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Research Article

Study the effect of transient vibration on multi-storey building structure according to equivalent spring-mass system performed by Ansys

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Abstract

The carried work has based on transient vibration response of multiple degrees of freedom (MDOF) system. By this work study of Time–history analysis and prediction of the displacement for excitation has done. For the MDOF system, we have taken the four-storey building to done transient vibration. We establish the equivalent spring-mass system. Transient analysis has done for both Undamped and Damped of the forced system of multiple degrees of freedom (MDOF) system. In the case of the Damped system, we have done three stages of damping, i.e., (1) Underdamped system, (2) Critically damped system, (3) Overdamped system. The time-history graph obtained for two different time stages i.e. 0.001 sec & 0.01 sec with initial time 0.000001 sec. The natural frequency has determined by both theoretical calculation and ANSYS. The whole study of transient vibration makes it possible to predict the damping values that oppose any kind of sudden impact or force vibration, such as blasts, earthquakes and tsunamis. The ANSYS is the modelling and simulation software is used to perform the transient vibration response. The Mode Superposition method is used by ANSYS to calculate the structure response.

Introduction

Vibration is a physical phenomenon of any structure. In the case of forced vibrations, the structure is made to vibrate under the control of external force. Commonly in engineering practice, there are three types of forcing functions, i.e. periodic, impulsive and random forcing functions. Impulsive forcing function cause transient vibration. Transient response analysis is the method for computing forced dynamic response. The purpose of a transient response analysis is to compute the behaviour of a structure subjected to time-varying excitation. The transient vibration makes the highly sudden impact which causes our structures is the collapse. The transient response analysis provides sufficient damping result for structures which resist various human-made or natural forces like earthquakes, tsunami, and blast and machine vibrations.

A multi-degree of freedom system (MDOF) may be a multi-storey building, a TV tower, a Bridge including its super-structure and sub-structure, a flexural member, a machine foundation, an underground metro station etc.

In this study according to the equivalent mass-spring system of the 4-storey building has been studied the transient vibration response. ANSYS software is used to perform the analysis. Before start the transient analysis, natural frequency has been known by ANSYS, and it has been compared with theoretical results to check the validation of the software.

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Determination of natural frequency

A four storey building masses of floor $m_1 = m_2 = m_3 = 55500$ kg and $m_4 = 27750$ kg building height of each floor is 3m, Forced applied in the 1st, 2nd, 3rd, storey i.e. $F_1 = 3500000$ N, $F_2 = 2500000$ N, $F_3 = 1500000$ N and $F_4 = 500000$ N, stiffness provided in each storey is 4×10^6 N/m (Figure 1).

Determine Natural Frequencies by the Matrix Method (Figures 2.1 - 2.6):

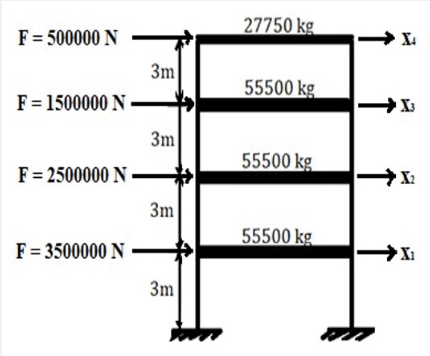

Figure 1: 4- Story building

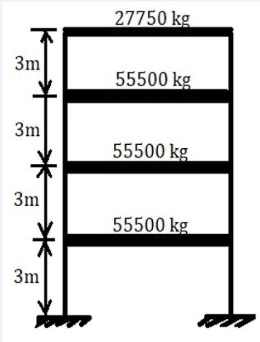

Figure 2.1: 4- Story building

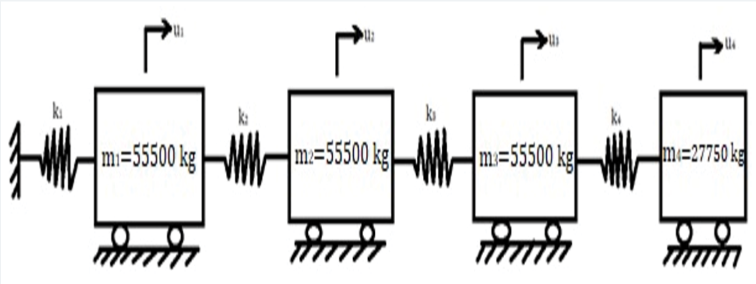

Figure 2.2: Equivalent mass-spring system.

