indicates that the performance of the GP models is good as seen from ‘r’ and ‘CE’ values. All ‘rmse’ values are higher than that obtained from developed ANN models.

The hypothesis obtained from the developed GP models is as below:

$$T = \frac{H^{1.3}\sqrt{D_{cmin}A_{swy}}h}{L\ A_{swx}{}^{0.9}\ \sqrt{W}} \qquad \text{Eq. (5.25)}$$

Upon substituting the values of the parameters other than H and W, the equation reduces to

$$T=\frac{0.0443H^{1.3}}{\sqrt{W}} \qquad \text{Eq. (5.26)}$$

Applying correction factor of 0.9, further the equation is reduced to

$$T=\frac{0.04H^{1.3}}{\sqrt{W}} \qquad \text{Eq. (5.27)}$$

It can be observed that inverse square root proportion of width of the building over period of vibration is shown by GP hypothesis.

**5.10 Application of WNN in Dynamic Analysis of Unsymmetrical Buildings**

WNN technique is also applied for performing dynamic analysis of shear wall dominant un symmetric R.C. building frames. The methodology, geometry and model formulation remain same as that for ANN modeling. The results are discussed in the following article.

**5.10.1 Results and Discussions**

WNN models are developed in three categories as in case of ANN modeling. The assessment of these models is presented in Table 5.21.

Table 5.21 Results of WNN Models

| Model | Architecture | Performance Parameters | $T_1$ | Epochs |
|---|---|---|---|---|
| WNN 1 | 8:4:1<br>8:6:1 | r | 0.99 | 18<br>17 |
| | | RMSE | 0.108 | |
| | | CE | 0.97 | |
| Model | Architecture | Performance Parameters | Maximum Base Shear | Epochs |
| WNN 2 | 8:4:1<br>8:16:1 | r | 0.98 | 43<br>29 |
| | | RMSE | 66.14 | |
| | | CE | 0.96 | |
| Model | Architecture | Performance Parameters | Maximum Top Floor Displacement | Epochs |
| WNN 3 | 8:4:1<br>8:11:1 | r | 0.99 | 36<br>27 |
| | | RMSE | 2.49 | |
| | | CE | 0.95 | |

Table 5.21 shows very satisfactory performance of WNN models. However, 'rmse' values obtained are more than that obtained from ANN models. Table 5.22 indicates the empirical equations for determining shorter period of vibration, obtained through validation and testing data set. Here also correction factor of 0.9 has been applied along the transverse direction.

Table 5.22 Empirical equations for shorter period of vibration

| Sr. No. | WNN Equation without correction | WNN Equation with correction |
|---|---|---|
| 1 | T= 0.0387 H | T= 0.0348 H |
| 2 | T= 0.108 $H^{0.75}$ | T= 0.097 $H^{0.75}$ |
| 3 | T=0.169 $H/\sqrt{W}$ | T=0.152 $H/\sqrt{W}$ |

Following equation is suggested for the estimation of shorter period of vibration.

T= 0.0348 H Eq. (5.28)

The predicted values of the lateral displacement by WNN technique are correlated with the height of the building. The following equation is obtained by regression analysis which is applied to the analytical data set of for validation.

$D_{max}$ = 0.63H Eq. (5.29)

Using Eq. 5.28 and Eq. 5.29, data set is generated in terms of the height of the building, minimum period of the building and maximum displacement of the buildings as shown in Table 5.23.

Table 5.23 Shorter period of vibration and Maximum top floor displacement

| H in meter | $T_{min}$ in seconds | $D_{max}$ in mm. | H in meter | $T_{min}$ in seconds | $D_{max}$ in mm. |
|---|---|---|---|---|---|
| 10 | 0.36 | 6.3 | 110 | 3.96 | 69.3 |
| 20 | 0.72 | 12.6 | 120 | 4.32 | 75.6 |
| 30 | 1.08 | 18.9 | 130 | 4.68 | 81.9 |
| 40 | 1.44 | 25.2 | 140 | 5.04 | 88.2 |
| 50 | 1.8 | 31.5 | 150 | 5.4 | 94.5 |
| 60 | 2.16 | 37.8 | 160 | 5.76 | 100.8 |
| 70 | 2.52 | 44.1 | 170 | 6.12 | 107.1 |
| 80 | 2.88 | 50.4 | 180 | 6.48 | 113.4 |
| 90 | 3.24 | 56.7 | 190 | 6.84 | 119.7 |
| 100 | 3.6 | 63 | 200 | 7.2 | 126 |

Based on data set presented in Table 5.23, following equation is obtained by regression analysis:

$D_{max} = 17.5\ T_{min}$ Eq. (5.30)

**5.11 Validation of equation of Period of Vibration**

The data set of period of vibration considered by Hatzigeorgiou and Kanapitsas, (2013), has been referred for the purpose of validating the equation suggested by the data driven techniques. The comparison is indicated in Table 5.24:

Table 5.24 Validation of Proposed Equations of Period of Vibration

| Height in m. | Width in m | $T_{medium\ dense\ sand}$ in Seconds | T by Eq. (5.1) in Seconds | T by Eq. (5.22) in Seconds | T by Eq.(5.27) in Seconds | T by Eq.(5.28) in Seconds | T by Eq.(5.8) in Seconds |
|---|---|---|---|---|---|---|---|
| 15.00 | 10.55 | 0.62 | 0.42 | 0.54 | 0.46 | 0.52 | 0.55 |
| 15.00 | 9.50 | 0.79 | 0.44 | 0.54 | 0.48 | 0.52 | 0.55 |
| 18.00 | 15.70 | 0.83 | 0.41 | 0.64 | 0.48 | 0.63 | 0.63 |
| 15.00 | 11.10 | 0.39 | 0.41 | 0.54 | 0.45 | 0.52 | 0.55 |
| 12.80 | 11.25 | 0.49 | 0.34 | 0.46 | 0.36 | 0.44 | 0.49 |
| 12.80 | 9.45 | 0.61 | 0.37 | 0.46 | 0.39 | 0.44 | 0.49 |
| 15.75 | 15.40 | 0.64 | 0.36 | 0.56 | 0.41 | 0.55 | 0.58 |
| 19.20 | 15.30 | 0.67 | 0.44 | 0.69 | 0.53 | 0.67 | 0.67 |
| 27.00 | 11.70 | 0.91 | 0.71 | 0.97 | 0.94 | 0.94 | 0.86 |
| 15.00 | 14.25 | 0.50 | 0.36 | 0.54 | 0.39 | 0.52 | 0.55 |
| 17.80 | 18.00 | 0.59 | 0.38 | 0.64 | 0.44 | 0.62 | 0.63 |
| 16.20 | 17.50 | 0.57 | 0.35 | 0.58 | 0.39 | 0.56 | 0.59 |
| 11.90 | 16.90 | 0.48 | 0.26 | 0.43 | 0.27 | 0.41 | 0.47 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15.00 | 12.95 | 0.51 | 0.37 | 0.54 | 0.42 | 0.52 | 0.55 |
| 15.00 | 10.15 | 0.58 | 0.42 | 0.54 | 0.471 | 0.52 | 0.55 |
| 9.00 | 24.45 | 0.23 | 0.16 | 0.32 | 0.16 | 0.31 | 0.38 |
| 18.00 | 14.00 | 0.57 | 0.43 | 0.65 | 0.51 | 0.63 | 0.63 |
| 8.80 | 23.45 | 0.36 | 0.16 | 0.32 | 0.15 | 0.31 | 0.38 |
| 8.80 | 20.55 | 0.36 | 0.17 | 0.32 | 0.16 | 0.31 | 0.38 |
| 8.80 | 20.30 | 0.51 | 0.17 | 0.32 | 0.17 | 0.31 | 0.37 |

Table 5.24 indicate that the equation Eq. (5.22) fairly estimate the period values close to those obtained for dense sand, than that obtained by using IS 1893 (Part1): 2002 recommended equation (Eq. 5.1). The equation suggested by Hatzigeorgiouand Kanapitsas (2013), gives closer values as it can be seen from the Table 5.24. But the form of the equation is quite tedious as against the Eq. (5.22). Also the Eq. (5.27) and Eq. (5.1) gives similar values of period of vibration. As IS 1893 (Part 1): 2002 recommends the use of Eq. (5.1) to determine base shear force, the base shear force found out using this equation might overestimate the base shear force. Eventually the buildings are required to be designed for excessive base shear force. In the next article, attempt is made to develop the response spectrum using period value obtained from Eq. (5.27) and spectral acceleration coefficients obtained for actual base shear force.

**5.12 Modified Response Spectrum**

Desai and Chaudhari(2014) have shown the comparison of actual response spectrum at important locations of Mumbai city with the response spectrum recommended by IS 1893 (Part 1): 2002, as shown in Figure 1.3 and Figure 1.4. The response spectrum suggested for 2475 years of return period has been considered for the further analysis. Average spectral acceleration is assumed as 0.455 m/s$^2$. Spectral acceleration coefficient for zone 3 is 2.84. The response spectrum in terms of spectral acceleration coefficients is shown below in Figure 5.10.

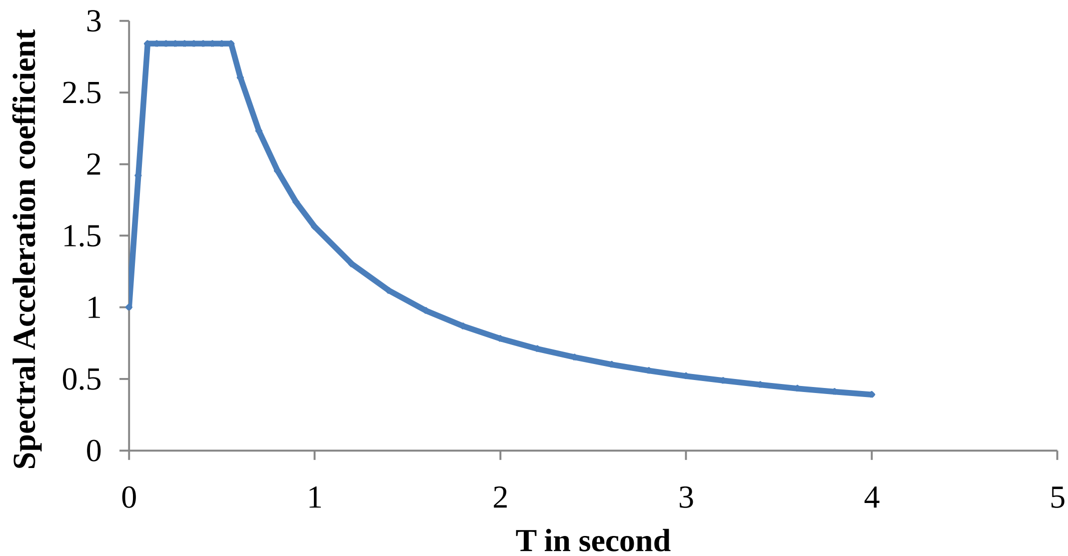


Figure 5.10 Spectral Acceleration Coefficients for Mumbai City (Desai and Chaudhary, 2014)

The spectral acceleration coefficients ($S_a/g$) are obtained using Figure 5.10 by substituting the actual values of period values from ETABS analysis. A data set is generated in terms of the period of vibration obtained using Eq. (5.27) and ($S_a/g$). Table 5.25 presents the data set so generated for which WNN technique is applied.

Table 5.25 Spectral Acceleration coefficient for WNN Modeling

| T in Seconds by Eq. (5.27) | Spectral Acceleration Coefficient | T in Seconds by Eq. (5.27) | Spectral Acceleration Coefficient |
|---|---|---|---|
| 1.57 | 1.01 | 1.18 | 0.80 |
| 1.46 | 1.10 | 1.08 | 0.87 |
| 1.35 | 1.19 | 0.99 | 0.95 |
| 1.24 | 1.31 | 0.90 | 1.04 |
| 1.13 | 1.44 | 0.81 | 1.15 |
| 1.03 | 1.59 | 0.72 | 1.28 |
| 0.93 | 1.77 | 0.64 | 1.45 |
| 0.83 | 2.00 | 3.68 | 0.42 |
| 0.73 | 2.28 | 3.52 | 0.44 |
| 0.64 | 2.64 | 3.36 | 0.46 |
| 0.55 | 3.12 | 3.20 | 0.48 |
| 1.96 | 0.96 | 3.04 | 0.51 |
| 1.84 | 1.03 | 2.88 | 0.53 |
| 1.73 | 1.10 | 2.73 | 0.56 |

| | | | |
|---|---|---|---|
| 1.62 | 1.19 | 2.57 | 0.60 |
| 1.51 | 1.28 | 2.42 | 0.63 |
| 1.40 | 1.39 | 2.27 | 0.67 |
| 1.29 | 1.52 | 2.88 | 0.38 |
| 1.19 | 1.67 | 2.73 | 0.41 |
| 1.09 | 1.84 | 2.59 | 0.43 |
| 0.99 | 2.05 | 2.45 | 0.46 |
| 0.89 | 2.30 | 2.31 | 0.48 |
| 1.78 | 0.54 | 2.18 | 0.51 |
| 1.68 | 0.57 | 2.05 | 0.55 |
| 1.58 | 0.61 | 1.92 | 0.59 |
| 1.47 | 0.65 | 1.79 | 0.63 |
| 1.37 | 0.69 | 1.66 | 0.68 |
| 1.27 | 0.74 | 1.53 | 0.74 |

Further db 30 wavelet is applied to the data set and the spectral acceleration coefficients are predicted. ANN and GP tools were also applied to predict the spectral acceleration coefficients but these tools did not give the satisfactory performance. Further several db wavelets were tried but db30 wavelet gave satisfactory results. Figure 5.11 shows the predicted values of spectral acceleration coefficient by WNN technique along with the curve which fits these values.

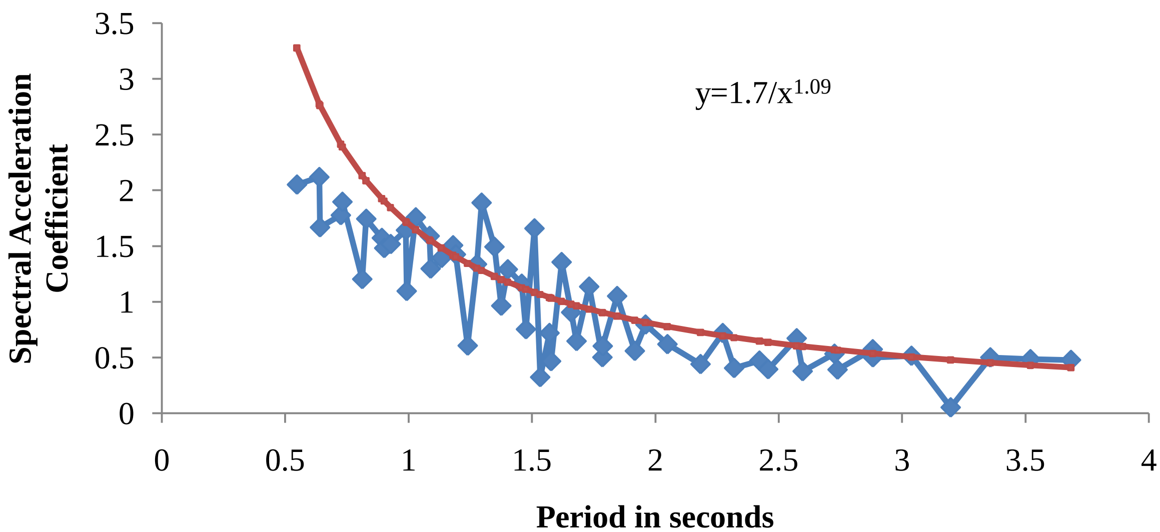


Figure 5.11 Spectral Acceleration Coefficients by WNN technique

IS 1893 (Part1): 2002 assumes the relation between the spectral acceleration coefficients and period of vibration for medium soil as:

$S_{a/g} = 1+15T \quad 0.00 \leq T \leq 0.10$ Eq. (5.31)

$S_{a/g} = 2.5 \quad 0.10 \leq T \leq 0.55$ Eq. (5.32)

$S_{a/g} = 1.36/T \quad 0.55 \leq T \leq 4.00$ Eq. (5.33)

Wavelet Neural Network technique has given following equation for the values of T between 0.55 seconds to 4.00 seconds:

$S_{a/g} = 1.70/ T^{1.09}$ Eq. (5.34)

Following the methodology adopted by IS 1893 (Part1):2002, spectral acceleration coefficients for other values of T are found out and presented in the Table 5.26.

