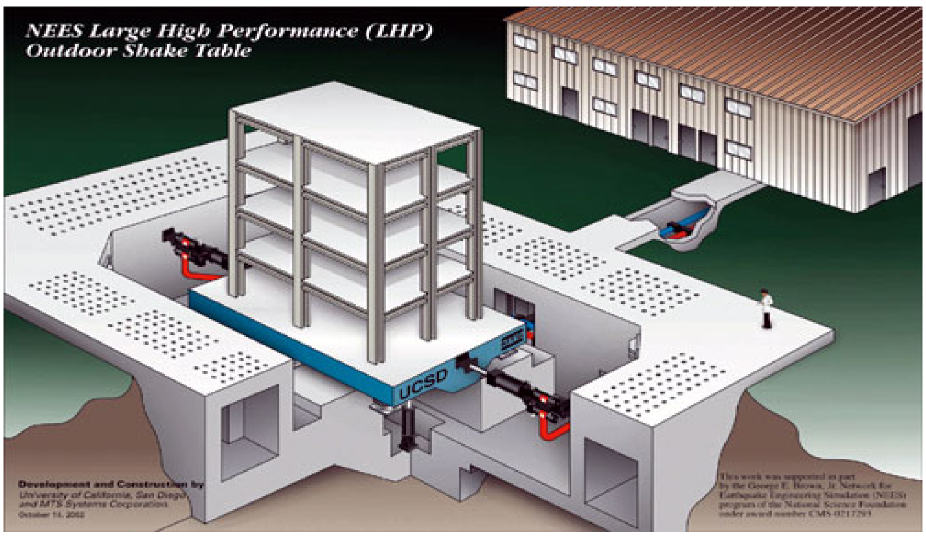
1. INTRODUCTION

1.1 INTRODUCTION

1.2 USES OF SHAKE TABLE

1.3 PURPOSE OF A SHAKE TABLE



1. INTRODUCTION

1.1 INTRODUCTION

Explore earthquake hazards and damage to buildings by constructing model buildings and subjecting the buildings to ground vibration (shaking similar to earthquake vibrations) on a small shake table. CIVIL constructions and engineering structures are designed to withstand a variety of operational loads and environ-mental conditions over decades of safe and economic usage. Earthquakes are part of this environment. Apart from destruction of life and property, they can have serious indirect consequences.

The exact simulation of earthquake motion has been a serious challenge to researchers and engineers. Shake table testing is being increasingly used in earthquake engineering research centers worldwide, as it is the only available means of nearly truly reproducing the dynamic effects that earthquakes impose on structures. A relatively simple system has been assembled with care to ensure an adequate replication of input motion by the shake table system. Subjective comparisons of input signal vs shake-table response, in both time and frequency domain have been utilized to provide a measure of the capabilities of the simulator to reproduce earthquake motions scaled according to similitude laws. This report discusses briefly various components of the shake table, its assembly and the investigations that were carried out to provide specific insights into its response characteristics.

A structure in the vicinity of an earthquake will experience random vibrations caused by the movement of its foundation. One may assume similar response if the base of the structure is shaken in a laboratory environment using the acceleration – time history recorded during the earthquake. By the same token, laboratory reproduction of associated displacement – time history would also have the same effect. This is the basis for the application of two-axis shake table to earthquake simulation.

Designing of a shaking table which produces vibrations in horizontal as well as in vertical direction. This is used for the analysis of the vibrations in a structure at the time of earthquake. Architects and engineers run simulations using models and shake tables to test the integrity of buildings and determine necessary reinforcements and to study dynamic structural behavior.

This will be the device for shaking the structural models or building components prototypes, with a wide range of simulated ground motions

1.2 USES OF SHAKE TABLE

- Building models
- Bridge models
- Components of buildings and bridges, such as beam and column connections, walls, and foundation.

1.3 PURPOSE OF A SHAKE TABLE

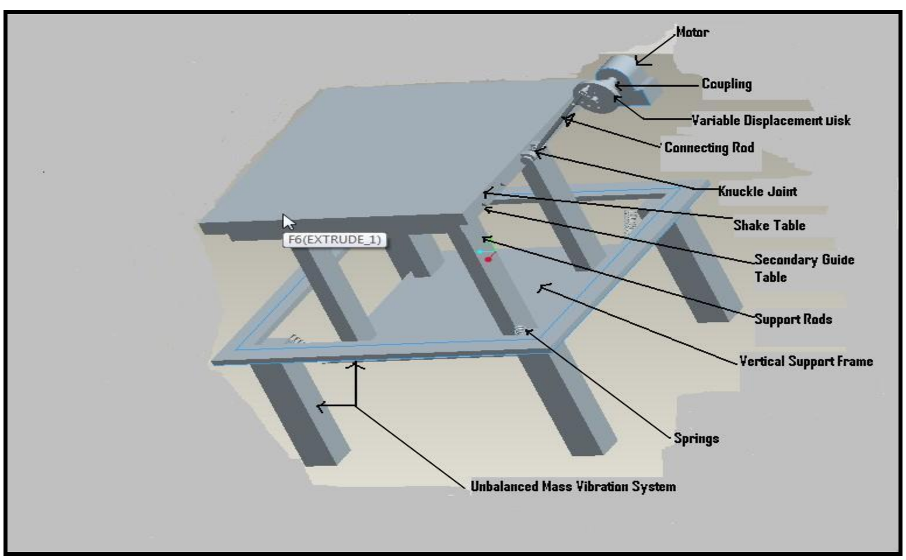
- Dynamic structural behavior of a small-scale structure.
- Test the resistance of the structures.
- Test for both horizontal and vertical type of vibrations.
- Sensitivity of structures of different types.
- Seismic research purpose.

2. PROJECT SPECIFICATIONS

2.1 SHAKE TABLE SPECIFICATION

2.2 COMPONENTS OF THE SHAKE TABLE

2.3 PROPOSED DESIGN AND MODEL



2. PROJECT SPECIFICATIONS

This chapter consists of the various provisions of the shake table such as maximum loading conditions, vibration amplitudes, different components of the system and the 3D view of the model.

2.1 SHAKE TABLE SPECIFICATION

- Shake table dimensions – 800 x 800 x 30 mm^3
- Minimum pay Load – 50 Kg (490 N)
- Bi axial – (Horizontal- Vertical)
- Amplitude Vertically = 0-10 mm
- Amplitude Horizontally = 0-25 mm
- Frequency = 0-25 Hz

2.2 COMPONENTS OF THE SHAKE TABLE

- Shake Table
- Secondary Guide Table
- Knuckle Joint
- Connecting Rod
- Bearing
- Nuts, Bolts (Internal Diameter of Bearing)
- Variable Displacement Disk
- Shaft, Key, Coupling
- Motor
- Supporting Rods
- Vertical Support Frame
- Unbalanced Mass Vibration System

