Experimental Response of Irregular Building Under Dynamic Loading

By

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DEPARTMENT OF CIVIL ENGINEERING

INSTITUTE OF TECHNOLOGY

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Major Project

Submitted in partial fulfillment of the requirements

for the degree of

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in

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(Computer Aided Structure Analysis and Design)

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Declaration

This is to certify that

a. The thesis comprises my work towards the Degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) at Nirma University and has not been submitted elsewhere for a degree.

b. Due acknowledgment has been made in the text to all source material used.

Devanshi R. Shah

Certificate

This is to certify that Major Project entitled **"Experimental Response of Irregular Building Under Dynamic Loading"** submitted by **Devanshi R. Shah (15MCLC25)**, towards the partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) of Nirma University, Ahmedabad is the record of work carried out by her under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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Abstract

Advancement to new construction technologies and invention of newer and more efficient material made possible to construct lighter and flexible structures with irregular geometry.Due to unsymmetrical distribution of mass and stiffness of irregular structure, it is expected to behave differently as compared to regular geometry structure when subjected to dynamic loading.Typically when irregular structures undergoes torsion, inducing additional shear to vertical structural elements.It has been found that many irregular structures are used for important building like school, hospital, industrial and commercial.This offers seismic hazard hence it is important to study the behaviour of irregular structures under dynamic loading.

In the present study, Irregular structures with irregularities plan geometries like L- and T- shape are studied through Single Degree of Freedom Systems (SDOF) and Multi Degree of Freedom System (MDOF) scaled building model through shake table.SDOF and MDOF building model are fabricated using Aluminum material and satisfies the planer irregularities provisions defined in IS 1893 (part -1)-2002.Apart SDOF model with material irregularity is also fabricated with three columns are made out of aluminum while fourth is made of mild steel.Also SDOF and MDOF building modes are subjected to free as well as forced vibrations to determine its behaviour in terms of Natural Frequency, Damping constant and Acceleration response of the mass.

It has been observed that L- shape building model shows larger acceleration response as compared to T-shape building model.Apart damping coefficient ζ is observed to be highest for building model with material irregularity followed by T-shaped building model and least is building with L- shape geometry.Forced vibration study on SDOF and MDOF systems indicates that for both the types transmissibility ratio is highest for L-shape building model.Transmissibility ratio for T shape building model is smaller than transmissibility ratio for L shape building model, but is slightly higher than transmissibility ratio of material irregularity building model.

Acknowledgement

I would like to thank my guide **Dr. Sharad P. Purohit,** whose keen interest and knowledge base helped me to carry out the major project work. His constant support and guidance during my project work equipped me with a great understanding of different aspects of the project work. He has shown keen interest in this work right from beginning and has been a great motivating factor in outlining the flow of my work.

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Abbreviation Notation and Nomenclature

LabVIEW .... Laboratory Virtual Instrument Engineering Workbench
SDOF .... Single Degree of Freedom
MDOF .... Multi Degree of Freedom
DMF .... Dynamic Magnification Factor
DAQ .... Data Acquisition System
TR .... Transmissibility Ratio
CM .... Centre of Mass
CS .... Cenrtre of Stiffness
ξ .... Damping Coefficient
ω_d .... Damped Natural Frequency
ω_n .... Natural Frequency
ω_f .... Forcing Frequency
η .... Frequency Ratio
m .... Mass of Member
L .... Length of Member
k .... Stiffness of Member
c .... Damping
c_{cr} .... Critical Damping
M .... Mass Matrix
K .... Stiffness Matrix
r .... Raduis of Gyration
E .... Modulus of Elasticity
I .... Moment of Inertia
λ .... Eigen Value
Φ .... Eigen Vector
δ .... Logarithmic Decrement

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Chapter 1

Introduction

1.1 General

Dynamic response of structure is very important phenomena in structure engineering field. In practical, various structures give different response when they are subjected to dynamic loading like earthquake, wind, strong gust etc.

Before designing any structure it is important to understand dynamic behaviour of that structure. Dynamic behaviour of any structure can be determined by any of both of the following ways:

1. Analytically
2. Experimentally

When structures are subjected to dynamic loading, inertia force are generated in the structure to resist that dynamic loading. Dynamic behaviour of that structure should be understand carefully. Regular Structures and Irregular Structures behave differently when they are subjected to dynamic loading.

- **Symmetric or regular structures**: When mass and stiffness is uniformly distributed in plan as well as in elevation of the structure then the structure is known as symmetric structure.

- **Asymmetric or irregular structure**: When mass and stiffness is not distributed uniformly in plan as well as in elevation of the structure then the structure is known as asymmetric structure. Structures possess various types of irregularities which is defined in IS:1893 (part-I)-2002.

1.2 Need of the Study

When structure is subjected to any type of dynamic loading, generated inertia force is assumed to act through Center of Mass (C.M.) of the structure. Vertical members resist these forces and resultant of these forces act through Center of Stiffness (C.S.).

When Center of Mass and Center of Stiffness do not coinside, eccentricities are developed in the building which produces torsion in the structural system. Torsional coupling generates greater damage in the buildings. So it is necessary to understand the response of structure having torsional coupling under dynamic loading.

1.3 Objective of the Study

Following objectives are identified for the present study.

- To study dynamic behaviour of Single Degree of Freedom (SDOF) building model with plan irregularity as well as material irregularity.
- To study dynamic behaviour of Multi Degree of Freedom (MDOF) building model with plan irregularity as well as material irregularity.
- To derive dynamic behaviour of SDOF and MDOF building model with different types of irregularities analytically.

1.4 Scope of the Work

In order to achieve the above outlined objectives of study, following scope of work is summarized:

- Study fundamentally different types of irregularities of building as defined in IS: 1893 (Part-1)-2002.
- Fabricate SDOF Building Models of Aluminum material with plan irregularities of different forms like L - shape T - shape. Also fabricate SDOF building model with material irregularity where in one column of building model is made up of mild steel material unlike Aluminum material.
- Same as SDOF building model, fabricate MDOF Building Models of Aluminum material with both plan irregularities of different forms like L - shape T - shape and material irregularity where in one column of building model is made up of mild steel material unlike Aluminum material.
- Development of experimental setup consisting of Shaketable, Uniaxial Accelerometers, Data Acquisition System, LabVIEW software, Computer Program connected to SDOF/MDOF building models.
- Extract dynamic response quantities like Natural Frequency, Damping Co-efficient and Acceleration of SDOF/MDOF building model subjected to Free Vibration as well as Forced Vibration.

1.5 Organization of the Report

The contents of major project report is divided into various chapters as below:

Chapter 1 presents the introduction and overview of Importance of understanding the dynamic behaviour of irregular building. The need of the study is discussed. It also includes objectives of the study and scope of the work.

Chapter 2 includes brief literature review of experimental work done previously using shake table.Review of some books used for analytical solution.

Chapter 3 covers the fundamentals of structural Dynamics which is helpful for understanding the dynmaics of the project.

Chapter 4 covers different types of irregularities and analytical problem formulation and solution of SDOF as well as MDOF irregular building models.

Chapter 5 covers the Experimental programme of all SDOF and MDOF irregular building models includes Free and Forced vibration imparted on both SDOF as well as MDOF irregular building models.

Chapter 6 covers results and discussion of the experimental work done on various models.

Finally, a summary of project, conclusion and recommendation for future work is discussed in **Chapter 7**.

Chapter 2

Literature Review

2.1 General

Structure when subjected to time dependent loads, i.e. dynamic loads, undergoes high level of stress developments. Thus it is important to measure dynamic response of the structure.This is generally done by performing experiments on the prototypes of the buildings in laboratory. From the recent literature it can be seen that utilization of various instruments like shake table, accelerometers, DAQ (Data Acquisition System) can help to understand dynamic behaviour of structures under dynamic loadings very properly.

2.2 Literature Review

2.2.1 Experimental Evaluation of Dynamic Properties

Manohar and Venkatesha[1] carried out experiment to understand the dynamics of a one-storied building frame with planar asymmetry subjected to harmonic base motions.For study single story single bay frame model was considered having rigid rectangular steel slab at the top and supported on four columns. Three columns were from aluminium and the fourth column was from steel material.Experimental set up is designed in such a way that the angle of incidence of the base motion on to the frame can be varied over 0 to $\pi/2$ It is mounted on a table that is driven by an electric motor.

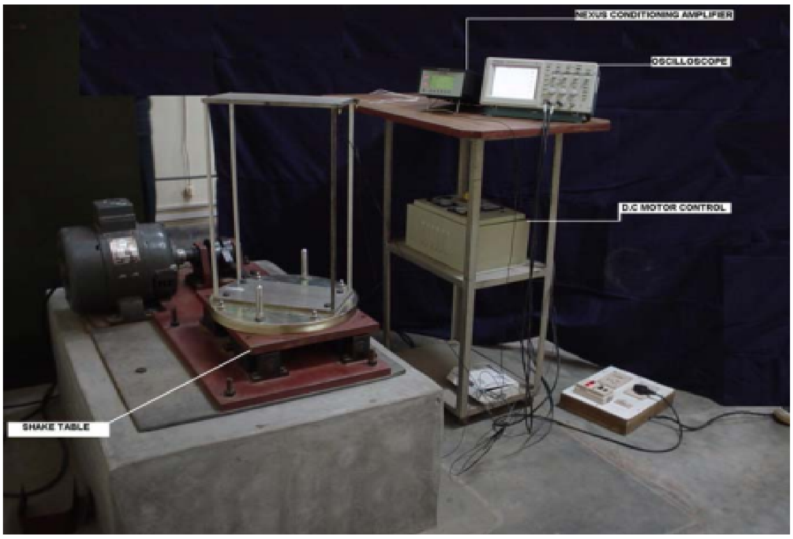


Figure 2.1: Experimental Setup for One-Story Building Frame

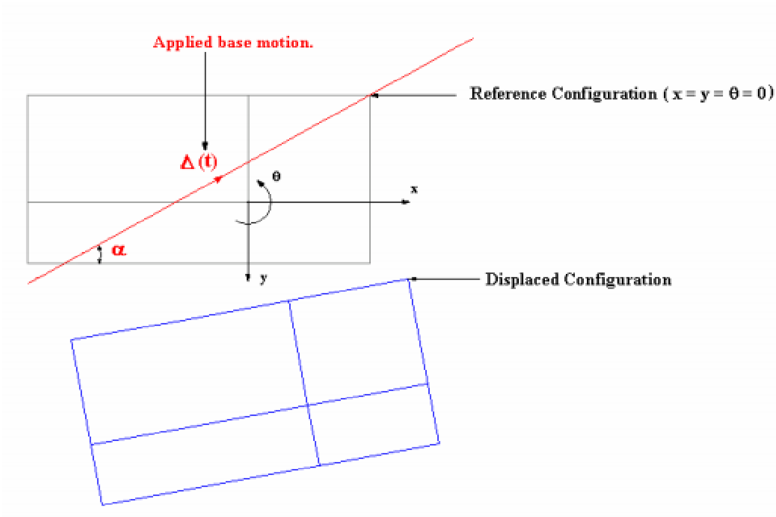


Figure 2.2: Displacement of the Steel Slab in its Own Plane

Table 2.1: Notations for Studies on One-story Building Frame

Accelerometer	Measurements
A1	Displacement along X axis ($\overline{X}$)
A2 & A3	Rotation ($\overline{X1}$, $\overline{X2}$)
A4	Base Motion ($\overline{Xg}$)
A5	Displacement along Y axis ($\overline{Y}$)
A6	Base Motion ($\overline{Yg}$)

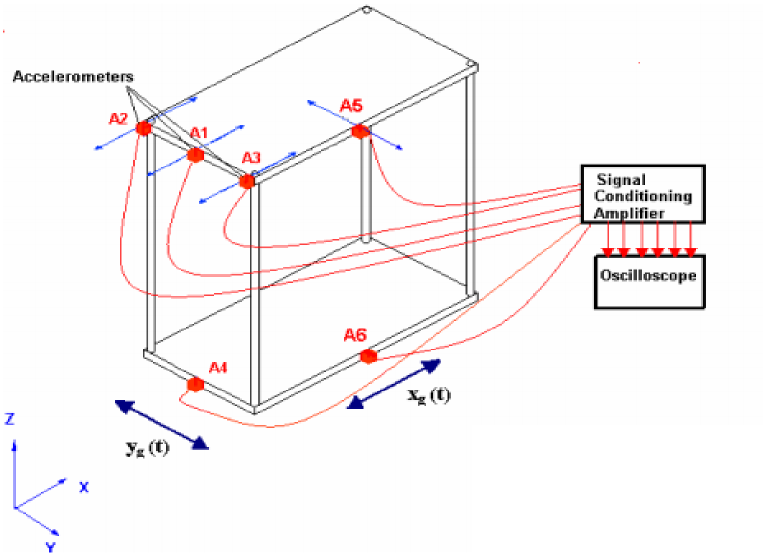


Figure 2.3: Setup for Studies on One-story Building Frame

Amplitude and phase spectra of absolute responses of one-story building frame subjected to harmonic base motion; where α =0; responses along x, y and θ direction as shown in Figure 2.4.

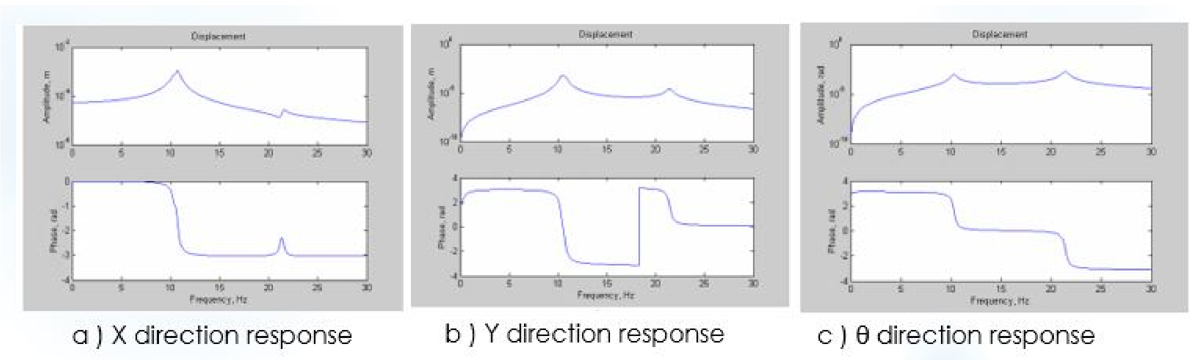


Figure 2.4: Amplitude and Phase Spectra of Absolute Responses of One-Story Building Frame

Brown [2] presented her work in the process of rehabilitation a shake table for use in seismic analysis of small scale model. LabVIEW 8.0 was used to write the controlling program for the shake table. In order to test seismic response of a prototype building. A 7-story reinforced concrete building was modelled in piano wire and plywood and tested on the shake table. The shake table recorded data from an accelerometer mounted on the model. The model was built to have the same resonant frequency as the prototype building. The model clearly shows modal forms and shows exaggerated deflection, as well as torsion caused by modelling inconsistencies. Reactions in the model correlate to the prototype.

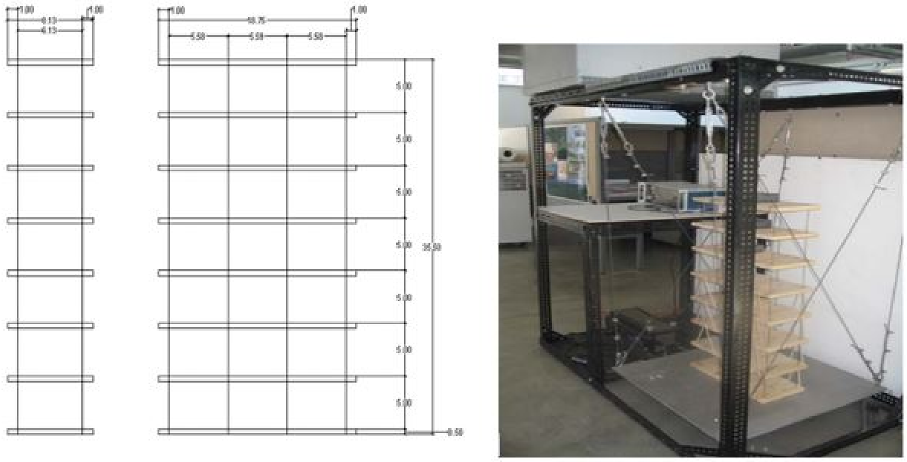


Figure 2.5: Model and Actual set up

Table 2.2: Testing Results of experiments

Test	Earthquake/ Frequency	How the test was recorded	Result/ comments
1	Northridge	Excel/ Notepad	Test recorded maximum deflections on Roof 6th , 3rd, and 2nd floors of model. 1/25/07
2	1 Hz	Excel/ Notepad	Accelerometer Test with Mass on Shake Table 11/29/06
3	1 Hz	Excel / Notepad	Accelerometer Test with No Mass on Shake Table 11/29/06
4	1 Hz	Excel / Notepad	Accelerometer Test after reattaching the accelerometer 11/29/06

Butterworth et. al. [3] have presented an experimental investigation on the damping properties of an 11 storey reinforced concrete shear core office building through forced vibration tests. Excitation was applied by means of a rotating eccentric mass exciter driven by a precisely controlled electric motor with electromagnetic and resistive braking capabilities. The exciter has generated a sinusoidal force amplitudes of 40 kN. Accelerometers along with data acquisition system were used to measure structural responses. Damping ratio for the building was calculated using free vibration decay, i.e. logarithmic decrement and half power bandwidth method. Figure 2.6 shows plan details of a building used for experimental testing.

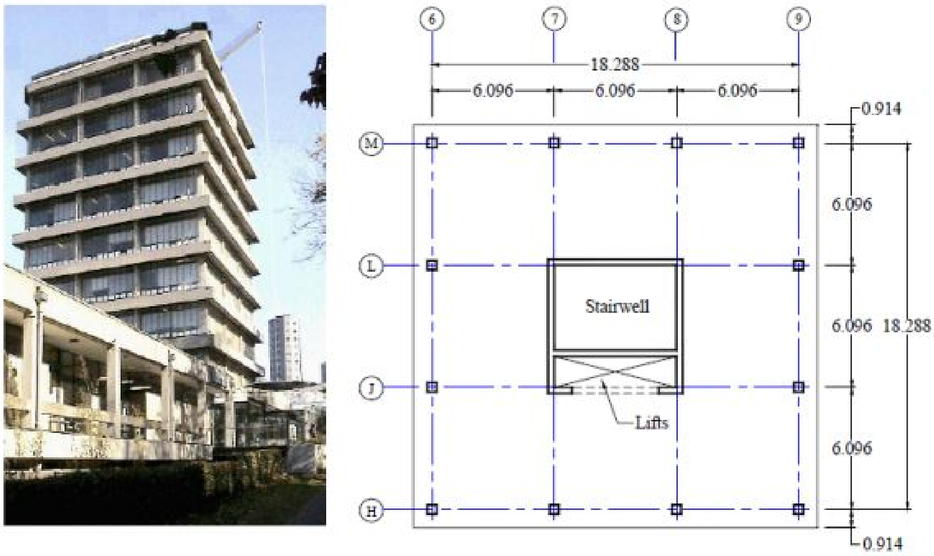


Figure 2.6: Plan of the Building used for Experiments

Here Figure 2.7 shows the typical free vibration time-history of level 14 displacement following excitation with in the 1st translational mode.
Free vibration decay of an ideal viscously damped system lies within an envelope

$$[u(t) = \pm A e^{\xi \omega t}] \tag{2.1}$$

Since value of ωn is known, we can get the value of ξ.

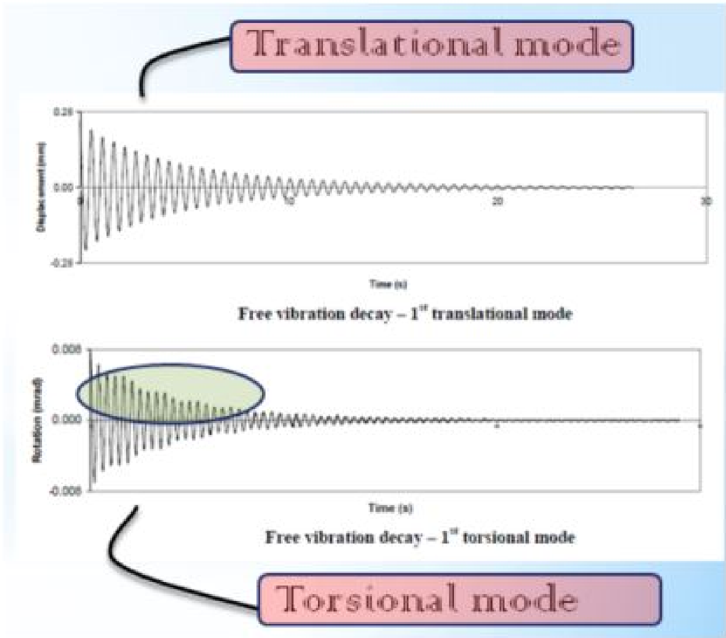


Figure 2.7: First Translational and Torsional Modes of Free Vibration Decay

Table 2.3: Damping Values Deduced From Fitted Exponential Envelopes

	1^{st} Translational		1^{st} Torsional	
	Resonant Frequency (Hz)	Damping Ratio (%)	Resonant Frequency (Hz)	Damping Ratio (%)
Trial 1	1.88	1.7	2.447	1.56
Trial 2	1.9	1.56	2.463	1.43
Trial 3	0.91	1.46	2.48	1.36

Sucuoglu and Akkar [4] described seismic analysis procedures and design principles developed for building structures. Analytical solution of one storey and multi-storey space frame structures subjected dynamic loading has been described. They considered dynamic degrees of freedom are defined at each story by using the rigid diaphragm assumption, leading to a diagonal mass matrix. Stiffness matrix is derived for 3D buildings with unsymmetrical stiffness distribution in plan, leading to a coupled stiffness matrix. The effect of unsymmetrical stiffness distribution on the mode shapes is discussed, with emphasis on torsional coupling.

Panchal D. B. [5] carried out experimental work to understand the control of dynamic response for a building model using different types of bracing like concentric, eccentric. The authors had carried out a small scale experiment was performed on a Shake Table in the laboratory. There were four types of building models were considered in experimental work: Uncontrolled SDOF, controlled SDOF, TDOF and MDOF. Response of all these model were studied in detail by conducting free and forced vibration test through uni axial shake table and Data Acquisition System LabVIEW 8.0. The dynamic properties like Natural Frequency and Damping co-efficient were obtained for both braced as well as unbraced building models. Various types of bracing eccentric as well as concentric bracing were used. It has been observed that among all types of bracing V type bracing yields maximum reduction in response quantities without much affecting natural frequency of the system.