Table 5.26 Spectral Acceleration Coefficients of modified Response Spectra

| T in Seconds | $S_{a/g}$ in $m/s^2$ |
|---|---|
| 0 | 1.00 |
| 0.05 | 2.13 |
| 0.1 | 3.26 |
| 0.2 | 3.26 |
| 0.3 | 3.26 |
| 0.4 | 3.26 |
| 0.55 | 3.26 |
| 0.7 | 2.51 |
| 0.8 | 2.17 |
| 0.9 | 1.91 |
| 1 | 1.7 |
| 1.5 | 1.09 |
| 2 | 0.80 |
| 2.5 | 0.63 |
| 3 | 0.51 |
| 3.5 | 0.43 |
| 4 | 0.37 |

Figure 5.12 shown below is the suggested modified response spectrum to find out the base shear force.

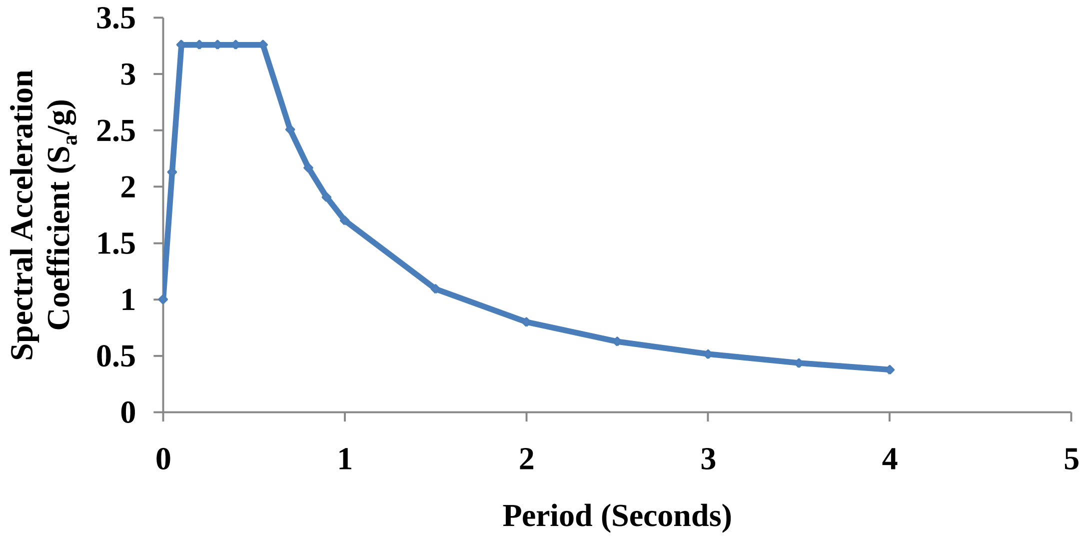


Figure 5.12 Suggested Modified Response Spectrum Coefficients

The validation of the suggested response spectrum coefficients as given in table 5.26 has been indicated in the Table 5.27.

Table 5.27 Comparison of Base Shear Force

| Sr.No. | Base Shear in KN (Actual) | Base Shear in KN (Mumbai City) | Base Shear in KN using modified response spectrum | Base Shear in KN using response spectrum recommended by IS 1893 (Part1):2002 |
|---|---|---|---|---|
| 1 | 1485.13 | 1755.12 | 1803.68 | 2210.25 |
| 2 | 1496.70 | 1807.15 | 1845.68 | 2208.45 |
| 3 | 1526.00 | 1845.23 | 1891.19 | 2206.41 |
| 4 | 1577.20 | 1887.30 | 1940.75 | 2204.11 |
| 5 | 1591.84 | 1934.34 | 1995.01 | 2201.48 |
| 6 | 1628.53 | 1983.66 | 2054.78 | 2198.44 |
| 7 | 1663.22 | 2030.78 | 2121.10 | 2194.89 |
| 8 | 1719.32 | 2105.73 | 2195.28 | 2190.71 |
| 9 | 1774.00 | 2181.16 | 2279.05 | 2185.68 |
| 10 | 1829.61 | 2258.43 | 2374.72 | 2179.54 |
| 11 | 1754.67 | 2363.77 | 2485.48 | 2171.86 |
| 12 | 1618.00 | 1879.77 | 2638.63 | 3556.60 |
| 13 | 1642.40 | 1908.23 | 2689.97 | 3556.15 |
| 14 | 1688.24 | 1938.50 | 2744.87 | 3555.65 |
| 15 | 1695.66 | 1970.13 | 2803.78 | 3555.10 |
| 16 | 1725.00 | 2004.10 | 2867.22 | 3554.49 |

| | | | | |
|---|---|---|---|---|
| 17 | 1756.14 | 2040.83 | 2935.82 | 3553.81 |
| 18 | 1789.72 | 2079.86 | 3010.34 | 3553.04 |
| 19 | 2073.00 | 2380.20 | 3979.55 | 5239.21 |
| 20 | 2347.00 | 2694.74 | 4947.88 | 5230.87 |

The comparison may better be observed through Figure 5.13.

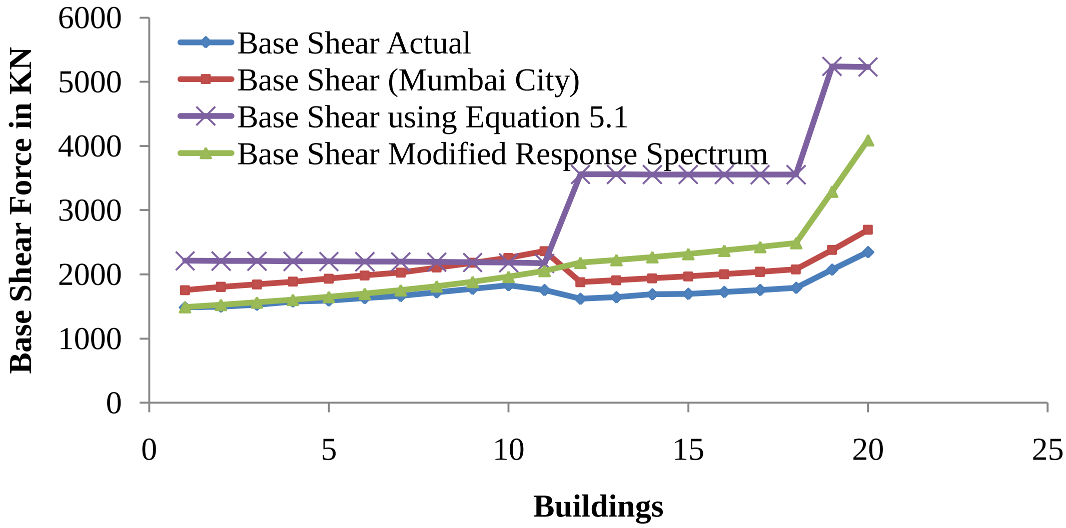


Figure 5.13 Comparison of Base Shear Force

Figure 5.13 shows suggested response spectrum coefficients gives close estimation of base shear force to the actual base shear force and base shear force found out for Mumbai City. It may also be observed that code recommended equation of period of vibration overestimates the base shear force.

**5.13 Concluding Remarks - Unsymmetrical buildings**

Three data driven techniques are applied for the dynamic analysis of shear wall dominant un-symmetric R.C. building frames. ANN and WNN techniques have given almost the same equation for determination of shorter period of vibration whereas the equation suggested by GP technique is of the different form but estimates the period values closer to those obtained by the equation suggested by many national building codes. The equation obtained by ANN and WNN techniques is found to be yielding the period values closer to the actual values. The period value derived from code recommended equation may over estimate the base shear force. To avoid overestimation of base shear, the modified response spectrum based on the WNN modeling is suggested.

# CHAPTER 6

# CONCLUSIONS AND FUTURE SCOPE

This chapter summarizes the findings of the research work undertaken and briefly discusses the future research possible in this area of the work.

## 6.1 Summary of the Current Work

In this thesis, applications of data driven tools are explored for performing dynamic analysis of building frames. These tools are applied for predicting natural periods of vibration, base shear force and top floor displacement for moment resisting frames and shear wall dominant buildings. To check adequacy of these tools, moment resisting frames are analysed and empirical equations are obtained from the testing and validation data set. These equations are further corrected for experimental error. In the study, experiments are performed on mild steel frames and negative error of 10.75% is observed in the period values of moment resisting frames. In case of shear wall dominant buildings, positive error of 9% cited in the literature is referred and applied.

It is worth to note that the empirical equations so obtained matches with the equations recommended by other researcher/s derived on the basis of measured values of the period of motion. Normally it is presumed that these tools require sizable data set to arrive at the fairly accurate results but identifying appropriate input parameters is also found as the governing factor to improve the accuracy of the developed model. Some of the key findings of the present study are presented in the next article.

## 6.2 Conclusions

The following conclusions are drawn based on the revealed results.

### 6.2.1 Proper selection of input parameters

Many national building codes/researchers have recommended period height relationship in different forms. But while developing the models to predict the period values input parameters which represent the geometry, mass and stiffness characteristics of the buildings need to be chosen. The models developed without using parameters pertaining to stiffness characteristics of the building gave unsatisfactory results, which are not presented in the thesis.

### 6.2.2 Development of models using experimental data set

An attempt is made to develop these models for the experimental data set available in the literature. It is observed that the models so developed showed consolidated performance. The reason may be in the smaller data set or insufficient input parameters available for developing these models. However the empirical equation obtained from the experimental dataset along Y direction matched with the derived empirical equations from these data driven tools after incorporating the experimental correction. Also the derived equation from experimental data set along X direction is similar to the equation recommended by New Zealand code. Hence the models are developed based on the analytical dataset and the empirical equations derived are corrected for experimental corrections.

### 6.2.3 Fundamental period of vibration

ANN, GP and WNN tools are used to predict the fundamental period of vibration.

**For moment resisting frames**:

All these tools suggested the same equation as mentioned below:

$T=0.038\ H$ Eq. (6.1)

The equation of period of vibration along X direction derived from ANN and WNN is very close to the one recommended by IS 1893 (Part1):2002. The equation along X direction derived from WNN is almost same as lower bound equation suggested by Goel and Chopra, 1997. The GP tool has shown the equation along X direction in terms of $3/4^{th}$ power of height of the building.

The equation of period of vibration along Y direction derived from ANN tool is close to the best fit equation recommended by Goel and Chopra (1997). The equation derived from WNN tool is close to the upper bound equation suggested by Goel and Chopra (1997).

**For shear wall dominant symmetric buildings**

ANN and WNN tools have suggested almost the equation for shorter period of vibration which is shown below:

$T= 0.22\ H$ Eq. (6.2)

The equation is validated with the measured period values referred by Lee, et al. (2000).

GP tool has suggested the equation as stated below:

$T= 0.0081\ H^{1.22}$ Eq. (6.3)

The equation determines the period values always lesser than the measured values referred by Lee, et al. (2000).

The equation suggested by IS 1893 (Part1):2002 has estimated the period values more than the measured values.

**For shear wall dominant unsymmetrical buildings**

ANN and WNN tools have suggested almost the same equation for shorter period of vibration which is shown below:

$$T= 0.36\, H \qquad \text{Eq. (6.4)}$$

The equation is validated with the measured period values referred by Hatzigeorgiou and Kanapitsas (2013). The equation estimates the values closer to the measured period values.

GP tool has suggested following equation:

$$T=\frac{0.04H^{1.3}}{\sqrt{W}} \qquad \text{Eq. (6.5)}$$

The inverse proportion of base dimension on the period of vibration is shown by GP tool.

It is observed that the values of period of vibration obtained using GP recommended equation is slightly more than the values by code recommended equation but lesser than the measured period values.

### 6.2.4 Base shear force and top floor displacement

In case of unsymmetrical buildings, the base shear obtained using code recommended period equation overestimates the base shear force. The Eq. (6.5) is used to find out the base shear force referring the modified response spectrum coefficients. The overestimation in the base shear force is reduced with the modifications suggested in the response spectrum. The top floor displacement is found to be a function of shorter period of vibration in case of symmetric and unsymmetrical shears wall dominant buildings.

### 6.2.5 Performance of data driven tools

ANN, GP and WNN tools performed equally well in case of predicting period of vibration of different types of buildings. GP and WNN tools have predicted the base shear force on higher side. ANN tool predicted base shear force fairly well. Top floor displacement values predicted by GP and WNN tools are also on higher side. ANN tool in this case also performed fairly well. In case of WNN tool, detail coefficients which are related to low scale and high frequency components values are removed from the database and the model is developed. This resulted in lower prediction of period values and higher prediction of base shear force and top floor displacement. GP tool works on the principle of survival of fittest. It derives the equation based on chosen functional nodes. This resulted in lower prediction of period values and higher prediction of base shear force and top floor displacement.

### 6.3 Future Research Scope

The results in this study and the conclusions drawn from them point towards the necessity of conducting non linear analysis of the structures. This research only focuses on dynamic analysis of reinforced concrete buildings performing linear analysis of the buildings. The future research directions may include:

1) Studying response of the buildings by performing non linear dynamic analysis of the buildings.

2) Studying the effect of soil structure interaction and masonry infill on the seismic behavior of the buildings.

3)Exploring real potential of wavelet transform to decompose the ground acceleration time history for non linear dynamic analysis of building frames. Particularly it will help in analyzing the buildings in seismic prone area that is zone numbers IV and V as suggested by BIS 1893 (Part1):2002.

In general, even though the data driven techniques selected for the present study are applied to the analytical data set, the empirical equations obtained from their predictions are observed to be yielding the values closer to the experimental values. This potential of data driven techniques may be further explored for performance based analysis. Further these techniques may be used for damage detection of the buildings as well.