2.3 PROPOSED DESIGN AND MODEL OF THE SHAKE TABLE

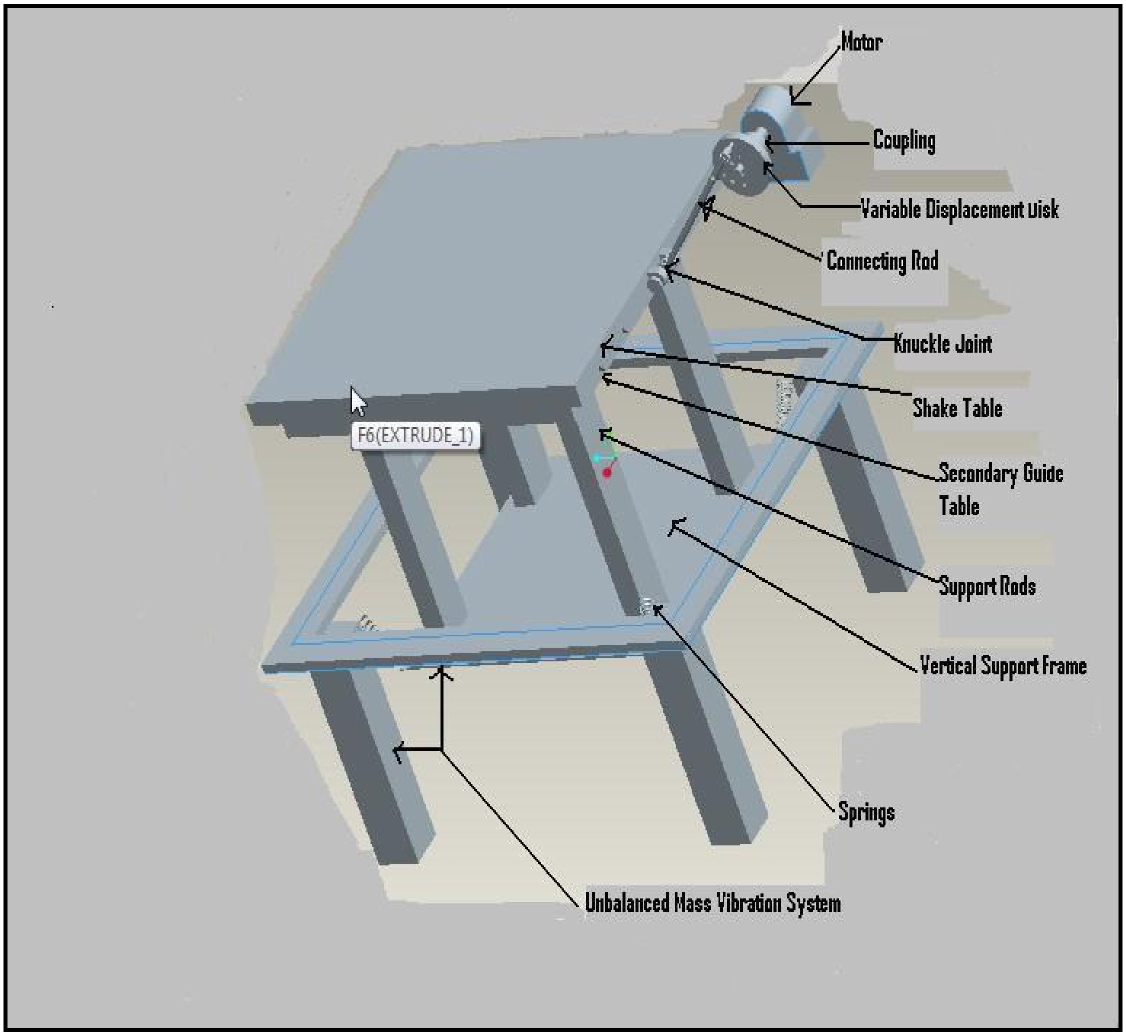
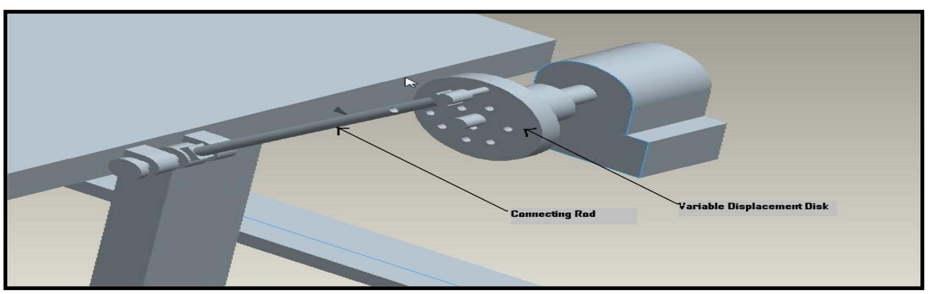
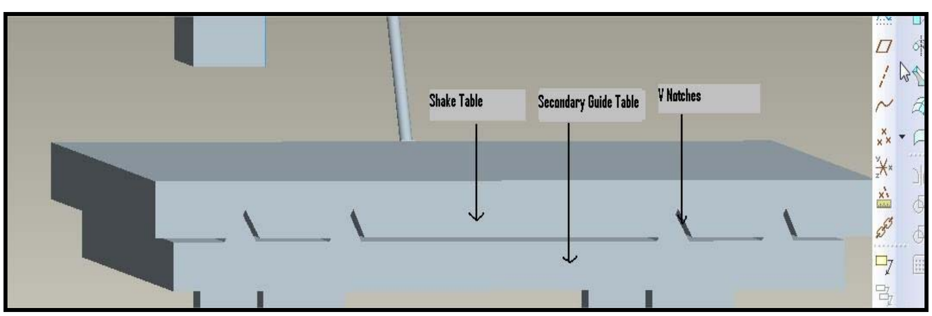


Figure 2.1 Proposed Design and Model of Shake Table

3. MECHANISM & KINEMATIC ARRANGEMENT

3.1. DESCRIPTION OF THE SYSTEM





3. MECHANISM & KINEMATIC ARRANGEMENT

3.1 DESCRIPTION OF THE SYSTEM

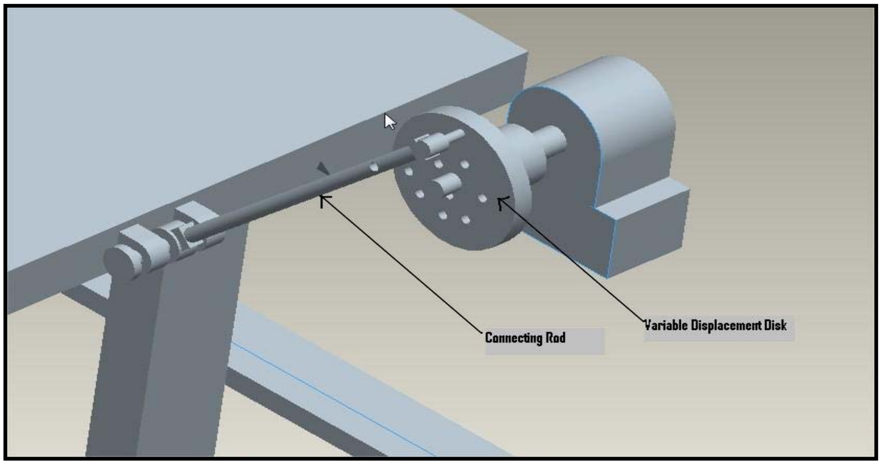


Figure 3.1 Motor and connecting rod assembly

- The motor is connected to the table for getting the vibratory movements of the shake table.
- The transmission is done with the help of connecting rod and variable displacement disk.

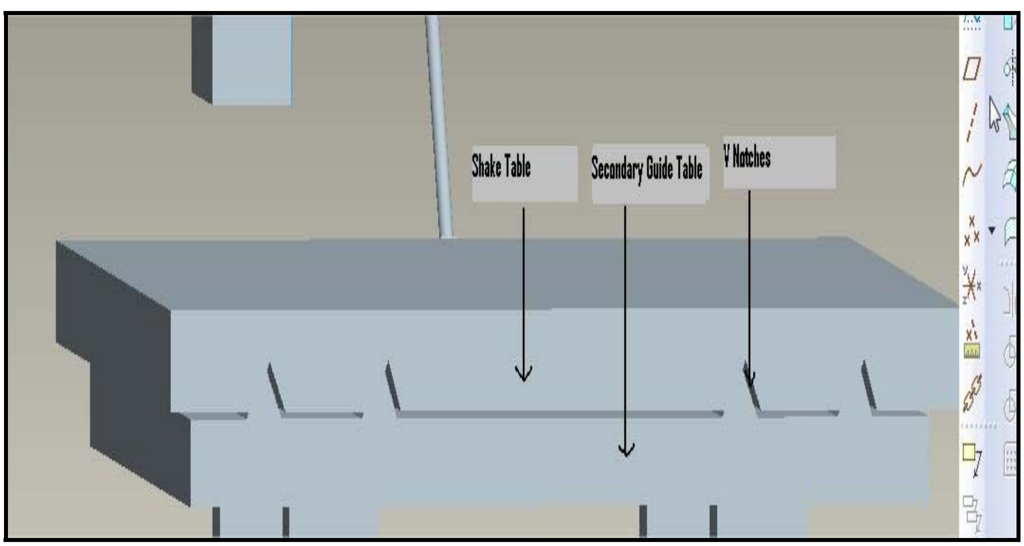


Figure 3.2 Shake Table Thickness

- There are two types of tables:
    a) Main shake table
    b) Secondary guide table
- The structural model is kept on the main table and secondary table guide the main table for vibration
- V- notches are provided on the main shake table

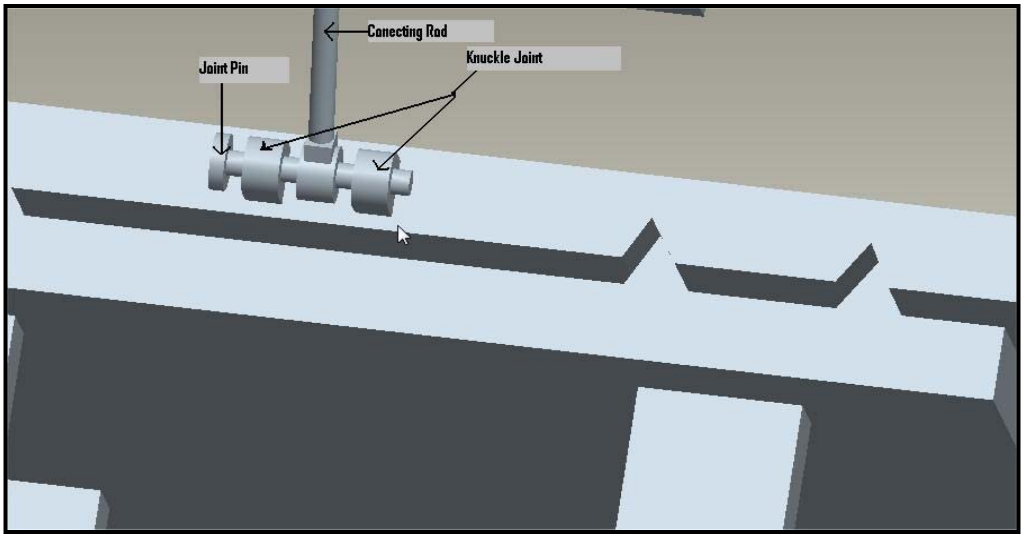


Figure 3.3 Connection through Joint Pin & Knuckle Joint

- The vibration is transmitted to the shake table through a knuckle joint provided in the mechanism
- The connection is done by providing joint pin