Patel H. Y. [6] carried out experimental work to understand the control of dynamic response of MDOF a building model using different types of bracings like concentric, eccentric and tuned mass dampers like single tuned mass dampers and multi tuned mass dampers. MDOF model has been prepared from aluminium and small scale experiment was performed on shake table. Response of this MDOF model was studied in detail by conducting free and forced vibration test through uniaxial shake table and Data Acquisition System LabView 8.0.Natural frequency, damping coefficient for free and force vibrations were obtained. Various types of bracings were provided in MDOF building model. Eccentric bracing shows better reduction in all dynamic response quantities compare to concentric bracings. Dynamic properties of MDOF system with single tuned mass dampers and multi tuned mass dampers were studied in detail. Both single TMD and multiple TMD shows maximum response reduction compare to bare model.

2.3 Summery

This chapter deals with understanding of various dynamic response of different types of structural systems through technical papers and reports. Experimental work carried out to determine dynamic properties like natural frequency, damping ratio etc was compiled.

With the help of literature review basic understanding of developing experimental program for capturing dynamic response of building models is developed.

Chapter 3

Fundamentals of Structural Dynamics

3.1 General

Structural Dynamics deals with the time dependent forces and motions. When any structure is subjected to such time dependent force i.e. dynamic loading, it undergoes motion and produces internal forces. The dynamic equilibrium equation for these forces is achieved through D'Alembert's principle or Newton's second law of motion for various mass elements.

All the real structures have an infinite number of masses and all are elastically connected. Thus all real structures consist of an infinite of degrees of freedom. This makes large number of equations of motion and computationally intensive analysis. Thus in dynamic analysis other coordinates are restrained and very few degrees of freedom is considered. Simple mathematical model with few degrees of freedom (DOF) is prepared to solve dynamic equation of equilibrium.

3.2 Free Vibrations of SDOF Systems [9]

3.2.1 Undamped Free Vibration

When a structure is disturbed from its static equilibrium position and then allowed to vibrate without any external dynamic excitation then it is known as free vibration of the structure.

Derivation of the Equation of Motion

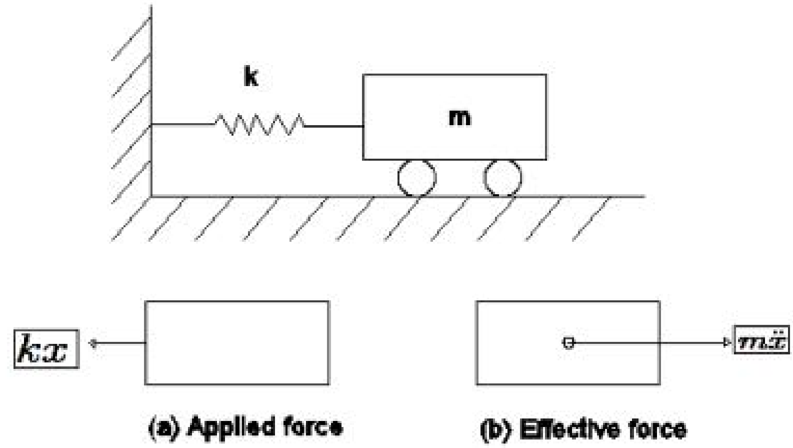


Figure 3.1: Free Body Diagram of Damped SDOF System

From the free-body diagrams, the equation of motion for the system is,

$$m\ddot{x} = -kx \tag{3.1}$$

$$m\ddot{x} + kx = 0 \tag{3.2}$$

Free vibration is initiated by disturbing the system from its static equilibrium position by imparting on the mass, some displacements x(0) and velocity $\dot{x}(0)$ at time zero, defined as the instant the motion is initiated. x=x(0) and $\dot{x} = x(0)$ are the initial conditions.

The solution to the homogeneous differential equation 3.2 is obtained using initial conditions by standard methods.The solution of above differential equation 3.2 can be expressed as,

$$x\left(t\right) = A_1 cos\omega_n t + A_2 sin\omega_n t \tag{3.3}$$

Here $A_1 and A_2$ are arbitrary constant. Above equation can also be expressed in the terms of initial displacement and initial velocity.

$$x\left(t\right) = x\left(0\right) cos\omega_n t + \left[\dot{x}\left(0\right)/\omega_n\right] sin\omega_n t \tag{3.4}$$

Where

$$\omega_n = \sqrt{\frac{k}{m}} \tag{3.5}$$

Amplitude of motion

$$A = \sqrt{A_1^2 + A_2^2} \tag{3.6}$$

Phase angle

$$tan^{-1}\left(\frac{A_1}{A_2}\right) \tag{3.7}$$

The time required for the undamped system to complete one cycle of free vibration is the natural period of vibration T_n.

$$T_n = \frac{2\pi}{\omega_n} \tag{3.8}$$

$$f_n = \frac{1}{T_n} \tag{3.9}$$

Here $[f_n]$ is natural frequency in H_z.

3.2.2 Damped Free vibration

For free vibration of SDOF system with damping, governing differential equation is,

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{3.10}$$

solution of this second order homogeneous differential equation is in the form of

$$x = e^{st} \tag{3.11}$$

Dividing equation by m gives

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 u = 0 \tag{3.12}$$

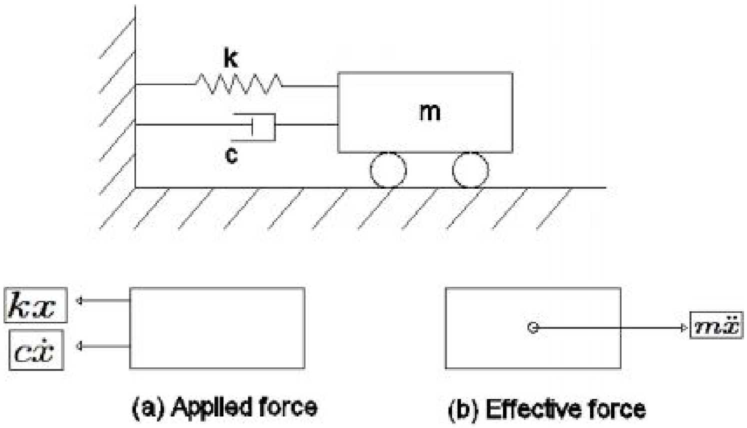


Figure 3.2: Free Body Diagram of Damped SDOF System

where

$$\zeta = \frac{c}{2m\omega_n} = \frac{c}{c_{cr}} = Damping\ Ratio$$

$$c_{cr} = 2m\omega_n = 2\sqrt{km} = Critical\ Damping\ Coefficient$$

roots of characteristic equation are

$$S_{1,2} = -\frac{c}{2m} \pm \sqrt{\left[\frac{c}{2m}\right]^2 - \frac{k}{m}} \tag{3.13}$$

$$S_{1,2} = (-\zeta \pm \sqrt{[\zeta^2 - 1]}\omega_n \tag{3.14}$$

The general solution of homogeneous equation can be written as,

$$x(t) = A_1 e^{s_1 t} + A_2 e^{s_2 t} \tag{3.15}$$

3.2.3 Types of Motion

The actual form of the solutions depends on the nature of roots given by equations 3.15 or 3.16. Depending on the nature of the roots of Eq. 3.15 and 3.16 ,i.e., imaginary(complex conjugate roots), real distinct [$\zeta < 1$] roots or real repeated roots [$\zeta = 1$], three types of motions are presented in Figure 3.3.

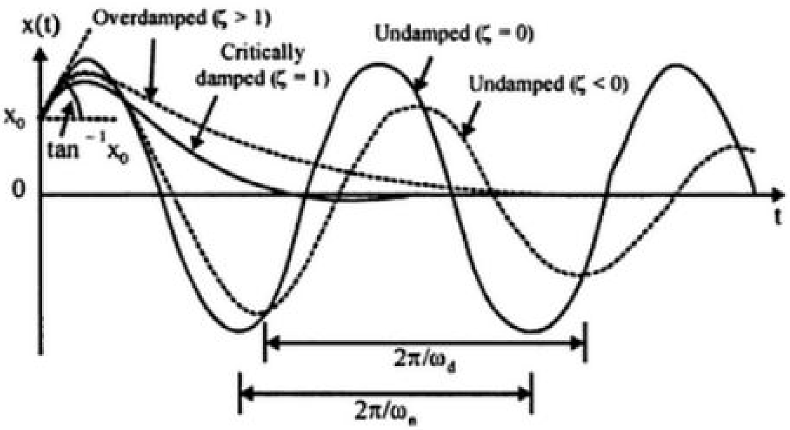


Figure 3.3: Response of Under Damped, Critically Damped and Overdamped Systems

CASE : 1 Under Damped System: If [$\zeta < 0$], the system is termed as under damped system. The roots of the characteristic equation are complex conjugates,corresponding to oscillatory motion with an exponential decay in amplitude. The solution can be obtained as,

$$x(t) = e^{-\zeta\omega_n t}[A_1 cos(\omega_d t) + A_2 sin(\omega_d t)] \tag{3.16}$$

Where [A_1] and [A_2] are arbitrary constants and can be determined by initial conditions of the system, and [ω_d] is the damped natural frequency of the system given by,

$$\omega_d = \omega_n \sqrt{(1 - \zeta^2)} \tag{3.17}$$

From [A_1] and [A_2] can be determined

$$A_1 = \dot{x_0} \tag{3.18}$$

and

$$A_2 = \frac{x_0 + \dot{\zeta}\omega_n \dot{x_0}}{\omega_d} \tag{3.19}$$

This equation now can be written as in terms of [x_0] and [$\dot{x}_0$]

$$x(t) = e^{-\zeta\omega_n t}[x_0 cos(\omega_d t) + \frac{x_0 + \dot{\zeta}\omega_n \dot{x_0}}{\omega_d} sin(\omega_d t)] \tag{3.20}$$

Logarithmic Decrement: In the free vibration of an underdamped system,displacement amplitude decays exponentially with time. The rate of decrease depends on the damping ratio $[\zeta]$.

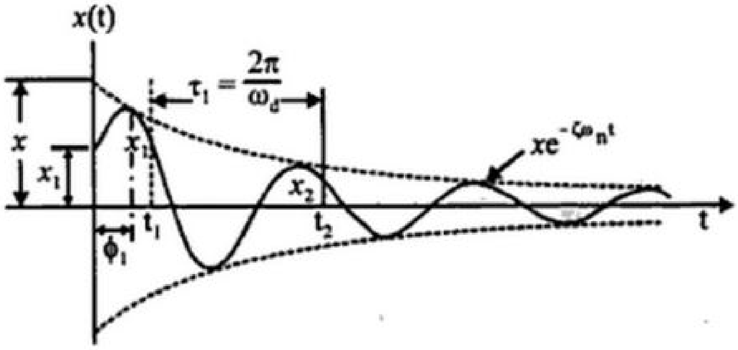


Figure 3.4: Displacement Response of SDOF System Under Free Vibration

if we consider displacement at time $[t_1]$ by $[x_1]$ $[\equiv]$ $[x(t_1)]$,then

$$x(t_1) = Ae^{-\zeta\omega_n t_1} sin(\omega_d t_1 + \phi) \tag{3.21}$$

The displacement at $[t_{1+\frac{2\pi}{\omega_d}}]$ is given by

$$x(t_{1+\frac{2\pi}{\omega_d}}) = Ae^{-\zeta\omega_n t_{1+\frac{2\pi}{\omega_d}}} sin(\omega_d t_1 + \phi) \tag{3.22}$$

The ratio $[u(t_1)]$ to $[t_{1+\frac{2\pi}{\omega_d}}]$ provides the measure of the decrease in displacement over one cycle of motion. The ratio is constant and does not vary with time. Its natural log with time is called logarithmic decrement and is denoted as $[\delta]$. The value of $[\delta]$ is given by,

$$\delta = ln(\frac{e^{\zeta\omega_n t_1}}{e^{-\zeta\omega_n t_{1+\frac{2\pi}{\omega_d}}} sin(\omega_d t_1 + \phi)}) \tag{3.23}$$

$$\delta = 2\pi\zeta\frac{\omega_n}{\omega_d} \tag{3.24}$$

$$\delta = 2\pi\frac{\zeta}{\sqrt{1-\zeta^2}} \tag{3.25}$$

For small values of $[\zeta]$, $[\delta \approx 2\pi\zeta]$. If $[\delta]$ is obtained from measurements and $[\zeta]$ is to be evaluated, we can use,

$$\zeta = \frac{\delta}{2\pi} \tag{3.26}$$

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{3.27}$$

CASE : 2 Critically Damped System: If $[\zeta = 0]$, the system is termed critically damped. The damping constant c is, in this case, denoted by $[c_{cr}]$ and its value is given by

$$c = c_{cr} = 2\sqrt{km} \tag{3.28}$$

$$c = c_{cr} = 2m\omega_n \tag{3.29}$$

The roots of Eq are now equal, so that

$$s_1 = s_2 = \frac{c_{cr}}{2m} = -\omega_n \tag{3.30}$$

The general solution is given by

$$x = (A_1 + A_2 t)e^{-\omega_n t} \tag{3.31}$$

Where $[A_1]$ and $[A_2]$ are arbitrary constants to be determined from initial conditions. Substitution of initial displacement and initial velocity, leads to the following values of $[A_1]$ and $[A_2]$.

$$A_1 = x_0 \tag{3.32}$$

$$A_2 = \frac{\dot{x_0}}{\omega_n} + x_0 \tag{3.33}$$

The general solution thus becomes,

$$x(t) = [x_0 + (\frac{\dot{x_0}}{\omega_n} + x_0)\omega_n t]e^{\omega_n t} \tag{3.34}$$

Since critical damping represents the limit of aperiodic damping, the motion returns to rest in the shortest time without oscillations. This property can be advantageously used in many practical vibration problems such as large guns, measuring instruments and electrical meters.

CASE : 3 Over Damped System: If $[\zeta > 0]$ or damping is greater than $[c_{cr}]$ the system is termed over damped system. The roots of the characteristic equation are purely real and distinct, corresponding to simple exponentially decaying motion.

$$\zeta = \frac{c}{c_{cr}} \tag{3.35}$$

$$c = c_{cr}\zeta \tag{3.36}$$

$$c = 2m\omega_n\zeta \tag{3.37}$$

Substitution of values gives,

$$s_1 = -\omega_n\zeta + \omega_n\sqrt{\zeta^2 - 1} \tag{3.38}$$

$$s_1 = -\omega_n\zeta - \omega_n\sqrt{\zeta^2 - 1} \tag{3.39}$$

If we denote

$$\omega_n\sqrt{\zeta^2 - 1} = \bar{\omega} \tag{3.40}$$

The general solution becomes

$$x(t) = e^{-\omega_n\zeta t}(A_1 e^{\overline{\omega}t} + A_2 e^{\overline{\omega}t}) \tag{3.41}$$

Where the arbitrary constants $[A_1]$ and $[A_2]$ are again determined by initial conditions.

3.3 Forced Vibration of SDOF System [9]

3.3.1 Undamped Force Vibration

The response of any structural system subjected to external force called forced response.In this fig simple SDOF undamped system is shown.

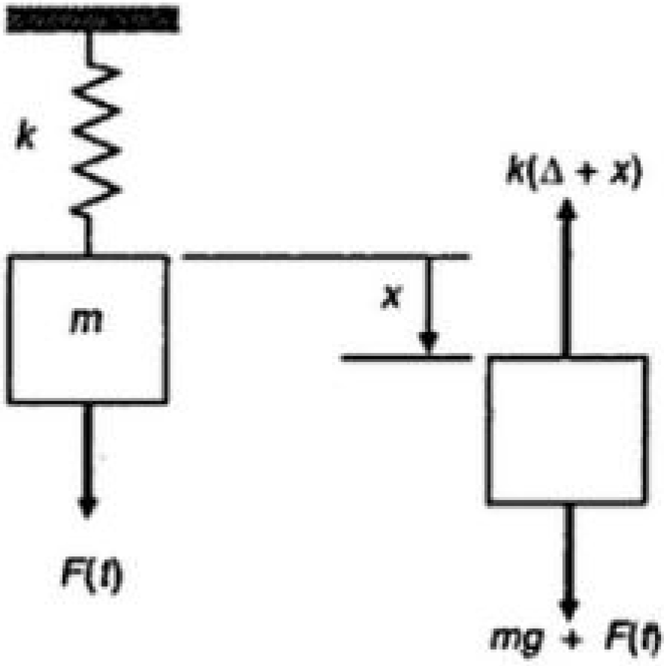


Figure 3.5: Forced Undamped Vibration of SDOF System

$$F(t) = F_0 sin\omega_f t \tag{3.42}$$

Equation of motion becomes,

$$m\ddot{x} + kx = F(t) \tag{3.43}$$

$$\ddot{x} + \frac{k}{m}x = \frac{F(t)}{m} \tag{3.44}$$

$$\ddot{x} + \frac{k}{m}x = \frac{F_0}{m} sin\omega_f t \tag{3.45}$$

Equation is a non homogeneous, second order differential equation with constant coefficients.Hence, the complete solution is the sum of homogeneous solution $x_h(t)$ and a particular solution $x_p(t)$ such that,

$$x(t) = x_h t + x_p t \tag{3.46}$$

where,

$$\ddot{x}_h + \frac{k}{m} x_h = 0 \tag{3.47}$$

and,

$$\ddot{x}_h + \frac{k}{m} x_p = \frac{F_0}{m} sin\omega_f t \tag{3.48}$$

Equation is a differential equation of motion for free vibration of simple harmonic oscillator, for which the solution is,

$$x_h(t) = A_1 cos\omega_f t + A_2 sin\omega_f t \tag{3.49}$$

In order to obtain the particular solution of equation, excitation force $[F(t)]$ is harmonic, the particular solution $[xp(t)]$ is also harmonic and has frequency $[\omega_f]$. Thus we assume the solution in the form,

$$x_p(t) = X cos\omega_f t \tag{3.50}$$

Where X is the unknown constant, which is obtained such that the assumed solution does satisfy the differential equation. X denotes the maximum amplitude of $[xp(t)]$. Substituting equation in we obtain

$$X = \frac{\frac{F_0}{m}}{\frac{k}{m} - \omega_f^2} \tag{3.51}$$

Multiplying both numerator and denominator by m/k, we obtain

$$x = \frac{\frac{F_0}{k}}{1 - (\frac{m}{k})\omega_f^2} = \frac{\frac{F_0}{k}}{1 - (\frac{\omega_f}{\omega_n})^2} \tag{3.52}$$

Hence the particular solution is given by,

$$x_p(t) = \frac{\frac{F_0}{k}}{k(1 - (\frac{\omega_f}{\omega_n})^2)} \tag{3.53}$$

The complete solution for the motion of the mass is

$$x_p(t) = A_1 cos\omega_n t + A_2 sin\omega_n t + \frac{\frac{F_0}{k}}{k(1 - (\frac{\omega_f}{\omega_n})^2)} \tag{3.54}$$

The constants $[A_1]$ and $[A_2]$ are again determined by initial conditions. The result is

$$A_1 = x_0 - \frac{F_0}{k - m\omega_f^2} \tag{3.55}$$

$$A_2 = \frac{\ddot{x_0}}{\omega_n} \tag{3.56}$$

Hence the complete solution is

$$x(t) = (x_0 - \frac{F_0}{(k - m\omega_f^2)})cos\omega_f t + \frac{\ddot{x_0}}{\omega_n} sin\omega_f t + \frac{\frac{F_0}{k}}{k(1 - (\frac{\omega_f}{\omega_n})^2)} \tag{3.57}$$

The maximum amplitude can also be expressed as

$$\frac{x}{\delta_{st}} = \frac{1}{1 - (\frac{\omega_f}{\omega_n})^2} \tag{3.58}$$

Where,

$$\frac{x}{\delta_{st}} = \frac{F_0}{k} \tag{3.59}$$

denotes the static deflection of the mass under a force $[F_0]$. The quantity $[\frac{x}{\delta_{st}}]$ represents the ratio of the dynamic to the static amplitude of motion and is called magnification factor.