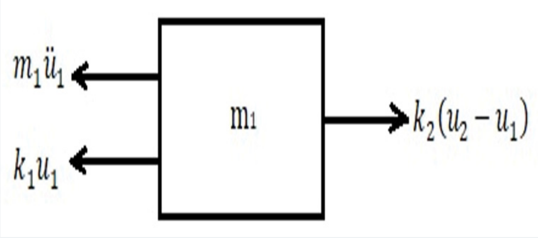

Figure 2.3: Free body diagram of mass 1.

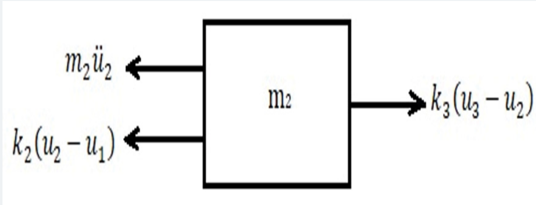

Figure 2.4: Free body diagram for mass 2.

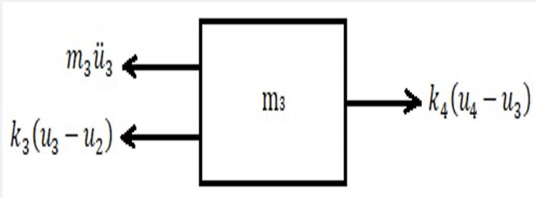

Figure 2.5: Free body diagram for mass 3.

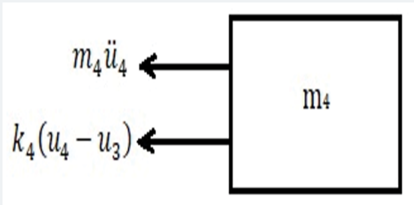

Figure 2.6: Free body diagram for mass m 4.

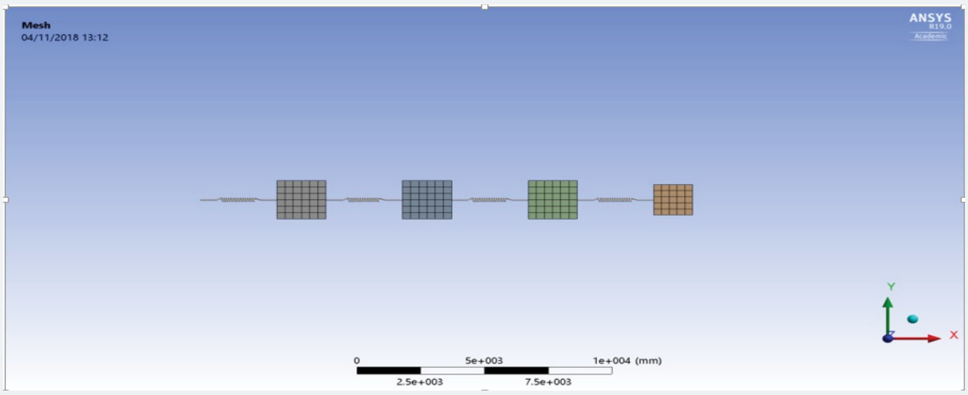

Figure 2.7: Meshed model of mass-spring system.

Masses is given as m_1 = 55500 kg, m_2 = 55500 kg, m_3 = 55500 kg, m_4 = 27750 kg

$$K_1 = k_2 = k_3 = k_4 = 2\times\frac{12EI}{L} = \frac{2\times12\times4.5\times10^6}{3^3} = 4\times10^6 \text{ N/m}$$

The following equation obtained from free body diagram

$$m_1\ddot{u}_1 + (k_1+k_2)u_1 - k_2u_2 = 0 \quad (1)$$

$$m_2\ddot{u}_2 - k_2u_1 + (k_2+k_3)u_2 - k_3u_3 = 0 \quad (2)$$

$$m_3\ddot{u}_3 - k_3u_2 + (k_3+k_4)u_3 - k_4u_4 = 0 \quad (3)$$

$$m_4 \ddot{u}_4 - k_4 u_3 + k_4 u_4 = 0 \tag{4}$$

Write the equations (1), (2), (3) & (4) into the equation of motion of an MDOF system subjected to undamped free vibration is given as