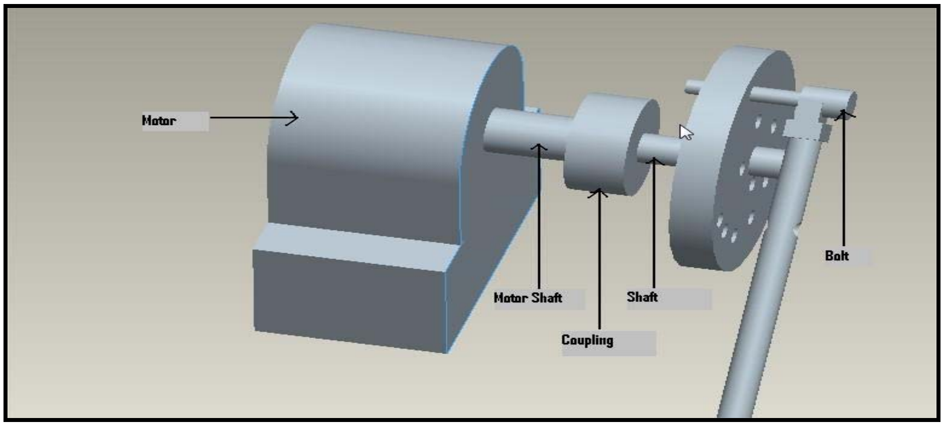


Figure 3.4 Drive system

- The vibratory movement mechanism system includes motor, motor shaft, driven shaft and coupling

- The motor shaft is connected to driven shaft with the help of coupling provided in the system

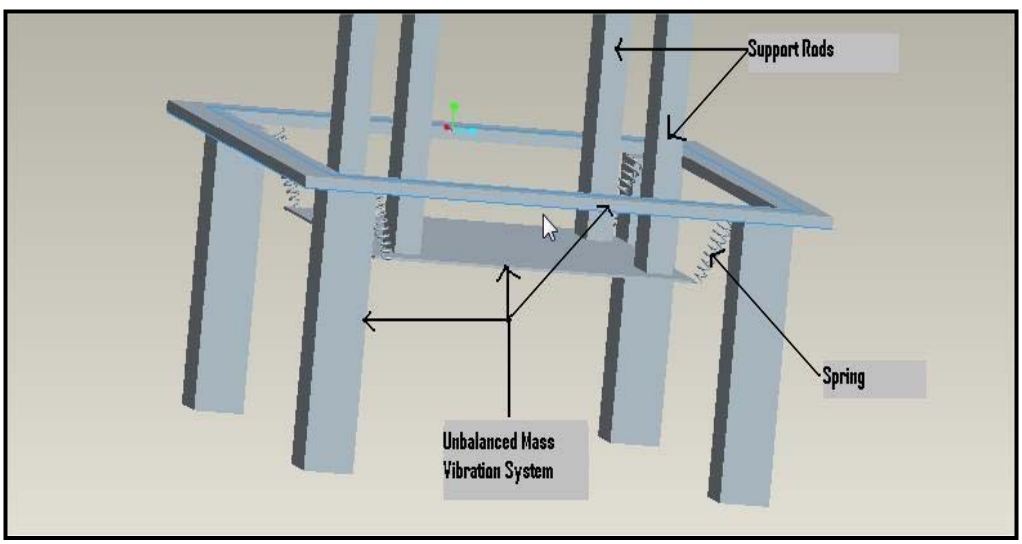
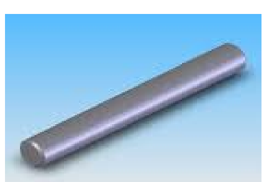


Figure 3.5 Spring mechanism for Shake table

- Springs are provided between two tables i.e. the shake table and the secondary table
- Four springs are used at four corners of the table
- Springs help to maintain the oscillatory motion of the shake table generated by the motor and transmitted by the mechanism

4. DESIGNING CALCULATION & PROCEDURE

4.1 DESIGN OF SUPPORTIND RODS
4.2 DESIGN OF SHAKE TABLE
4.3 DESIGN OF KNUCKLE JOINT
4.4 DESIGN OF CONNECTING ROD
4.5 DESIGN OF BEARING
4.6 DESIGN OF SHAFT
4.7 DESIGN OF KEY



4. DESIGNING CALCULATION & PROCEDURE

4.1 DESIGN OF SUPPORTING RODS

Here considering the supporting rods as a strut and analyzing the rod under the bulking load, because the rod is under compressive load.

Here we are checking the rods for stable equilibrium, because we want the rods to came to the original position while removing the axial loads.

NOTE: -Considering the definition of the strut as a bar or as a member of a structure in any position and on axial compressive load.

- Here the column is of type one end fixed and other end free

Now using the fundamental values,

$P_e = \pi^2 EI/4l^2$

Taking bulking load as the maximum payload capacity.

So,

P_e = 50kg

Taking factor of safety as 5

So,

P_e = 2450N

= 2.45 KN

Now E (modulus of elasticity of aluminum) = 68.9 GPa

Taking I = 400mm

So solving for I

$2450 = \pi^2 * 68.9 * 10^9 * I / 4 * (400)^2$

Or I = 0.00232mm^4

Taking square section and side as b

$b^4/12 = 0.00232$

b = 0.4084 mm

But we are taking the dimensions

The supporting rods as,

= 400 mm * 10 mm * 10 mm

4.2 DESIGN OF THE SHAKE TABLE

Size = 800 $\times$800 $\times$30 mm^3

Thickness taken is 30 mm.

So volume = 800 $\times$800 $\times$30 mm^3

Volume = 0.0192 m^3

Material taken is [7075-T6] Aluminum Alloy, which has the following qualities,

Density = 2.7 Mg/m^3

Shear Modulus = 70 GPa

Young's modulus = 70 GPa

Yield stress = 500 GPa

- Why Aluminium Alloy?

  - Light weight
  - Low cost [66Rs./ kg]
  - Easily Available
  - Suitable for purpose

So the weight of the table = Volume * Density

= 0.0192 m^3 * 2.7 Mg/m^3

= 51.84 Kg

Nearly Taken as 52 Kg

4.3 DESIGN OF KNUCKLE JOINT :-

- Why knuckle joint

Answer: - Knuckle joint is appropriate for this purpose because

- The knuckle joint is used to transmit axial tensile force.
- These joint permits limited angular moments between rods about the axis of pin.
- This joint is used where either the axis coincide or intersect and lie in one plane.

So the knuckle joint is appropriate for this purpose.

NOTE: Here fork of the knuckle joint will be connected to table and eye will be connected to the connecting rod.

Total weight of table will be around.

Total Weight = 52 + 50(pay load) = 102 Kg

So Total Force = 102 * 9.8 (Newtons)

= 1014.97 (Newtons)

Taken Factor Of Safety (FOS) = 1.2

So Total Effective Force (P) = 1319.472 Newton

i) **Now tensile failure of Rods**

$$\sigma_t = \frac{p}{\frac{\pi}{4}D^2}$$

D- Diameter of rod

σ_t- Permissible tensile stress.

Material of the Rod Taken is M.S. 1020 (40C8)

Which has the following qualities: -

S_{yt}=400 N $/mm^2$

Taken FOS =4

$\sigma_t = \frac{400}{4} = 100$

$100 = \frac{1319.47}{\frac{\pi}{4}D^2}$

D= 4.099 mm

For Standard Diameter of Shaft it is rounded off to 5mm

ii**) Buckling failures for a Rod**

a) Jordan's parabolic formula-

$$P_c = a\sigma_y[1 - \frac{\sigma_y}{4n\pi^2 E}\left(\frac{L}{r}\right)^2]$$

For L/r <120 (steels)

b) Straight line formula-

$$P_c = [\sigma_y - \frac{2\sigma_Y}{3\pi^2}\left(\frac{L}{r}\right)^2\sqrt{\frac{\sigma_Y}{3n E}}]$$

For L/r < 120 (steels)

n = coefficient of end friction

P_c = *buckling Load*

E= Young's Modulus

A= Area of cross section

L= length of the column

r = least radius of gyration.

$P_c = 1319\ N, n = 1, E = 210 \times 10^{-3}\ N/mm^2, A = \pi r^2, L = 200\ mm, \sigma_y = 380\ N/mm^2$

Taking F.O.S. = 4

σ_{ys}= 380/4 = 95 N/mm^2

Taking permissible yield stress = 50 N/mm^2

Jordan's parabolic formula -

$$P_c = a\sigma_y[1 - \frac{\sigma_y}{4n\pi^2 E}\left(\frac{L}{r}\right)^2]$$

$$1319 = \pi r^2 \times 50\ [1 - \frac{50}{4\pi r^2 \times 1 \times 210 \times 10^3}\left(\frac{200}{r}\right)^2$$

On solving for the value of r (radius)

r = 4.0128 mm

Then Diameter = 8.0256

For Standard Diameter of Shaft it is rounded off to 9mm.