3.3.2 Forced Damped Vibrations

Consider a viscously damped SDOF spring-mass system shown in Figure 3.6.
equation of motion is

$$m\ddot{x} + c\dot{x} + kx = F_0 sin\omega_f t \tag{3.60}$$

$$\ddot{x} + \frac{c}{m\ddot{x}} + \frac{k}{mx} = \frac{F_0}{m} sin\omega_f t \tag{3.61}$$

This is a homogeneous equation. The particular solution or the steady state solution $[x_p]$ can be assumed in the form,

$$x_p = A_1 sin\omega_f t + A_2 cos\omega_f t \tag{3.62}$$

which gives the following equations for the velocity and acceleration

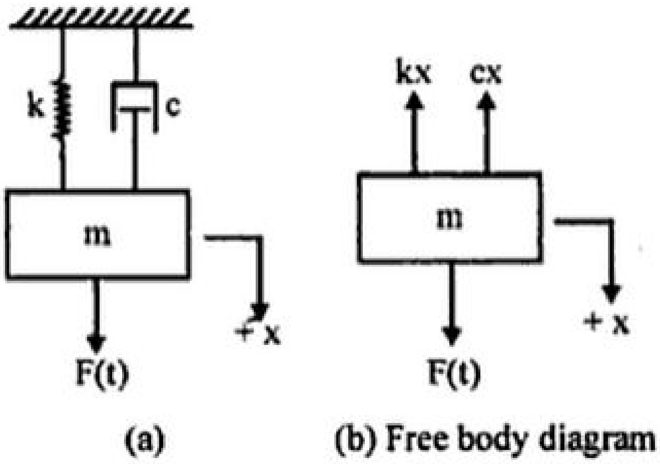


Figure 3.6: Forced Damped Vibration of SDOF System

$$\dot{x_p} = \omega_f A_1 cos\omega_f t - \omega_f A_2 sin\omega_f t \tag{3.63}$$

$$\ddot{x_p} = \omega_f^2 A_1 cos\omega_f t - \omega_f^2 A_2 sin\omega_f t \tag{3.64}$$

$$[(k - \omega_f^2 m)A_1 - c\omega_f A_2]sin\omega_f t + [(k - \omega_f^2 m)A_2 + c\omega_f A_1]cos\omega_f t = F_0 sin\omega_f t \tag{3.65}$$

Two algebraic equations in $[A_1]$ and $[A_2]$

$$[(k - \omega_f^2 m)A_1 - c\omega_f A_2] = F_0 \tag{3.66}$$

$$[(k - \omega_f^2 m)A_2 + c\omega_f A_1] = 0 \tag{3.67}$$

Dividing by stiffness coefficient

$$(1 - \eta^2)A_1 - 2\zeta\eta A_2 = X_0 \tag{3.68}$$

$$(1 - \eta^2)A_2 - 2\zeta\eta A_1 = 0 \tag{3.69}$$

Where

$$\eta = \frac{\omega_f}{\omega_n} \tag{3.70}$$

$$\zeta = \frac{c}{c_{cr}} = \frac{c}{2m\omega_n} \tag{3.71}$$

$$X_0 = \frac{F_0}{k} \tag{3.72}$$

where, $[c_{cr}] = [2m\omega_n]$ is the critical damping coefficient. Solving these two algebraic equations simultaneously gives the values of $[A_1]$ and $[A_2]$.

$$A_1 = \frac{((1-\eta^2))X_0}{(1-\eta^2)^2 + (2\zeta\eta)^2} \tag{3.73}$$

$$A_1 = \frac{(-2\zeta\eta)X_0}{(1-\eta^2)^2 + (2\zeta\eta)^2} \tag{3.74}$$

Hence, the steady state solution can be written as

$$x_p = \frac{X_0}{(1-\eta^2)^2 + (2\zeta\eta)^2}[(1-\eta^2)sin\omega_f t - (2\zeta\eta)cos\omega_f t] \tag{3.75}$$

This can be written as

$$x_p = \frac{X_0}{(1-\eta^2)^2 + (2\zeta\eta)^2}sin(\omega_f t - \phi) \tag{3.76}$$

$[X_0]$ is the amplitude and $[\phi]$ is the phase angle

$$\phi = tan^{-1}[\frac{2\zeta\eta}{(1-\eta^2)}] \tag{3.77}$$

$$x_p = X_0\beta sin(\omega_f t - \phi) \tag{3.78}$$

Where, $[\beta]$ is known as Magnification factor. Fig shows plot of Dynamic magnification factor versus Frequency ratio $[\eta]$.

3.4 Experimental Evaluation of Damping[8]

Damping plays important role in influencing the dynamic response of structures.Its accurate prediction is essential for most of the dynamic analysis. Note that, damping is

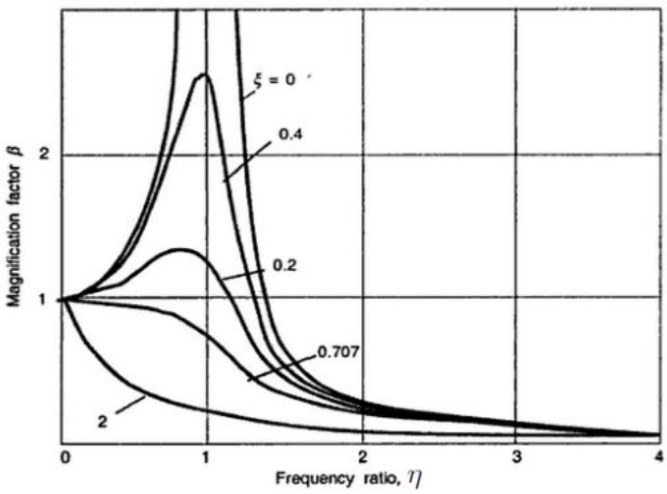


Figure 3.7: Forced Damped Vibration of SDOF System

a property which cannot be determined from other structural properties. Also, it is a quantity which is difficult to quantify. There are various types of damping that can be modelled for structural dynamic analysis. However most common among all is viscous damping which is a velocity dependent quantity.

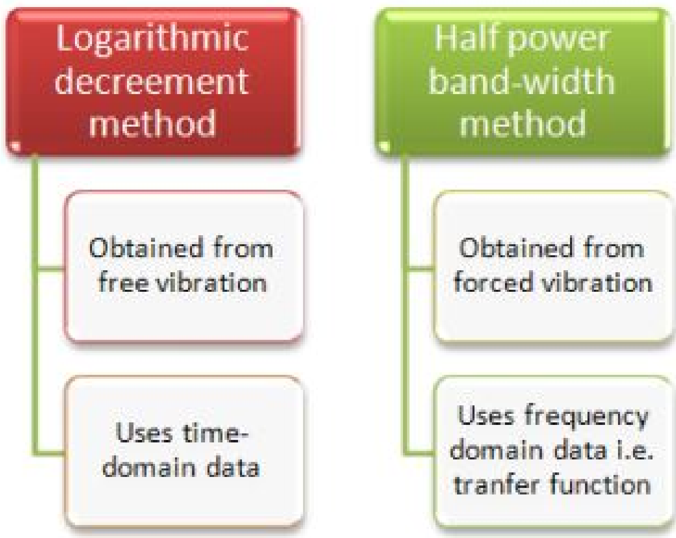


Figure 3.8: Damping Evaluation Method

3.4.1 Free Vibration Test : Logarithmic Decrement

In this method, SDOF and MDOF models are subjected to free vibration. For system being under damped, dynamic response exponentially decays. Taking ratio of successive peaks of response and considering logarithm of this values gives damping present in the system.

3.4.2 Force Vibration Test: Half Power Bandwidth

In this method, SDOF and MDOF models are subjected to forced vibration. Considering frequency ratios of excitation applied to natural frequency of system, dynamic magnification and response is extracted. Tracking peak value of response, damping is estimated.

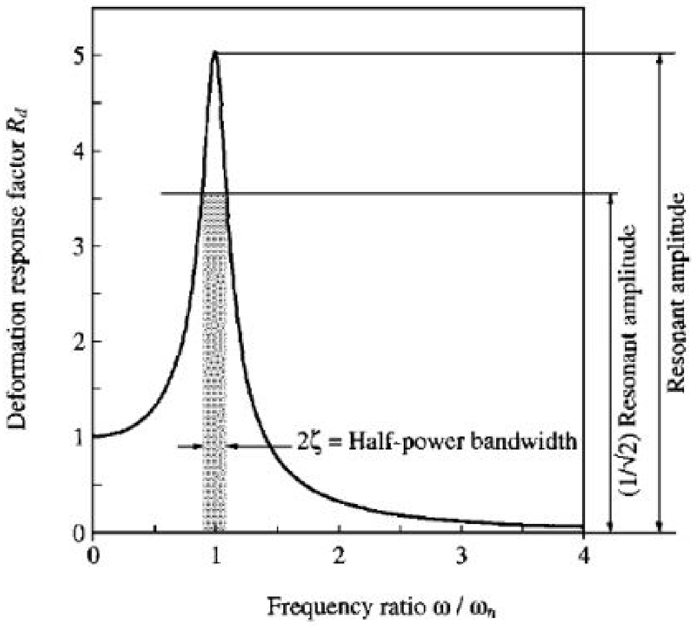


Figure 3.9: Half Power Bandwidth Method

Estimation of damping in a structure can be carried in frequency domain through half power band width approach. In this method, two forcing frequencies $[\omega_a]$ and $[\omega_b]$ are extracted on either side of the resonant frequency considering amplitude $[A_2 = \frac{1}{\sqrt{2}}]$ times the amplitude of resonant frequency amplitude $[A_1]$. For small value of $[\xi]$,

$$2\zeta = \frac{\omega_a - \omega_b}{\omega_n} \tag{3.79}$$

3.5 Summery

Detailed fundamental study of single degree of freedom system as well as multi degree of freedom system has been carried out. It is evident that damping plays very significant role in the dynamic behaviour of structural system.

Chapter 4

Problem Formulation

4.1 General

In this chapter various types of irregularities and dynamic analysis of SDOF and MDOF irregular models have been covered. Understanding about the dynamic analysis of any irregular structure requires accurate measurement of dynamic properties. Eigen value problem has been solved to determine mode shape of the structure and from the natural frequency of the structure can be calculated.

To determine mode shape of the structure in irregular structure mass and stiffness matrix of various irregular structure need to be calculated and from that, eigen value problem can be solved.

4.2 Types of Irregularities in Building

4.2.1 Types of Structural Irregularities

Regular Structures and Irregular Structures behave differently when they are subjected to dynamic loading.

- **Symmetric or regular structures:** Mass and stiffness is uniformly distributed in plan as well as in elevation.
- **Asymmetric or irregular structure:** Mass and stiffness is not distributed uniformly in plan as well as in elevation.

Buildings having irregularities show major damage during earthquakes. There are various types of irregularities given in IS 1893 : 2002 (PART 1)[7].

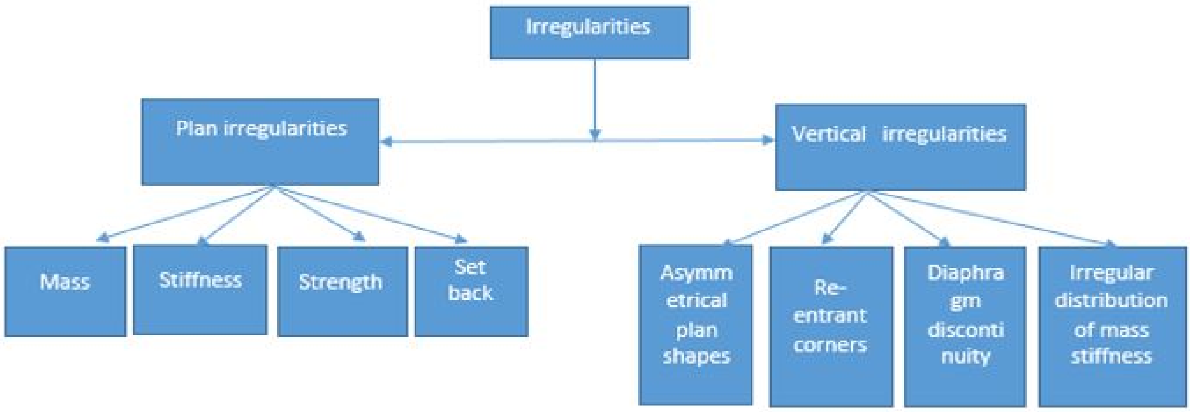


Figure 4.1: Types of Irregularities [7]

4.2.2 Definitions of Irregular Buildings — Plan Irregularities

Plan irregularities for a building includes Torsional Irregularity, Re-entrant Corners, Diaphragm Discontinuity, Out of Plane Offsets and Non Parallel Systems. In the following section each of these irregularities are discussed in brief.

- **Torsion Irregularity**

  To be considered when floor diaphragms are rigid in their own plan in relation to the vertical structural elements that resist the lateral forces. Torsional irregularity to be considered to exist when the maximum storey drift, computed with design eccentricity, at one end of the structures transverse to an axis is more than 1.2 times the average of the storey drifts at the two ends of the structure.

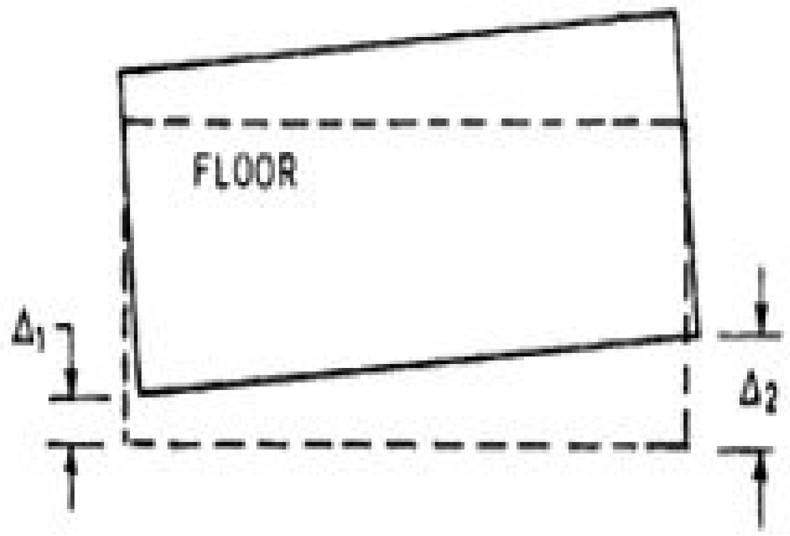


Figure 4.2: Torsion Irregularity of the Building [7]

- **Re-entrant Corners**

  Plan configurations of a structure and its lateral force resisting system contain re-entrant corners, where both projections of the structure beyond the re-entrant corner are greater than 15 percent of its plan dimension in the given direction.

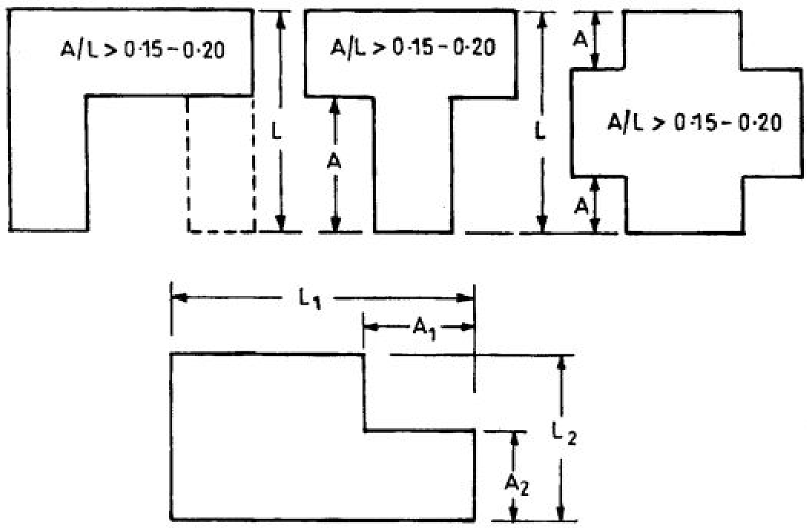


Figure 4.3: Re-entrant Corners for the Building [7]

- **Diaphragm Discontinuity**

  Diaphragms with abrupt discontinuities or variations in stiffness, including those having cut-out or open areas greater than 50 percent of the gross enclosed diaphragm area, or changes in effective diaphragm stiffness of more than 50 percent from one storey to the next.

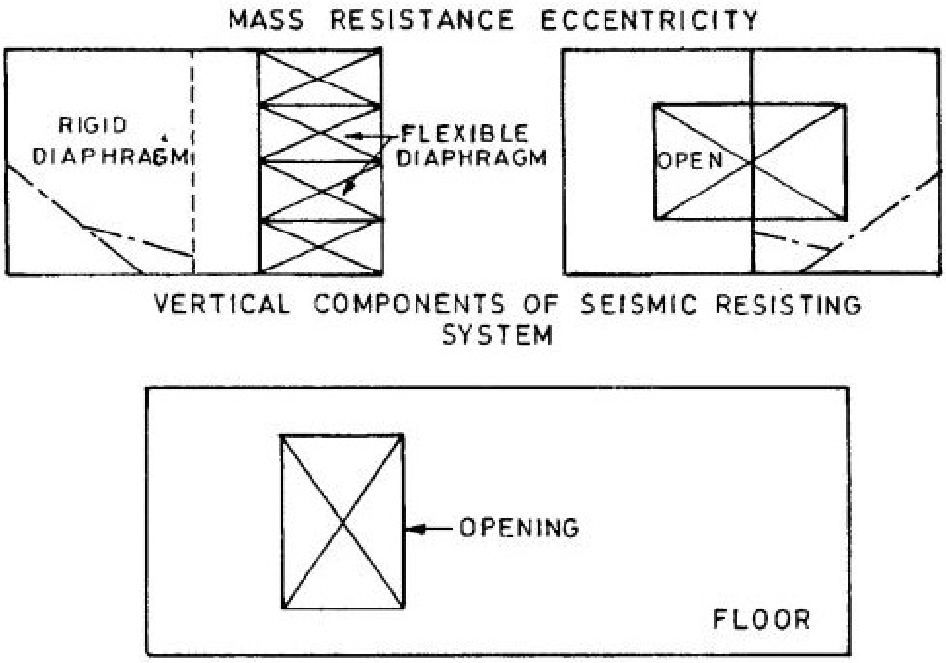


Figure 4.4: Diaphragm Discontinuity for Building [7]

- **Out-of-Plane Offsets**

  Discontinuities in a lateral force resistance path, such as out-of-plane offsets of vertical elements.

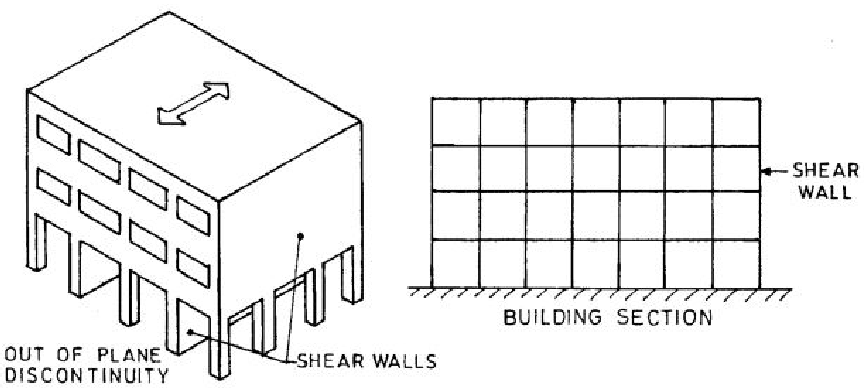


Figure 4.5: Out-of-Plane Offsets [3]

- **Non-parallel Systems**

  The vertical elements resisting the lateral force are not parallel to or symmetric about the major orthogonal axes or the lateral force resisting elements.

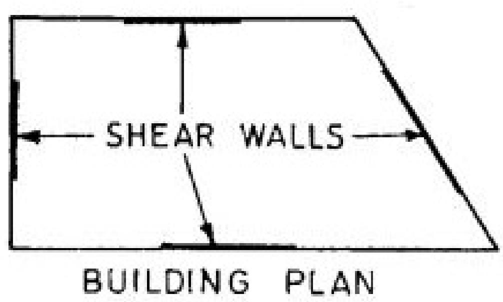


Figure 4.6: Non-parallel Systems for a Building [7]

4.2.3 Definitions of Irregular Buildings — Vertical Irregularities

- **Mass Irregularity**

  Mass Irregularities shall be considered to exist where the seismic weight of any storey is more than 200 percent of that of its adjacent storeys. The irregularity need not be considered in case of roofs.

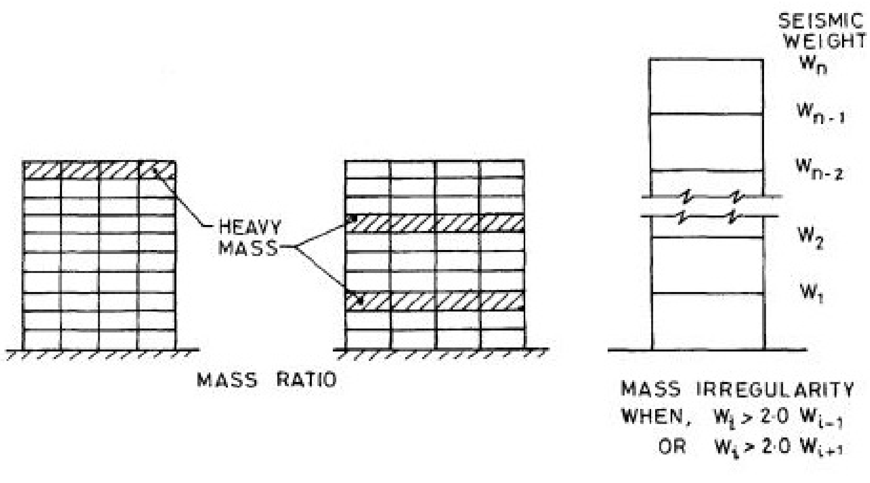


Figure 4.7: Mass Irregularity of Building[7]

- **Stiffness Irregularity**

  A soft storey is one in which the lateral stiffness is less than 70 percent of that in the storey above or less than 80 percent of the average lateral stiffness of the three storeys above.

  A extreme soft storey is one in which the lateral stiffness is less than 60 percent of that in the storey above or less than 70 percent of the average stiffness of the three storeys above. For example, buildings on STILTS will fall under this category.

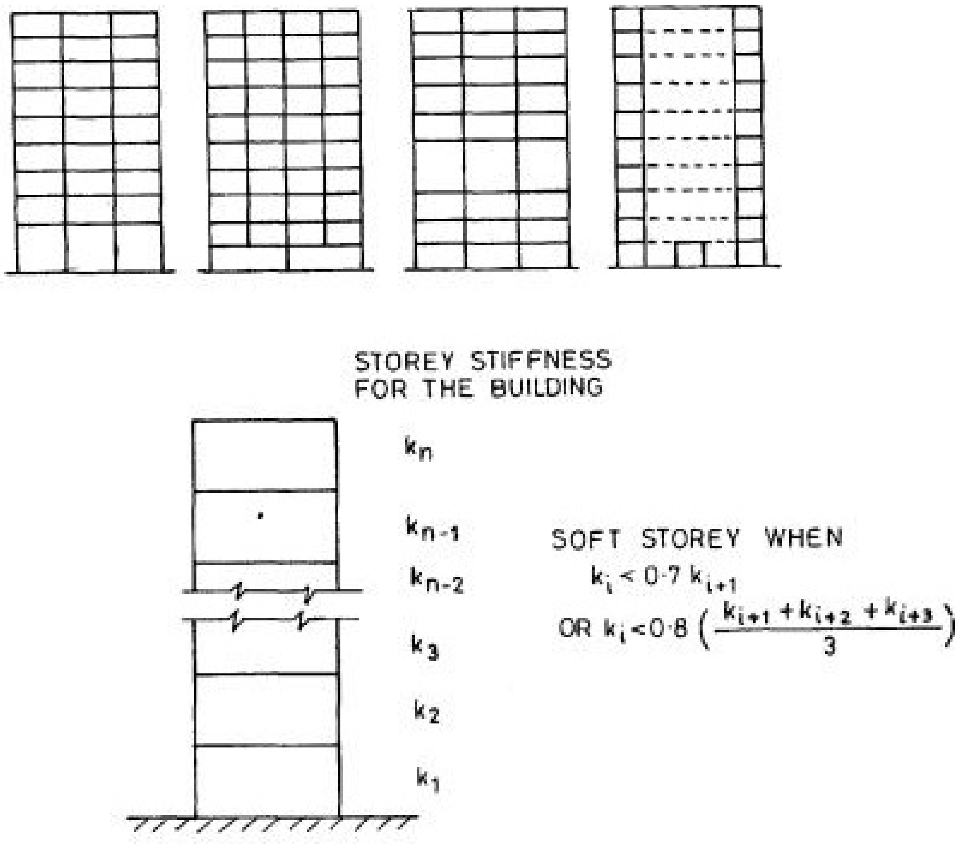


Figure 4.8: Stiffness Irregularity [7]

- **Vertical Geometric Irregularity**

  Vertical Geometric Irregularity shall be considered to exist where the horizontal dimension of the lateral force resisting system in any storey is more than 150 percent of that in its adjacent storey.