# CHAPTER 7

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# APPENDIX A

Database used for Development of Data Driven Models for Moment Resisting Frames

Table A1- Data Along X Direction

| L (m) | W (m) | $N_c$ | $N_B$ | $W_{cmin}$ ( m) | $W_{cmax}$( m) | $D_{cmin}$ (m) | $D_{cmax}$ (m) | H (m) | h (m) | n | $T_{1x}$ (seconds) | $BS_x$ (KN) | Top Displacement x (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 9 | 20 | 31 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.61 | 204.85 | 4.19 |
| 14 | 10.5 | 20 | 31 | 0.3 | 0.3 | 0.3 | 0.3 | 14 | 3.5 | 4 | 0.84 | 200.12 | 5.82 |
| 11.5 | 11.5 | 16 | 24 | 0.3 | 0.45 | 0.3 | 0.45 | 14 | 3.5 | 4 | 0.55 | 280.77 | 3.76 |
| 14 | 14 | 16 | 24 | 0.3 | 0.45 | 0.3 | 0.45 | 12 | 3 | 4 | 0.45 | 332.42 | 2.51 |
| 16 | 15 | 42 | 71 | 0.45 | 0.45 | 0.45 | 0.45 | 14 | 3.5 | 4 | 0.37 | 558.98 | 1.70 |
| 17 | 20 | 36 | 60 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.69 | 464.37 | 4.75 |
| 32 | 26 | 99 | 178 | 0.3 | 0.45 | 0.3 | 0.45 | 12 | 3 | 4 | 0.47 | 1451.02 | 2.82 |
| 36 | 27 | 63 | 110 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.77 | 999.66 | 5.34 |
| 24 | 24 | 49 | 84 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.74 | 677.80 | 5.08 |
| 22.5 | 22.5 | 49 | 84 | 0.3 | 0.3 | 0.3 | 0.3 | 15 | 3 | 5 | 0.83 | 681.98 | 5.75 |
| 18.5 | 18.75 | 36 | 60 | 0.3 | 0.3 | 0.3 | 0.3 | 15 | 3 | 5 | 0.86 | 474.74 | 5.98 |
| 16 | 11.5 | 20 | 31 | 0.3 | 0.45 | 0.3 | 0.45 | 17.5 | 3.5 | 5 | 0.69 | 363.43 | 4.77 |
| 32 | 32 | 81 | 144 | 0.3 | 0.3 | 0.3 | 0.3 | 17.5 | 3.5 | 5 | 1.26 | 902.38 | 9.00 |
| 23 | 20 | 49 | 84 | 0.3 | 0.53 | 0.3 | 0.53 | 15 | 3 | 5 | 0.47 | 938.56 | 2.75 |
| 24 | 18 | 45 | 76 | 0.45 | 0.45 | 0.45 | 0.45 | 17.5 | 3.5 | 5 | 0.54 | 1048.29 | 3.67 |
| 31 | 19 | 77 | 136 | 0.3 | 0.53 | 0.3 | 0.53 | 15 | 3 | 5 | 0.45 | 1351.35 | 2.52 |
| 31.3 | 12.5 | 50 | 85 | 0.45 | 0.53 | 0.45 | 0.53 | 15 | 3 | 5 | 0.32 | 904.53 | 1.30 |
| 30.5 | 20.5 | 63 | 110 | 0.45 | 0.45 | 0.45 | 0.45 | 17.5 | 3.5 | 5 | 0.51 | 1452.25 | 3.24 |
| 22 | 13 | 28 | 45 | 0.3 | 0.53 | 0.3 | 0.53 | 17.5 | 3.5 | 5 | 0.50 | 674.91 | 3.19 |
| 24 | 18 | 63 | 110 | 0.3 | 0.45 | 0.3 | 0.45 | 18 | 3 | 6 | 0.65 | 1029.28 | 4.53 |
| 24 | 24 | 81 | 144 | 0.3 | 0.53 | 0.3 | 0.53 | 21 | 3.5 | 6 | 0.74 | 1298.48 | 5.18 |
| 19 | 23 | 56 | 97 | 0.45 | 0.45 | 0.45 | 0.45 | 18 | 3 | 6 | 0.43 | 1234.08 | 2.32 |
| 19 | 14 | 35 | 58 | 0.45 | 0.45 | 0.45 | 0.45 | 21 | 3.5 | 6 | 0.56 | 819.30 | 3.90 |
| 25.5 | 10.5 | 32 | 52 | 0.53 | 0.6 | 0.53 | 0.6 | 18 | 3 | 6 | 0.30 | 806.08 | 1.16 |
| 25.5 | 22 | 64 | 112 | 0.45 | 0.6 | 0.45 | 0.6 | 18 | 3 | 6 | 0.38 | 1533.72 | 1.84 |
| 19.5 | 17 | 30 | 49 | 0.3 | 0.45 | 0.3 | 0.45 | 18 | 3 | 6 | 0.64 | 709.34 | 4.41 |
| 17 | 18 | 25 | 40 | 0.45 | 0.6 | 0.45 | 0.6 | 18 | 3 | 6 | 0.37 | 761.79 | 1.72 |
| 14 | 12 | 16 | 24 | 0.3 | 0.45 | 0.3 | 0.45 | 21 | 3.5 | 6 | 0.78 | 341.88 | 5.48 |
| 14 | 8 | 12 | 17 | 0.3 | 0.53 | 0.3 | 0.53 | 21 | 3.5 | 6 | 0.58 | 344.91 | 3.98 |
| 26 | 24 | 49 | 84 | 0.45 | 0.45 | 0.45 | 0.45 | 21 | 3 | 7 | 0.66 | 1621.30 | 4.56 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 35 | 14 | 40 | 67 | 0.3 | 0.53 | 0.3 | 0.53 | 21 | 3 | 7 | 0.69 | 1243.54 | 4.82 |
| 18 | 20.5 | 36 | 60 | 0.45 | 0.6 | 0.45 | 0.6 | 24.5 | 3.5 | 7 | 0.62 | 1230.11 | 4.32 |
| 18 | 13 | 24 | 38 | 0.6 | 0.6 | 0.6 | 0.6 | 24.5 | 3.5 | 7 | 0.46 | 957.70 | 2.74 |
| 26.3 | 19.5 | 56 | 97 | 0.3 | 0.45 | 0.3 | 0.45 | 21 | 3 | 7 | 0.80 | 1091.61 | 5.61 |
| 22.5 | 17.5 | 42 | 71 | 0.53 | 0.53 | 0.53 | 0.53 | 21 | 3 | 7 | 0.39 | 1275.04 | 1.93 |
| 24.5 | 21 | 72 | 127 | 0.3 | 0.53 | 0.3 | 0.53 | 24.5 | 3.5 | 7 | 0.79 | 1291.96 | 5.55 |
| 26 | 21 | 72 | 127 | 0.45 | 0.6 | 0.45 | 0.6 | 24.5 | 3.5 | 7 | 0.50 | 1979.54 | 3.15 |
| 26 | 25 | 72 | 127 | 0.6 | 0.6 | 0.6 | 0.6 | 24.5 | 3.5 | 7 | 0.38 | 2356.11 | 1.82 |
| 23.5 | 24.5 | 56 | 97 | 0.45 | 0.45 | 0.45 | 0.45 | 21 | 3 | 7 | 0.52 | 1718.97 | 3.42 |
| 24 | 20 | 63 | 110 | 0.3 | 0.53 | 0.3 | 0.53 | 24 | 3 | 8 | 0.64 | 1514.68 | 4.42 |
| 21 | 27 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 28 | 3.5 | 8 | 0.52 | 2415.53 | 3.44 |
| 28.5 | 28 | 81 | 144 | 0.3 | 0.53 | 0.3 | 0.53 | 28 | 3.5 | 8 | 0.98 | 1607.00 | 6.91 |
| 18 | 25 | 45 | 76 | 0.6 | 0.6 | 0.6 | 0.6 | 24 | 3 | 8 | 0.38 | 1847.15 | 1.81 |
| 22.8 | 21.5 | 64 | 112 | 0.53 | 0.53 | 0.53 | 0.53 | 24 | 3 | 8 | 0.39 | 1932.50 | 1.99 |
| 21 | 21.5 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 24 | 3 | 8 | 0.39 | 1927.73 | 1.94 |
| 18 | 24.5 | 54 | 93 | 0.53 | 0.6 | 0.53 | 0.6 | 24 | 3 | 8 | 0.44 | 1904.18 | 2.50 |
| 9.75 | 18.75 | 24 | 38 | 0.53 | 0.6 | 0.53 | 0.6 | 28 | 3.5 | 8 | 0.50 | 822.89 | 3.22 |
| 19.5 | 23 | 56 | 97 | 0.6 | 0.6 | 0.6 | 0.6 | 24 | 3 | 8 | 0.35 | 2019.88 | 1.59 |
| 23.5 | 29.75 | 64 | 112 | 0.3 | 0.53 | 0.3 | 0.53 | 24 | 3 | 8 | 0.81 | 1778.35 | 5.65 |
| 24.5 | 32 | 81 | 144 | 0.6 | 0.6 | 0.6 | 0.6 | 27 | 3 | 9 | 0.44 | 3607.76 | 2.46 |
| 21 | 25.5 | 56 | 97 | 0.53 | 0.53 | 0.53 | 0.53 | 27 | 3 | 9 | 0.49 | 2126.67 | 3.07 |
| 24 | 25 | 63 | 110 | 0.6 | 0.6 | 0.6 | 0.6 | 27 | 3 | 9 | 0.37 | 2496.99 | 1.78 |
| 17 | 25 | 45 | 76 | 0.53 | 0.6 | 0.53 | 0.6 | 27 | 3 | 9 | 0.44 | 1751.50 | 2.51 |
| 21.5 | 21 | 48 | 82 | 0.53 | 0.53 | 0.53 | 0.53 | 27 | 3 | 9 | 0.48 | 1881.51 | 2.89 |
| 23 | 18 | 42 | 71 | 0.6 | 0.6 | 0.6 | 0.6 | 27 | 3 | 9 | 0.40 | 1729.49 | 2.03 |
| 18 | 15.5 | 30 | 49 | 0.53 | 0.53 | 0.53 | 0.53 | 27 | 3 | 9 | 0.50 | 1312.66 | 3.24 |
| 21 | 15.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 27 | 3 | 9 | 0.45 | 1548.58 | 2.62 |
| 21 | 14 | 35 | 58 | 0.45 | 0.6 | 0.45 | 0.6 | 27 | 3 | 9 | 0.47 | 1272.10 | 2.77 |
| 19.5 | 14 | 30 | 49 | 0.45 | 0.6 | 0.45 | 0.6 | 27 | 3 | 9 | 0.48 | 1153.42 | 2.93 |
| 24 | 24 | 81 | 144 | 0.6 | 0.6 | 0.6 | 0.6 | 30 | 3 | 10 | 0.40 | 3321.01 | 2.05 |
| 18.5 | 29 | 63 | 110 | 0.6 | 0.6 | 0.6 | 0.6 | 30 | 3 | 10 | 0.42 | 2897.48 | 2.30 |
| 29 | 18.5 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 35 | 3.5 | 10 | 0.61 | 2555.43 | 4.22 |
| 28.5 | 24 | 63 | 110 | 0.6 | 0.6 | 0.6 | 0.6 | 35 | 3.5 | 10 | 0.63 | 3161.71 | 4.36 |
| 26 | 18.5 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 35 | 3.5 | 10 | 0.61 | 2362.37 | 4.27 |
| 25.5 | 14 | 45 | 76 | 0.6 | 0.6 | 0.6 | 0.6 | 30 | 3 | 10 | 0.44 | 2000.84 | 2.43 |
| 32.5 | 22 | 80 | 142 | 0.53 | 0.53 | 0.53 | 0.53 | 30 | 3 | 10 | 0.55 | 3718.76 | 3.81 |
| 27.5 | 19 | 63 | 110 | 0.53 | 0.6 | 0.53 | 0.6 | 35 | 3.5 | 10 | 0.61 | 2444.80 | 4.24 |
| 21 | 25.5 | 63 | 110 | 0.53 | 0.6 | 0.53 | 0.6 | 30 | 3 | 10 | 0.47 | 2507.58 | 2.85 |
| 13.5 | 25.5 | 45 | 76 | 0.45 | 0.6 | 0.45 | 0.6 | 30 | 3 | 10 | 0.58 | 1565.65 | 4.06 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | 22 | 56 | 97 | 0.6 | 0.6 | 0.6 | 0.6 | 33 | 3 | 11 | 0.47 | 2637.01 | 2.82 |
| 29 | 28 | 72 | 127 | 0.75 | 0.75 | 0.75 | 0.75 | 33 | 3 | 11 | 0.34 | 4200.10 | 1.43 |
| 25 | 28 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 33 | 3 | 11 | 0.55 | 3403.30 | 3.81 |
| 23.5 | 20.5 | 36 | 60 | 0.75 | 0.75 | 0.75 | 0.75 | 33 | 3 | 11 | 0.35 | 2550.62 | 1.59 |
| 13 | 12 | 25 | 40 | 0.6 | 0.75 | 0.6 | 0.75 | 38.5 | 3.5 | 11 | 0.46 | 1232.50 | 2.71 |
| 17 | 12 | 30 | 49 | 0.6 | 0.75 | 0.6 | 0.75 | 38.5 | 3.5 | 11 | 0.47 | 1541.21 | 2.82 |
| 12.5 | 18.5 | 24 | 38 | 0.75 | 0.75 | 0.75 | 0.75 | 33 | 3 | 11 | 0.34 | 1427.12 | 1.46 |
| 13 | 25 | 28 | 45 | 0.6 | 0.75 | 0.6 | 0.75 | 33 | 3 | 11 | 0.46 | 1768.45 | 2.68 |
| 31 | 17 | 45 | 76 | 0.6 | 0.75 | 0.6 | 0.75 | 33 | 3 | 11 | 0.43 | 2833.23 | 2.40 |
| 25.5 | 14 | 40 | 67 | 0.6 | 0.75 | 0.6 | 0.75 | 36 | 3 | 12 | 0.44 | 2350.21 | 2.43 |
| 33 | 32 | 81 | 144 | 0.6 | 0.6 | 0.6 | 0.6 | 36 | 3 | 12 | 0.57 | 5416.78 | 3.99 |
| 19 | 12 | 30 | 49 | 0.53 | 0.6 | 0.53 | 0.6 | 36 | 3 | 12 | 0.54 | 1437.69 | 3.73 |
| 21 | 18.75 | 42 | 71 | 0.75 | 0.75 | 0.75 | 0.75 | 36 | 3 | 12 | 0.38 | 2628.07 | 1.87 |
| 28 | 18.5 | 42 | 71 | 0.6 | 0.6 | 0.6 | 0.6 | 36 | 3 | 12 | 0.58 | 2570.17 | 4.00 |
| 27.5 | 9 | 32 | 52 | 0.6 | 0.75 | 0.6 | 0.75 | 36 | 3 | 12 | 0.41 | 1792.74 | 2.12 |
| 28 | 9 | 32 | 52 | 0.6 | 0.6 | 0.6 | 0.6 | 36 | 3 | 12 | 0.48 | 1585.72 | 2.94 |
| 21 | 24.5 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 36 | 3 | 12 | 0.54 | 3349.07 | 3.67 |
| 25 | 23 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 36 | 3 | 12 | 0.51 | 3324.48 | 3.33 |
| 31.5 | 15 | 40 | 67 | 0.75 | 0.75 | 0.75 | 0.75 | 36 | 3 | 12 | 0.42 | 2992.03 | 2.24 |
| 20 | 12 | 35 | 58 | 0.75 | 0.75 | 0.75 | 0.75 | 39 | 3 | 13 | 0.36 | 2019.55 | 1.66 |
| 29 | 20 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 45.5 | 3.5 | 13 | 0.80 | 2635.66 | 5.63 |
| 19.5 | 25.5 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 39 | 3 | 13 | 0.48 | 3024.40 | 2.98 |
| 21 | 28 | 70 | 123 | 0.75 | 0.75 | 0.75 | 0.75 | 39 | 3 | 13 | 0.36 | 4406.21 | 1.66 |
| 27.5 | 20 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 39 | 3 | 13 | 0.54 | 3359.07 | 3.74 |
| 19 | 17.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 39 | 3 | 13 | 0.68 | 1792.27 | 4.76 |
| 28 | 19 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 39 | 3 | 13 | 0.59 | 3139.60 | 4.13 |
| 24 | 12 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 39 | 3 | 13 | 0.46 | 2152.58 | 2.75 |
| 14 | 24 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 39 | 3 | 13 | 0.55 | 2411.05 | 3.86 |
| 13.5 | 12 | 16 | 24 | 0.75 | 0.75 | 0.75 | 0.75 | 39 | 3 | 13 | 0.43 | 1173.52 | 2.37 |
| 20 | 12 | 35 | 58 | 0.75 | 0.75 | 0.75 | 0.75 | 42 | 3 | 14 | 0.39 | 2173.26 | 1.93 |
| 29 | 20 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 49 | 3.5 | 14 | 0.86 | 2643.14 | 6.08 |
| 19.5 | 25.5 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 42 | 3 | 14 | 0.52 | 3254.09 | 3.45 |
| 21 | 28 | 70 | 123 | 0.75 | 0.75 | 0.75 | 0.75 | 42 | 3 | 14 | 0.39 | 4741.27 | 1.92 |
| 27.5 | 20 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 42 | 3 | 14 | 0.58 | 3381.60 | 4.05 |
| 19 | 17.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 42 | 3 | 14 | 0.73 | 1796.20 | 5.14 |
| 28 | 19 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 42 | 3 | 14 | 0.64 | 3145.18 | 4.45 |
| 24 | 12 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 42 | 3 | 14 | 0.50 | 2316.24 | 3.18 |
| 14 | 24 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 42 | 3 | 14 | 0.59 | 2390.51 | 4.11 |
| 13.5 | 12 | 16 | 24 | 0.75 | 0.75 | 0.75 | 0.75 | 42 | 3 | 14 | 0.46 | 1262.80 | 2.74 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 12 | 35 | 58 | 0.75 | 0.75 | 0.75 | 0.75 | 45 | 3 | 15 | 0.42 | 2326.94 | 2.21 |
| 29 | 20 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 52.5 | 3.5 | 15 | 0.92 | 2650.87 | 6.53 |
| 19.5 | 25.5 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 45 | 3 | 15 | 0.56 | 3407.08 | 3.87 |
| 21 | 28 | 70 | 123 | 0.75 | 0.75 | 0.75 | 0.75 | 45 | 3 | 15 | 0.42 | 5076.25 | 2.20 |
| 27.5 | 20 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 45 | 3 | 15 | 0.62 | 3386.85 | 4.34 |
| 19 | 17.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 45 | 3 | 15 | 0.78 | 1800.21 | 5.51 |
| 28 | 19 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 45 | 3 | 15 | 0.68 | 3150.80 | 4.78 |
| 24 | 12 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 45 | 3 | 15 | 0.53 | 2479.73 | 3.65 |
| 14 | 24 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 45 | 3 | 15 | 0.63 | 2394.29 | 4.41 |
| 13.5 | 12 | 16 | 24 | 0.75 | 0.75 | 0.75 | 0.75 | 45 | 3 | 15 | 0.50 | 1352.07 | 3.14 |
| 12 | 9 | 20 | 31 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.76 | 156.06 | 5.24 |
| 14 | 10.5 | 20 | 31 | 0.23 | 0.3 | 0.23 | 0.3 | 14 | 3.5 | 4 | 1.05 | 153.41 | 7.36 |
| 11.5 | 11.5 | 16 | 24 | 0.23 | 0.3 | 0.23 | 0.3 | 14 | 3.5 | 4 | 1.16 | 121.81 | 8.19 |
| 14 | 14 | 16 | 24 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.96 | 176.92 | 6.69 |
| 16 | 15 | 42 | 71 | 0.23 | 0.3 | 0.23 | 0.3 | 14 | 3.5 | 4 | 0.96 | 285.83 | 6.70 |
| 17 | 20 | 36 | 60 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.82 | 366.66 | 5.67 |
| 32 | 26 | 99 | 178 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.76 | 983.96 | 5.23 |
| 36 | 27 | 63 | 110 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.92 | 807.65 | 6.38 |
| 24 | 24 | 49 | 84 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.87 | 546.58 | 6.07 |
| 22.5 | 22.5 | 49 | 84 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.71 | 751.07 | 4.95 |
| 18.5 | 18.75 | 36 | 60 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.75 | 509.08 | 5.19 |
| 16 | 11.5 | 20 | 31 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.13 | 212.32 | 8.01 |
| 32 | 32 | 81 | 144 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.09 | 1035.41 | 7.68 |
| 23 | 20 | 49 | 84 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.77 | 658.40 | 5.31 |
| 24 | 18 | 45 | 76 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.07 | 491.18 | 7.55 |
| 31 | 19 | 77 | 136 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.71 | 966.88 | 4.95 |
| 31.3 | 12.5 | 50 | 85 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.76 | 612.40 | 5.29 |
| 30.5 | 20.5 | 63 | 110 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 0.97 | 759.90 | 6.79 |
| 22 | 13 | 28 | 45 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.09 | 318.98 | 7.70 |
| 24 | 18 | 63 | 110 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 0.82 | 765.17 | 5.70 |
| 24 | 24 | 81 | 144 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.06 | 852.57 | 7.50 |
| 19 | 23 | 56 | 97 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 0.80 | 769.20 | 5.60 |
| 19 | 14 | 35 | 58 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.12 | 382.51 | 8.01 |
| 25.5 | 10.5 | 32 | 52 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 0.98 | 393.15 | 6.92 |
| 25.5 | 22 | 64 | 112 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 0.87 | 856.55 | 6.12 |
| 19.5 | 17 | 30 | 49 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 0.92 | 460.35 | 6.47 |
| 17 | 18 | 25 | 40 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 1.00 | 382.35 | 7.08 |
| 14 | 12 | 16 | 24 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.27 | 198.75 | 9.13 |
| 14 | 8 | 12 | 17 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.50 | 123.66 | 11.01 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 24 | 49 | 84 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 0.94 | 949.07 | 6.62 |
| 35 | 14 | 40 | 67 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 0.99 | 734.82 | 7.04 |
| 18 | 20.5 | 36 | 60 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 1.19 | 540.24 | 8.53 |
| 18 | 13 | 24 | 38 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 1.29 | 329.37 | 9.34 |
| 26.3 | 19.5 | 56 | 97 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 0.80 | 1028.92 | 5.59 |
| 22.5 | 17.5 | 42 | 71 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 0.82 | 757.18 | 5.75 |
| 24.5 | 21 | 72 | 127 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 0.94 | 1021.47 | 6.64 |
| 26 | 21 | 72 | 127 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 0.92 | 1089.11 | 6.46 |
| 26 | 25 | 72 | 127 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 0.97 | 1179.87 | 6.83 |
| 23.5 | 24.5 | 56 | 97 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 0.78 | 1137.06 | 5.45 |
| 24 | 20 | 63 | 110 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 0.81 | 1129.49 | 5.66 |
| 21 | 27 | 49 | 84 | 0.23 | 0.45 | 0.23 | 0.45 | 28 | 3.5 | 8 | 1.30 | 831.97 | 9.40 |
| 28.5 | 28 | 81 | 144 | 0.23 | 0.45 | 0.23 | 0.45 | 28 | 3.5 | 8 | 1.12 | 1363.20 | 8.01 |
| 18 | 25 | 45 | 76 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 0.91 | 877.87 | 6.39 |
| 22.8 | 21.5 | 64 | 112 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 0.80 | 1177.53 | 5.62 |
| 21 | 21.5 | 49 | 84 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 0.96 | 862.25 | 6.82 |
| 18 | 24.5 | 54 | 93 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 0.89 | 925.89 | 6.27 |
| 9.75 | 18.75 | 24 | 38 | 0.23 | 0.45 | 0.23 | 0.45 | 28 | 3.5 | 8 | 1.17 | 348.37 | 8.38 |
| 19.5 | 23 | 56 | 97 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 0.85 | 1003.79 | 6.00 |
| 23.5 | 29.75 | 64 | 112 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 0.91 | 1336.45 | 6.39 |
| 24.5 | 32 | 81 | 144 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.83 | 1857.29 | 5.86 |
| 21 | 25.5 | 56 | 97 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.80 | 1335.64 | 5.60 |
| 24 | 25 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.76 | 1605.22 | 5.30 |
| 17 | 25 | 45 | 76 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.76 | 1149.50 | 5.32 |
| 21.5 | 21 | 48 | 82 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.77 | 1208.99 | 5.39 |
| 23 | 18 | 42 | 71 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.83 | 1005.18 | 5.84 |
| 18 | 15.5 | 30 | 49 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.80 | 721.16 | 5.63 |
| 21 | 15.5 | 36 | 60 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.79 | 853.86 | 5.55 |
| 21 | 14 | 35 | 58 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.80 | 778.95 | 5.63 |
| 19.5 | 14 | 30 | 49 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.83 | 688.48 | 5.81 |
| 24 | 24 | 81 | 144 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 0.75 | 1848.08 | 5.26 |
| 18.5 | 29 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 0.80 | 1536.38 | 5.63 |
| 29 | 18.5 | 48 | 82 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.23 | 1029.38 | 8.90 |
| 28.5 | 24 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.24 | 1303.53 | 8.93 |
| 26 | 18.5 | 48 | 82 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.24 | 948.18 | 8.98 |
| 25.5 | 14 | 45 | 76 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 0.91 | 940.59 | 6.43 |
| 32.5 | 22 | 80 | 142 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 0.83 | 1970.22 | 5.84 |
| 27.5 | 19 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.09 | 1252.52 | 7.80 |
| 21 | 25.5 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 0.80 | 1532.27 | 5.62 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13.5 | 25.5 | 45 | 76 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 0.81 | 1017.31 | 5.72 |
| 22 | 22 | 56 | 97 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 0.81 | 1536.72 | 5.70 |
| 29 | 28 | 72 | 127 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 0.87 | 2197.62 | 6.10 |
| 25 | 28 | 49 | 84 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 0.92 | 1676.56 | 6.50 |
| 23.5 | 20.5 | 36 | 60 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 0.93 | 1178.45 | 6.57 |
| 13 | 12 | 25 | 40 | 0.23 | 0.6 | 0.23 | 0.6 | 38.5 | 3.5 | 11 | 1.00 | 515.38 | 7.12 |
| 17 | 12 | 30 | 49 | 0.23 | 0.6 | 0.23 | 0.6 | 38.5 | 3.5 | 11 | 1.03 | 634.37 | 7.31 |
| 12.5 | 18.5 | 24 | 38 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 0.88 | 675.62 | 6.18 |
| 13 | 25 | 28 | 45 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 0.91 | 861.37 | 6.40 |
| 31 | 17 | 45 | 76 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 0.97 | 1290.25 | 6.86 |
| 25.5 | 14 | 40 | 67 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.96 | 1051.29 | 6.83 |
| 33 | 32 | 81 | 144 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.93 | 2763.41 | 6.59 |
| 19 | 12 | 30 | 49 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.88 | 785.67 | 6.20 |
| 21 | 18.75 | 42 | 71 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.99 | 1102.84 | 7.03 |
| 28 | 18.5 | 42 | 71 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.03 | 1284.34 | 7.33 |
| 27.5 | 9 | 32 | 52 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.00 | 762.34 | 7.12 |
| 28 | 9 | 32 | 52 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.96 | 801.78 | 6.83 |
| 21 | 24.5 | 56 | 97 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.88 | 1603.07 | 6.23 |
| 25 | 23 | 48 | 82 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.97 | 1517.62 | 6.89 |
| 31.5 | 15 | 40 | 67 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.12 | 1102.50 | 8.04 |