Straight line formula

$$P_c = [\sigma_y - \frac{2\sigma_y}{3\pi^2}\left(\frac{L}{r}\right)^2\sqrt{\frac{\sigma_y}{3nE}}]$$

Putting the values

$$1319 = [1319 - \frac{2 \times 50}{3\pi^2}\left(\frac{200}{r}\right)^2\sqrt{\frac{\sigma_y}{3nE}}]$$

On solving for r (radius)

r= 3.9822 mm

So Diameter = 7.9644

So for standard diameter of Shaft; D= 8 mm

NOTE : So now from theory of tensile failure of rods we get the diameter of the rod D= 5 mm, and from buckling criteria we are getting the value D= 9mm

Taking buckling criteria into consideration

Diameter of rod = 9 mm

Length of rod= 200 mm

iii) **Shear failure of pin:-**

The pin is subjected to double shear

$\tau = shear\ stress\ in\ pin.$

$$\tau = \frac{p}{2A}$$

Then D= $\sqrt{\frac{2p}{\tau\pi}}$

Material used for pin is **40C8**

Properties of this material

S_{ut}=600 N $/mm^2$

S_{yt} = 400 N $/mm^2$

Taking F.O.S. =4

So

σ_t = 100 N $/mm^2$

Taking permissible shear stress = 20 N $/mm^2$

D= $\sqrt{\frac{2\times 966.28}{3.14\times 20}}$

D= 5.54 mm

D= 6 mm (Diameter of Pin)

iv) **Bending criteria of pin**

Material used is 40C8

So,

$S_{yt} = 400 \text{ N} /mm^2$

Taking F.O.S. = 5

So,

$\sigma_b = 80 \text{ N} /mm^2$

So taking permissible bending stress as $80 \text{ N} /mm^2$

So

$$\sigma_b = \frac{32}{\pi d^3} \times \frac{p}{d} [\frac{b}{4} + \frac{a}{3}]$$

Now taking 10 mm as rod diameter

So,

a = 0.75 $\times$ 10 =7.5

b=1.25$\times$ 10 = 12.5

now putting the values

$$50 = \frac{32}{\pi d^3} \times \frac{966}{2} [\frac{12.5}{4} + \frac{7.5}{3}]$$

$d^3 = 61.92 \times 5.625$

d= 7.02 mm

d= 8 mm

So taking bending failure in consideration of pin we take d= 8 mm for the pin

So diameter of pin head = 10 mm

Also the length of the joint = 2a+b = 32.5 mm

Now design calculation of d_o and d

$d_o = outer\ diameter\ of\ the\ fork$

d= internal diameter of fork

d= $8mm^{+0.2mm}$

$d_o = 2d = 16\ mm$

4.4 DESIGN OF CONNECTING ROD

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Taking buckling criteria into consideration

Diameter of rod = 9 mm

And length of rod= 200 mm

4.5 DESIGN OF BEARING

A bearing is a mechanical element that permits relative motion between two parts with minimum friction. It has following functions.

- Free rotation of the shaft

- Support for the rotating element
- Transfer forces of shaft do housing or foundation.

The bearing used here are radial deep groove ball bearing.

According to the standards
For shaft diameter D1= 12 mm
Stepped diameter d= 10 mm

The series to be applied here is deep groove ball bearing series 60. (6000)

Here d=10 mm, D1 = 12 mm, d= 20 mm
D2=18 mm, B= 8 mm, r= 0.5 mm

The deep groove ball bearing is used here because it has the following advantages-

- Deep groove ball bearing takes load in radial as well as axial direction.
- Due to relatively large size of the balls, deep groove ball bearing has high load carrying capacity.
- Due to point contact between the balls and races frictional losses and temperature rise is less in this bearing.
- It generates lesser noise due to point contact.

4.6 DESIGN OF SHAFT OF VARIABLE DISPLACEMENT DISK

The shaft is rotating machine element which is circular in cross section ,that supports transmission element like gears ,pulley ,rockets and transmits power .

The mechanical taken here by us for the design of the shaft of variable displacement disk is 40C8.

It is hardened carbon steel.
It has following qualities.

S_{yt}=380 N/mm^2

S_{ut}=600 N/mm^2

so strength in shear is

S_{ys}= 0.5 S_{yt}
= 190 N/mm^2

Now taking factor of safety of 2

$$\tau_{max} = \frac{S_{ys}}{F.O.S} = \frac{190}{2} = 95 \text{ N}/mm^2$$

Now considering the maximum shear stress theory are there negligible bending moment in the shaft, and because failure can occur primarily due to shear, thus

$$\tau_{max} = \frac{16}{\pi d^3} \times M_t$$

but

$$M_t = 1319 \times 40 \; N.mm$$

$$95 = \frac{16}{\pi d^3} \times 1319 \times 40$$

D= 14.14 mm

so using standard shaft diameter

d=16 mm

Length of the shaft (long series)= 40 mm

4.7 DESIGN OF KEY BETWEEN VARIABLE DISPLACEMENT DISK AND SHAFT

A key is a machine element that is used to connect transmission shaft to rotating machine elements like pulley, gear, sprocket, or flywheel.

The function of the key served here are: -

- Transmission of torque from shaft to the variable displacement disk of the mating element.
- Prevention of relative motion between the shaft and VDD.

The key used here is sunk parallel rectangular key.

Material used is 50C4, Hardened carbon steel, which has the following properties.

S_{yt}=700 N/mm^2

S_{ut}=460 N/mm^2

$\sigma_t = \frac{S_{ys}}{F.O.S}$ =460/3=153.33 N/mm^2

Taking factor of safety as 3.

$S_{ys} = 0.5\ S_{yt} = 230\ N/mm^2$

From the Indian standards I.S. 2048-1962 we get for a 16 mm shaft diameter.

Cross section is of 5×5 mm²

Width b = 5 mm

Height h = 5 mm

Keyway depth of shaft is 3 mm

Keyway depth in V.D.D. = 2.3 mm

Now for shear criteria:-

$$\tau = \frac{2M_t}{dbl}$$

$$76.67 = \frac{2 \times 1319 \times 40}{16 \times 5 \times l}$$

So L = 17.20 mm

For compression criteria :-

$$\sigma_c = \frac{4M_t}{dhl}$$

$$153.33 = \frac{4 \times 1319 \times 40}{16 \times 5 \times l}$$

L= 17.20 mm

So length is taken as 18 mm.

The required dimension of the key are

b(width)= 5 mm

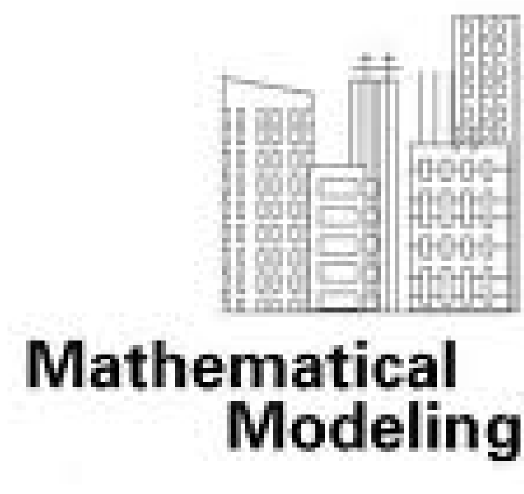
h (height) = 5 mm

d (length) = 18 mm

key is of $18 \times 5 \times 5$ dimension.

5. MATHEMATICAL MODELING & SIMULATION

5.1 ASSUMPTION
5.2 CALCULATION
5.3 CONCLUSION



5. MATHEMATICAL MODELING & SIMULATION

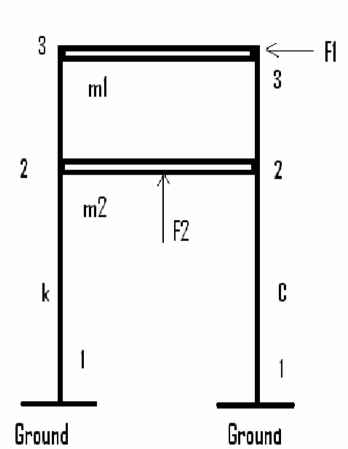
5.1 ASSUMPTIONS

- Forced type vibrations
- Dampers
- Damped forced vibration with multiple degree of freedom system.

5.2 CALCULATION

Considering

- m1(mass of shake table) =52kg
- m2(mass of secondary guide table) =52kg
- c1 = c2 = c3 = c4 = c (dampers)
- k1 = k2 = k3 = k4 = k (springs)



[m] = mass matrix

[c] = damping matrix

[k] = stiffness matrix

[F] = force matrix

$$\begin{bmatrix} m1 & 0 \\ 0 & m2 \end{bmatrix} \begin{bmatrix} D''x1 \\ D''x2 \end{bmatrix} + \begin{bmatrix} -4c & 0 \\ 0 & -4c \end{bmatrix} \begin{bmatrix} D'x1 \\ D'x2 \end{bmatrix} + \begin{bmatrix} -4k & 0 \\ 0 & -4k \end{bmatrix} \begin{bmatrix} x1 \\ x2 \end{bmatrix} = \begin{bmatrix} F1 \\ F2 \end{bmatrix}$$