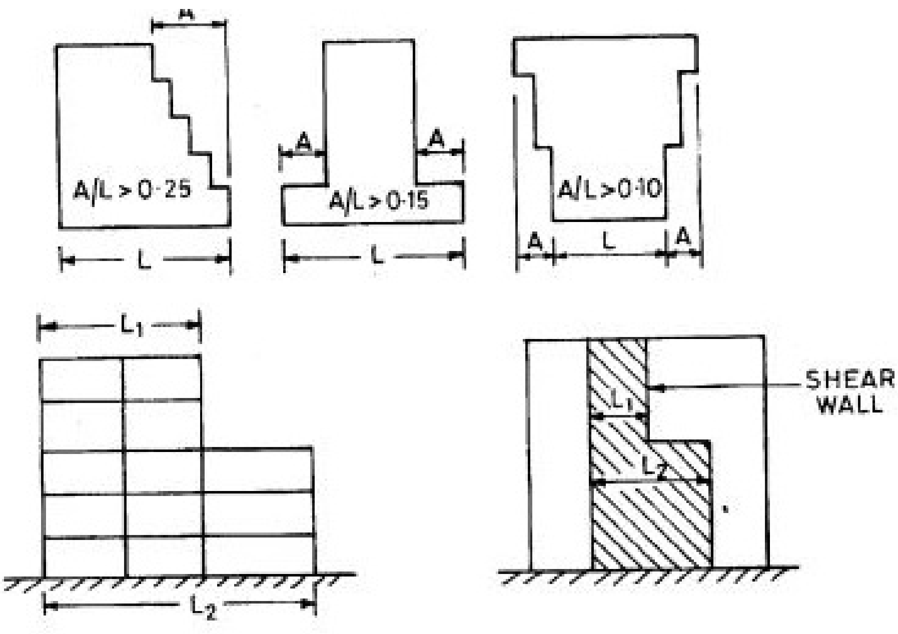


Figure 4.9: Vertical Geometric Irregularity [7]

- **Discontinuity in Capacity — Weak Storey**

  A weak storey is one in which the storey lateral strength is less than 80 percent of that in the storey above, The storey lateral strength is the total strength of all seismic force resisting elements sharing the storey shear in the considered direction.

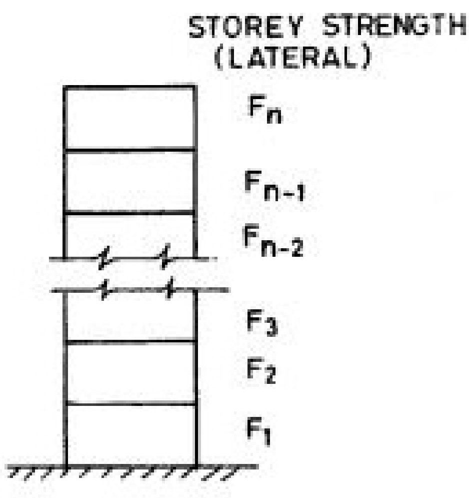


Figure 4.10: Discontinuity in Capacity — Weak Storey [7]

- **In-Plane Discontinuity in Vertical Elements Resisting Lateral Force**

  An in-plane offset of the lateral force resisting elements greater than the length of those elements.

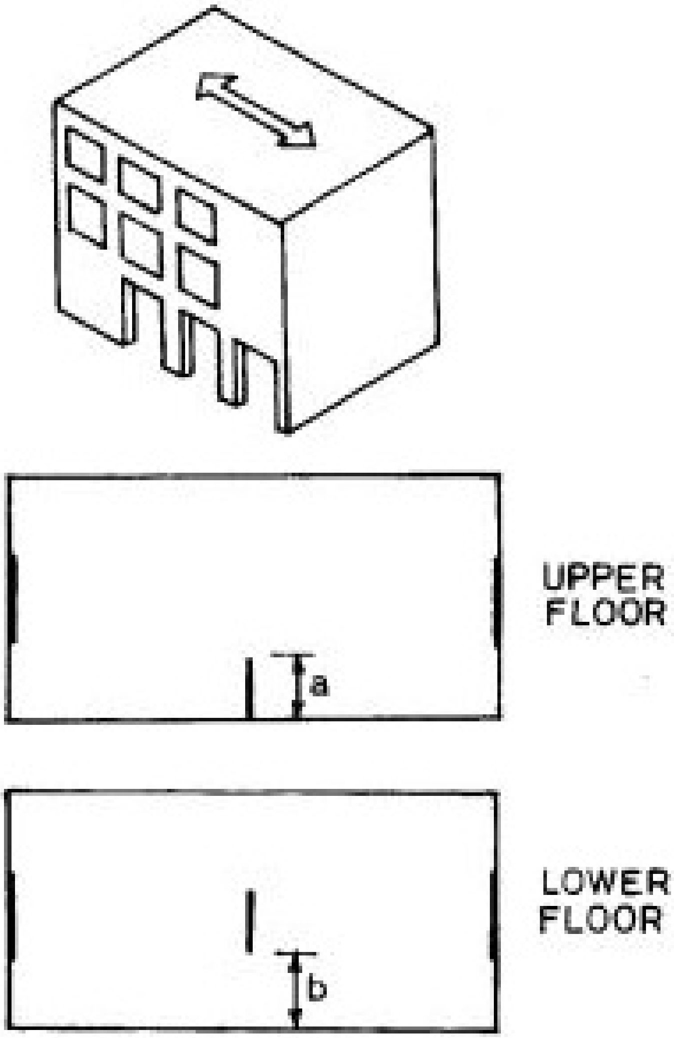


Figure 4.11: In-Plane Discontinuity in Vertical Elements Resisting Lateral Force [7]

4.3 Analytical Problem Formulation

In this section Problem Formulation & Building model with plan irregularities is stated analytically. Analytical approach to determine mass and stiffness matrix of Building model is given in detail. By calculating Eigen values and Eigen Vectors for these space frame structures, natural frequencies and mode shapes can be obtained.

To analyse the structure, floors are considered as rigid diaphragm that leads to diagonal mass matrix and stiffness matrix can be calculated from unsymmetrical stiffness distribution that leads to coupled stiffness matrix.The effect of unsymmetrical stiffness distribution emphasis on torsional coupling.The motion of the each slab is defined by three dynamic degrees of freedom defined at the center of mass and whole mass of the structure is confined at the slab.However distribution of the mass can be done evenly to the adjacent floors.

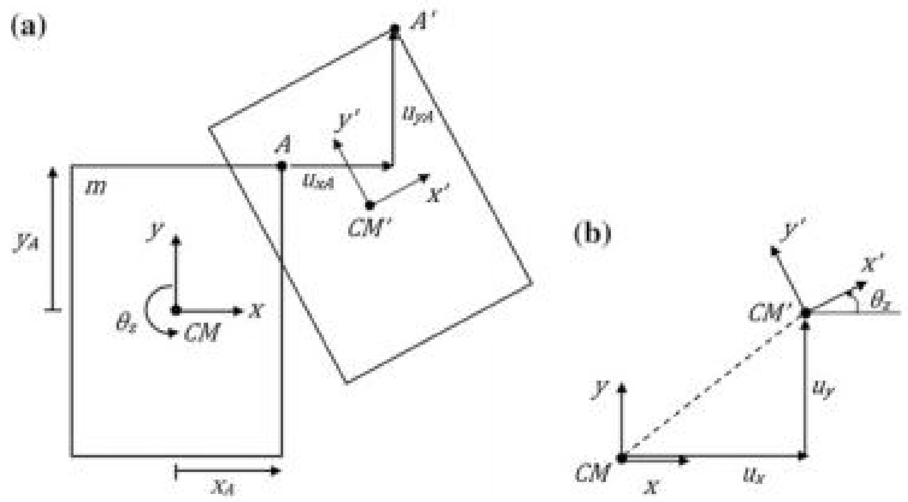


Figure 4.12: (a) Motion of a Rigid Slab in its Own Plane, (b) Motion of the Centre of Mass [5]

4.3.1 Analytical Solution of Single Storey 3 D Structure

To carry out analytical solution of single storey structure mass and stiffness matrix has been prepared and eigen values can be determined.

Mass matrix can be calculated by considering two translation masses in both the x and y direction . It is shown as $[m_i]$ and mass moment of inertia $[I_i]$ can be calculated about z-axis.As the translational and rotational masses of each story represents the translational and rotational dynamic degrees of freedom of that story, mass matrix can be constructed as a diagonal matrix since and hence there is no translational-rotational coupling between the mass coefficients.

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & I_1 \end{bmatrix}$$

Stiffness matrix can be calculated by applying direct stiffness matrix and by choosing three DOFs at the centre of the mass.The i^{th} column is located at distances x_i and y_i from the co-ordinate center. Direct stiffness method is applied for each DOF separately.

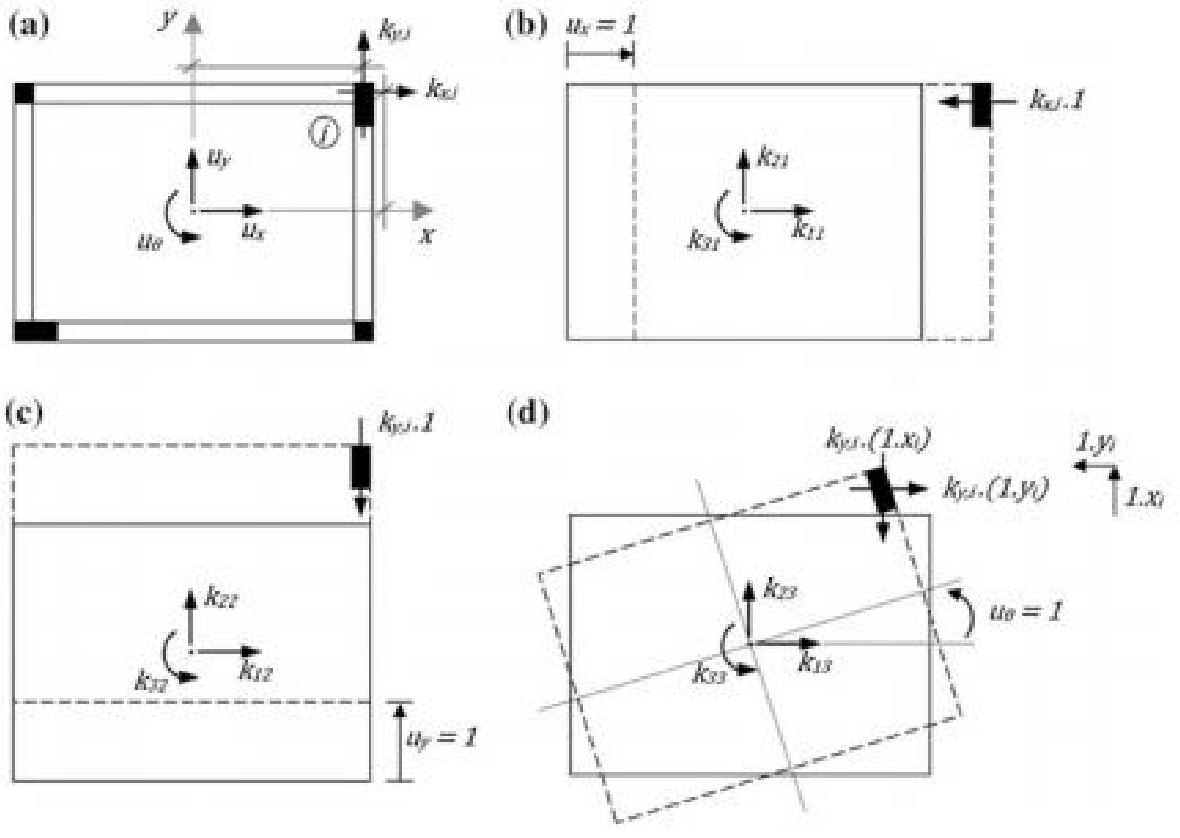


Figure 4.13: Calculation of Stiffness Coefficients for One Storey Space Frame [5]

First of all applying unit displacement in x direction (u_x=1, u_y=0 , u_z=0). All column will resist this motion and inducing force $k_{xi}.1 = k_{xi}$. Where as k_{xx} , k_{yx}, $k_{\theta x}$ are the coordinates that constrain the displacement in u_x]=1, u_y =0 , u_z. This can be represented as,

$$k_{xx} = \sum k_{xi}, k_{yx} = 0, k_{\theta x} = \sum(-k_{xi}.y_i) \tag{4.1}$$

Same way applying unit displacement in y direction (u_x=0, u_y=1 , u_z =0) and calculating coordinates.

$$k_{xy} = 0, k_{yy} = \sum k_{yi}, k_{\theta y} = \sum(k_{yi}.x_i) \tag{4.2}$$

when unit rotation is given in z direction (u_x = 0,u_y=0,u_z =1), coordinated can be calculated as below.

$$k_{x\theta} = \sum(-k_{xi}.y_i), k_{y\theta} = \sum(k_{yi}.x_i), k_{\theta\theta} = \sum[(k_{xi}.y_i^2) + (k_{yi}.x_i^2)] \tag{4.3}$$

The complete stiffness matrix can be written as

$$\begin{bmatrix} \sum k_{xi} & 0 & \sum(-k_{xi}.y_i) \\ 0 & \sum k_{yi} & \sum(k_{yi}.x_i) \\ \sum(-k_{xi}.y_i) & \sum(k_{yi}.x_i) & \sum[(k_{xi}.y_i^2) + (k_{yi}.x_i^2)] \end{bmatrix}$$

Detail calculations for single storey L shape T shape and Material irregularity model is discussed in Appendix A.

4.3.2 Analytical Solution of Multi Storey 3 D Structure

Analytical solution for multi storey space frame can be done same as per the solution carried out for single storey structures. Mass matrix and stiffness matrix can be prepared. Stiffness coefficients would be calculated according to the influence coefficient method for multi storey structures.

Diagonal Mass matrix is prepared by calculating translation mass m_i and rotational mass I_i for both the floors.Lumpled mass is considered for calculation of this mass matrix.

$$\begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & I_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_2 \end{bmatrix}$$

Stiffness matrix is prepared by calculating stiffness coefficients. Unit displacement in x and y direction (u_x=1) ($u_y = 1$)as well as unit rotation ($u_\theta = 1$) about z-axis is applied at both the floors.

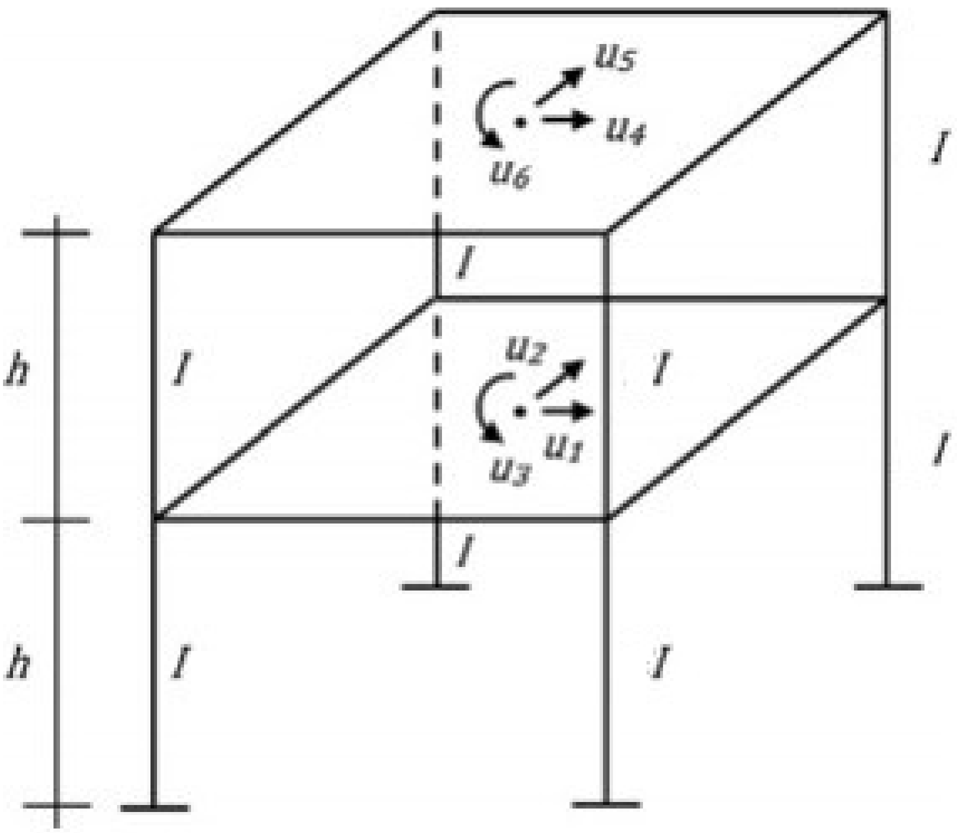


Figure 4.14: Two storey 3D space frame [5]

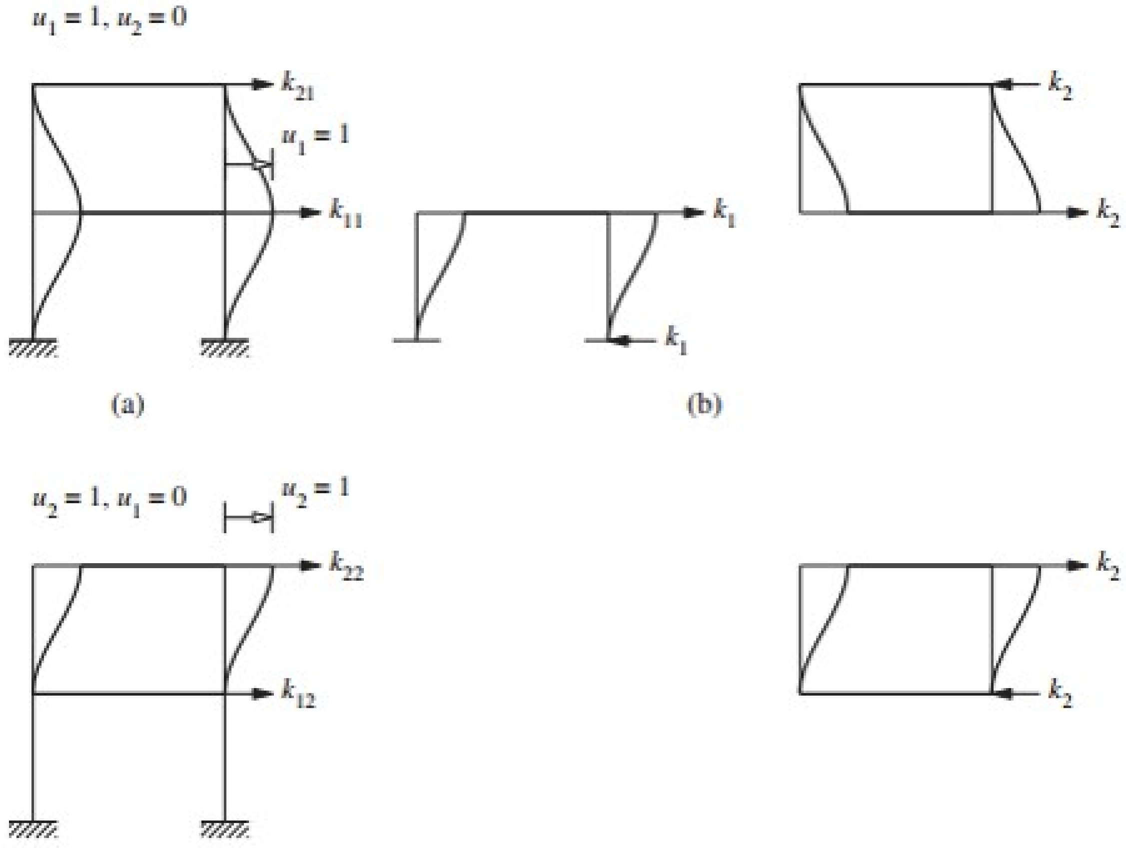


Figure 4.15: Calculation of stiffness coefficients for two storey space frame [5]

Coefficients are calculated and stiffness matrix is prepared is shown below.

$$\begin{bmatrix} 2(\sum k_{xi}) & 0 & 2(\sum -k_{xi}y_i) & (\sum k_{xi}) & 0 & (\sum -k_{xi}y_i) \\ 0 & 2(\sum k_{yi}) & 2(\sum k_{yi}x_i) & 0 & (\sum k_{yi}) & (\sum k_{yi}x_i) \\ 2(\sum -k_{xi}y_i) & 2(\sum k_{yi}x_i) & 2(\sum k_{xi}y_i^2) + (\sum k_{yi}x_i^2) & (-2)(\sum -k_{xi}y_i) & (\sum k_{yi}x_i) & (\sum k_{xi}y_i^2) + (\sum k_{yi}x_i^2) \\ (\sum k_{xi}) & 0 & (-2)(\sum -k_{xi}y_i) & (\sum k_{yi}x_i) & 0 & (\sum -k_{xi}y_i) \\ 0 & (\sum k_{yi}) & (\sum k_{yi}x_i) & 0 & (\sum k_{yi}) & (\sum k_{yi}x_i) \\ (\sum -k_{xi}y_i) & (\sum k_{yi}x_i) & (\sum k_{xi}y_i^2) + (\sum k_{yi}x_i^2) & (\sum -k_{xi}y_i) & (\sum k_{yi}x_i) & (\sum k_{xi}y_i^2) + (\sum k_{yi}x_i^2) \end{bmatrix}$$

Detailed calculation of two storey L shape T shape and material irregular structures is shown in Appendix A.