$$[m]\{\ddot{u}\} + [k]\{u\} = \{0\} \tag{5}$$

$$\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \\ \ddot{u}_4 \end{Bmatrix} + \begin{bmatrix} (k_1+k_2) & -k_2 & 0 & 0 \\ -k_2 & (k_2+k_3) & -k_3 & 0 \\ 0 & -k_3 & (k_3+k_4) & -k_4 \\ 0 & 0 & -k_4 & k_4 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{Bmatrix} = 0 \tag{6}$$

$$1000 \begin{bmatrix} 55.5 & 0 & 0 & 0 \\ 0 & 55.5 & 0 & 0 \\ 0 & 0 & 55.5 & 0 \\ 0 & 0 & 0 & 27.75 \end{bmatrix} \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \\ \ddot{u}_4 \end{Bmatrix} + 4\times10^6 \begin{bmatrix} 2 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_3 \end{Bmatrix} = 0 \tag{7}$$

The characteristic equation is $\left|(k) - (m)\omega_n^2\right| = 0$

$$\left| 4\times10^2 \begin{bmatrix} 2 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix} - 1000\omega_n^2 \begin{bmatrix} 55.5 & 0 & 0 & 0 \\ 0 & 55.5 & 0 & 0 \\ 0 & 0 & 55.5 & 0 \\ 0 & 0 & 0 & 27.75 \end{bmatrix} \right| = 0 \tag{8}$$

$$\left| \begin{bmatrix} 2 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix} - -2.5\times10^{-4}\omega_n^2 \begin{bmatrix} 55.5 & 0 & 0 & 0 \\ 0 & 55.5 & 0 & 0 \\ 0 & 0 & 55.5 & 0 \\ 0 & 0 & 0 & 27.75 \end{bmatrix} \right| = 0 \tag{9}$$

Let $2.5 \times 10^{-4}\omega_n^2 = \lambda$ we get

$$\left| \begin{bmatrix} (2-55.5\lambda) & -1 & 0 & 0 \\ -1 & (2-55.5\lambda) & -1 & 0 \\ 0 & -1 & (2-55.5\lambda) & -1 \\ 0 & 0 & -1 & (1-27.75\lambda) \end{bmatrix} \right| = 0 \tag{10}$$

Expanding the determinant, we get

$$4743970.031\lambda^4 - 683815.5\lambda^3 + 30802.5\lambda^2 - 444\lambda + 1 = 0 \tag{11}$$

Solving the above equation, we get

$\lambda^1 = 0.00274308 = \lambda^2 = 0.0222456 = \lambda^3 = 0.0498264 = \lambda^4 = 0.069329$

We know that $2.5\times10^{-4}\omega_n^2 = \lambda$

Thus $2.5\times10^{-4}\omega_1^2 = \lambda_1 = 0.00274308$

$$\omega_1^2 = \frac{0.00274308}{2.5\times10^{-4}} = \omega_1 = 3.3125\frac{rad}{s} = 0.53\,Hz$$

$$\omega_2^2 = \frac{0.0222456}{2.5\times10^{-4}} = \omega_2 = 9.433\frac{rad}{s} = 1.5\,Hz$$

$$\omega_3^2 = \frac{0.0498264}{2.5\times10^{-4}} = \omega_3 = 14.12\frac{rad}{s} = 2.25\,Hz$$

$$\omega_4^2 = \frac{0.069329}{2.5\times10^{-4}} = \omega_4 = 16.6528\frac{rad}{s} = 2.65\,Hz$$

The Natural frequencies (or) Eigen values are

$\omega_1 = 0.53\,Hz$

$\omega_2 = 1.5\,Hz$

$\omega_3 = 2.25\,Hz$

$\omega_4 = 2.65\,Hz$

Determination of natural frequencies by ANSYS

Material and Geometry: Structural steel used for making masses m1, m2, m3 and m4 with density 7850 kg/m^3 and young modulus and Poisson's ratio of steel is 2×〖10〗^11Pa and 0.3 after that draw geometry by open Model dialog box from analysis systems of the toolbox and attach springs and provide stiffness value to all as 4×〖10〗^6N/m.

Meshing: Meshing divides the whole components into many small elements to distribute applied load uniformly to whole components. All faces were selected for mesh generation and the total number of nodes and elements were observed at 4431 and 773 respectively.

Frequencies obtained by ANSYS: The obtained frequency results are shown in table 1 Mode and Frequency.