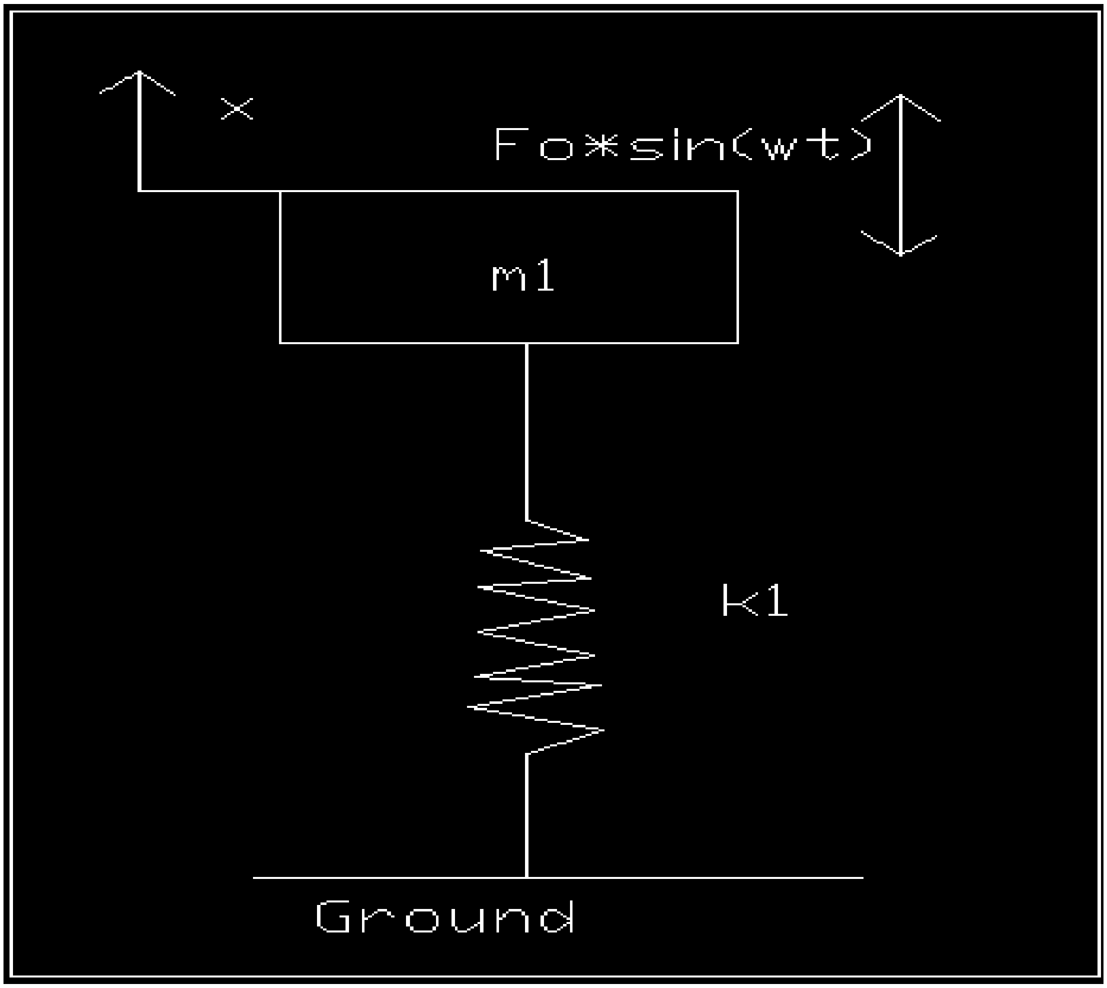


Figure 5.1 Mathematical Modeling of Vibration System I

For Stimulation Purpose we are using: -

- Considering undamped system.
- Single degree of freedom system.
- Simple spring mass system.

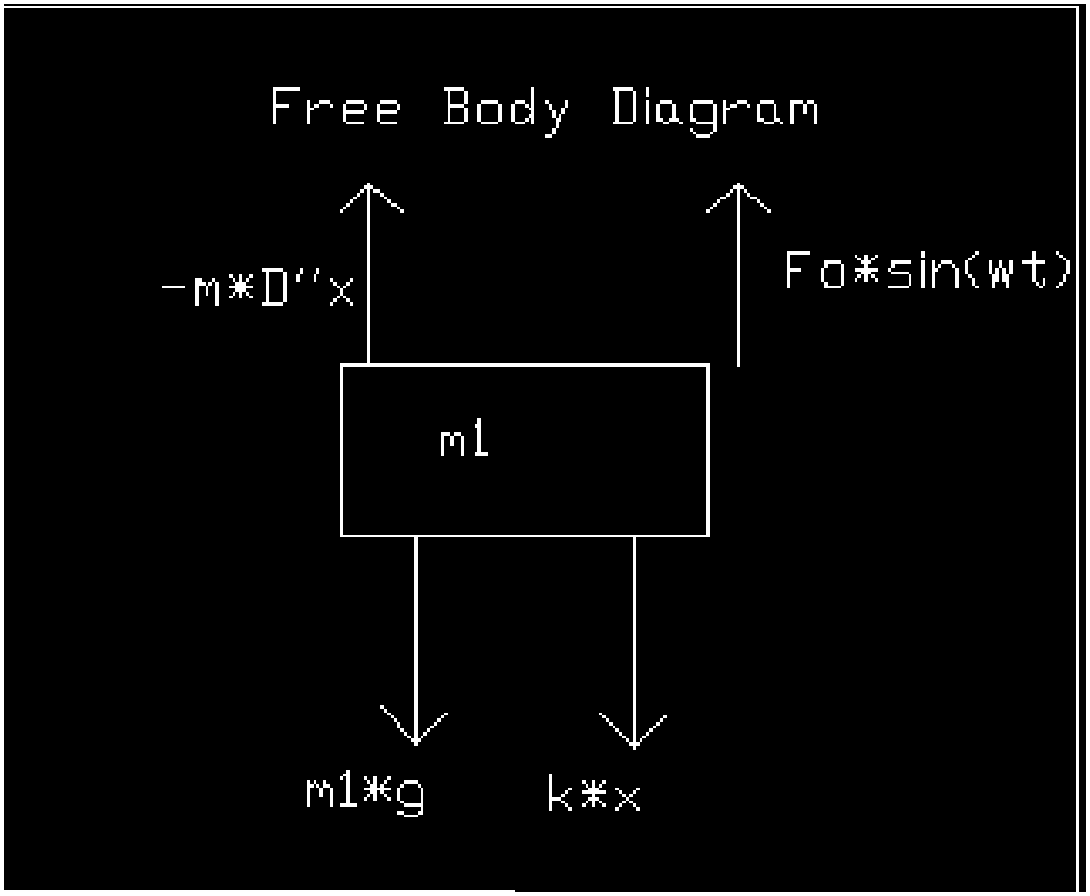
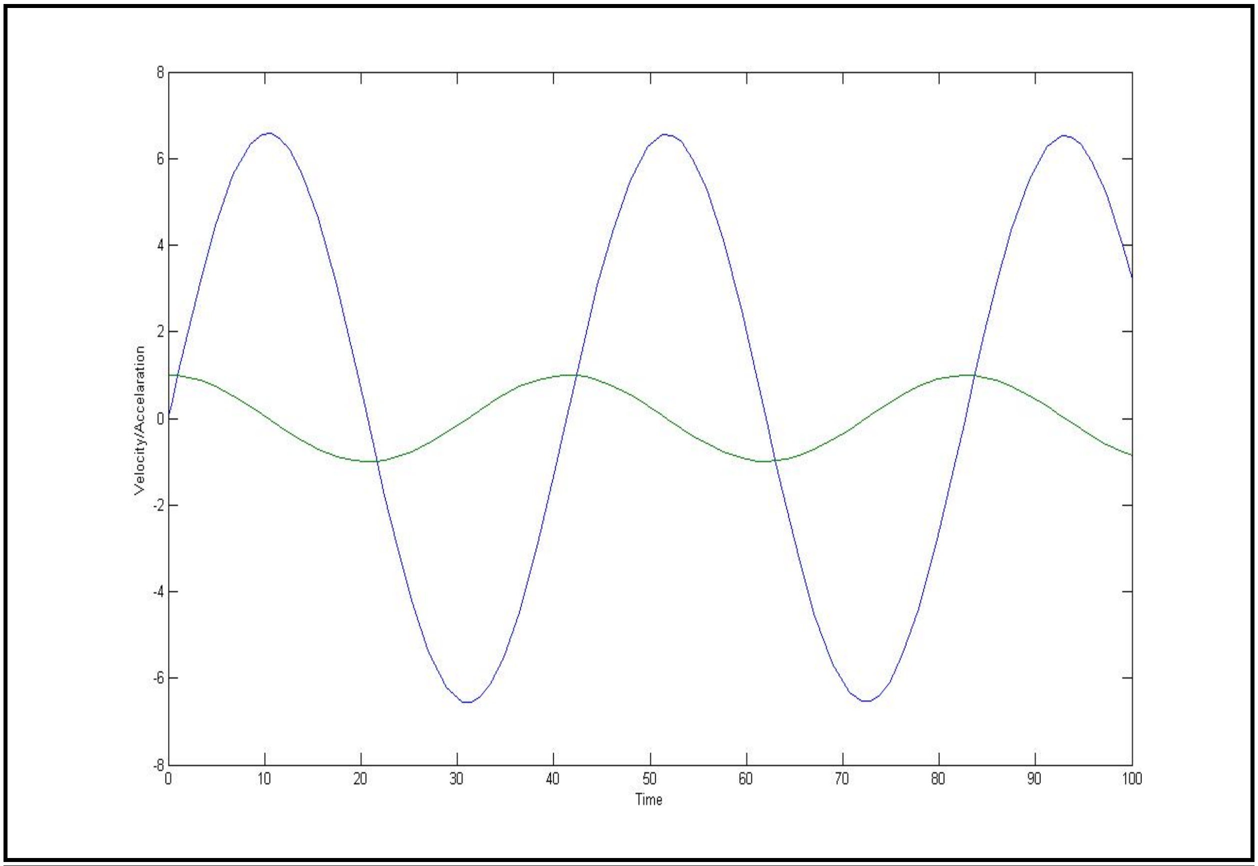


Figure 5.2 Mathematical Modeling of Vibration System II

Equation came out from the modeling process

m1*D''x + k1*x = Fo* Sin(wt)

NOTE: - According to the free body diagram of the model the m1*g factor will also come into picture but this factor is not taken into account because this system is a dynamic equilibrium.



Blue Curve represents Velocity Green Curve represents Acceleration

Figure 5.3 Curve between Displacement/Velocity and Time

5.3 Conclusion

- After simulation the curve plotted of displacement/velocity with respect to time.
- We are getting the outputs of velocity and displacement in the form of sine curve.