4.4 Summary

In this chapter various types of irregularities defined in IS:1893 (PART :1)-2002 discussed in detail.Plan irregularities such as Torsional Irregularity, Re-entrant Corners, Diaphragm Discontinuity, Out of Plane Offsets and Non Parallel Systems are described in brief. Apart analytical approach has been carried out to determine mass and stiffness matrix of building model.

Chapter 5

Experimental Programme

5.1 General

Dynamic behaviour irregular structure can be well understood by performing Experiment on scale model of buildings. A SDOF building model as well as MDOF building models are considered in the present study and dynamic behaviour is studied through free and forced vibration.

As a part of experimental work six building models having planar and material irregularities are fabricated to study their dynamic behavior under free and force excitations. Three building models each for SDOF and MDOF system are prepared at workshop facility, Institute of Technology, Nirma University.

5.2 Development of Scale Model

Dynamic behavior of these irregular building models are studied with the help of Shake Table, Data Acquisition System and Computer program. All six irregular building models are prepared as a lump mass model. Lump mass model is prepared by using Aluminum flats having size 25mm $\times$ 3mm as a column of building model and Aluminum plate having size 300mm $\times$ 300mm as a rigid floor in building model.

5.2.1 Fabrication of SDOF Models

5.2.2 SDOF Irregular Building Model: L shape

L shape Aluminum plates and Aluminum columns are connected with alen screws.Fabrication of this L shape building model has been done in workshop. As shown in Figure 5.1 the floor dimension of L shape model is 300mm $\times$ 150mm and height of the building model 415mm.

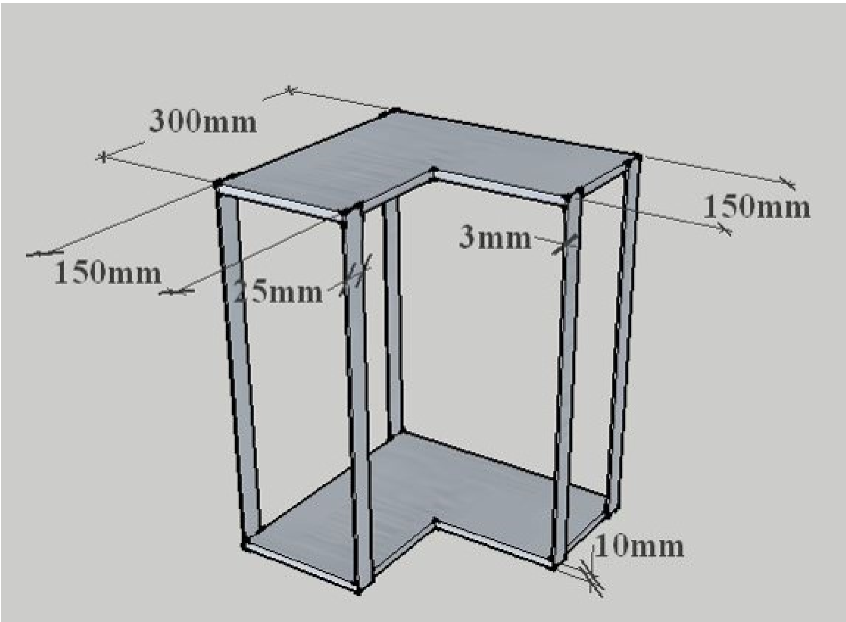


Figure 5.1: SDOF Building Model with planar irregularity L-Shape

5.2.3 SDOF Irregular Building Model: T Shape

Aluminum plates are cut in T shape and Aluminum columns are connected with the plates with the help of alen screws. Fabrication of model has been done in workshop. As shown in Figure 5.1 the floor dimension of T shape model is 300mm $\times$ 150mm. Width of web is 100mm and height of the building model 415mm.

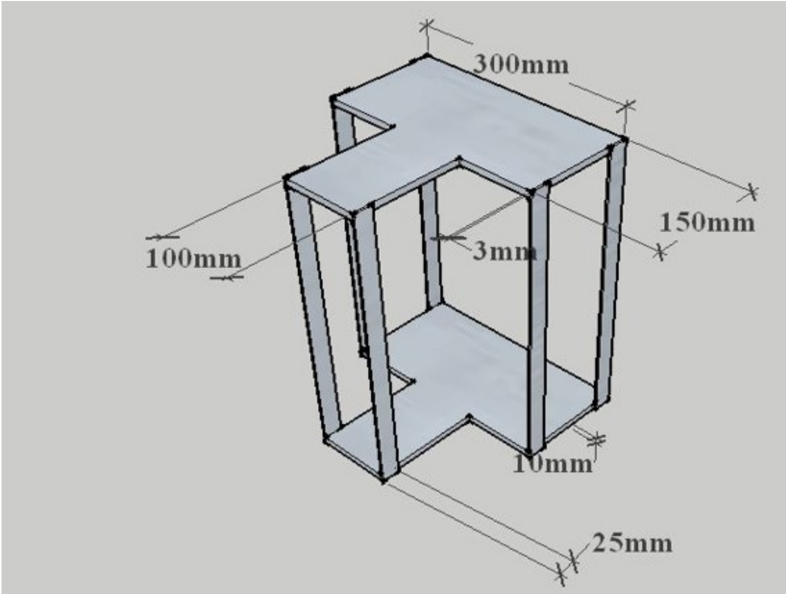


Figure 5.2: SDOF Building Model with planar irregularity T-Shape

5.2.4 SDOF Irregular Building Model : Material Irregularity

In this irregular model one column of mild steel material and other three columns from Aluminum material is connected with the rigid Aluminum plate.The detailed dimensions of the model is shown in following Figure 5.3. Dimension of rigid floor is 300mm × 150mm and height of the building model 415mm.

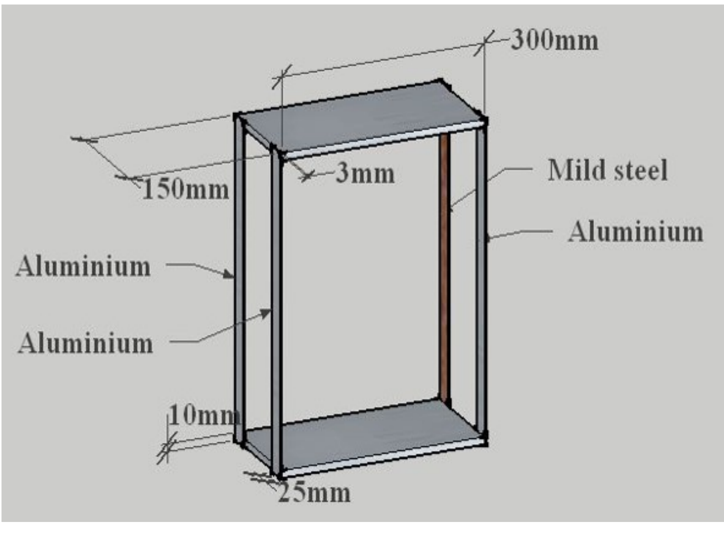


Figure 5.3: SDOF Building Model with Material Irregularity

5.2.5 Fabrication of MDOF Models

5.2.6 MDOF Irregular Building Model: L shape

L shape MDOF Building model is prepared from Aluminum plates and Aluminum flats same as SDOF L model. Dimensions and diagram is shown in following Figure 5.4. Floor dimension is 300mm × 150mm which is same as SDOF Building model and height of the model is 830mm.

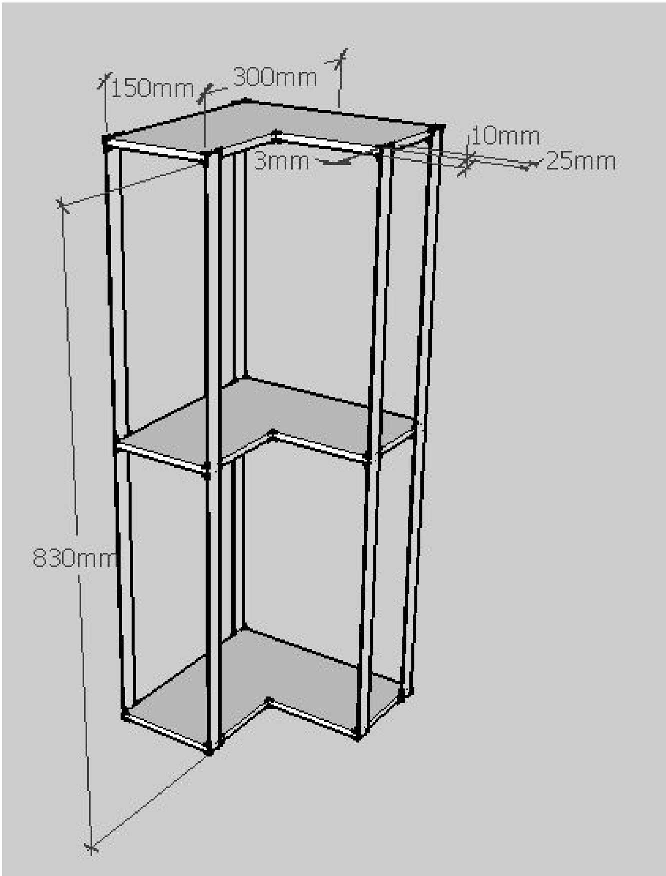


Figure 5.4: MDOF Building Model with Planar Irregularity L-shape

5.2.7 MDOF Irregular Building Model: T shape

T shape MDOF Building model is fabricated from Aluminum plates and Aluminum flats .Dimensions and diagram is shown in following Figure 5.5. In floor dimension, size of web is 300mm × 100mm, size of flange is 300mm × 150mm and height of the model 830mm.

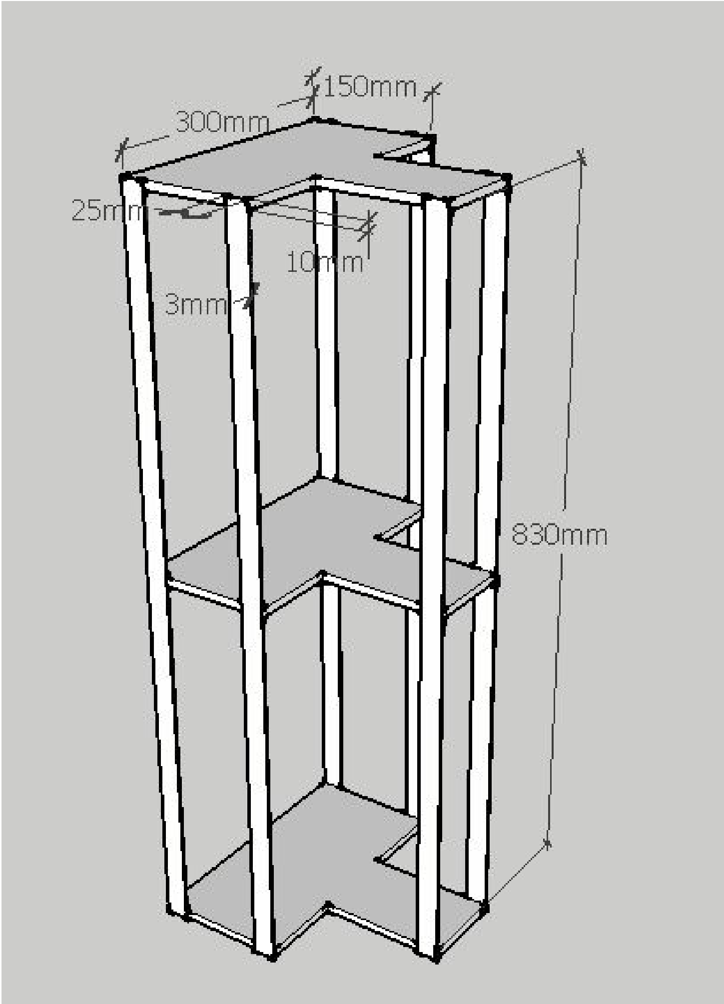


Figure 5.5: MDOF Building Model with Planar Irregularity T-shape

5.2.8 MDOF Irregular Building Model: Material Irregularity

Material irregular MDOF Building model is also fabricated by connecting Aluminum plates with three Aluminum columns and one mild steel column. Dimensions are shown in below Figure 5.6. Floor Dimension is 300mm × 150mm and height of the model 830mm.

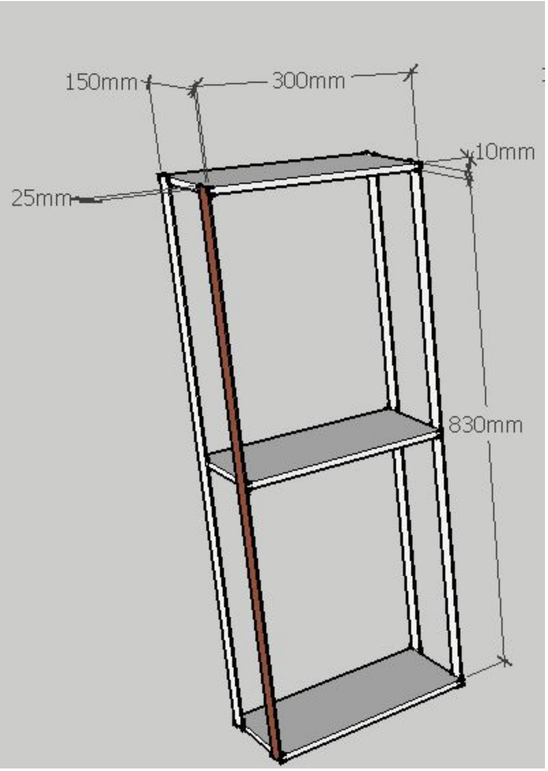


Figure 5.6: MDOF Building Model with Material Irregularity

5.3 Instrumentation for Experimental Setup

By performing this experiment on irregular SDOF and MDOF building model, Natural Frequency and Coefficient of Damping of each of the building model is determined. Figure 5.7 shows instrumentation set up for experiments.

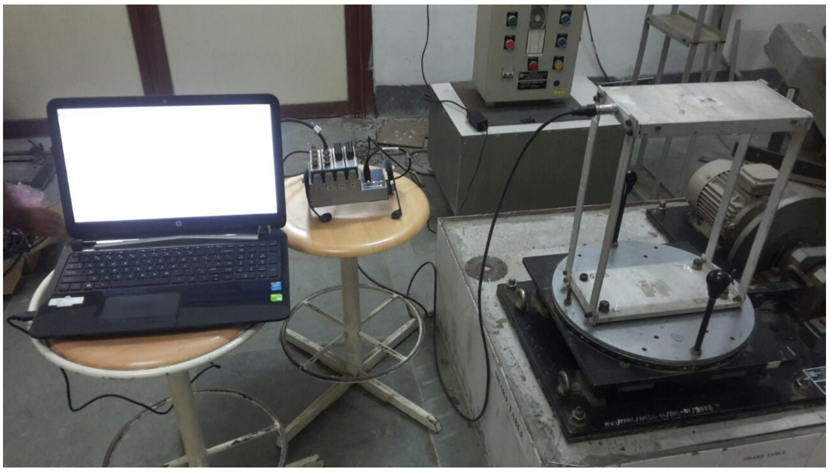


Figure 5.7: Instrumentation Set Up

Following various instruments are used to carry out experimental work.

- **Shake table**
- **Accelerometers**
- **Data Acquisition System**
- **Computer with data processing software**

5.3.1 Shake Table

Shake table is a versatile tool used in earthquake engineering and structural dynamics for small scale research work. Shake table is used to simulate the condition of earthquake with known frequency and amplitude of vibration.it consist of four major part drive unit ,eccentric cam unit , shake table and control unit. Figure 5.8 shows the shake table available at structures laboratory of institute of Technology, Nirma university, Ahmadabad. It is an uni-axial shake table having capacity of 30 kg.

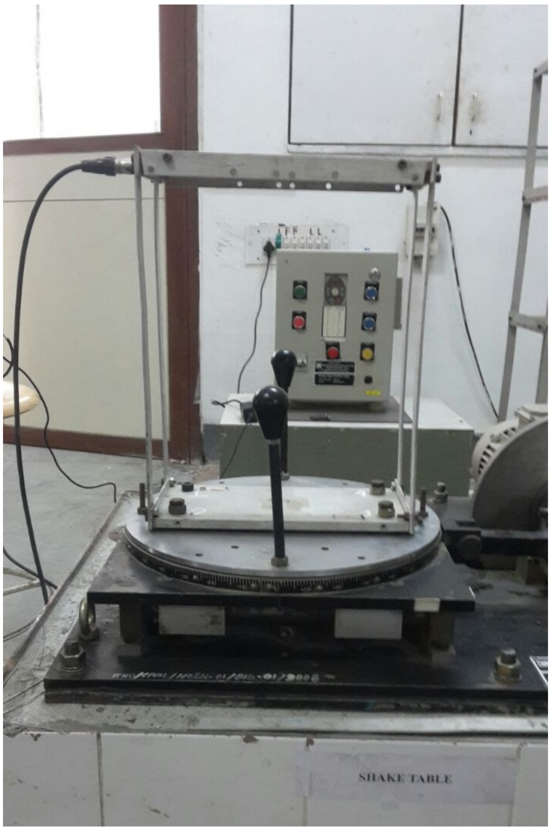


Figure 5.8: Uni-axial Shake table

Technical specifications of uni-axial shake table is shown in Table 5.1. Maximum operating capacity of shake table is 25 Hz and with this frequency amplitude of motion can be achieved is 10 mm.

Table 5.1: Technical Specifications

1	Motion	Horizontal
2	Load capacity	30 Kg
3	Operating frequncy	0-25 Hz
4	Frequncy control	(+/-3)
5	Amplitude	0-10mm
6	Resolution	1mm
7	Table size	400mm x 400mm
8	Roataing table diameter	390mm

5.3.2 Accelerometers

Accelerometer is a transducer whose electrical output is proportional to acceleration.It is a very common device to measure the acceleration, produced due to dynamic motion of structure or structural elements. It is available with connecting cable as well-as wireless type. It is pasted onto the surface of the test element by either using magnetic base or by using adhesive glue or by threaded screw.

The basic operating principle of the accelerometer is that, it measures the force exerted by a body as a result of a change in the velocity i.e. acceleration. A moving body possesses an inertia which tends to resist this acceleration. The force caused by vibration causes the mass to "squeeze" the piezoelectric material present inside the accelerometer. An electrical output of this piezoelectric element is proportional to the change in its length when the it is in compression or proportional to the change in shear angle when the element is in shear. Thus accelerometer converts a physical force into an equivalent electrical signal. Accelerometer should be attached to the structural element whose acceleration is to be measured in the direction parallel to the direction of motion as shown in Figure 5.9.

Figure 5.9: Accelerometers

5.3.3 Data Acquisition System

Data acquisition is the process of sampling signals that measure real world physical conditions and convert them into digital numeric values that can be manipulated by a computer. These real conditions are mostly physical quantities such as temperature,pressure, wind, distance, acceleration, etc. In civil Engineering applications the most common types of sensors measure displacement(LVDT), acceleration(accelerometer),force(force transducer) and strain(strain gauges). Data acquisition systems (abbreviated with the acronym DAS or DAQ) convert analog waveforms into digital values for processing. In automated data acquisition systems the sensors transmit a voltage or current signal directly to a computer via a data acquisition board. Figure 5.10 shows Data Acquisition System.

5.3.4 Computer with Data Processing Software

LabVIEW stands for Laboratory Virtual Instrument Engineering Workbench. It is a graphical programming language that allows data acquisition, and pre/post processing of acquired data. Lab VIEW relies on graphical symbols rather than textual language to describe programming actions. LabVIEW programs are called Virtual Instruments (VIs) because their appearance and operation imitate actual instruments.

Figure 5.10: Data Acquisition System

Figure 5.11: Computer with Data Processing Software

5.4 Summary

In this chapter detail description about fabrication and all dimensions of Irregular building models are discussed. All fabricated building models are tested in the laboratory. Experimental set up required to perform the test and various instruments are discussed in detail.

Chapter 6

Results and Conclusion

6.1 General

Dynamic behaviour of SDOF and MDOF irregular building models can be determined by carrying out Experimental programme. Free and Force Vibration test were performed on both SDOF and MDOF irregular building models. Coefficient of Damping and Natural Frequency of all the building models has been determined by applying Free and Force excitations.

6.2 Evaluation of Dynamic Properties of SDOF Systems

6.2.1 Free Vibration Test

To determine the dynamic properties like Natural Frequency and Coefficient of Damping more precisely Free Vibration Test was performed on regular building model as well as irregular SDOF and MDOF building models on Uni axial Shake Table.

6.2.2 Bare Model

Simple SDOF Bare building model was mounted on the Shake table and subjected to Free excitations. Experimental response was captured in LabVIEW. Figure 6.1 shows the filtered extracted signal of SDOF bare model. Here gradual decrement in the Amplitude of the signal can be seen clearly.