Database used for Development of Data Driven Models for Moment Resisting Frames

Table A2 Data along Y Direction

| L (m) | W (m) | $N_c$ | $N_B$ | $W_{cmin}$ (m) | $W_{cmax}$(m) | $D_{cmin}$ (m) | $D_{cmax}$ (m) | H (m) | h (m) | n | $T_{1y}$ (seconds) | $B_{Sy}$(KN) | Top Displacement $_y$ (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 9 | 20 | 31 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.61 | 204.85 | 4.19 |
| 14 | 10.5 | 20 | 31 | 0.3 | 0.3 | 0.3 | 0.3 | 14 | 3.5 | 4 | 0.84 | 200.12 | 5.82 |
| 11.5 | 11.5 | 16 | 24 | 0.3 | 0.45 | 0.3 | 0.45 | 14 | 3.5 | 4 | 0.55 | 280.77 | 3.76 |
| 14 | 14 | 16 | 24 | 0.3 | 0.45 | 0.3 | 0.45 | 12 | 3 | 4 | 0.45 | 332.42 | 2.51 |
| 16 | 15 | 42 | 71 | 0.45 | 0.45 | 0.45 | 0.45 | 14 | 3.5 | 4 | 0.37 | 558.98 | 1.70 |
| 17 | 20 | 36 | 60 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.69 | 464.37 | 4.75 |
| 32 | 26 | 99 | 178 | 0.3 | 0.45 | 0.3 | 0.45 | 12 | 3 | 4 | 0.47 | 1451.02 | 2.82 |
| 36 | 27 | 63 | 110 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.77 | 999.66 | 5.34 |
| 24 | 24 | 49 | 84 | 0.3 | 0.3 | 0.3 | 0.3 | 12 | 3 | 4 | 0.74 | 677.80 | 5.08 |
| 22.5 | 22.5 | 49 | 84 | 0.3 | 0.3 | 0.3 | 0.3 | 15 | 3 | 5 | 0.83 | 681.98 | 5.75 |
| 18.5 | 18.75 | 36 | 60 | 0.3 | 0.3 | 0.3 | 0.3 | 15 | 3 | 5 | 0.86 | 474.74 | 5.98 |
| 16 | 11.5 | 20 | 31 | 0.3 | 0.45 | 0.3 | 0.45 | 17.5 | 3.5 | 5 | 0.69 | 363.43 | 4.77 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | 32 | 81 | 144 | 0.3 | 0.3 | 0.3 | 0.3 | 17.5 | 3.5 | 5 | 1.26 | 902.38 | 9.00 |
| 23 | 20 | 49 | 84 | 0.3 | 0.53 | 0.3 | 0.53 | 15 | 3 | 5 | 0.47 | 938.56 | 2.75 |
| 24 | 18 | 45 | 76 | 0.45 | 0.45 | 0.45 | 0.45 | 17.5 | 3.5 | 5 | 0.54 | 1048.29 | 3.67 |
| 31 | 19 | 77 | 136 | 0.3 | 0.53 | 0.3 | 0.53 | 15 | 3 | 5 | 0.45 | 1351.35 | 2.52 |
| 31.25 | 12.5 | 50 | 85 | 0.45 | 0.53 | 0.45 | 0.53 | 15 | 3 | 5 | 0.32 | 904.53 | 1.30 |
| 30.5 | 20.5 | 63 | 110 | 0.45 | 0.45 | 0.45 | 0.45 | 17.5 | 3.5 | 5 | 0.51 | 1452.25 | 3.24 |
| 22 | 13 | 28 | 45 | 0.3 | 0.53 | 0.3 | 0.53 | 17.5 | 3.5 | 5 | 0.50 | 674.91 | 3.19 |
| 24 | 18 | 63 | 110 | 0.3 | 0.45 | 0.3 | 0.45 | 18 | 3 | 6 | 0.65 | 1029.28 | 4.53 |
| 24 | 24 | 81 | 144 | 0.3 | 0.53 | 0.3 | 0.53 | 21 | 3.5 | 6 | 0.74 | 1298.48 | 5.18 |
| 19 | 23 | 56 | 97 | 0.45 | 0.45 | 0.45 | 0.45 | 18 | 3 | 6 | 0.43 | 1234.08 | 2.32 |
| 19 | 14 | 35 | 58 | 0.45 | 0.45 | 0.45 | 0.45 | 21 | 3.5 | 6 | 0.56 | 819.30 | 3.90 |
| 25.5 | 10.5 | 32 | 52 | 0.53 | 0.6 | 0.53 | 0.6 | 18 | 3 | 6 | 0.30 | 806.08 | 1.16 |
| 25.5 | 22 | 64 | 112 | 0.45 | 0.6 | 0.45 | 0.6 | 18 | 3 | 6 | 0.38 | 1533.72 | 1.84 |
| 19.5 | 17 | 30 | 49 | 0.3 | 0.45 | 0.3 | 0.45 | 18 | 3 | 6 | 0.64 | 709.34 | 4.41 |
| 17 | 18 | 25 | 40 | 0.45 | 0.6 | 0.45 | 0.6 | 18 | 3 | 6 | 0.37 | 761.79 | 1.72 |
| 14 | 12 | 16 | 24 | 0.3 | 0.45 | 0.3 | 0.45 | 21 | 3.5 | 6 | 0.78 | 341.88 | 5.48 |
| 14 | 8 | 12 | 17 | 0.3 | 0.53 | 0.3 | 0.53 | 21 | 3.5 | 6 | 0.58 | 344.91 | 3.98 |
| 26 | 24 | 49 | 84 | 0.45 | 0.45 | 0.45 | 0.45 | 21 | 3 | 7 | 0.66 | 1621.30 | 4.56 |
| 35 | 14 | 40 | 67 | 0.3 | 0.53 | 0.3 | 0.53 | 21 | 3 | 7 | 0.69 | 1243.54 | 4.82 |
| 18 | 20.5 | 36 | 60 | 0.45 | 0.6 | 0.45 | 0.6 | 24.5 | 3.5 | 7 | 0.62 | 1230.11 | 4.32 |
| 18 | 13 | 24 | 38 | 0.6 | 0.6 | 0.6 | 0.6 | 24.5 | 3.5 | 7 | 0.46 | 957.70 | 2.74 |
| 26.25 | 19.5 | 56 | 97 | 0.3 | 0.45 | 0.3 | 0.45 | 21 | 3 | 7 | 0.80 | 1091.61 | 5.61 |
| 22.5 | 17.5 | 42 | 71 | 0.53 | 0.53 | 0.53 | 0.53 | 21 | 3 | 7 | 0.39 | 1275.04 | 1.93 |
| 24.5 | 21 | 72 | 127 | 0.3 | 0.53 | 0.3 | 0.53 | 24.5 | 3.5 | 7 | 0.79 | 1291.96 | 5.55 |
| 26 | 21 | 72 | 127 | 0.45 | 0.6 | 0.45 | 0.6 | 24.5 | 3.5 | 7 | 0.50 | 1979.54 | 3.15 |
| 26 | 25 | 72 | 127 | 0.6 | 0.6 | 0.6 | 0.6 | 24.5 | 3.5 | 7 | 0.38 | 2356.11 | 1.82 |
| 23.5 | 24.5 | 56 | 97 | 0.45 | 0.45 | 0.45 | 0.45 | 21 | 3 | 7 | 0.52 | 1718.97 | 3.42 |
| 24 | 20 | 63 | 110 | 0.3 | 0.53 | 0.3 | 0.53 | 24 | 3 | 8 | 0.64 | 1514.68 | 4.42 |
| 21 | 27 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 28 | 3.5 | 8 | 0.52 | 2415.53 | 3.44 |
| 28.5 | 28 | 81 | 144 | 0.3 | 0.53 | 0.3 | 0.53 | 28 | 3.5 | 8 | 0.98 | 1607.00 | 6.91 |
| 18 | 25 | 45 | 76 | 0.6 | 0.6 | 0.6 | 0.6 | 24 | 3 | 8 | 0.38 | 1847.15 | 1.81 |
| 22.75 | 21.5 | 64 | 112 | 0.53 | 0.53 | 0.53 | 0.53 | 24 | 3 | 8 | 0.39 | 1932.50 | 1.99 |
| 21 | 21.5 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 24 | 3 | 8 | 0.39 | 1927.73 | 1.94 |
| 18 | 24.5 | 54 | 93 | 0.53 | 0.6 | 0.53 | 0.6 | 24 | 3 | 8 | 0.44 | 1904.18 | 2.50 |
| 9.75 | 18.75 | 24 | 38 | 0.53 | 0.6 | 0.53 | 0.6 | 28 | 3.5 | 8 | 0.50 | 822.89 | 3.22 |
| 19.5 | 23 | 56 | 97 | 0.6 | 0.6 | 0.6 | 0.6 | 24 | 3 | 8 | 0.35 | 2019.88 | 1.59 |
| 23.5 | 29.75 | 64 | 112 | 0.3 | 0.53 | 0.3 | 0.53 | 24 | 3 | 8 | 0.81 | 1778.35 | 5.65 |
| 24.5 | 32 | 81 | 144 | 0.6 | 0.6 | 0.6 | 0.6 | 27 | 3 | 9 | 0.44 | 3607.76 | 2.46 |
| 21 | 25.5 | 56 | 97 | 0.53 | 0.53 | 0.53 | 0.53 | 27 | 3 | 9 | 0.49 | 2126.67 | 3.07 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 25 | 63 | 110 | 0.6 | 0.6 | 0.6 | 0.6 | 27 | 3 | 9 | 0.37 | 2496.99 | 1.78 |
| 17 | 25 | 45 | 76 | 0.53 | 0.6 | 0.53 | 0.6 | 27 | 3 | 9 | 0.44 | 1751.50 | 2.51 |
| 21.5 | 21 | 48 | 82 | 0.53 | 0.53 | 0.53 | 0.53 | 27 | 3 | 9 | 0.48 | 1881.51 | 2.89 |
| 23 | 18 | 42 | 71 | 0.6 | 0.6 | 0.6 | 0.6 | 27 | 3 | 9 | 0.40 | 1729.49 | 2.03 |
| 18 | 15.5 | 30 | 49 | 0.53 | 0.53 | 0.53 | 0.53 | 27 | 3 | 9 | 0.50 | 1312.66 | 3.24 |
| 21 | 15.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 27 | 3 | 9 | 0.45 | 1548.58 | 2.62 |
| 21 | 14 | 35 | 58 | 0.45 | 0.6 | 0.45 | 0.6 | 27 | 3 | 9 | 0.47 | 1272.10 | 2.77 |
| 19.5 | 14 | 30 | 49 | 0.45 | 0.6 | 0.45 | 0.6 | 27 | 3 | 9 | 0.48 | 1153.42 | 2.93 |
| 24 | 24 | 81 | 144 | 0.6 | 0.6 | 0.6 | 0.6 | 30 | 3 | 10 | 0.40 | 3321.01 | 2.05 |
| 18.5 | 29 | 63 | 110 | 0.6 | 0.6 | 0.6 | 0.6 | 30 | 3 | 10 | 0.42 | 2897.48 | 2.30 |
| 29 | 18.5 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 35 | 3.5 | 10 | 0.61 | 2555.43 | 4.22 |
| 28.5 | 24 | 63 | 110 | 0.6 | 0.6 | 0.6 | 0.6 | 35 | 3.5 | 10 | 0.63 | 3161.71 | 4.36 |
| 26 | 18.5 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 35 | 3.5 | 10 | 0.61 | 2362.37 | 4.27 |
| 25.5 | 14 | 45 | 76 | 0.6 | 0.6 | 0.6 | 0.6 | 30 | 3 | 10 | 0.44 | 2000.84 | 2.43 |
| 32.5 | 22 | 80 | 142 | 0.53 | 0.53 | 0.53 | 0.53 | 30 | 3 | 10 | 0.55 | 3718.76 | 3.81 |
| 27.5 | 19 | 63 | 110 | 0.53 | 0.6 | 0.53 | 0.6 | 35 | 3.5 | 10 | 0.61 | 2444.80 | 4.24 |
| 21 | 25.5 | 63 | 110 | 0.53 | 0.6 | 0.53 | 0.6 | 30 | 3 | 10 | 0.47 | 2507.58 | 2.85 |
| 13.5 | 25.5 | 45 | 76 | 0.45 | 0.6 | 0.45 | 0.6 | 30 | 3 | 10 | 0.58 | 1565.65 | 4.06 |
| 22 | 22 | 56 | 97 | 0.6 | 0.6 | 0.6 | 0.6 | 33 | 3 | 11 | 0.47 | 2637.01 | 2.82 |
| 29 | 28 | 72 | 127 | 0.75 | 0.75 | 0.75 | 0.75 | 33 | 3 | 11 | 0.34 | 4200.10 | 1.43 |
| 25 | 28 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 33 | 3 | 11 | 0.55 | 3403.30 | 3.81 |
| 23.5 | 20.5 | 36 | 60 | 0.75 | 0.75 | 0.75 | 0.75 | 33 | 3 | 11 | 0.35 | 2550.62 | 1.59 |
| 13 | 12 | 25 | 40 | 0.6 | 0.75 | 0.6 | 0.75 | 38.5 | 3.5 | 11 | 0.46 | 1232.50 | 2.71 |
| 17 | 12 | 30 | 49 | 0.6 | 0.75 | 0.6 | 0.75 | 38.5 | 3.5 | 11 | 0.47 | 1541.21 | 2.82 |
| 12.5 | 18.5 | 24 | 38 | 0.75 | 0.75 | 0.75 | 0.75 | 33 | 3 | 11 | 0.34 | 1427.12 | 1.46 |
| 13 | 25 | 28 | 45 | 0.6 | 0.75 | 0.6 | 0.75 | 33 | 3 | 11 | 0.46 | 1768.45 | 2.68 |
| 31 | 17 | 45 | 76 | 0.6 | 0.75 | 0.6 | 0.75 | 33 | 3 | 11 | 0.43 | 2833.23 | 2.40 |
| 25.5 | 14 | 40 | 67 | 0.6 | 0.75 | 0.6 | 0.75 | 36 | 3 | 12 | 0.44 | 2350.21 | 2.43 |
| 33 | 32 | 81 | 144 | 0.6 | 0.6 | 0.6 | 0.6 | 36 | 3 | 12 | 0.57 | 5416.78 | 3.99 |
| 19 | 12 | 30 | 49 | 0.53 | 0.6 | 0.53 | 0.6 | 36 | 3 | 12 | 0.54 | 1437.69 | 3.73 |
| 21 | 18.75 | 42 | 71 | 0.75 | 0.75 | 0.75 | 0.75 | 36 | 3 | 12 | 0.38 | 2628.07 | 1.87 |
| 28 | 18.5 | 42 | 71 | 0.6 | 0.6 | 0.6 | 0.6 | 36 | 3 | 12 | 0.58 | 2570.17 | 4.00 |
| 27.5 | 9 | 32 | 52 | 0.6 | 0.75 | 0.6 | 0.75 | 36 | 3 | 12 | 0.41 | 1792.74 | 2.12 |
| 28 | 9 | 32 | 52 | 0.6 | 0.6 | 0.6 | 0.6 | 36 | 3 | 12 | 0.48 | 1585.72 | 2.94 |
| 21 | 24.5 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 36 | 3 | 12 | 0.54 | 3349.07 | 3.67 |
| 25 | 23 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 36 | 3 | 12 | 0.51 | 3324.48 | 3.33 |
| 31.5 | 15 | 40 | 67 | 0.75 | 0.75 | 0.75 | 0.75 | 36 | 3 | 12 | 0.42 | 2992.03 | 2.24 |
| 20 | 12 | 35 | 58 | 0.75 | 0.75 | 0.75 | 0.75 | 39 | 3 | 13 | 0.36 | 2019.55 | 1.66 |
| 29 | 20 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 45.5 | 3.5 | 13 | 0.80 | 2635.66 | 5.63 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.5 | 25.5 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 39 | 3 | 13 | 0.48 | 3024.40 | 2.98 |
| 21 | 28 | 70 | 123 | 0.75 | 0.75 | 0.75 | 0.75 | 39 | 3 | 13 | 0.36 | 4406.21 | 1.66 |
| 27.5 | 20 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 39 | 3 | 13 | 0.54 | 3359.07 | 3.74 |
| 19 | 17.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 39 | 3 | 13 | 0.68 | 1792.27 | 4.76 |
| 28 | 19 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 39 | 3 | 13 | 0.59 | 3139.60 | 4.13 |
| 24 | 12 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 39 | 3 | 13 | 0.46 | 2152.58 | 2.75 |
| 14 | 24 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 39 | 3 | 13 | 0.55 | 2411.05 | 3.86 |
| 13.5 | 12 | 16 | 24 | 0.75 | 0.75 | 0.75 | 0.75 | 39 | 3 | 13 | 0.43 | 1173.52 | 2.37 |
| 20 | 12 | 35 | 58 | 0.75 | 0.75 | 0.75 | 0.75 | 42 | 3 | 14 | 0.39 | 2173.26 | 1.93 |
| 29 | 20 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 49 | 3.5 | 14 | 0.86 | 2643.14 | 6.08 |
| 19.5 | 25.5 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 42 | 3 | 14 | 0.52 | 3254.09 | 3.45 |
| 21 | 28 | 70 | 123 | 0.75 | 0.75 | 0.75 | 0.75 | 42 | 3 | 14 | 0.39 | 4741.27 | 1.92 |
| 27.5 | 20 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 42 | 3 | 14 | 0.58 | 3381.60 | 4.05 |