6. ANALYSIS OF THE STRUCTURE

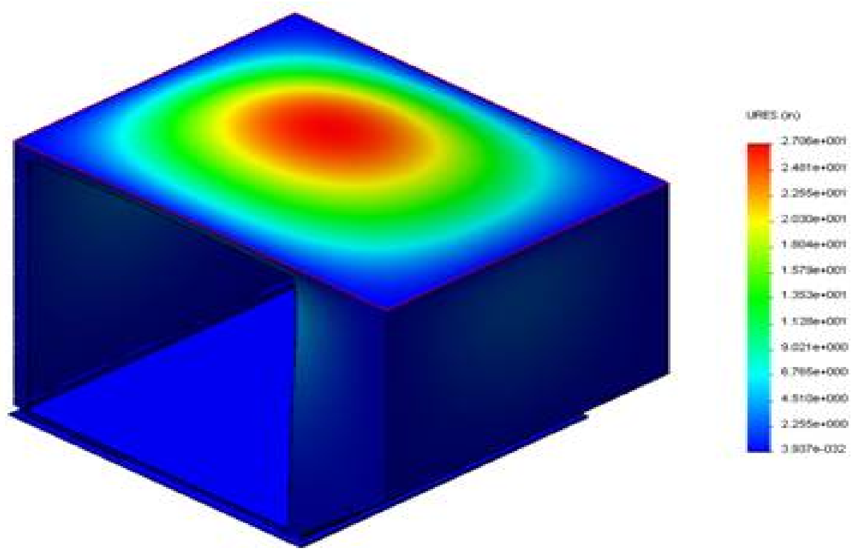
6.1 STEPS FOR VIBRATIONAL ANALYSIS

6.1.1 ANALYSIS FOR VERTICAL MOTION

6.1.2 ANALYSIS FOR HORIZONTAL MOTION

6.1.3 ANALYSIS FOR SIMULTANEOUS VIBRATION

6.2 CONCLUSION



6. ANALYSIS OF THE STRUCTURE

6.1 STEPS FOR VIBRATIONAL ANALYSIS

- Convert the physical system to simplified mathematical model
- Determine the equation of motion l of the system
- Solve the equation of motion to obtain the response
- Interpretation of the result for the physical system.

To convert the physical system into simpler models one may use the concept of equivalent system. To determine the equation of motion basically one may use eitherthe vector approach with the Newtonian approach or d'Alembert principle based onfree body diagram or one may go for scalar approach using the energy concept. Inscalar approach one may use Lagrange method, which is a differential procedure orextended Hamilton's principle based on integral procedure. Different methods/laws/principle used to determine the equation of motion of the vibratingsystems are summarized below

- For the analysis point of view we have taken maximum aspect ratio as 5
- Taking part material as Aluminum 6061.
- This aspect ratio helped in :-
- Improving element angle quality.
- For maximum element size mesh control.
- Minimum edge angle is kept below 6 degree.
- Maximum edge angle is kept above 150 degree.

NOTE: -

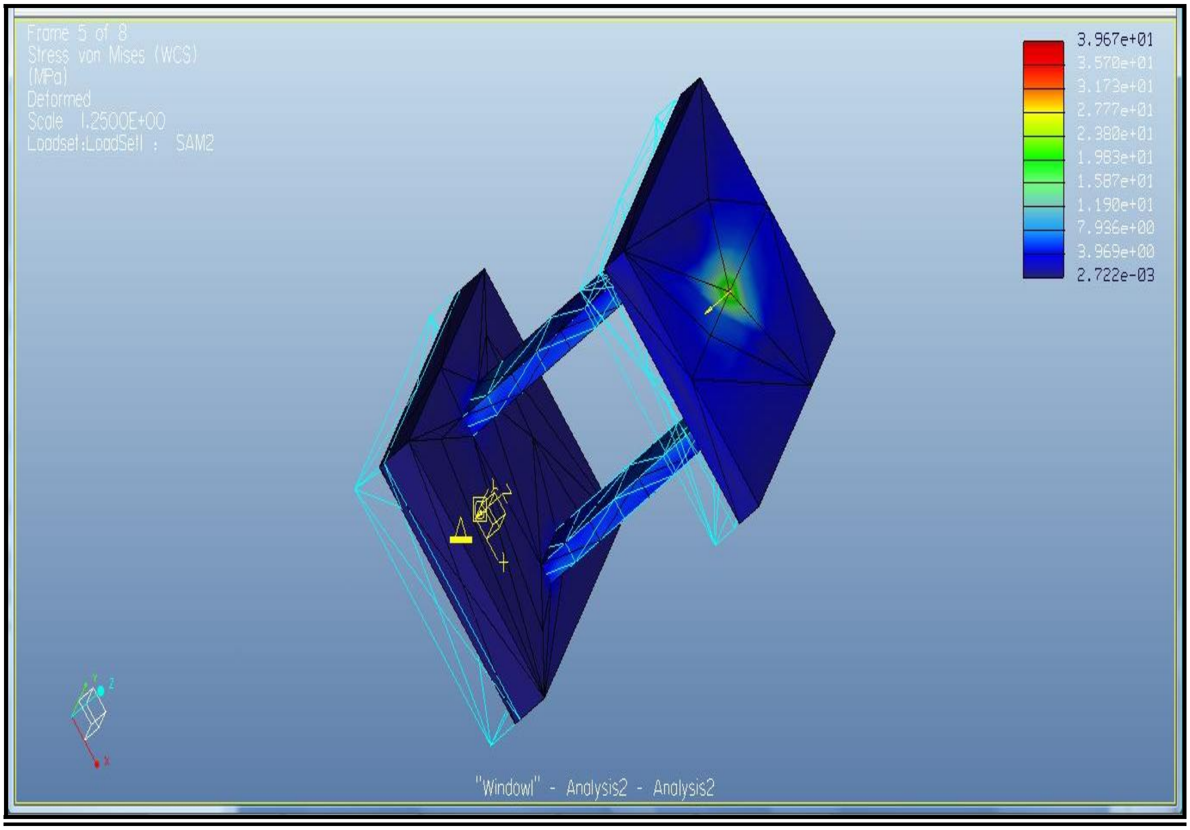
- The analysis of this model is done using the PRO-Engineering CAE and PRO-Engineering Mechanica.
- Here the analysis is done considering the different motions of the system.
- Analysis is also done by considering only 1D motion as well as with simultaneous motion.

- We have experimented for total 4 analysis i.e. only vertical vibrations, only horizontal vibrations, vertical vibrations when gravity force is considered, and atlast the combined effect of all the vibrations.

6.1.1 ANALYSIS FOR VERTICAL MOTION

Conditions under which the analysis is done

- Number of elements = 59
- Number of nodes created = 108
- Maximum edge angle = 167.47
- Minimum edge angle = 5.41
- Aspect ratio = 4.89

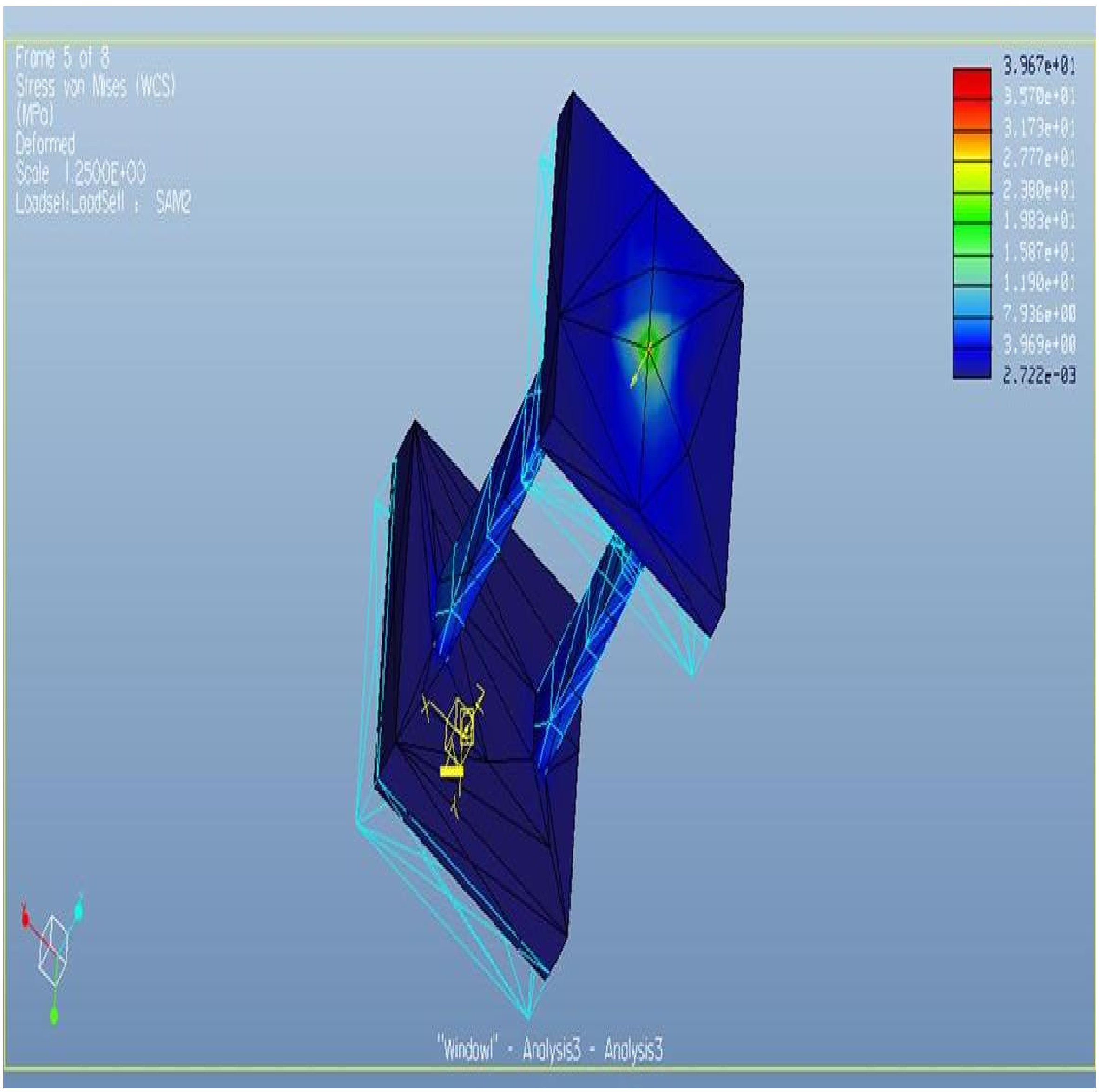


- **NOTE: -** Conclusion of all the analysis is given at the end of this chapter.