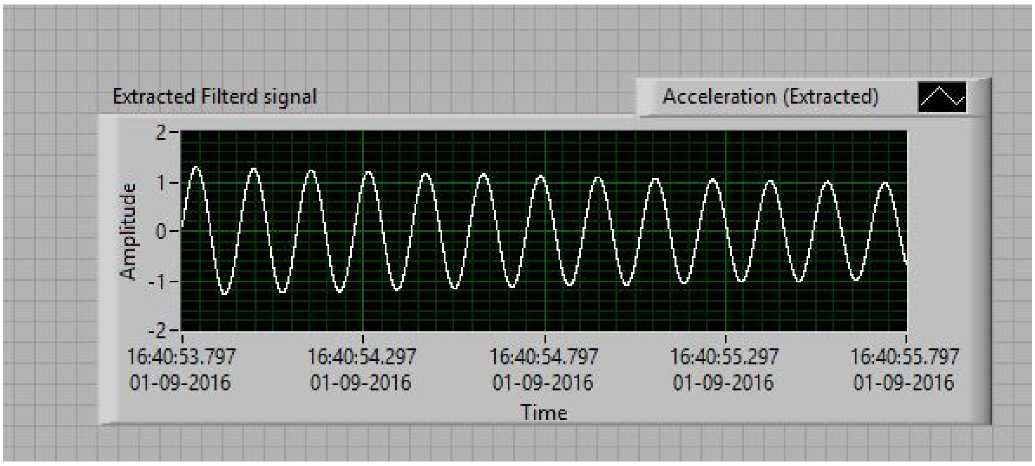


Figure 6.1: Acceleration Response of Bare Regular SDOF Building Model Undergoing Free Vibration

After getting Acceleration Response of building model, Fast Fourier Transform can be produced in LabVIEW software. It is shown in Figure 6.2. Natural Frequency of the structure is 6.3 Hz. After capturing the Natural frequency of the structure Coefficient

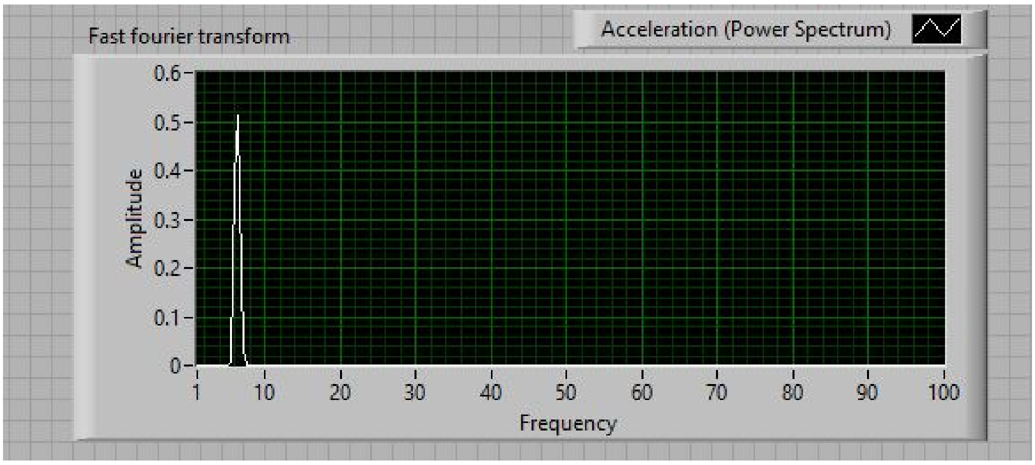


Figure 6.2: Fundamental Frequency Extraction for Bare Regular SDOF Model Through Fast Fourier Transform Techniques

of Damping (ξ) can be calculated with the help of Logarithmic decrement method.Here Table 6.1 shows the calculation for coefficient of damping (ξ) of SDOF bare model. Damping from Logarithmic decrement method is 0.7413%.

Table 6.1: Damping Co-efficient (ξ) of Bare Regular SDOF System Obtained Through Logarithmic Decrement Method

Peak	**Amplitude**	**No. of cycles**										
		1	2	3	4	5	6	7	8	9	10	11
0	0.2274	1.0133	0.9858	0.9507	0.9142	0.8910	0.8611	0.8382	0.8125	0.7864	0.7634	0.7413
1	0.2134	0.9583	0.9194	0.8812	0.8604	0.8307	0.8090	0.7838	0.7581	0.7357	0.7141	
2	0.2009	0.8805	0.8426	0.8277	0.7988	0.7791	0.7547	0.7295	0.7078	0.6870		
3	0.1901	0.8047	0.8013	0.7715	0.7538	0.7296	0.7043	0.6832	0.6628			
4	0.1807	0.7980	0.7550	0.7368	0.7108	0.6842	0.6629	0.6425				
5	0.1719	0.7120	0.7063	0.6817	0.6558	0.6359	0.6166					
6	0.1644	0.7005	0.6666	0.6370	0.6169	0.5976						
7	0.1573	0.6327	0.6052	0.5890	0.5718							
8	0.1512	0.5778	0.5671	0.5515								
9	0.1458	0.5564	0.5384									
10	0.1408	0.5203										
11	0.1363											

6.2.3 L shape SDOF Model

L shape SDOF Model was mounted on Uni Axial Shake Table and Free Vibration is applied. Acceleration Response was captured in labVIEW. Figure 6.3 shows the filtered extracted signal of L shape SDOF Model.

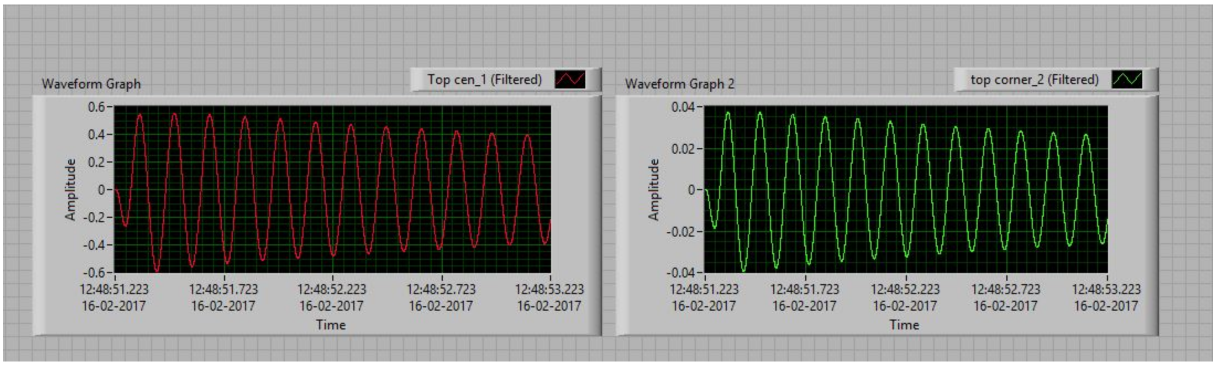


Figure 6.3: Acceleration Response of L-Shape SDOF Building Model Undergoing Free Vibration

Here, Fast Fourier Transform for L shape SDOF Model is generated in LabVIEW software. It is shown in figure 6.4. Natural Frequency of the L shape SDOF Model is 6.4 Hz.

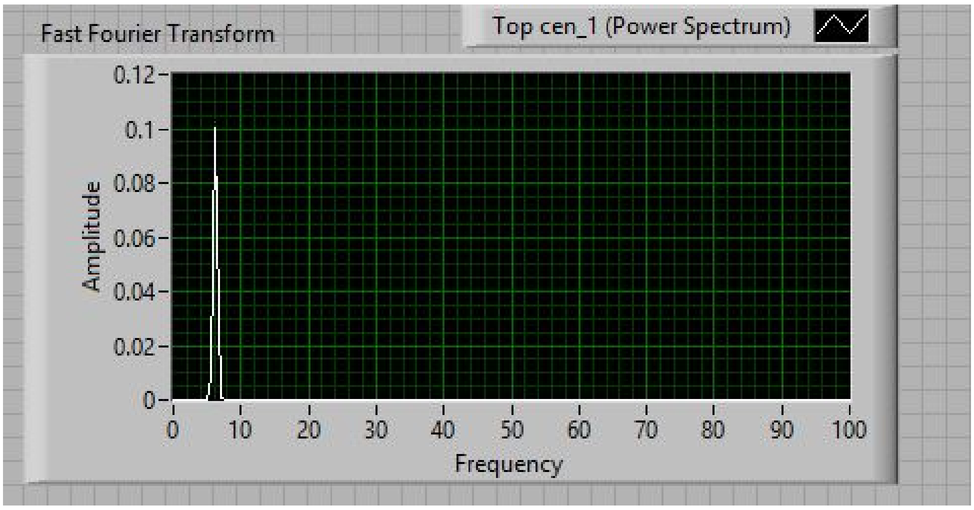


Figure 6.4: Fundamental Frequency Extraction for L-Shape SDOF Building Model Through Fast Fourier Transform Techniques

After capturing the Natural Frequency of the structure Coefficient of Damping (ξ) can be calculated with the help of Logarithmic decrement method.Here Table 6.2 shows the Logarithmic decrement method for calculating Coefficient of Damping (ξ) of L shape model. Damping Co-efficient (ξ) from Logarithmic decrement method is 1.07%.

Table 6.2: Damping Co-efficient (ξ) of L-Shape SDOF System Obtained Through Logarithmic Decrement Method

Peak	**Amplitude**	**No. of cycles**											
		1	2	3	4	5	6	7	8	9	10	11	12
0	0.4831	1.1788	1.1534	1.0705	1.1314	1.0894	1.0719	1.0721	1.0662	1.0618	1.0565	1.0641	1.0763
1	0.4486	1.1280	1.0163	1.1156	1.0671	1.0505	1.0543	1.0501	1.0472	1.0429	1.0526	1.0670	
2	0.4179	0.9046	1.1094	1.0468	1.0311	1.0395	1.0372	1.0357	1.0323	1.0442	1.0609		
3	0.3948	1.3142	1.1178	1.0733	1.0732	1.0637	1.0575	1.0505	1.0617	1.0783			
4	0.3635	0.9215	0.9529	0.9929	1.0010	1.0062	1.0065	1.0256	1.0488				
5	0.3430	0.9843	1.0286	1.0276	1.0274	1.0236	1.0430	1.0670					
6	0.3225	1.0730	1.0492	1.0417	1.0334	1.0547	1.0808						
7	0.3014	1.0255	1.0261	1.0202	1.0502	1.0823							
8	0.2826	1.0267	1.0175	1.0584	1.0966								
9	0.2650	1.0084	1.0743	1.1198									
10	0.2487	1.1402	1.1756										
11	0.2315	1.2110											
12	0.2145												

6.2.4 T shape SDOF Model

T shape model was given Free Vibration after it was Mounted on Shake Table. Acceleration Response was captured in LabVIEW software. Figure 6.5 shows the filtered extracted signal of Acceleration of T shape SDOF Model.

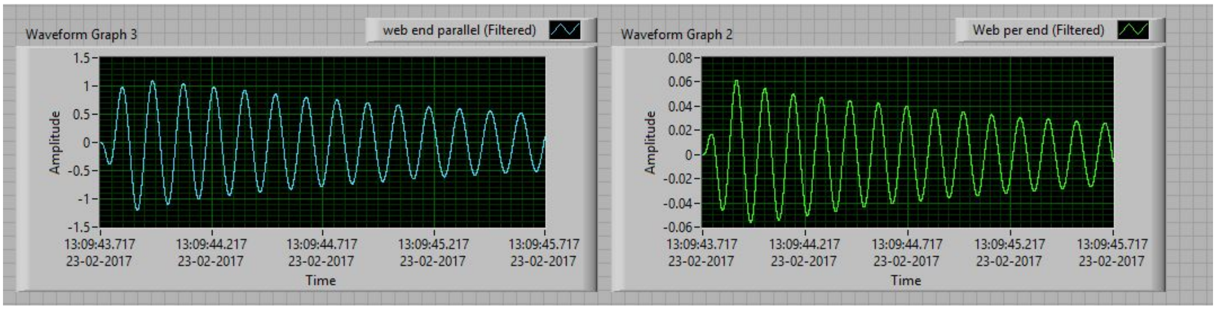


Figure 6.5: Acceleration Response of T Shape SDOF Building Model Undergoing Free Vibration

Here, Fast Fourier Transform for T shape SDOF Model is generated in LabVIEW software. It is shown in Figure 6.6 Natural Frequency of the structure is 7.14 Hz.

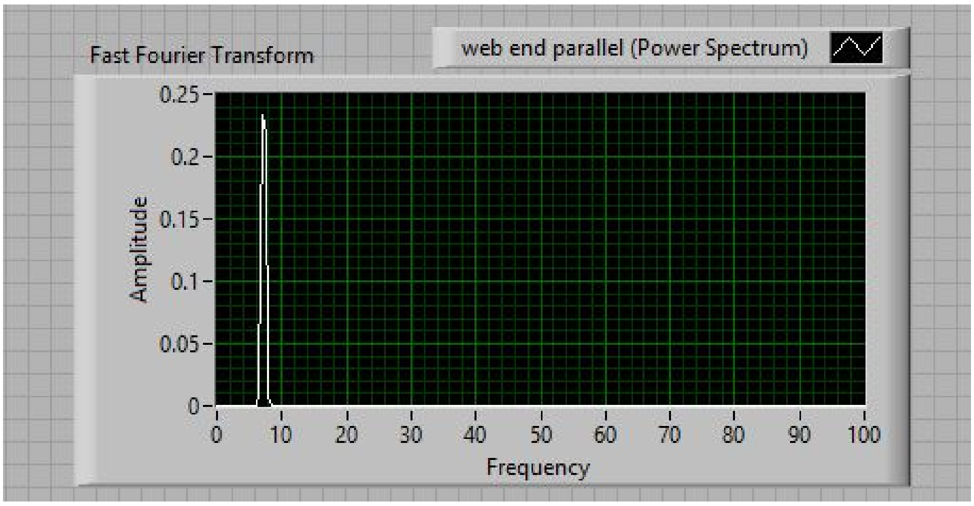


Figure 6.6: Fundamental Frequency Extraction for T-Shape SDOF Building Model Through Fast Fourier Transform Techniques

After capturing the Natural Frequency of the structure,Co-efficient of Damping (ξ) can be calculated with the help of Logarithmic decrement method.Here Table 6.3 shows the Logarithmic decrement method for calculating Damping Co-efficient (ξ) of T shape Model. Damping Co-efficient (ξ) from Logarithmic decrement method is 1.68%.

Table 6.3: Damping Co-efficient (ξ) of T-Shape SDOF System Obtained Through Logarithmic Decrement Method

Peak	Amplitude	No. of cycles											
		1	2	3	4	5	6	7	8	9	10	11	12
0	0.1352	1.9601	2.0201	2.0494	2.0720	1.9641	1.8780	1.8294	1.7831	1.7381	1.7111	1.7106	1.6881
1	0.1195	2.0802	2.0941	2.1093	1.9651	1.8616	1.8076	1.7579	1.7103	1.6834	1.6857	1.6634	
2	0.1049	2.1080	2.1238	1.9267	1.8069	1.7531	1.7041	1.6575	1.6338	1.6419	1.6217		
3	0.0919	2.1396	1.8360	1.7065	1.6643	1.6234	1.5824	1.5661	1.5836	1.5677			
4	0.0803	1.5323	1.4900	1.5058	1.4943	1.4709	1.4705	1.5041	1.4962				
5	0.0729	1.4476	1.4926	1.4816	1.4556	1.4581	1.4994	1.4910					
6	0.0666	1.5376	1.4986	1.4582	1.4607	1.5098	1.4983						
7	0.0605	1.4596	1.4185	1.4351	1.5029	1.4904							
8	0.0552	1.3774	1.4228	1.5173	1.4981								
9	0.0506	1.4682	1.5872	1.5384									
10	0.0461	1.7063	1.5735										
11	0.0414	1.4407											
12	0.0379												

6.2.5 SDOF Model with Material Irregularity

On the Shake Table, Material Irregular model mounted and was subjected to Free Vibrations. Acceleration Response was captured which is shown in figure 6.7.Filtered extracted signal of Acceleration of Material Irregular model subjected to Free Vibrations.

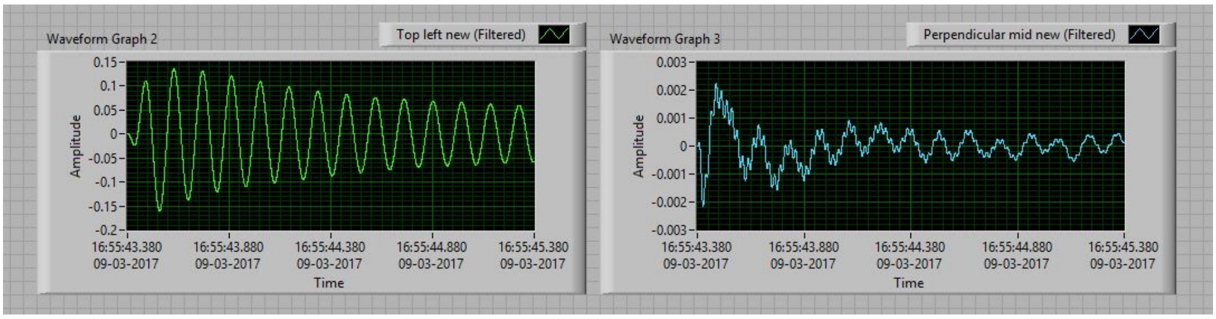


Figure 6.7: Acceleration Response of SDOF Building Model with Material Irregularity Undergoing Free Vibration

Fast Fourier Transform for Material Irregular SDOF model can be produced in LabVIEW software. It is shown in figure 6.8. Natural Frequency of the structure is 6.31 Hz

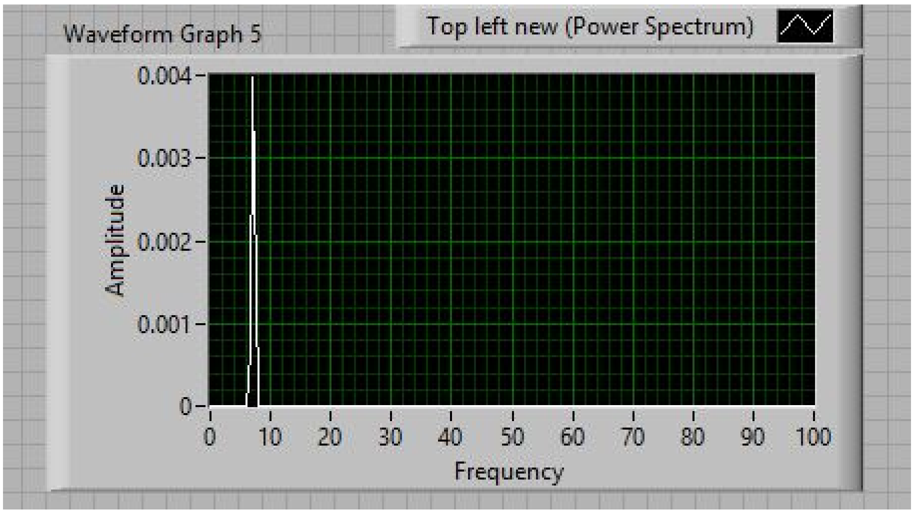


Figure 6.8: Fundamental Frequency Extraction for SDOF Building Model with Material Irregularity Through Fast Fourier Transform Techniques

After capturing the Natural Frequency of the SDOF Building Model with Material Irregularity, Damping Co-efficient (ξ) can be calculated with the help of Logarithmic decrement method.Here Table 6.4 shows the Logarithmic decrement method for calculating Damping Co-efficient (ξ) of Material Irregular model. Damping Co-efficient (ξ) from Logarithmic decrement method is obtained 2.69%.

Table 6.4: Damping Co-efficient (ξ) of SDOF System with Material Irregularity Obtained Through Logarithmic Decrement Method

Peak	**Amplitude**	**No. of cycles**											
		1	2	3	4	5	6	7	8	9	10	11	12
0	1.5483	2.6852	2.6540	2.6602	2.6930	2.7284	2.7330	2.7191	2.6970	2.6784	2.6703	2.6764	2.6942
1	1.3078	2.6229	2.6477	2.6956	2.7392	2.7426	2.7247	2.6987	2.6775	2.6686	2.6756	2.6950	
2	1.1091	2.6725	2.7319	2.7779	2.7725	2.7451	2.7113	2.6853	2.6743	2.6814	2.7023		
3	0.9376	2.7914	2.8307	2.8059	2.7632	2.7190	2.6875	2.6746	2.6825	2.7056			
4	0.7867	2.8700	2.8131	2.7539	2.7010	2.6667	2.6551	2.6670	2.6948				
5	0.6568	2.7563	2.6958	2.6446	2.6158	2.6122	2.6331	2.6698					
6	0.5523	2.6353	2.5888	2.5690	2.5761	2.6085	2.6554						
7	0.4680	2.5422	2.5359	2.5564	2.6018	2.6594							
8	0.3989	2.5295	2.5635	2.6216	2.6887								
9	0.3403	2.5974	2.6677	2.7418									
10	0.2890	2.7380	2.8140										
11	0.2433	2.8900											
12	0.2029												

6.2.6 Force Vibration Test

Force Vibration testing is carried out to understand the dynamic behaviour of SDOF irregular building models under Harmonic Base excitations. In Force Vibration testing all the SDOF irregular building models are mounted on the shake table. Shake table is vibrated at various forcing frequency.

Dynamic behaviour of all the SDOF irregular building models at various frequency has been observed. At the condition of resonance. All irregular building models give maximum Acceleration Response.

6.2.7 L shape SDOF Model

L shape model mounted on shake table and base excitation is given through shake table at various frequency. Maximum response captured at the resonance and it is shown in Figure 6.9.

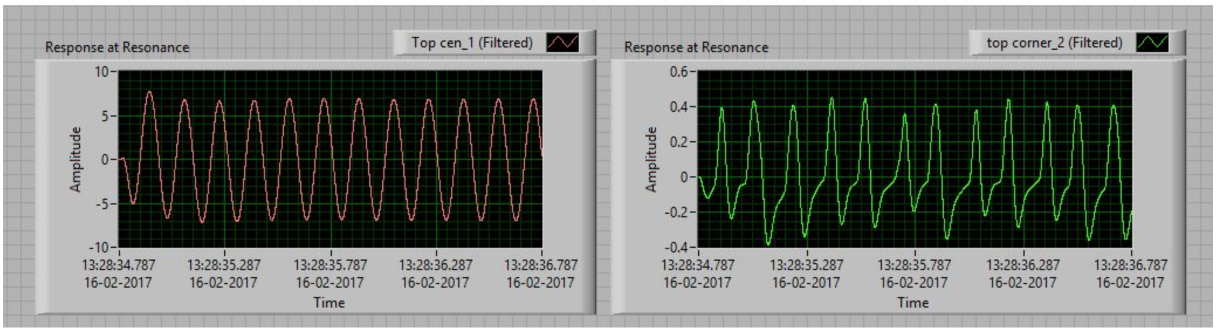


Figure 6.9: Acceleration Response of L-Shape SDOF Building Model Undergoing Force Vibration

Transmissibility plot has been generated for L shape SDOF building model and Natural Frequency has been obtained.Here in figure 6.10 the transmissibility plot for L shape SDOF model for vibrations capture in parallel directions as well as perpendicular direction has been shown.