| 19 | 17.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 42 | 3 | 14 | 0.73 | 1796.20 | 5.14 |
| 28 | 19 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 42 | 3 | 14 | 0.64 | 3145.18 | 4.45 |
| 24 | 12 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 42 | 3 | 14 | 0.50 | 2316.24 | 3.18 |
| 14 | 24 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 42 | 3 | 14 | 0.59 | 2390.51 | 4.11 |
| 13.5 | 12 | 16 | 24 | 0.75 | 0.75 | 0.75 | 0.75 | 42 | 3 | 14 | 0.46 | 1262.80 | 2.74 |
| 20 | 12 | 35 | 58 | 0.75 | 0.75 | 0.75 | 0.75 | 45 | 3 | 15 | 0.42 | 2326.94 | 2.21 |
| 29 | 20 | 48 | 82 | 0.6 | 0.6 | 0.6 | 0.6 | 52.5 | 3.5 | 15 | 0.92 | 2650.87 | 6.53 |
| 19.5 | 25.5 | 48 | 82 | 0.6 | 0.75 | 0.6 | 0.75 | 45 | 3 | 15 | 0.56 | 3407.08 | 3.87 |
| 21 | 28 | 70 | 123 | 0.75 | 0.75 | 0.75 | 0.75 | 45 | 3 | 15 | 0.42 | 5076.25 | 2.20 |
| 27.5 | 20 | 56 | 97 | 0.53 | 0.75 | 0.53 | 0.75 | 45 | 3 | 15 | 0.62 | 3386.85 | 4.34 |
| 19 | 17.5 | 36 | 60 | 0.53 | 0.6 | 0.53 | 0.6 | 45 | 3 | 15 | 0.78 | 1800.21 | 5.51 |
| 28 | 19 | 49 | 84 | 0.6 | 0.6 | 0.6 | 0.6 | 45 | 3 | 15 | 0.68 | 3150.80 | 4.78 |
| 24 | 12 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 45 | 3 | 15 | 0.53 | 2479.73 | 3.65 |
| 14 | 24 | 35 | 58 | 0.6 | 0.75 | 0.6 | 0.75 | 45 | 3 | 15 | 0.63 | 2394.29 | 4.41 |
| 13.5 | 12 | 16 | 24 | 0.75 | 0.75 | 0.75 | 0.75 | 45 | 3 | 15 | 0.50 | 1352.07 | 3.14 |
| 12 | 9 | 20 | 31 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.76 | 156.06 | 5.24 |
| 14 | 10.5 | 20 | 31 | 0.23 | 0.3 | 0.23 | 0.3 | 14 | 3.5 | 4 | 1.05 | 153.41 | 7.36 |
| 11.5 | 11.5 | 16 | 24 | 0.23 | 0.3 | 0.23 | 0.3 | 14 | 3.5 | 4 | 1.16 | 121.81 | 8.19 |
| 14 | 14 | 16 | 24 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.96 | 176.92 | 6.69 |
| 16 | 15 | 42 | 71 | 0.23 | 0.3 | 0.23 | 0.3 | 14 | 3.5 | 4 | 1.05 | 262.76 | 7.35 |
| 17 | 20 | 36 | 60 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.89 | 336.84 | 6.20 |
| 32 | 26 | 99 | 178 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.88 | 853.46 | 6.09 |
| 36 | 27 | 63 | 110 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 1.03 | 724.57 | 7.18 |
| 24 | 24 | 49 | 84 | 0.23 | 0.3 | 0.23 | 0.3 | 12 | 3 | 4 | 0.98 | 490.21 | 6.82 |
| 22.5 | 22.5 | 49 | 84 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.87 | 616.86 | 6.10 |
| 18.5 | 18.75 | 36 | 60 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.87 | 437.23 | 6.10 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | 11.5 | 20 | 31 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.13 | 212.32 | 8.01 |
| 32 | 32 | 81 | 144 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.41 | 806.74 | 10.23 |
| 23 | 20 | 49 | 84 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.94 | 541.09 | 6.56 |
| 24 | 18 | 45 | 76 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.17 | 449.37 | 8.34 |
| 31 | 19 | 77 | 136 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.87 | 794.08 | 6.10 |
| 31.25 | 12.5 | 50 | 85 | 0.23 | 0.38 | 0.23 | 0.38 | 15 | 3 | 5 | 0.84 | 559.20 | 5.83 |
| 30.5 | 20.5 | 63 | 110 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.18 | 626.32 | 8.42 |
| 22 | 13 | 28 | 45 | 0.23 | 0.38 | 0.23 | 0.38 | 17.5 | 3.5 | 5 | 1.09 | 318.98 | 7.70 |
| 24 | 18 | 63 | 110 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 1.00 | 629.60 | 7.04 |
| 24 | 24 | 81 | 144 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.38 | 664.65 | 9.98 |
| 19 | 23 | 56 | 97 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 1.02 | 612.00 | 7.18 |
| 19 | 14 | 35 | 58 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.23 | 350.24 | 8.85 |
| 25.5 | 10.5 | 32 | 52 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 0.98 | 393.15 | 6.92 |
| 25.5 | 22 | 64 | 112 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 1.11 | 682.42 | 7.87 |
| 19.5 | 17 | 30 | 49 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 1.01 | 420.87 | 7.14 |
| 17 | 18 | 25 | 40 | 0.23 | 0.38 | 0.23 | 0.38 | 18 | 3 | 6 | 1.10 | 349.76 | 7.82 |
| 14 | 12 | 16 | 24 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.27 | 198.75 | 9.13 |
| 14 | 8 | 12 | 17 | 0.23 | 0.38 | 0.23 | 0.38 | 21 | 3.5 | 6 | 1.29 | 142.91 | 9.26 |
| 26 | 24 | 49 | 84 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 1.21 | 743.16 | 8.71 |
| 35 | 14 | 40 | 67 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 1.12 | 656.72 | 7.98 |
| 18 | 20.5 | 36 | 60 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 1.45 | 449.29 | 10.60 |
| 18 | 13 | 24 | 38 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 1.29 | 329.37 | 9.34 |
| 26.25 | 19.5 | 56 | 97 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 1.03 | 803.14 | 7.32 |
| 22.5 | 17.5 | 42 | 71 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 1.00 | 625.50 | 7.08 |
| 24.5 | 21 | 72 | 127 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 1.27 | 766.65 | 9.18 |
| 26 | 21 | 72 | 127 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 1.24 | 816.85 | 8.92 |
| 26 | 25 | 72 | 127 | 0.23 | 0.45 | 0.23 | 0.45 | 24.5 | 3.5 | 7 | 1.35 | 857.00 | 9.83 |
| 23.5 | 24.5 | 56 | 97 | 0.23 | 0.45 | 0.23 | 0.45 | 21 | 3 | 7 | 1.06 | 849.68 | 7.49 |
| 24 | 20 | 63 | 110 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 1.04 | 882.11 | 7.42 |
| 21 | 27 | 49 | 84 | 0.23 | 0.45 | 0.23 | 0.45 | 28 | 3.5 | 8 | 1.68 | 655.77 | 12.47 |
| 28.5 | 28 | 81 | 144 | 0.23 | 0.45 | 0.23 | 0.45 | 28 | 3.5 | 8 | 1.57 | 996.62 | 11.62 |
| 18 | 25 | 45 | 76 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 1.27 | 636.72 | 9.17 |
| 22.75 | 21.5 | 64 | 112 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 1.08 | 880.73 | 7.72 |
| 21 | 21.5 | 49 | 84 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 1.25 | 675.87 | 8.98 |
| 18 | 24.5 | 54 | 93 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 1.25 | 671.19 | 9.00 |
| 9.75 | 18.75 | 24 | 38 | 0.23 | 0.45 | 0.23 | 0.45 | 28 | 3.5 | 8 | 1.43 | 289.73 | 10.42 |
| 19.5 | 23 | 56 | 97 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 1.15 | 751.85 | 8.27 |
| 23.5 | 29.75 | 64 | 112 | 0.23 | 0.45 | 0.23 | 0.45 | 24 | 3 | 8 | 1.23 | 1002.55 | 8.82 |
| 24.5 | 32 | 81 | 144 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.24 | 1268.65 | 8.97 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 25.5 | 56 | 97 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.14 | 949.26 | 8.17 |
| 24 | 25 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.13 | 1093.15 | 8.08 |
| 17 | 25 | 45 | 76 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.13 | 782.85 | 8.10 |
| 21.5 | 21 | 48 | 82 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.10 | 858.41 | 7.85 |
| 23 | 18 | 42 | 71 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.12 | 752.75 | 8.03 |
| 18 | 15.5 | 30 | 49 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.01 | 576.75 | 7.19 |
| 21 | 15.5 | 36 | 60 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 1.00 | 682.74 | 7.09 |
| 21 | 14 | 35 | 58 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.92 | 681.95 | 6.50 |
| 19.5 | 14 | 30 | 49 | 0.23 | 0.53 | 0.23 | 0.53 | 27 | 3 | 9 | 0.95 | 602.90 | 6.71 |
| 24 | 24 | 81 | 144 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 1.12 | 1258.58 | 8.02 |
| 18.5 | 29 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 1.20 | 1048.39 | 8.61 |
| 29 | 18.5 | 48 | 82 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.56 | 831.88 | 11.51 |
| 28.5 | 24 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.67 | 986.62 | 12.46 |
| 26 | 18.5 | 48 | 82 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.57 | 766.47 | 11.62 |
| 25.5 | 14 | 45 | 76 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 1.04 | 824.52 | 7.43 |
| 32.5 | 22 | 80 | 142 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 1.19 | 1402.19 | 8.53 |
| 27.5 | 19 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 35 | 3.5 | 10 | 1.48 | 945.99 | 10.85 |
| 21 | 25.5 | 63 | 110 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 1.19 | 1045.50 | 8.58 |
| 13.5 | 25.5 | 45 | 76 | 0.23 | 0.53 | 0.23 | 0.53 | 30 | 3 | 10 | 1.21 | 694.51 | 8.74 |
| 22 | 22 | 56 | 97 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 1.13 | 1119.76 | 8.08 |
| 29 | 28 | 72 | 127 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 1.28 | 1516.37 | 9.27 |
| 25 | 28 | 49 | 84 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 1.28 | 1226.14 | 9.27 |
| 23.5 | 20.5 | 36 | 60 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 1.20 | 926.42 | 8.62 |
| 13 | 12 | 25 | 40 | 0.23 | 0.6 | 0.23 | 0.6 | 38.5 | 3.5 | 11 | 1.17 | 447.10 | 8.37 |
| 17 | 12 | 30 | 49 | 0.23 | 0.6 | 0.23 | 0.6 | 38.5 | 3.5 | 11 | 1.19 | 550.52 | 8.59 |
| 12.5 | 18.5 | 24 | 38 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 1.13 | 530.43 | 8.09 |
| 13 | 25 | 28 | 45 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 1.26 | 629.65 | 9.12 |
| 31 | 17 | 45 | 76 | 0.23 | 0.6 | 0.23 | 0.6 | 33 | 3 | 11 | 1.12 | 1118.74 | 8.05 |
| 25.5 | 14 | 40 | 67 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.12 | 911.56 | 8.02 |
| 33 | 32 | 81 | 144 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.45 | 1828.91 | 10.61 |
| 19 | 12 | 30 | 49 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.02 | 680.47 | 7.27 |
| 21 | 18.75 | 42 | 71 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.28 | 868.46 | 9.24 |
| 28 | 18.5 | 42 | 71 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.33 | 1012.48 | 9.65 |
| 27.5 | 9 | 32 | 52 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.00 | 762.34 | 7.12 |
| 28 | 9 | 32 | 52 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 0.96 | 801.78 | 6.83 |
| 21 | 24.5 | 56 | 97 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.30 | 1107.12 | 9.47 |
| 25 | 23 | 48 | 82 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.44 | 1052.28 | 10.53 |
| 31.5 | 15 | 40 | 67 | 0.23 | 0.6 | 0.23 | 0.6 | 36 | 3 | 12 | 1.30 | 958.24 | 9.47 |