Figure 6.1 Analysis for Vertical Motion

i) <u>Analysis for Vertical motion considering Gravity Force</u>

- The conditions under which the analysis is done are same as that of the done in only vertical motion.



- **NOTE: -** Conclusion of all the analysis is given at the end of this chapter.

Figure 6.2 Analysis for Vertical motion considering Gravity Force

6.1.2 ANALYSIS FOR HORIZONTAL MOTION

Conditions under which the analysis is done

- Number of elements = 259
- Number of nodes created = 101
- Maximum edge angle = 167.47
- Minimum edge angle = 5.41
- Aspect ratio = 4.77

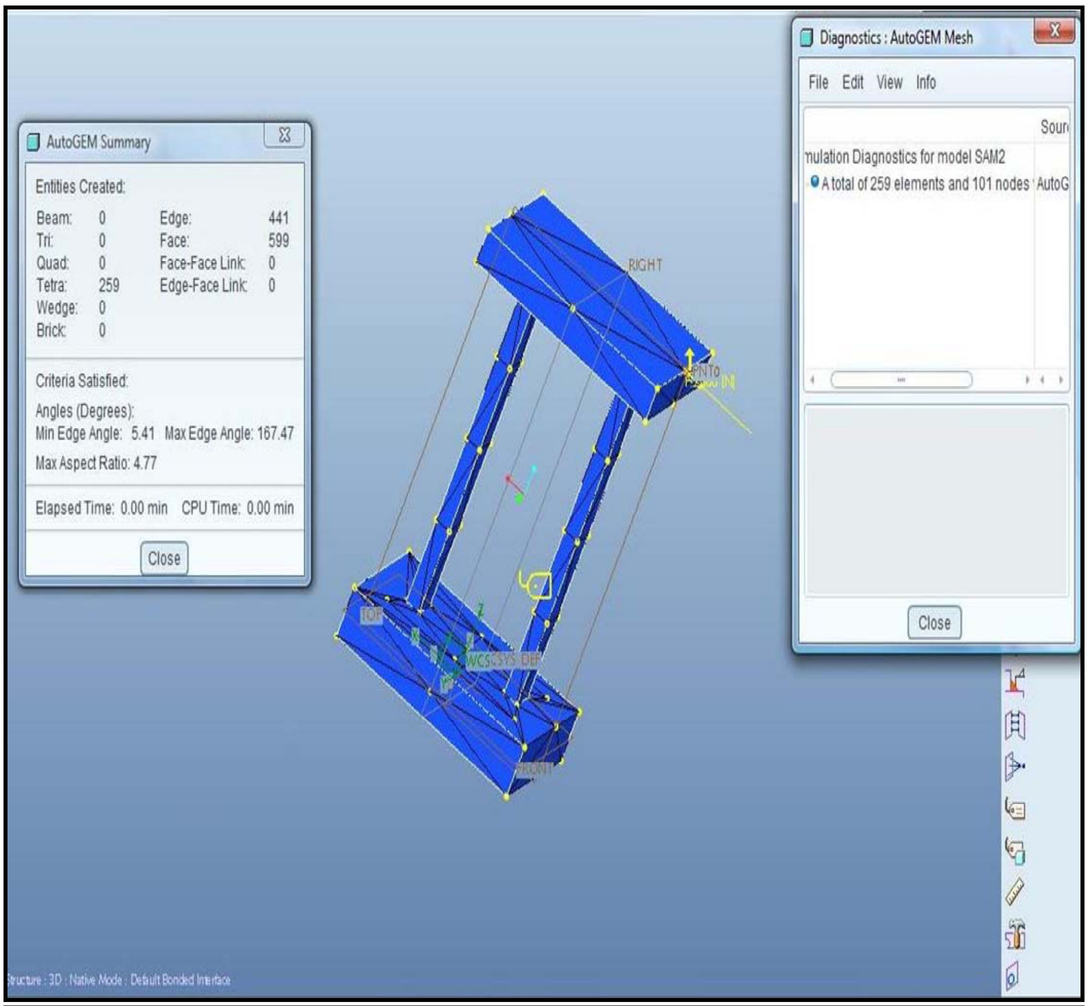
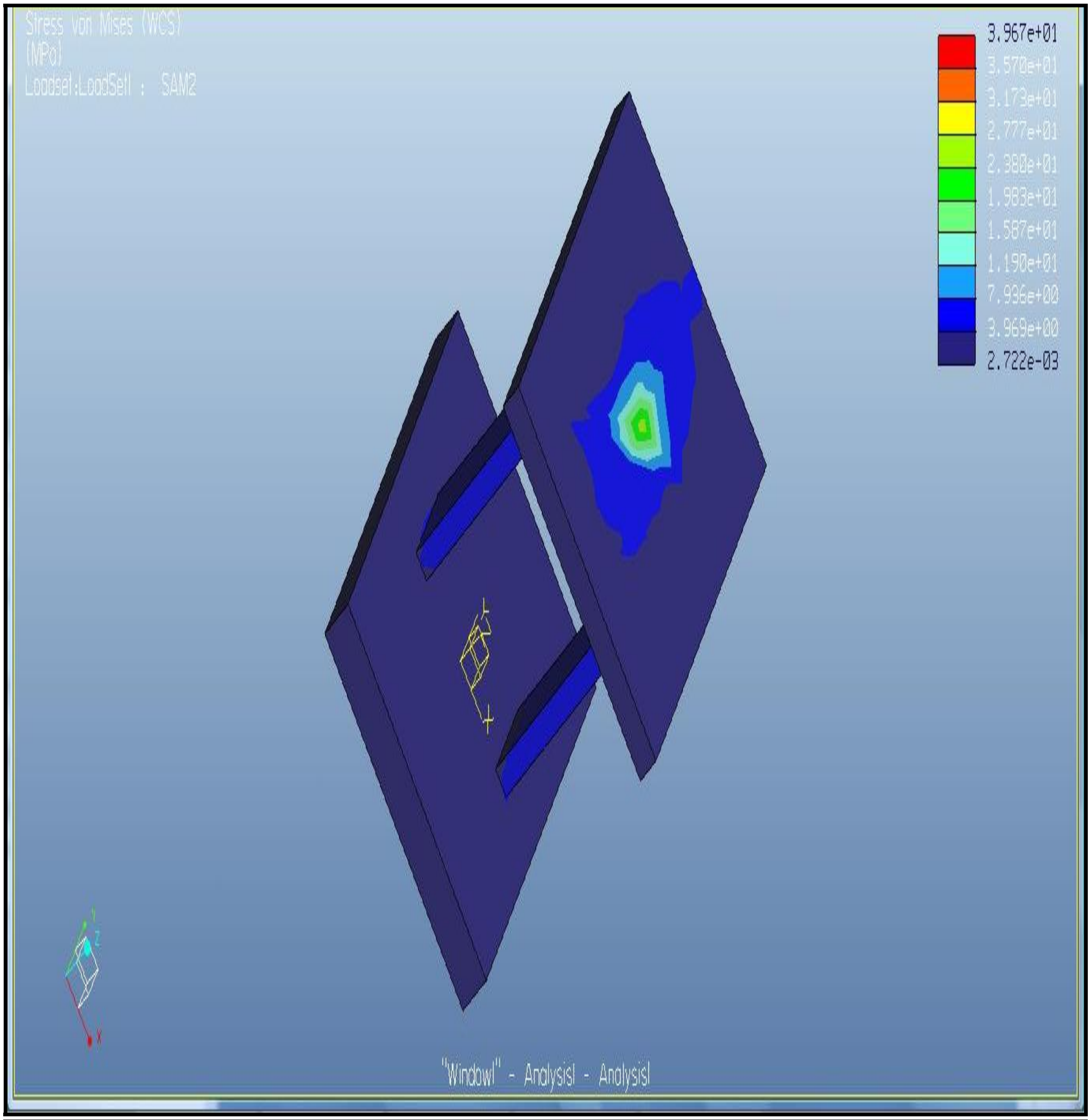


Figure 6.3 Analysis for horizontal motion



- **NOTE: -** Conclusion of all the analysis is given at the end of this chapter.