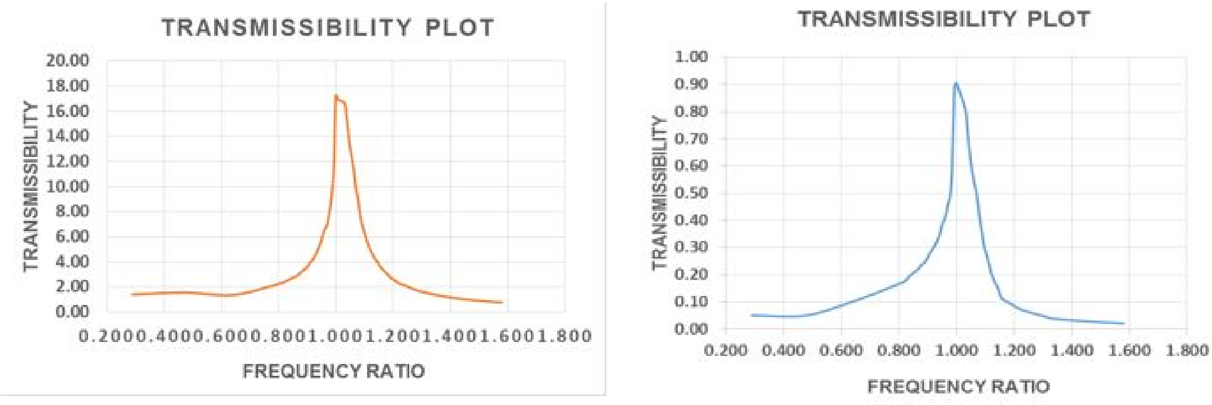


Figure 6.10: Transmissibility Plot for L-Shape SDOF Building Model Obtained Through Forced Vibration Test in Parallel and Perpendicular Directions

6.2.8 T shape SDOF Model

Force vibration of T shape model has been taken at various forcing frequency. Maximum response has been captured at resonance condition shown in Figure 6.11

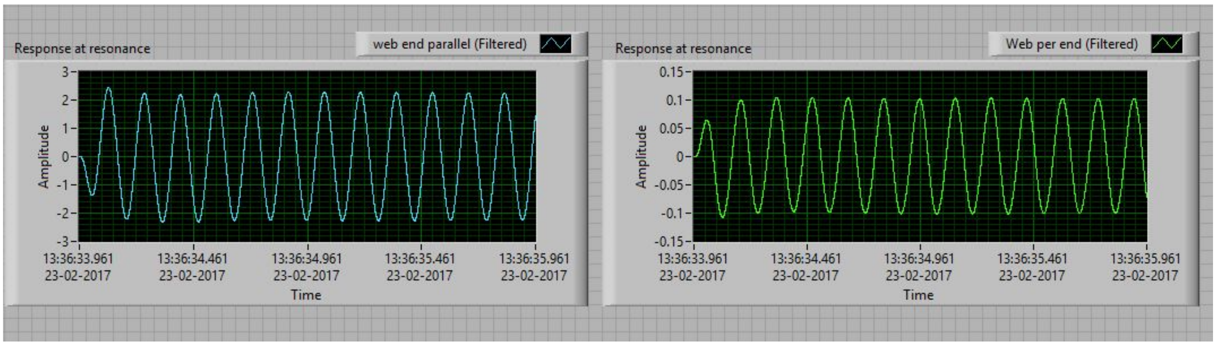


Figure 6.11: Acceleration Response of T-Shape SDOF Building Model Undergoing Force Vibration

Transmissibility plot has been generated for T shape SDOF building model and Natural Frequency has been obtained.Here in Figure 6.11 the transmissibility plot for T shape SDOF model for vibrations capture in parallel directions as well as in perpendicular direction.

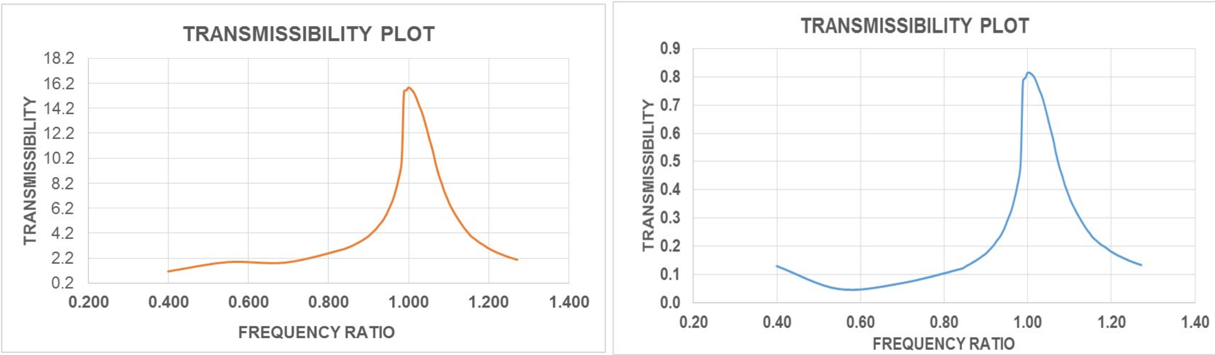


Figure 6.12: Transmissibility Plot for T-Shape SDOF Building Model Obtained Through Forced Vibration Test in Parallel and Perpendicular Directions

6.2.9 SDOF Model with Material Irregularity

Material Irregular model has been taken on the shake table and various forcing frequency were applied. Maximum response has been captured at resonance condition shown in Figure 6.13

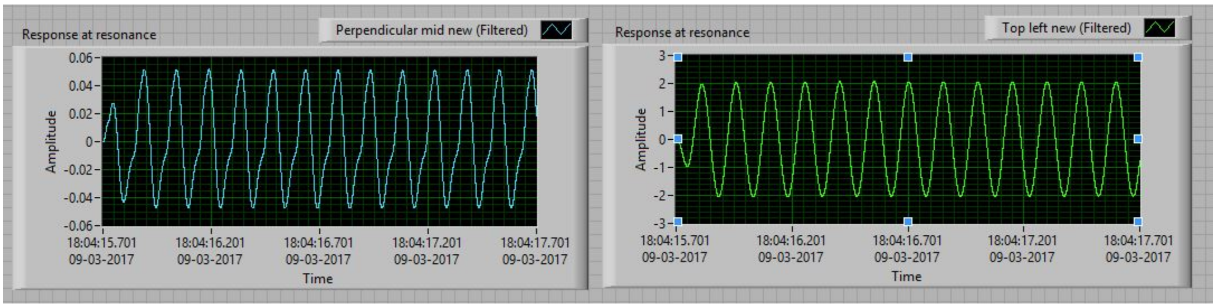


Figure 6.13: Acceleration Response of SDOF Building Model with Material Irregularity Undergoing Force Vibration

Transmissibility plot has been generated for SDOF Building Model with Material Irregularity Undergoing Force Vibration and Natural Frequency has been obtained.Here in figure 6.11 the transmissibility plot for SDOF Building model with Material Irregularity is shown. vibrations capture in parallel directions as well as perpendicular direction has been shown.

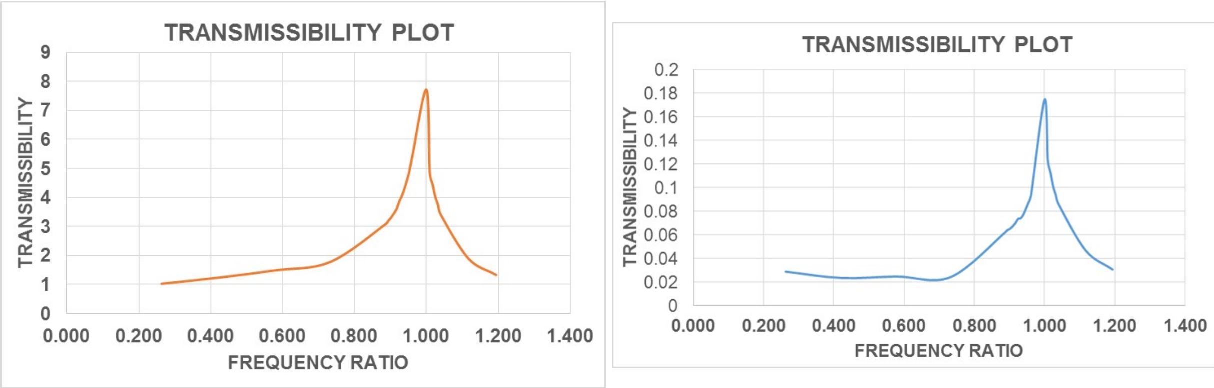


Figure 6.14: Transmissibility Plot for Material Irregular SDOF Building Model Obtained Through Forced Vibration Test in Parallel and Perpendicular Directions

6.3 Evaluation of Dynamic Properties of MDOF Systems

6.3.1 Free Vibration Test

To determine the dynamic properties like Natural Frequency and Coefficient of Damping (ξ) more precisely, Free Vibration Test was performed on regular building model as well as irregular SDOF and MDOF building models on Uni axial Shake Table.

6.3.2 L shape MDOF Model

L Shape MDOF model was mounted and tested on shake table and Free Vibration was given to the building model. Figure 6.15 shows the filtered extracted L shape MDOF model .

Here, Fast Fourier Transforms graph can be generated in LabVIEW software. It is shown in figure 6.16. Natural frequency of the structure is 3.3 Hz

After capturing the Natural frequency of the structure, Co-efficient of Damping (ξ) can be calculated with the help of Logarithmic decrement method. Here Table 6.5 shows the Logarithmic decrement method for calculating damping of L shape MDOF model.

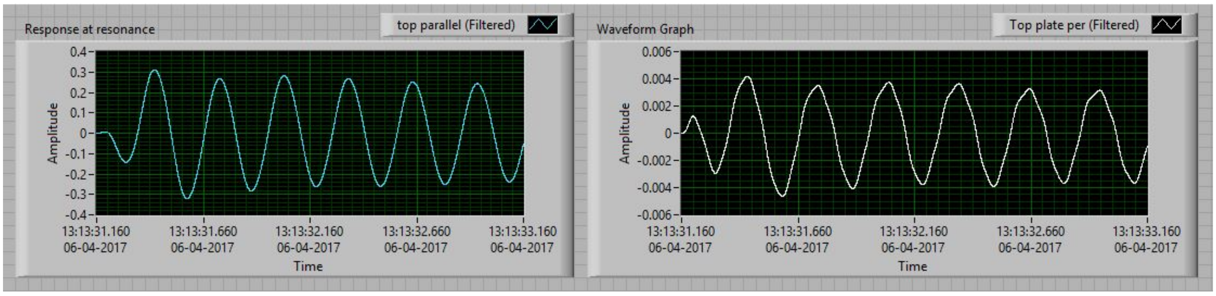


Figure 6.15: Acceleration Response of L Shape MDOF Building Model Undergoing Free Vibration

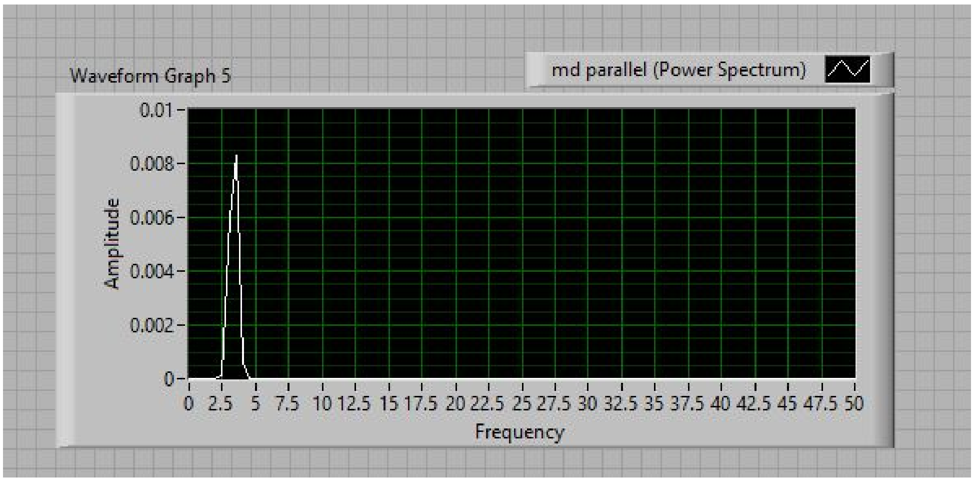


Figure 6.16: Fundamental Frequency Extraction for L-Shape MDOF Building Model Through Fast Fourier Transform Techniques

Table 6.5: Damping Co-efficient (ξ) of L-Shape MDOF System Obtained Through Logarithmic Decrement Method

Peak	Amplitude	No of cycles								
		1	2	3	4	5	6	7	8	9
0	0.0244646	2.5009	2.2246	2.2302	2.1688	2.1705	2.0538	2.0307	1.9723	1.9478
1	0.0209061	1.9482	2.0948	2.0581	2.0879	1.9644	1.9523	1.8968	1.8787	
2	0.018497	2.2413	2.1131	2.1345	1.9684	1.9531	1.8882	1.8687		
3	0.0160667	1.9849	2.0811	1.8775	1.8811	1.8176	1.8066			
4	0.0141825	2.1772	1.8237	1.8465	1.7758	1.7710				
5	0.0123688	1.4702	1.6811	1.6420	1.6694					
6	0.0112773	1.8920	1.7278	1.7358						
7	0.0100131	1.5637	1.6576							
8	0.009076	1.7516								
9	0.00813									

Damping Co-efficient (ξ) obtained from Logarithmic decrement method is 0.7236%

6.3.3 T shape MDOF Model

T shape MDOF model was tested first on Shake table and experimental response was captured, figure 6.17 shows the filtered extracted signal of T shape MDOF model.

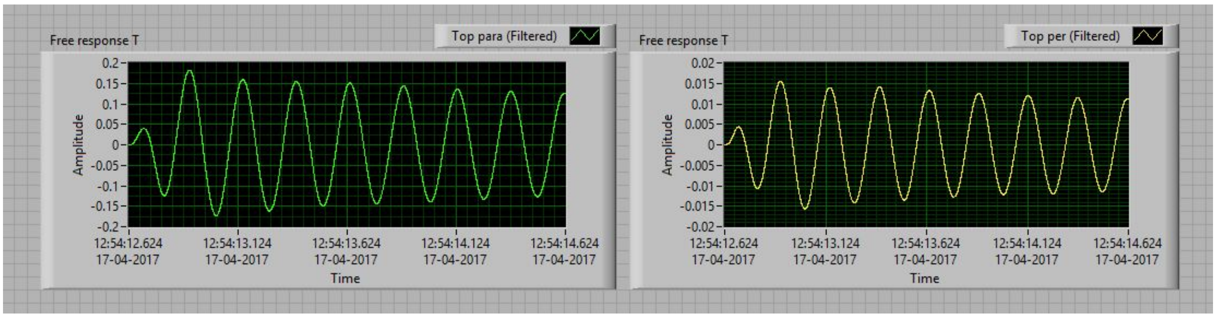


Figure 6.17: Acceleration Response of T-Shape MDOF Building Model Undergoing Free Vibration

In LabVIEW software, Fast Fourier Transform can be obtained. It is shown in figure 6.18. Natural frequency of the structure is 4.07 Hz

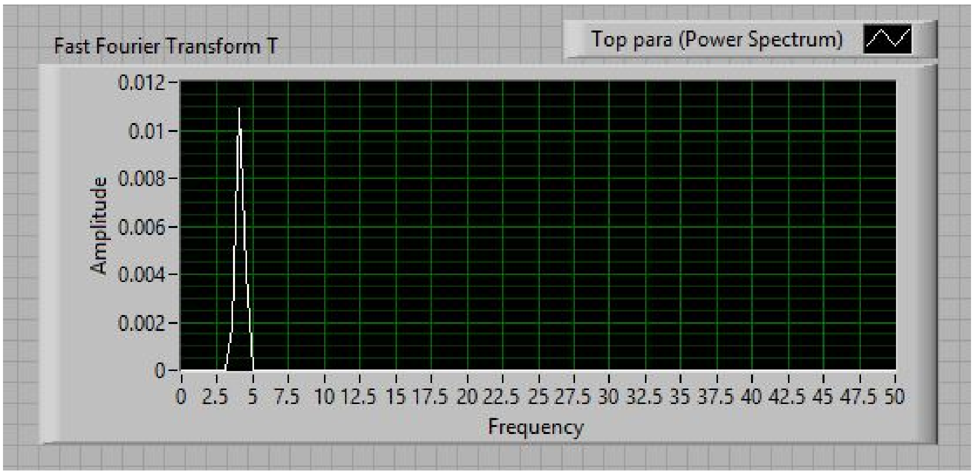


Figure 6.18: Fundamental Frequency Extraction for T-Shape MDOF Building Model Through Fast Fourier Transform Techniques

After capturing the Natural frequency of the structure Damping Co-efficient (ξ) can be calculated with the help of Logarithmic decrement method.Here Table 6.6 shows the Logarithmic decrement method for calculating damping of T shape MDOF model.

Table 6.6: Damping Co-efficient (ξ) of T-Shape MDOF System Obtained Through Logarithmic Decrement Method

Peak	**Amplitude**	**No of cycles**								
		1	2	3	4	5	6	7	8	9
0	0.143327	1.2669	1.0971	1.0455	1.0728	1.2736	1.3017	1.3401	1.2470	1.2444
1	0.132359	0.9273	0.9348	1.0081	1.2753	1.3086	1.3523	1.2442	1.2416	
2	0.124867	0.9422	1.0484	1.3913	1.4039	1.4373	1.2970	1.2865		
3	0.117689	1.1546	1.6158	1.5578	1.5610	1.3679	1.3438			
4	0.109453	2.0769	1.7594	1.6965	1.4212	1.3817				
5	0.09606	1.4419	1.5063	1.2026	1.2078					
6	0.0877389	1.5706	1.0830	1.1298						
7	0.079493	0.5953	0.9094							
8	0.0765746	1.2234								
9	0.0709086									

Damping Co-efficient (ξ) calculated from Logarithmic decrement method is 1.24%

6.3.4 Material Irregular MDOF Model

On the Shake Table MDOF model with material Irregularity is mounted and Free vibration is given to the structure. Experimental response was captured, figure 6.19 shows the filtered extracted signal of Material Irregular MDOF mode.

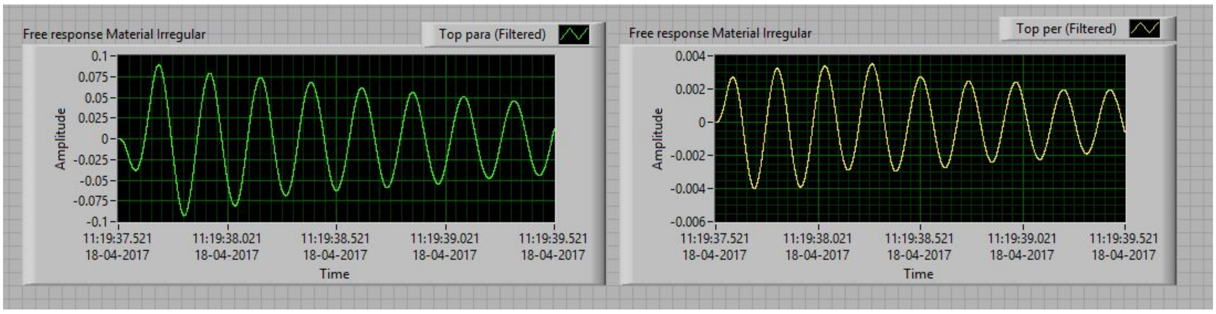


Figure 6.19: Acceleration Response of MDOF Building Model with Material Irregularity Undergoing Free Vibration

Fundamental Natural frequency of the structure is 4.3 Hz which is obtained by generating Fast Fourier Transforms in LabVIEW software.

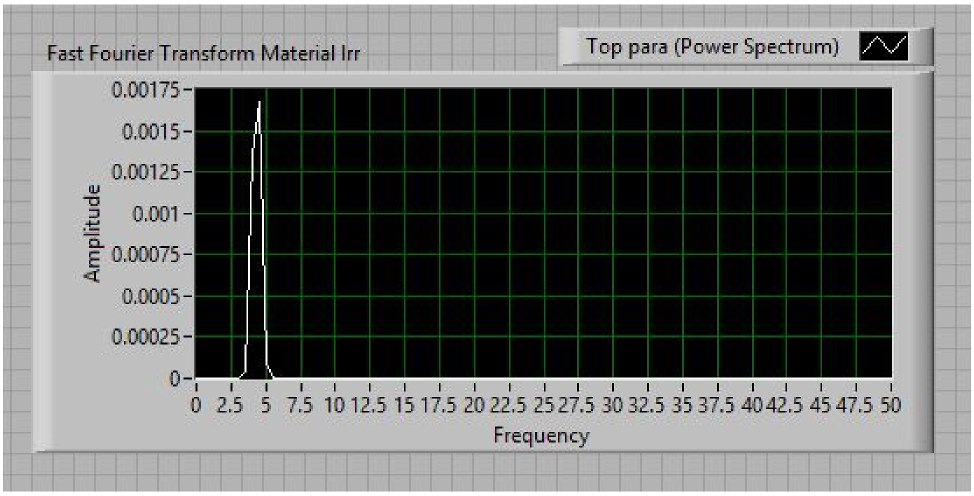


Figure 6.20: Fundamental Frequency Extraction for Material Irregularity MDOF Building Model Through Fast Fourier Transform Techniques

After capturing the Natural frequency of the structure Damping Co-efficient (ξ) can be calculated with the help of Logarithmic decrement method. Here Table 6.7 shows the Logarithmic decrement method for calculating damping of Material Irregular MDOF model.

Table 6.7: Damping Co-efficient (ξ) of MDOF System with Material Irregular Obtained Through Logarithmic Decrements Method

Peak	**Amplitude**	**Number of cycles**								
		1	2	3	4	5	6	7	8	9
0	0.0244646	2.5009	2.2246	2.2302	2.1688	2.1705	2.0538	2.0307	1.9723	1.9478
1	0.0209061	1.9482	2.0948	2.0581	2.0879	1.9644	1.9523	1.8968	1.8787	
2	0.018497	2.2413	2.1131	2.1345	1.9684	1.9531	1.8882	1.8687		
3	0.0160667	1.9849	2.0811	1.8775	1.8811	1.8176	1.8066			
4	0.0141825	2.1772	1.8237	1.8465	1.7758	1.7710				
5	0.0123688	1.4702	1.6811	1.6420	1.6694					
6	0.0112773	1.8920	1.7278	1.7358						
7	0.0100131	1.5637	1.6576							
8	0.009076	1.7516								
9	0.00813									

Damping Co-efficient (ξ) calculated from Logarithmic decrement method is 1.94%

6.3.5 Force Vibration Test

Force vibration of all MDOF model has also been carried out and response at various frequency measured. At resonance condition maximum response has been captured.

L shape MDOF Model

L shape model was mounted on shake table and base excitation is given through shake table at various frequency. Maximum response captured at the resonance and it is shown in figure 6.21.