# APPENDIX B

Database used for Development of Data Driven Models for Moment Resisting Frames

Table B1 Data Along X Direction

| n | L (m) | W (m) | H (m) | h (m) | $W_{cmin}$ (m) | $W_{cmax}$ (m) | $T_x$ (seconds) | $BS_X$ (KN) | Top $Displacement_x$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 13 | 16 | 12 | 39 | 3 | 0.23 | 0.6 | 1.47 | 245.00 | 15.10 |
| 12 | 16 | 12 | 36 | 3 | 0.23 | 0.6 | 1.35 | 246.40 | 13.70 |
| 11 | 16 | 12 | 33 | 3 | 0.23 | 0.6 | 1.23 | 247.70 | 12.40 |
| 10 | 16 | 12 | 30 | 3 | 0.23 | 0.6 | 1.11 | 248.90 | 11.10 |
| 9 | 16 | 12 | 27 | 3 | 0.23 | 0.6 | 1.00 | 250.00 | 9.90 |
| 8 | 16 | 12 | 24 | 3 | 0.23 | 0.6 | 0.88 | 250.77 | 8.60 |
| 7 | 16 | 12 | 21 | 3 | 0.23 | 0.6 | 0.77 | 251.40 | 7.50 |
| 6 | 16 | 12 | 18 | 3 | 0.23 | 0.6 | 0.66 | 251.73 | 6.30 |
| 5 | 16 | 12 | 17 | 3 | 0.23 | 0.6 | 0.55 | 252.33 | 5.20 |
| 20 | 28 | 20 | 60 | 3 | 0.3 | 1 | 1.78 | 1048.20 | 18.50 |
| 19 | 28 | 20 | 57 | 3 | 0.3 | 1 | 1.68 | 1052.50 | 17.40 |
| 18 | 28 | 20 | 54 | 3 | 0.3 | 1 | 1.59 | 1056.74 | 16.40 |
| 17 | 28 | 20 | 51 | 3 | 0.3 | 1 | 1.49 | 1061.00 | 15.30 |
| 16 | 28 | 20 | 48 | 3 | 0.3 | 1 | 1.40 | 1065.17 | 14.30 |
| 15 | 28 | 20 | 45 | 3 | 0.3 | 1 | 1.31 | 1069.37 | 13.30 |
| 14 | 28 | 20 | 42 | 3 | 0.3 | 1 | 1.21 | 1073.57 | 12.30 |
| 13 | 28 | 20 | 39 | 3 | 0.3 | 1 | 1.12 | 1077.80 | 11.40 |
| 12 | 28 | 20 | 36 | 3 | 0.3 | 1 | 1.03 | 1082.00 | 10.40 |
| 11 | 28 | 20 | 33 | 3 | 0.3 | 1 | 0.94 | 1086.00 | 9.50 |
| 10 | 28 | 20 | 30 | 3 | 0.3 | 1 | 0.85 | 1091.00 | 8.50 |
| 9 | 28 | 20 | 27 | 3 | 0.3 | 1 | 0.76 | 1095.70 | 7.60 |
| 8 | 28 | 20 | 24 | 3 | 0.3 | 1 | 0.67 | 1100.73 | 6.70 |
| 20 | 48 | 31.5 | 60 | 3 | 0.3 | 1 | 1.82 | 2768.50 | 18.40 |
| 19 | 48 | 31.5 | 57 | 3 | 0.3 | 1 | 1.72 | 2773.71 | 17.40 |
| 18 | 48 | 31.5 | 54 | 3 | 0.3 | 1 | 1.63 | 2778.74 | 16.50 |
| 17 | 48 | 31.5 | 51 | 3 | 0.3 | 1 | 1.54 | 2783.89 | 15.50 |
| 16 | 48 | 31.5 | 48 | 3 | 0.3 | 1 | 1.44 | 2788.88 | 14.50 |
| 15 | 48 | 31.5 | 45 | 3 | 0.3 | 1 | 1.35 | 2793.80 | 13.50 |
| 14 | 48 | 31.5 | 42 | 3 | 0.3 | 1 | 1.26 | 2798.63 | 12.60 |
| 13 | 48 | 31.5 | 39 | 3 | 0.3 | 1 | 1.16 | 2803.40 | 11.60 |
| 12 | 48 | 31.5 | 36 | 3 | 0.3 | 1 | 1.07 | 2808.11 | 10.70 |
| 11 | 48 | 31.5 | 33 | 3 | 0.3 | 1 | 0.98 | 2812.77 | 9.70 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 48 | 31.5 | 30 | 3 | 0.3 | 1 | 0.89 | 2817.38 | 8.80 |
| 9 | 48 | 31.5 | 27 | 3 | 0.3 | 1 | 0.80 | 2822.00 | 7.90 |
| 8 | 48 | 31.5 | 24 | 3 | 0.3 | 1 | 0.71 | 2826.57 | 6.90 |
| 7 | 48 | 31.5 | 21 | 3 | 0.3 | 1 | 0.62 | 2831.20 | 6.00 |
| 6 | 48 | 31.5 | 18 | 3 | 0.3 | 1 | 0.53 | 2737.40 | 4.90 |
| 5 | 48 | 31.5 | 15 | 3 | 0.3 | 1 | 0.44 | 2271.63 | 3.30 |
| 10 | 20 | 12 | 30 | 3 | 0.23 | 0.46 | 1.38 | 236.10 | 13.60 |
| 9 | 20 | 12 | 27 | 3 | 0.23 | 0.46 | 1.24 | 236.34 | 12.20 |
| 8 | 20 | 12 | 24 | 3 | 0.23 | 0.46 | 1.11 | 236.42 | 10.70 |
| 7 | 20 | 12 | 21 | 3 | 0.23 | 0.46 | 0.97 | 236.29 | 9.30 |
| 6 | 20 | 12 | 18 | 3 | 0.23 | 0.46 | 0.83 | 235.86 | 7.90 |
| 5 | 20 | 12 | 15 | 3 | 0.23 | 0.46 | 0.69 | 235.00 | 6.50 |
| 4 | 20 | 12 | 12 | 3 | 0.23 | 0.46 | 0.55 | 233.30 | 5.10 |
| 10 | 36 | 27 | 30 | 3 | 0.23 | 0.6 | 1.43 | 908.28 | 14.00 |
| 9 | 36 | 27 | 27 | 3 | 0.23 | 0.6 | 1.29 | 908.27 | 12.50 |
| 8 | 36 | 27 | 24 | 3 | 0.23 | 0.6 | 1.14 | 907.88 | 11.10 |
| 7 | 36 | 27 | 21 | 3 | 0.23 | 0.6 | 1.00 | 907.00 | 9.60 |
| 6 | 36 | 27 | 18 | 3 | 0.23 | 0.6 | 0.86 | 905.28 | 8.20 |
| 5 | 36 | 27 | 15 | 3 | 0.23 | 0.6 | 0.71 | 902.37 | 6.70 |
| 4 | 36 | 27 | 12 | 3 | 0.23 | 0.6 | 0.57 | 897.26 | 5.30 |