Figure 6.4 Analysis for horizontal motion

6.1.3 ANALYSIS FOR SIMULTANEOUS HORIZONTAL AND VERTICAL VIBRATION

Conditions under which the analysis is done

- Number of elements = 276

- Number of nodes created = 104
- Maximum edge angle = 167.15
- Minimum edge angle = 6.31
- Aspect ratio = 4.93

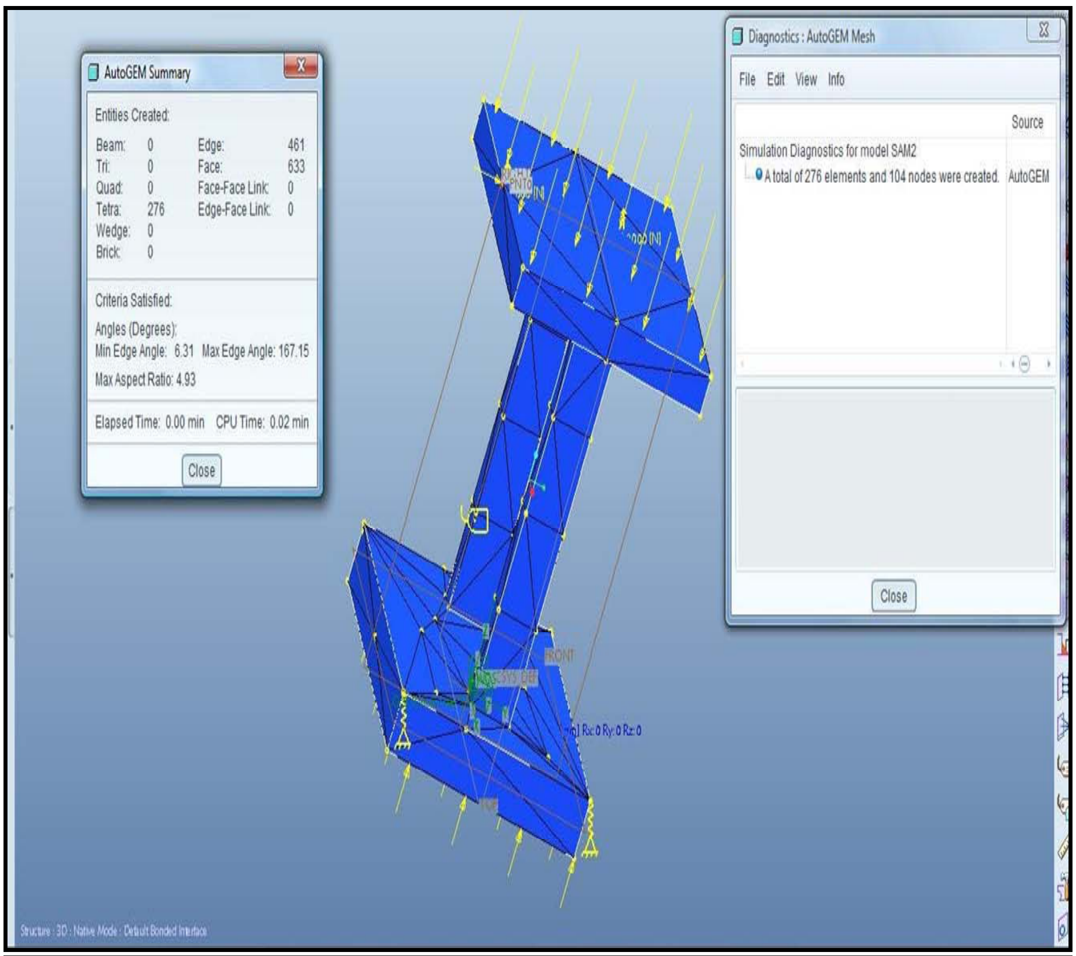
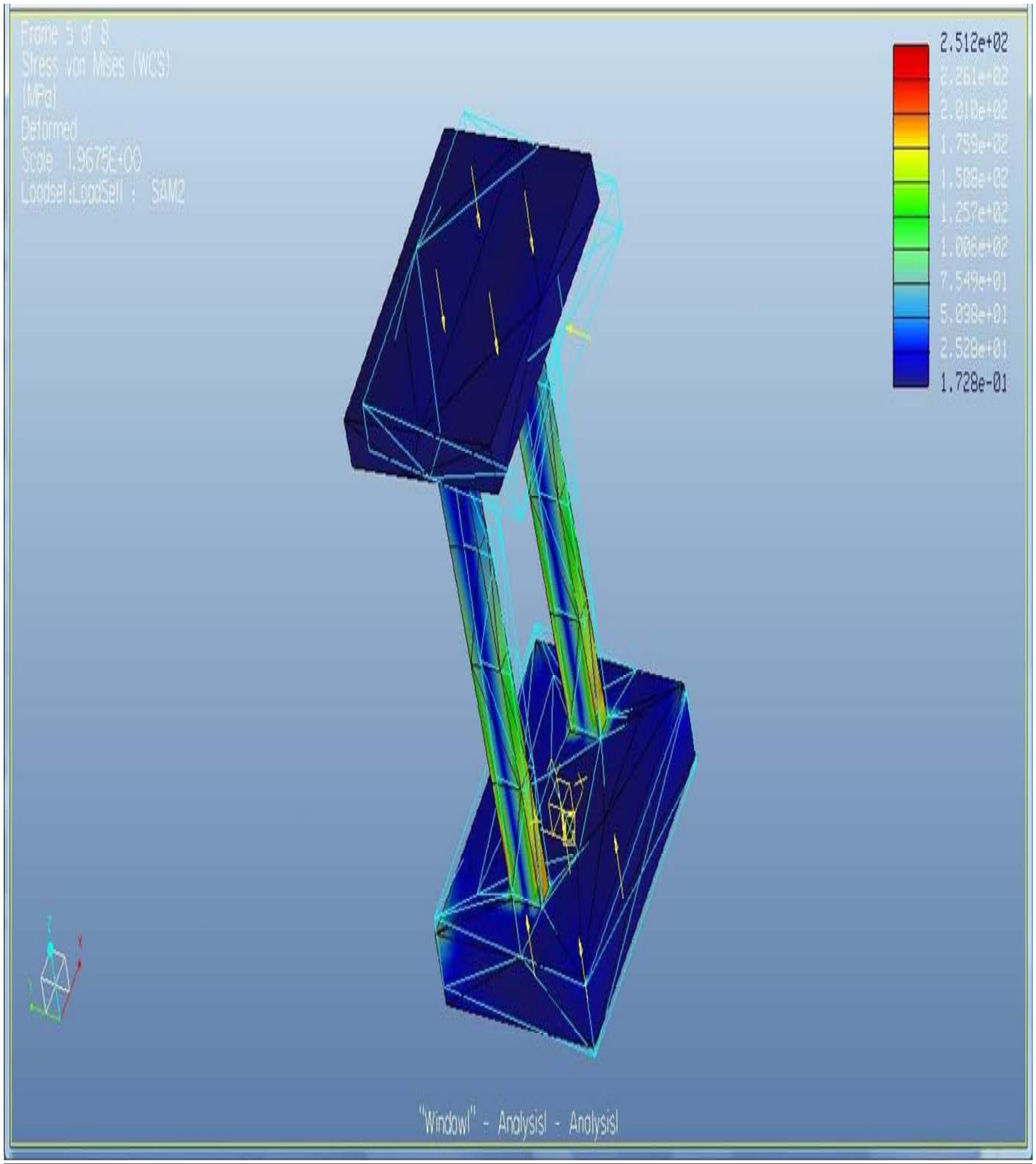


Figure 6.5 Analysis for simultaneous horizontal and vertical vibration



- **NOTE: -** Conclusion of all the analysis is given at the end of this chapter.

Figure 6.6 Analysis for simultaneous horizontal and vertical vibration

6.2 CONCLUSION

- Stress distribution is shown by different color.
- The structure is under permissible stresses.

- As the analysis done with aspect ratio below 5 so the meshing of the elements is continuous and proper.

- As this mechanical component is subjected to bi-axial stresses, so for the analysis purpose the maximum principal stress theory is used.
- While analyzing the different motions of the model in the stresses coming on the model are very nominal in nature. As no stresses are going beyond the green limits (see from the figure).
- While analyzing the vertical motion the stress coming on the shake table are not concentrated but uniformly distributed. But for the sack of simplicity for analysis we have taken it as point load.
- The analysis while considering the both horizontal and vertical vibration is the most appropriate to the original physical situation. Because in this analysis the self weight is also taken into consideration.

7. FUTURE SCOPE

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Building in earthquake country can be a tricky business. Architects and engineers run simulations using models and shake tables to test the integrity of buildings and determine necessary reinforcements.

Earthquakes are measured by the Richter Scale, a logarithmic measurement system. In this scale, an earthquake of 5.0 represents a tenfold increase in amplitude (and about 31 times more energy released) than a 4.0 earthquake. An earthquake measuring 5.3 would be considered moderate, a 6.3 would be considered strong, and 7.0 or higher is usually considered severe.

The design of the shake table is completely described in this report. This includes the simulation and the analysis of the working model. The analysis is done by very sophisticated software and with precision.

The future scope of the project is to manufacture the model with the dimensions given in the report. Some standard components such as locking nut, locking bolt, circlips etc. are to be designed. After completing the assembly of the different components of the table, this can be used for the experiments purpose.
The upper surface of the table is such that the buildings prototype to be used can be of wooden, concrete or any other reinforced material.