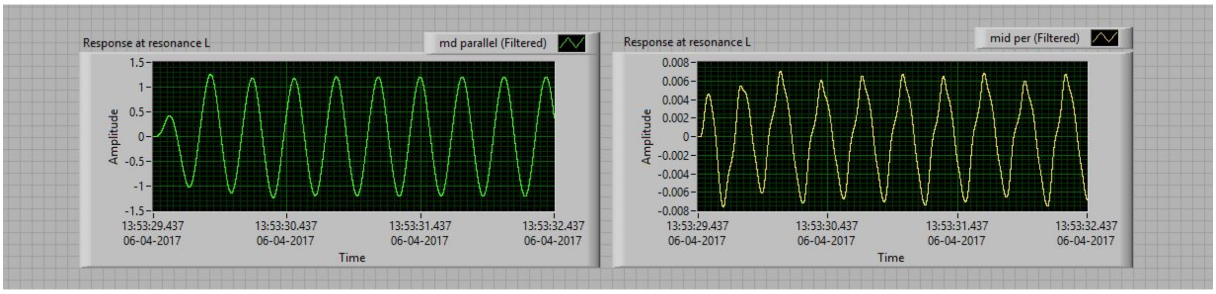


Figure 6.21: Acceleration Response of L-Shape MDOF Building Model Undergoing Force Vibration

Transmissibility plot has been generated for L shape structure in parallel as well as perpendicular direction and Natural frequency has been obtained.

6.3.6 T shape MDOF Model

T shape model mounted on shake table and base excitation is given through shake table at various frequency. Maximum response captured at the resonance and it is shown in Figure 6.23.

Transmissibility plot for parallel and perpendicular direction has been generated for T shape structure and Natural frequency has been obtained.

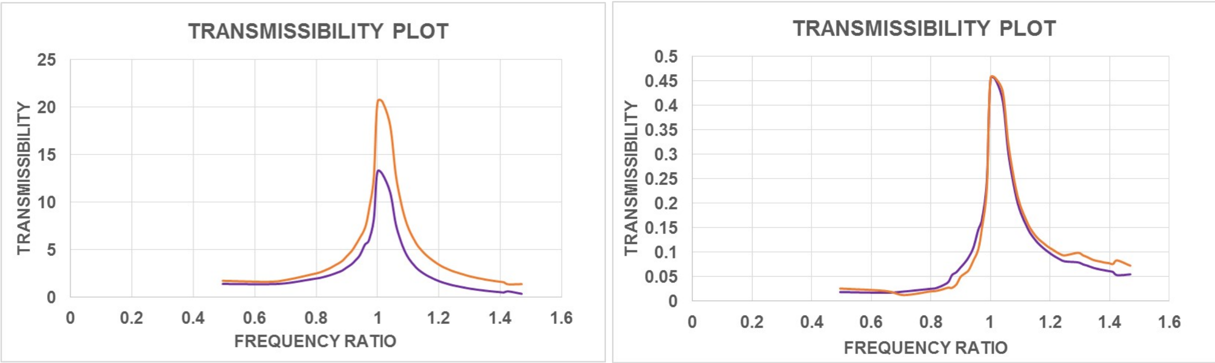


Figure 6.22: Transmissibility Plot for L-Shape SDOF Building Model Obtained Through Forced Vibration Test in Parallel and Perpendicular Directions

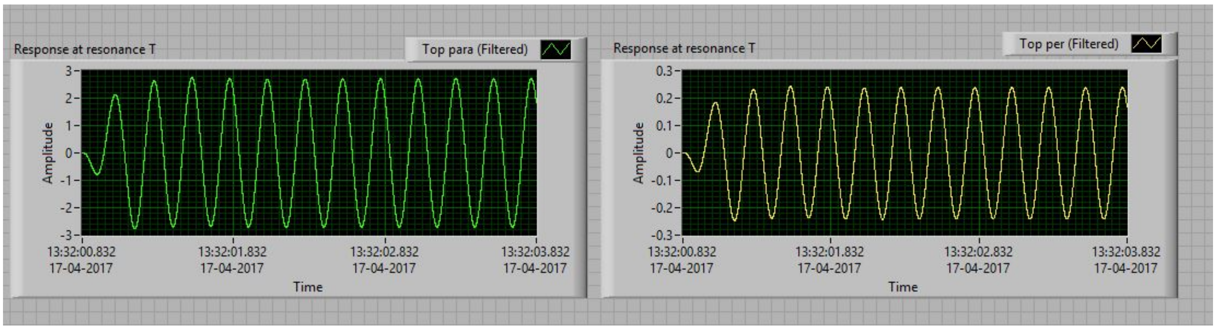


Figure 6.23: Acceleration Response of T-Shape MDOF Building Model Undergoing Force Vibration

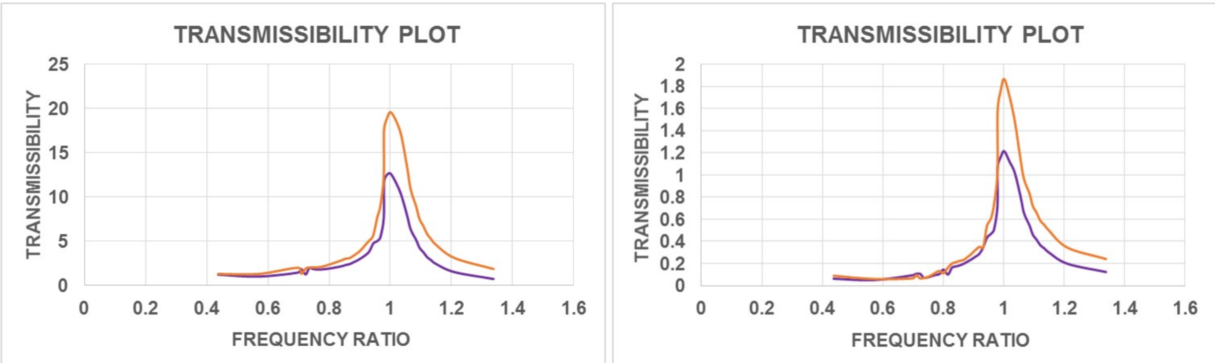


Figure 6.24: Transmissibility Plot for T-Shape SDOF Building Model Obtained Through Forced Vibration Test in Parallel and Perpendicular Directions

6.3.7 Material Irregular MDOF Model

After mounting MDOF model with Material Irregularity on Shake table,base excitation is given at various forcing frequency. Maximum response captured at the resonance and it is shown in Figure 6.25.

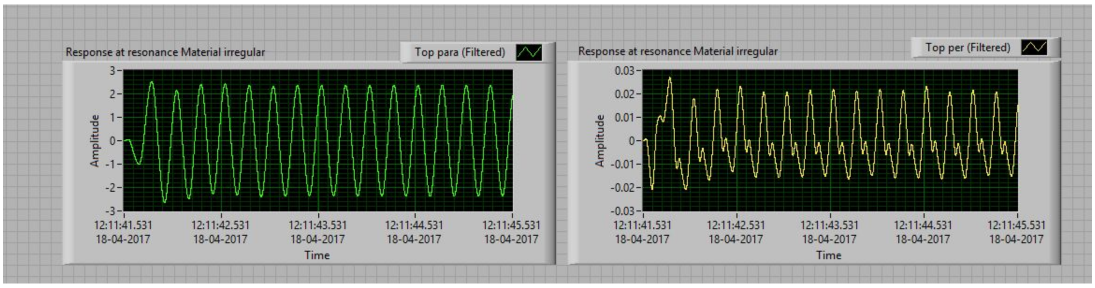
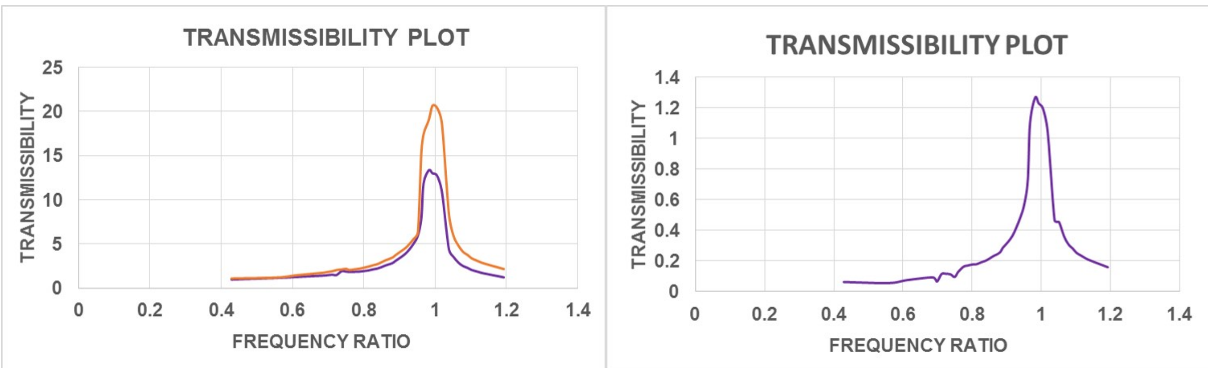


Figure 6.25: Acceleration Response of MDOF Building Model with Material Irregularities Undergoing Force Vibration

Transmissibility plot for parallel and perpendicular direction has been generated for Material Irregular model and Natural frequency has been obtained.



(a) Response in parallel

(b) Response in perpendicular

Figure 6.26: Transmissibility Plot for MDOF Building Model with Material Irregularity Obtained Through Forced Vibration Test in Parallel and Perpendicular Directions

6.4 Results

The results of an experimental work which includes Free and Force Vibration on SDOF and MDOF building models is shown in Table 6.8.

Table 6.8: Natural Frequencies, Transmissibility and Damping Co-efficient Results for L-Shape, T-Shape and Model with Material Irregularities

Type of Model	**Natural Frequency (Wn Hz) Ist Mode**	**Transmissibility**				**Damping (ξ%)**	
		Parallel		**Perpendicular**		**Free Vibrations**	**Force Vibrations**
L shape	3.3	Top	20.69	Top	0.457	0.7246	3.04
		Mid	13.33	Mid	0.456		
T shape	4.7	Top	19.56	Top	1.89	1.24	3.71
		Mid	12.63	Mid	1.21		
Material Irregularity Model	4.3	Top	19.05	Top	1.26	1.94	3.37
		Mid	13.34	Mid	-		

6.5 Summary

In this chapter results of whole experimental work has been presented. Free and Force vibration results of all SDOF and MDOF irregular Building model has been presented and transmissibility plot has been generated for both SDOF irregular and MDOF irregular structure.

Chapter 7

Summary, Conclusions and Future Scope

7.1 Summary

Advent of lighter building materials and new construction techniques have led to the more flexible structural systems now a days. Dynamic response of these structural systems subjected to Earthquake, Strong gust, Wind is very important. Dynamic properties such as Natural Frequencies, Mode Shapes, Damping Properties, Transmissibility are highly responsible for dynamic response of any structural system. Thus, to understand the dynamic behaviour of any structural system, it is essential to understand these dynamic properties very well.While mass and stiffness of any structural system can be estimated analytically, damping property of the structural system one of the difficult to estimate analytically.Hence, dynamic behaviour of structural system and damping property are determined Experimentally with greater reliability.

In the present study attempt is made to study effect of planar and material irregularities on dynamic behaviour through scaled building models.Two scaled building models representing planar irregularity with L-shape and T-shape diaphragm each for both SDOF and MDOF system, respectively are fabricated from Aluminum material. One scaled building model, representing material irregularity with one column made from mild steel material unlike aluminum material material each for both SDOF and MDOF system respectively are fabricated.

All these SDOF and MDOF scaled building models are subjected to free as well as force vibration to derive basic dynamic properties that includes natural frequency, mode shapes Acceleration response and damping coefficients. The above dynamic properties are derived through measurement of acceleration response from SDOF and MDOF system through Accelerometers, Data Acquisition System, LabVIEW software, computer system. Experimental results obtained are supported with analytical formulation and solution for SDOF and MDOF system.

7.2 Conclusion

Following conclusions are derived based on the present study carried out

- Natural frequency of L- shape SDOF irregular system determined analytically and experimentally shows good agreement.Apart,natural frequencies derived for L shape MDOF irregular system through Analytical and Experimental methods also shows agreement.

- Damping Co-efficient evaluated using Logarithmic decrement shows marginal increase for L shape building model as compared to regular building model. This is attributed to increase in number of columns for L-shape model.For both L-shaped SDOF and MDOF systems logarithmic decrement method yields more fair estimate as compared to half-power bandwidth method.

- Transmissibility of L-shape SDOF and MDOF system is significantly high as compared to regular model. The higher transmissibility values in L shape SDOF and MDOF irregular building model is due to planar irregularity.

- Natural frequency of T-shape SDOF irregular system is determined analytically as well as experimentally. Both the results obtained accorded well with each other.Apart, natural frequencies derived for T shape MDOF irregular system through Analytical and Experimental methods also shows agreement.

- Co-efficient of Damping is evaluated using Logarithmic decrement method. The results show minor increment in damping for T shape building model as compared to SDOF bare model. This increment is due to increase in number of columns for T-shape model.Logarithmic decrement method gives more fair estimate of damping coefficient as compared to half-power bandwidth method.

- Transmissibility of T-shape is higher for SDOF and MDOF system as compared to regular building model.

7.3 Future scope of work

Following work may be attempted as future scope of work to present work.

- In the present study two types of irregularity namely planar and material irregularities are studied.However, other types of irregularity for the building model as described in IS:1893(Part-1)-2002 can be adopted to study their effect on dynamic behaviour of the building, both analytically and experimentally.
- Mitigation of ill-effects of planar and material irregularity for building models can be attempted. These may be done by either identifying critical parameters of the building models or employing response control techniques in the building models.
- Effect of different types of boundary conditions of support on dynamic behaviour of SDOF and MDOF building model may be studied.

Appendix A

Detailed Calculation of SDOF & MDOF Building Models

A.1 Calculation for Single Storey Models

Mass matrix and Stiffness matrix can be prepared for single storey structures.

A.1.1 Planer Irregularity Models

Following Data are taken for Planer Irregularity model.

L-Shape

Mass Matrix can be prepared as below

$$M = W_{plate} + \frac{1}{2}W_{col} \tag{A.1}$$

$$I_{cm} = M_1 r^2; r^2 = \frac{I_{zz}}{A}; I_{zz} = I_{xx} + I_{yy} \tag{A.2}$$

Here, M_1 = Mass of the Top plate , I_{cm} = Mass Moment of Inertia , r = Radius of Gyration and A= area of plate

Table A.1: Data for Planer Irregularity Model

Width of Flat	b	=	0.025	m
Thickness of Flat	d	=	0.003	m
Modulas of Elasticity	E	=	6.90×10^{10}	N/m^2
Height of Column	L	=	0.42	m
Moment of Inertia	I_x	=	5.63×10^{-11}	m^4
	I_y	=	3.91×10^{-9}	m4
Stiffness in X Direction	K_x	=	651.64	N/m
Stiffness in X Direction	K_y	=	45252.86	N/m
Mass of the Model	M_1	=	2.26	kg
	M_2	=	2.06	kg
Mass Moment of Inertia	Icm_1	=	0.0310	mm^4
	Icm_2	=	0.0283	mm^4

$$M = \begin{bmatrix} 2.138 & 0 & 0 \\ 0 & 2.138 & 0 \\ 0 & 0 & 0.0293 \end{bmatrix}$$

Stiffness matrix is generated as below

$$K = \begin{bmatrix} 3771.84 & 0 & 75.43 \\ 0 & 2.61 \times 10^5 & 7845.48 \\ 75.43 & 7845.48 & 4087.31 \end{bmatrix}$$

Natural Frequency can be obtained by eigen value analysis.

$$\omega_n = \begin{bmatrix} 6.6835 \\ 49.8879 \\ 64.3194 \end{bmatrix}$$

T shape

For T shape single storey mass matrix is calculated as below.

$$M = W_{plate} + \frac{1}{2}W_{col} \tag{A.3}$$

$$I_{cm} = M_1 r^2; r^2 = \frac{I_{zz}}{A}; I_{zz} = I_{xx} + I_{yy} \tag{A.4}$$

$$M = \begin{bmatrix} 1.88 & 0 & 0 \\ 0 & 1.88 & 0 \\ 0 & 0 & 0.0224 \end{bmatrix}$$

Stiffness matrix is generated as below

$$K = \begin{bmatrix} 3909.84 & 0 & 150.87 \\ 0 & 2.61 \times 10^5 & 0 \\ 150.87 & 0 & 2179.3 \end{bmatrix}$$

Natural Frequency can be obtained by eigen value analysis.

$$\omega_n = \begin{bmatrix} 7.1187 \\ 49.7552 \\ 59.3009 \end{bmatrix}$$

A.1.2 Material Irregularity Models

Data required For material irregularity model analysis

Material Irregularity Type

Mass matrix can be calculated as below

$$M_{slab} = (\rho_{alu} + A_{plate} + t_{plate}) \tag{A.5}$$

$$M_{col} = 3(\rho_{alu} + A_{col}\frac{h}{2}) + \rho_{steel} + A_{col}\frac{h}{2} \tag{A.6}$$

$$I_{cm} = M_{col} r_1^2 + M_{slab} r_2^2 r^2 = \frac{a^2 + b^2}{12} \tag{A.7}$$

mass matrix can be written as below

Table A.2: Data For Material Irregularity Model

Width of Flat	b_{al}	=	0.025	m
Thickness of Flat	d_{al}	=	0.003	m
Modulus of Elasticity	E_{al}	=	6.90×10^{10}	N/m^2
Modulus of Elasticity	E_s	=	2.00×10^{11}	N/m^2
Height of Column	L	=	0.415	m
Moment of Inertia	I_x	=	5.63×10^{-11}	m^4
	I_y	=	3.91×10^{-09}	m^4
Cross-sectional Area of Aluminium	A_{al}	=	0.000075	m^2
Cross-sectional Area of Steel	A_s	=	0.000075	m^2
Longer Dimension of plate	a	=	0.3	m
Shorter Dimension of plate	b	=	0.15	m
	t	=	0.010	m
Density of Aluminium	al	=	2830	Kg/m^3
Density of Steel	s	=	7850	Kg/m^3
Stiffness in X direction	Kx_{al}	=	651.64	N/m
Stiffness in X direction	Ky_{al}	=	45252.86	N/m
Stiffness in X direction	Kx_s	=	1.89×10^3	N/m
Stiffness in Y direction	Ky_s	=	1.31×10^5	N/m
Mass of Aluminum Column		=	0.044041875	Kg
Mass of Steel Column		=	0.122165625	Kg
Mass of Aluminium Slab		=	1.2735	Kg
Mass moment of Inertia		=	0.08808375	
Mass moment of Inertia		=	0.24433125	

$$M = \begin{bmatrix} 2.083 & 0 & 0 \\ 0 & 2.083 & 0 \\ 0 & 0 & 0.0288 \end{bmatrix}$$

Stiffness matrix is generated as below.

$$K = \begin{bmatrix} 3708.7 & 0 & -89.51 \\ 0 & 2.61 \times 10^5 & 12362.1 \\ -89.51 & 12362.1 & 5800 \end{bmatrix}$$

Natural Frequency can be obtained by Eigen value analysis.

$$\omega_n = \begin{bmatrix} 6.7136 \\ 51.3010 \\ 83.5611 \end{bmatrix}$$

A.1.3 Calculation for Two Storey Models

A.1.4 Planer Irregularity Models

L shape

Mass Matrix

$$M = \begin{bmatrix} 2.255 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.255 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0310 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.055 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.055 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0283 \end{bmatrix}$$

Stiffness Matrix

$$K = \begin{bmatrix} 6516.41 & 0 & 162.91 & -3258.21 & 0 & 81.46 \\ 0 & 452528.65 & 11313.22 & 0 & -226264.33 & 5656.61 \\ 162.91 & 11313.22 & 8649.27 & -81.46 & 5656.61 & 5438.58 \\ -3258.21 & 0 & -81.46 & 3258.21 & 0 & 81.46 \\ 0 & -226264.33 & 5656.61 & 0 & 226264.33 & 5656.61 \\ 81.46 & 5656.61 & 5438.58 & 81.46 & 5656.61 & 5377.90 \end{bmatrix}$$

Natural frequency can be obtained by solving eigen value problem in MATLAB.

$$\omega_n = \begin{bmatrix} 104.79 \\ 82.30 \\ 3.8560 \\ 9.9155 \\ 33.8646 \\ 29.1740 \end{bmatrix}$$

T shape

Mass Matrix

$$M = \begin{bmatrix} 1.728 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.728 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0206 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.704 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.704 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0203 \end{bmatrix}$$

stiffness Matrix

$$K = \begin{bmatrix} 7819.70 & 0 & 293.24 & -3909.85 & 0 & -146.62 \\ 0 & 543034.38 & 0 & 0 & -271517.19 & 0 \\ 293.24 & 0 & 8726.34 & -146.620 & 4363.17 & \\ -3909.85 & 0 & -146.62 & 3909.85 & 0 & 146.62 \\ 0 & -271517.19 & 0 & 0 & 271517.19 & 0 \\ -146.62 & 0 & 4363.17 & 146.62 & 0 & 4363.17 \end{bmatrix}$$

Natural frequency can be obtained by solving eigen value problem in MATLAB.

$$\omega_n = \begin{bmatrix} 118.7579 \\ 12.2259 \\ 4.7016 \\ 45.5216 \\ 102.2774 \\ 39.1878 \end{bmatrix}$$

A.1.5 Material Irregularity Models

Material Irregular Model

Mass Matrix

$$M = \begin{bmatrix} 1.782 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.782 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.528 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.528 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.026 \end{bmatrix}$$

stiffness Matrix

$$K = \begin{bmatrix} 7687.48 & 0 & -185.58 & -3843.74 & 0 & 92.79 \\ 0 & 533852.64 & 25774.46 & 0 & -4590.87 & -12887.23 \\ -185.58 & 25774.46 & 12054.93 & 92.79 & 12887.23 & 6027.46 \\ -3843.74 & 0 & 92.79 & 3843.74 & 0 & -92.79 \\ 0 & -4590.87 & 12887.23 & 0 & 266926.32 & 12887.23 \\ 92.79 & -12887.23 & 6027.46 & -92.79 & 12887.23 & 6027.46 \end{bmatrix}$$

Natural frequency can be obtained by solving eigen value problem in MATLAB.

$$\omega_n = \begin{bmatrix} 142.43 \\ 92.67 \\ 4.82 \\ 12.20 \\ 31.14 \\ 63.08 \end{bmatrix}$$

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