Database used for Development of Data Driven Models for Moment Resisting Frames

Table B2 Data Along Y Direction

| n | L (m) | W (m) | H (m) | h (m) | $D_{cmin}$ (m) | $D_{cmax}$ (m) | $T_Y$ (seconds) | $BS_Y$ (KN) | Top Floor $Displacement_Y$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 13 | 16 | 12 | 39 | 3 | 0.23 | 0.6 | 1.44 | 562.00 | 33.60 |
| 12 | 16 | 12 | 36 | 3 | 0.23 | 0.6 | 1.32 | 567.10 | 30.40 |
| 11 | 16 | 12 | 33 | 3 | 0.23 | 0.6 | 1.20 | 572.10 | 27.40 |
| 10 | 16 | 12 | 30 | 3 | 0.23 | 0.6 | 1.08 | 576.00 | 24.40 |
| 9 | 16 | 12 | 27 | 3 | 0.23 | 0.6 | 0.97 | 580.00 | 21.60 |
| 8 | 16 | 12 | 24 | 3 | 0.23 | 0.6 | 0.85 | 582.10 | 18.90 |
| 7 | 16 | 12 | 21 | 3 | 0.23 | 0.6 | 0.74 | 584.00 | 16.20 |
| 6 | 16 | 12 | 18 | 3 | 0.23 | 0.6 | 0.64 | 585.04 | 13.70 |
| 5 | 16 | 12 | 17 | 3 | 0.23 | 0.6 | 0.53 | 567.74 | 10.80 |
| 20 | 28 | 20 | 60 | 3 | 0.3 | 1 | 1.57 | 1186.24 | 16.80 |
| 19 | 28 | 20 | 57 | 3 | 0.3 | 1 | 1.48 | 1195.50 | 15.80 |
| 18 | 28 | 20 | 54 | 3 | 0.3 | 1 | 1.39 | 1204.50 | 14.70 |
| 17 | 28 | 20 | 51 | 3 | 0.3 | 1 | 1.31 | 1213.50 | 13.70 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 16 | 28 | 20 | 48 | 3 | 0.3 | 1 | 1.22 | 1222.23 | 12.80 |
| 15 | 28 | 20 | 45 | 3 | 0.3 | 1 | 1.13 | 1231.00 | 11.80 |
| 14 | 28 | 20 | 42 | 3 | 0.3 | 1 | 1.05 | 1239.60 | 10.90 |
| 13 | 28 | 20 | 39 | 3 | 0.3 | 1 | 0.97 | 1248.22 | 10.00 |
| 12 | 28 | 20 | 36 | 3 | 0.3 | 1 | 0.89 | 1256.90 | 9.10 |
| 11 | 28 | 20 | 33 | 3 | 0.3 | 1 | 0.80 | 1265.70 | 8.20 |
| 10 | 28 | 20 | 30 | 3 | 0.3 | 1 | 0.73 | 1274.65 | 7.40 |
| 9 | 28 | 20 | 27 | 3 | 0.3 | 1 | 0.65 | 1284.10 | 6.60 |
| 8 | 28 | 20 | 24 | 3 | 0.3 | 1 | 0.57 | 1294.30 | 5.70 |
| 20 | 48 | 31.5 | 60 | 3 | 0.3 | 1 | 1.38 | 3649.25 | 14.40 |
| 19 | 48 | 31.5 | 57 | 3 | 0.3 | 1 | 1.30 | 3668.06 | 13.60 |
| 18 | 48 | 31.5 | 54 | 3 | 0.3 | 1 | 1.23 | 3686.70 | 12.70 |
| 17 | 48 | 31.5 | 51 | 3 | 0.3 | 1 | 1.15 | 3705.19 | 11.90 |
| 16 | 48 | 31.5 | 48 | 3 | 0.3 | 1 | 1.08 | 3723.61 | 11.10 |
| 15 | 48 | 31.5 | 45 | 3 | 0.3 | 1 | 1.01 | 3742.00 | 10.30 |
| 14 | 48 | 31.5 | 42 | 3 | 0.3 | 1 | 0.94 | 3760.53 | 9.60 |
| 13 | 48 | 31.5 | 39 | 3 | 0.3 | 1 | 0.86 | 3779.25 | 8.80 |
| 12 | 48 | 31.5 | 36 | 3 | 0.3 | 1 | 0.79 | 3798.38 | 8.00 |
| 11 | 48 | 31.5 | 33 | 3 | 0.3 | 1 | 0.72 | 3818.17 | 7.30 |
| 10 | 48 | 31.5 | 30 | 3 | 0.3 | 1 | 0.65 | 3839.00 | 6.60 |
| 9 | 48 | 31.5 | 27 | 3 | 0.3 | 1 | 0.58 | 3861.37 | 5.90 |
| 8 | 48 | 31.5 | 24 | 3 | 0.3 | 1 | 0.51 | 3669.00 | 4.90 |
| 7 | 48 | 31.5 | 21 | 3 | 0.3 | 1 | 0.45 | 3203.23 | 3.60 |
| 6 | 48 | 31.5 | 18 | 3 | 0.3 | 1 | 0.38 | 2737.40 | 2.60 |
| 5 | 48 | 31.5 | 15 | 3 | 0.3 | 1 | 0.31 | 2271.63 | 1.70 |
| 10 | 20 | 12 | 30 | 3 | 0.23 | 0.46 | 1.20 | 272.00 | 12.00 |
| 9 | 20 | 12 | 27 | 3 | 0.23 | 0.46 | 1.07 | 273.33 | 10.70 |
| 8 | 20 | 12 | 24 | 3 | 0.23 | 0.46 | 0.95 | 273.34 | 9.30 |
| 7 | 20 | 12 | 21 | 3 | 0.23 | 0.46 | 0.83 | 274.94 | 8.00 |
| 6 | 20 | 12 | 18 | 3 | 0.23 | 0.46 | 0.71 | 275.02 | 6.80 |
| 5 | 20 | 12 | 15 | 3 | 0.23 | 0.46 | 0.59 | 274.35 | 5.50 |
| 4 | 20 | 12 | 12 | 3 | 0.23 | 0.46 | 0.48 | 238.00 | 3.80 |
| 10 | 36 | 27 | 30 | 3 | 0.23 | 0.6 | 1.00 | 1301.30 | 9.90 |
| 9 | 36 | 27 | 27 | 3 | 0.23 | 0.6 | 0.90 | 1304.62 | 8.80 |
| 8 | 36 | 27 | 24 | 3 | 0.23 | 0.6 | 0.79 | 1307.64 | 7.80 |
| 7 | 36 | 27 | 21 | 3 | 0.23 | 0.6 | 0.69 | 1310.32 | 6.70 |
| 6 | 36 | 27 | 18 | 3 | 0.23 | 0.6 | 0.59 | 1312.59 | 5.70 |
| 5 | 36 | 27 | 15 | 3 | 0.23 | 0.6 | 0.49 | 1184.14 | 4.20 |
| 4 | 36 | 27 | 12 | 3 | 0.23 | 0.6 | 0.39 | 943.25 | 2.60 |

**APPENDIX C**

Database used for Development of Data Driven Models for Shear Wall Dominant Symmetric Building

Table C1 Data Along X Direction

| L (m) | W (m) | H (m) | A ($m^2$) | $W_{cmin}$ (m) | $W_{cmax}$ (m) | H (m) | $A_{swx}$ (m2) | $T_x$(seconds) | $BS_X$ (KN) | $TFD_X$ (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 49 | 25 | 48 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 0.77 | 8310 | 8 |
| 49 | 25 | 54 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 0.881 | 8240 | 9.2 |
| 49 | 25 | 57 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 0.9378 | 8169.7 | 9.7 |
| 49 | 25 | 60 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 0.994 | 8180 | 10.4 |
| 49 | 25 | 66 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 1.1 | 8130 | 11.6 |
| 49 | 25 | 69 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 1.165 | 8100 | 12.2 |
| 49 | 25 | 75 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 1.281 | 8048.4 | 13.3 |
| 49 | 25 | 78 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 1.339 | 8023 | 14 |
| 49 | 25 | 81 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 1.397 | 8000 | 14.6 |
| 49 | 25 | 81 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 1.456 | 7970 | 15.3 |
| 49 | 25 | 90 | 1225 | 1.2 | 1.5 | 3 | 1.75 | 1.575 | 7924 | 16.5 |
| 25 | 20 | 48 | 500 | 0.23 | 0.6 | 3 | 1 | 1.705 | 652.83 | 20.7 |
| 25 | 20 | 45 | 500 | 0.23 | 0.6 | 3 | 1 | 1.566 | 666 | 19.1 |
| 25 | 20 | 42 | 500 | 0.23 | 0.6 | 3 | 1 | 1.429 | 680.7 | 17.4 |
| 25 | 20 | 39 | 500 | 0.23 | 0.6 | 3 | 1 | 1.295 | 697.25 | 15.8 |
| 25 | 20 | 36 | 500 | 0.23 | 0.6 | 3 | 1 | 1.163 | 716.11 | 14.2 |
| 25 | 20 | 33 | 500 | 0.23 | 0.6 | 3 | 1 | 1.034 | 737.92 | 12.6 |
| 25 | 20 | 30 | 500 | 0.23 | 0.6 | 3 | 1 | 0.908 | 763.56 | 11.1 |
| 25 | 20 | 27 | 500 | 0.23 | 0.6 | 3 | 1 | 0.784 | 794.28 | 9.5 |
| 25 | 20 | 24 | 500 | 0.23 | 0.6 | 3 | 1 | 0.67 | 831 | 8 |
| 25 | 20 | 21 | 500 | 0.23 | 0.6 | 3 | 1 | 0.565 | 888.2 | 6.6 |
| 36 | 28 | 90 | 1008 | 0.3 | 1 | 3 | 1.2 | 2.3 | 2505 | 25.2 |
| 36 | 28 | 87 | 1008 | 0.3 | 1 | 3 | 1.2 | 2.21 | 2519.8 | 24.1 |
| 36 | 28 | 84 | 1008 | 0.3 | 1 | 3 | 1.2 | 2.12 | 2290.3 | 23.1 |
| 36 | 28 | 81 | 1008 | 0.3 | 1 | 3 | 1.2 | 2.033 | 2288.3 | 22.1 |
| 36 | 28 | 78 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.946 | 2565 | 21.1 |
| 36 | 28 | 75 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.859 | 2580.3 | 20.1 |
| 36 | 28 | 72 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.773 | 2596 | 19.1 |
| 36 | 28 | 69 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.689 | 2612 | 18.2 |
| 36 | 28 | 66 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.605 | 2628.2 | 17.3 |
| 36 | 28 | 63 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.522 | 2644.9 | 16.3 |
| 36 | 28 | 60 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.44 | 2662 | 15.4 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 36 | 28 | 57 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.358 | 2679.8 | 14.5 |
| 36 | 28 | 54 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.277 | 2698.3 | 13.7 |
| 36 | 28 | 51 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.197 | 2717.6 | 12.8 |
| 36 | 28 | 48 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.118 | 2737.8 | 11.9 |
| 46 | 28 | 45 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 2.062 | 1218.3 | 23.3 |
| 46 | 28 | 42 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.898 | 1235 | 21.5 |
| 46 | 28 | 39 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.735 | 1253.5 | 19.8 |
| 46 | 28 | 36 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.575 | 1274.2 | 18 |
| 46 | 28 | 33 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.417 | 1297.5 | 16.2 |
| 46 | 28 | 30 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.261 | 1324.2 | 14.4 |
| 46 | 28 | 27 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.108 | 1355 | 12.7 |
| 46 | 28 | 24 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.958 | 1391 | 10.9 |
| 46 | 28 | 21 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.812 | 1434.5 | 9.2 |
| 46 | 28 | 18 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.67 | 1488.2 | 7.5 |
| 45 | 28 | 90 | 1260 | 0.23 | 1 | 3 | 1 | 3.36 | 1666.2 | 36.6 |
| 45 | 28 | 87 | 1260 | 0.23 | 1 | 3 | 1 | 3.23 | 1674.5 | 35.3 |
| 45 | 28 | 84 | 1260 | 0.23 | 1 | 3 | 1 | 3.104 | 1683.3 | 33.9 |
| 45 | 28 | 81 | 1260 | 0.23 | 1 | 3 | 1 | 2.977 | 1692.4 | 32.5 |
| 45 | 28 | 78 | 1260 | 0.23 | 1 | 3 | 1 | 2.85 | 1702 | 31.2 |
| 45 | 28 | 75 | 1260 | 0.23 | 1 | 3 | 1 | 2.724 | 1712 | 29.8 |
| 45 | 28 | 72 | 1260 | 0.23 | 1 | 3 | 1 | 2.598 | 1722.7 | 28.5 |
| 45 | 28 | 69 | 1260 | 0.23 | 1 | 3 | 1 | 2.473 | 1734 | 27.2 |
| 45 | 28 | 66 | 1260 | 0.23 | 1 | 3 | 1 | 2.349 | 1746 | 25.8 |
| 45 | 28 | 63 | 1260 | 0.23 | 1 | 3 | 1 | 2.225 | 1758.8 | 24.5 |
| 45 | 28 | 60 | 1260 | 0.23 | 1 | 3 | 1 | 2.102 | 1772.6 | 23.2 |
| 45 | 28 | 57 | 1260 | 0.23 | 1 | 3 | 1 | 1.98 | 1787.5 | 21.9 |
| 45 | 28 | 54 | 1260 | 0.23 | 1 | 3 | 1 | 1.859 | 1803.6 | 20.6 |
| 45 | 28 | 51 | 1260 | 0.23 | 1 | 3 | 1 | 1.738 | 1821.1 | 19.3 |
| 30 | 24 | 45 | 720 | 0.23 | 0.6 | 3 | 1 | 1.54 | 654.84 | 18.8 |
| 30 | 24 | 42 | 720 | 0.23 | 0.6 | 3 | 1 | 1.406 | 669.3 | 17.2 |
| 30 | 24 | 39 | 720 | 0.23 | 0.6 | 3 | 1 | 1.274 | 685.56 | 15.6 |
| 30 | 24 | 36 | 720 | 0.23 | 0.6 | 3 | 1 | 1.144 | 704.11 | 14 |
| 30 | 24 | 33 | 720 | 0.23 | 0.6 | 3 | 1 | 1.017 | 725.56 | 12.4 |
| 30 | 24 | 30 | 720 | 0.23 | 0.6 | 3 | 1 | 0.892 | 750.78 | 10.9 |
| 30 | 24 | 27 | 720 | 0.23 | 0.6 | 3 | 1 | 0.771 | 781 | 9.4 |
| 30 | 24 | 24 | 720 | 0.23 | 0.6 | 3 | 1 | 0.66 | 817.97 | 7.9 |
| 30 | 24 | 21 | 720 | 0.23 | 0.6 | 3 | 1 | 0.556 | 858.7 | 6.4 |
| 30 | 24 | 18 | 720 | 0.23 | 0.6 | 3 | 1 | 0.455 | 734.23 | 4 |

Database used for Development of Data Driven Models for Shear Wall Dominant Symmetric Building

Table C2 Data Along Y Direction

| L (m) | W (m) | H(m) | A ($m^2$) | $D_{cmin}$(m) | $D_{cmax}$ (m) | h (m) | $A_{swy}$($m^2$) | $T_y$ (seconds) | $BS_Y$ (KN) | $TFD_Y$ (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 49 | 25 | 48 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 0.72 | 8770 | 7.6 |
| 49 | 25 | 54 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 0.838 | 8670 | 8.8 |
| 49 | 25 | 57 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 0.894 | 8611.1 | 9.4 |
| 49 | 25 | 60 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 0.951 | 8550 | 10.1 |
| 49 | 25 | 66 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 1.06 | 8440 | 11.4 |
| 49 | 25 | 69 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 1.127 | 8380 | 12.1 |
| 49 | 25 | 75 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 1.248 | 8167.6 | 13.6 |
| 49 | 25 | 78 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 1.311 | 8195 | 14.3 |
| 49 | 25 | 81 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 1.374 | 8130 | 15.1 |
| 49 | 25 | 81 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 1.439 | 8070 | 15.9 |
| 49 | 25 | 90 | 1225 | 1.2 | 1.5 | 3 | 1.05 | 1.572 | 7940.7 | 17.5 |
| 25 | 20 | 48 | 500 | 0.23 | 0.6 | 3 | 0.8 | 1.615 | 689 | 18.6 |
| 25 | 20 | 45 | 500 | 0.23 | 0.6 | 3 | 0.8 | 1.489 | 700 | 17.2 |
| 25 | 20 | 42 | 500 | 0.23 | 0.6 | 3 | 0.8 | 1.366 | 712.4 | 15.8 |
| 25 | 20 | 39 | 500 | 0.23 | 0.6 | 3 | 0.8 | 1.244 | 725.83 | 14.4 |
| 25 | 20 | 36 | 500 | 0.23 | 0.6 | 3 | 0.8 | 1.125 | 740.64 | 13.1 |
| 25 | 20 | 33 | 500 | 0.23 | 0.6 | 3 | 0.8 | 1.008 | 757.23 | 11.7 |
| 25 | 20 | 30 | 500 | 0.23 | 0.6 | 3 | 0.8 | 0.893 | 776 | 10.4 |
| 25 | 20 | 27 | 500 | 0.23 | 0.6 | 3 | 0.8 | 0.781 | 797.7 | 9.1 |
| 25 | 20 | 24 | 500 | 0.23 | 0.6 | 3 | 0.8 | 0.66 | 823 | 7.8 |
| 25 | 20 | 21 | 500 | 0.23 | 0.6 | 3 | 0.8 | 0.549 | 854.13 | 6.5 |
| 36 | 28 | 90 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.9 | 3023 | 22 |
| 36 | 28 | 87 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.82 | 3056.2 | 20.9 |
| 36 | 28 | 84 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.74 | 2789.2 | 19.9 |
| 36 | 28 | 81 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.66 | 2781.8 | 18.9 |
| 36 | 28 | 78 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.581 | 3155.7 | 17.9 |
| 36 | 28 | 75 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.504 | 3189 | 16.9 |
| 36 | 28 | 72 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.429 | 3222.4 | 16 |
| 36 | 28 | 69 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.355 | 3255.8 | 15.1 |
| 36 | 28 | 66 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.282 | 3289.2 | 14.2 |
| 36 | 28 | 63 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.211 | 3322.7 | 13.3 |
| 36 | 28 | 60 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.142 | 3356.1 | 12.5 |
| 36 | 28 | 57 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.074 | 3389.7 | 11.7 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 36 | 28 | 54 | 1008 | 0.3 | 1 | 3 | 1.2 | 1.007 | 3423.3 | 10.9 |
| 36 | 28 | 51 | 1008 | 0.3 | 1 | 3 | 1.2 | 0.941 | 3457 | 10.1 |
| 36 | 28 | 48 | 1008 | 0.3 | 1 | 3 | 1.2 | 0.877 | 3491 | 9.4 |
| 46 | 28 | 45 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.58 | 1585.8 | 17.1 |
| 46 | 28 | 42 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.464 | 1600.3 | 15.8 |
| 46 | 28 | 39 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.346 | 1616.5 | 14.6 |
| 46 | 28 | 36 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.228 | 1634.7 | 13.3 |
| 46 | 28 | 33 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 1.11 | 1655.3 | 12.1 |
| 46 | 28 | 30 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.995 | 1678.8 | 10.9 |
| 46 | 28 | 27 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.88 | 1706 | 9.6 |
| 46 | 28 | 24 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.767 | 1737.7 | 8.4 |
| 46 | 28 | 21 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.656 | 1775.1 | 7.2 |
| 46 | 28 | 18 | 1288 | 0.23 | 0.6 | 3 | 0.8 | 0.547 | 1833 | 6 |
| 45 | 28 | 90 | 1260 | 0.23 | 1 | 3 | 0.8 | 2.688 | 2082.7 | 30 |
| 45 | 28 | 87 | 1260 | 0.23 | 1 | 3 | 0.8 | 2.57 | 2098.8 | 28.6 |
| 45 | 28 | 84 | 1260 | 0.23 | 1 | 3 | 0.8 | 2.47 | 2114.9 | 27.3 |
| 45 | 28 | 81 | 1260 | 0.23 | 1 | 3 | 0.8 | 2.364 | 2131.1 | 26.1 |
| 45 | 28 | 78 | 1260 | 0.23 | 1 | 3 | 0.8 | 2.258 | 2147.5 | 24.8 |
| 45 | 28 | 75 | 1260 | 0.23 | 1 | 3 | 0.8 | 2.155 | 2164 | 23.6 |
| 45 | 28 | 72 | 1260 | 0.23 | 1 | 3 | 0.8 | 2.052 | 2180.7 | 22.4 |
| 45 | 28 | 69 | 1260 | 0.23 | 1 | 3 | 0.8 | 1.951 | 2197.5 | 21.3 |
| 45 | 28 | 66 | 1260 | 0.23 | 1 | 3 | 0.8 | 1.852 | 2214.6 | 20.1 |
| 45 | 28 | 63 | 1260 | 0.23 | 1 | 3 | 0.8 | 1.753 | 2232 | 19 |
| 45 | 28 | 60 | 1260 | 0.23 | 1 | 3 | 0.8 | 1.656 | 2249.9 | 17.9 |
| 45 | 28 | 57 | 1260 | 0.23 | 1 | 3 | 0.8 | 1.56 | 2268.1 | 16.8 |
| 45 | 28 | 54 | 1260 | 0.23 | 1 | 3 | 0.8 | 1.466 | 2286.9 | 15.8 |
| 45 | 28 | 51 | 1260 | 0.23 | 1 | 3 | 0.8 | 1.372 | 2306.4 | 14.7 |
| 30 | 24 | 45 | 720 | 0.23 | 0.6 | 3 | 0.8 | 1.465 | 688.56 | 16.9 |
| 30 | 24 | 42 | 720 | 0.23 | 0.6 | 3 | 0.8 | 1.343 | 700.55 | 15.5 |
| 30 | 24 | 39 | 720 | 0.23 | 0.6 | 3 | 0.8 | 1.223 | 713.71 | 14.2 |
| 30 | 24 | 36 | 720 | 0.23 | 0.6 | 3 | 0.8 | 1.106 | 728.3 | 12.8 |
| 30 | 24 | 33 | 720 | 0.23 | 0.6 | 3 | 0.8 | 0.991 | 744.6 | 11.5 |
| 30 | 24 | 30 | 720 | 0.23 | 0.6 | 3 | 0.8 | 0.878 | 763 | 10.2 |
| 30 | 24 | 27 | 720 | 0.23 | 0.6 | 3 | 0.8 | 0.768 | 784.41 | 8.9 |
| 30 | 24 | 24 | 720 | 0.23 | 0.6 | 3 | 0.8 | 0.653 | 809.51 | 7.7 |
| 30 | 24 | 21 | 720 | 0.23 | 0.6 | 3 | 0.8 | 0.54 | 839.9 | 6.4 |
| 30 | 24 | 18 | 720 | 0.23 | 0.6 | 3 | 0.8 | 0.432 | 734.23 | 4.3 |

# APPENDIX D

Table D1 Database used for Development of Data Driven Models for Shear Wall Dominant Un symmetric Building

| L (m) | W (m) | H (m) | $D_{cmin}$ (m) | $D_{cmax}$ (m) | h (m) | $A_{swx}(m^2)$ | $A_{swy}$ ($m^2$) | T (seconds) | $BS_{max}$ (KN) | $TFD_{max}$ (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 43 | 20.7 | 54 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 1.545 | 1485.13 | 11 |
| 43 | 20.7 | 51 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 1.416 | 1496.7 | 11.5 |
| 43 | 20.7 | 48 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 1.304 | 1526 | 12.6 |
| 43 | 20.7 | 45 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 1.194 | 1577.2 | 12.8 |
| 43 | 20.7 | 42 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 1.086 | 1591.84 | 14.1 |
| 43 | 20.7 | 39 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 0.982 | 1628.53 | 14.2 |
| 43 | 20.7 | 36 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 0.884 | 1663.22 | 15.4 |
| 43 | 20.7 | 33 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 0.78 | 1719.32 | 15.8 |
| 43 | 20.7 | 30 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 0.683 | 1774 | 16.7 |
| 43 | 20.7 | 27 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 0.592 | 1829.61 | 17.5 |
| 43 | 20.7 | 27 | 0.3 | 1.5 | 3 | 1.761 | 1.95 | 0.501 | 1754.67 | 18.1 |
| 33.75 | 22.4 | 66 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 1.615 | 1258 | 19.2 |
| 33.75 | 22.4 | 63 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 1.512 | 1278.74 | 19.5 |
| 33.75 | 22.4 | 60 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 1.412 | 1300.87 | 20.9 |
| 33.75 | 22.4 | 57 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 1.313 | 1324.67 | 20.9 |
| 33.75 | 22.4 | 54 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 1.215 | 1350.35 | 22.3 |
| 33.75 | 22.4 | 51 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 1.12 | 1378.14 | 22.7 |
| 33.75 | 22.4 | 48 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 1.027 | 1408.33 | 23.8 |
| 33.75 | 22.4 | 45 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 0.936 | 1441.21 | 24.6 |
| 33.75 | 22.4 | 42 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 0.847 | 1477.16 | 25.3 |
| 33.75 | 22.4 | 39 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 0.761 | 1516.58 | 26.5 |
| 33.75 | 22.4 | 36 | 0.2 | 1.3 | 3 | 3.468 | 4.578 | 0.677 | 1560 | 28.1 |
| 35 | 27 | 66 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 2.89 | 2073 | 28.7 |
| 35 | 27 | 63 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 2.73 | 2096 | 30.8 |
| 35 | 27 | 60 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 2.57 | 2120.22 | 31.2 |
| 35 | 27 | 57 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 2.41 | 2145.66 | 33.4 |
| 35 | 27 | 54 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 2.25 | 2172.9 | 33.6 |
| 35 | 27 | 51 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 2.102 | 2202.14 | 33.8 |
| 35 | 27 | 48 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 1.95 | 2233.75 | 35.3 |
| 35 | 27 | 45 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 1.8 | 2268.1 | 36.4 |
| 35 | 27 | 42 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 1.65 | 2305.65 | 36.4 |
| 35 | 27 | 39 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 1.506 | 2347 | 37.2 |
| 35 | 27 | 36 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 1.36 | 2392.8 | 37.5 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | 27 | 33 | 0.3 | 1.5 | 3 | 1.5 | 2.784 | 1.22 | 2444 | 39.1 |
| 39 | 13 | 87 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 3.706 | 1545.33 | 39.2 |
| 39 | 13 | 84 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 3.543 | 1560.21 | 39.3 |
| 39 | 13 | 81 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 3.382 | 1576 | 41.2 |
| 39 | 13 | 78 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 3.22 | 1444.8 | 41.8 |
| 39 | 13 | 75 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 3.068 | 1459.84 | 42.2 |
| 39 | 13 | 72 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 2.915 | 1475.17 | 43.3 |
| 39 | 13 | 69 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 2.76 | 1490.84 | 44.2 |
| 39 | 13 | 66 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 2.61 | 1507 | 45.1 |
| 39 | 13 | 63 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 2.47 | 1523.55 | 45.3 |
| 39 | 13 | 60 | 0.3 | 1.4 | 3 | 2.907 | 4.293 | 2.326 | 1540.78 | 47.4 |
| 49.5 | 16 | 78 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 4.03 | 1543.42 | 48 |
| 49.5 | 16 | 75 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 3.825 | 1551.72 | 48.3 |
| 49.5 | 16 | 72 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 3.622 | 1572.76 | 49.5 |
| 49.5 | 16 | 69 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 3.423 | 1595 | 51 |
| 49.5 | 16 | 66 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 3.227 | 1618 | 53.8 |
| 49.5 | 16 | 63 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 3.034 | 1642.4 | 54 |
| 49.5 | 16 | 60 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 2.844 | 1688.24 | 57 |
| 49.5 | 16 | 57 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 2.658 | 1695.66 | 59.7 |
| 49.5 | 16 | 54 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 2.475 | 1725 | 60 |
| 49.5 | 16 | 51 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 2.295 | 1756.14 | 65.9 |
| 49.5 | 16 | 48 | 0.2 | 1.4 | 3 | 1.29 | 4.5 | 2.119 | 1789.72 | 72.4 |

## APPENDIX E

## List of Publications

### Publications in International Journals

1) S.G.Joshi, Shreenivas Londhe, Naveen Kwatra (2014), "Determination of Natural Periods of Vibration using Genetic Programming", Earthquakes and Structures, Vol. 6, No. 2, 201-216.

2) S.G.Joshi, Shreenivas Londhe, Naveen Kwatra (2014), "Application of Artificial Neural Network for Dynamic Analysis of Building Frames", Computers and Concrete , Vol.13, No.6, 765-780.

### Publications in National Conferences

S.G.Joshi, Shreenivas Londhe, Naveen Kwatra (2011), "Dynamic Analysis of Symmetric Building Frames using Data Driven Tools – A Review", National Conference on Recent Developments in Civil Engineering and Infrastructure Development, 21-22 Dec. 2011, JaypeeUniersity of Engineering and Technology, Guna (M.P.)

S.G.Joshi, Shreenivas Londhe, Naveen Kwatra (2013), "Comparison of Artificial Neural Networks and Wavelet Neural Networks for Dynamic Analysis of building Frame s", National Conference Techstreams, Pillai HOC College of Engineering and Technoloy, Rasayani, Raigad, Maharshtra.