Comparison of Theoretical calculation and ANSYS: The theoretical solved result almost matched with ANSYS results. Hence solution from theoretical solved results is valid and acceptable.

Transient vibration response of undamped of forced system using ansys

The 4-storey undamped of the forced system shown in figure 3.1

Equivalent undamped Spring-Mass system of 4-storey building with external applied force:

Table 1: Mode and Frequency.

Mode	Frequencies
1	0.52719
2	1.5013
3	2.2469
4	2.6504

	Theoretical result	ANSYS
Frequency 1 (Hz)	0.53	0.52719
Frequency 2 (Hz)	1.5	1.5013
Frequency 3 (Hz)	2.25	2.2469
Frequency 4 (Hz)	2.65	2.6504

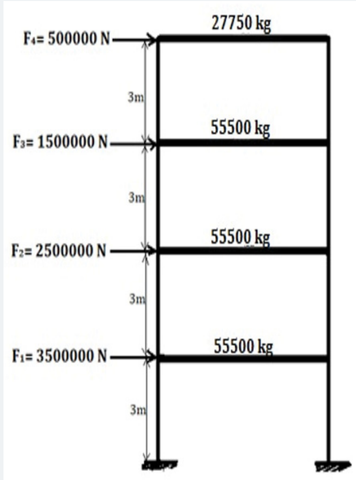

Figure 3.1: Undamped 4-storey building.

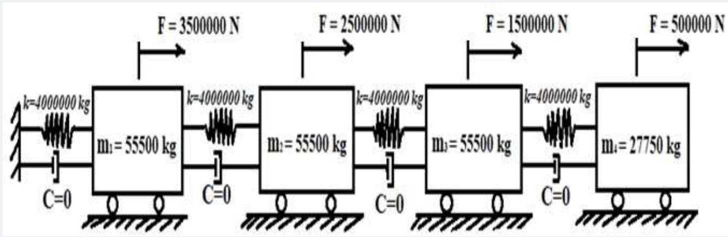

Figure 3.2: Equivalent Undamped spring-mass system.

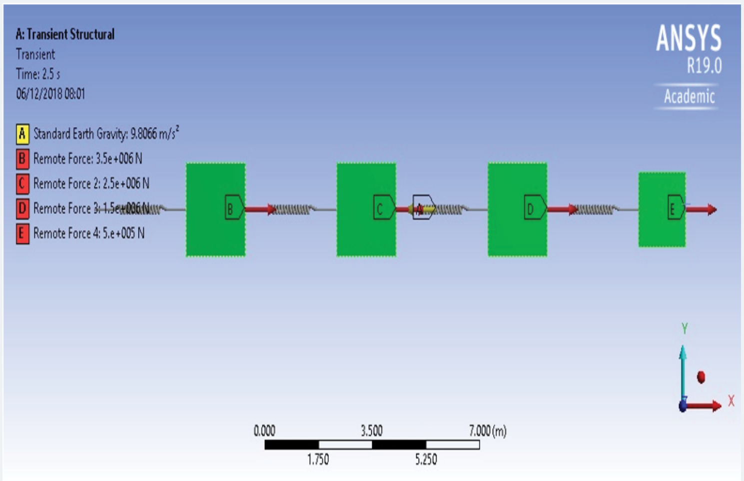

Figure 3.3: Undamped spring-mass Model by ANSYS for Undamped of Forced system.

Equivalent Spring-mass model in ANSYS for 4-DOF Undamped of Forced System:

4-DOF Transient Vibration Response graph for Undamped of Forced System obtained by ANSYS:

The 4-DOF Transient Vibration Response for (t) = 0.001 sec, (t) = 0.01 sec, initial time has taken 0.000001 sec.

At the time (t) = 0.001 sec: The Transient Vibration Response for 4-DOF Undamped system obtained by ANSYS has shown below.

At time (t) =0.01 sec:

Analysis result for mdof forced vibration of undamped system

- Result for Max. & Min. Transient Response of MDOF forced vibration of Undamped system at two different time stages, i.e. $(t)_1$ = 0.001 sec, $(t)_2$ = 0.01 sec, presented in table 2.
- Maximum displacement over time (t) =0.01 sec presented in table 2.1

Transient vibration response for damped of forced system using ansys

4-dof transient vibration response for damped of forced system:

For Underdamped system:

If the damping ratio $(\rho) = \frac{c}{2m\omega_n} < 1.0$ it is called underdamped system.

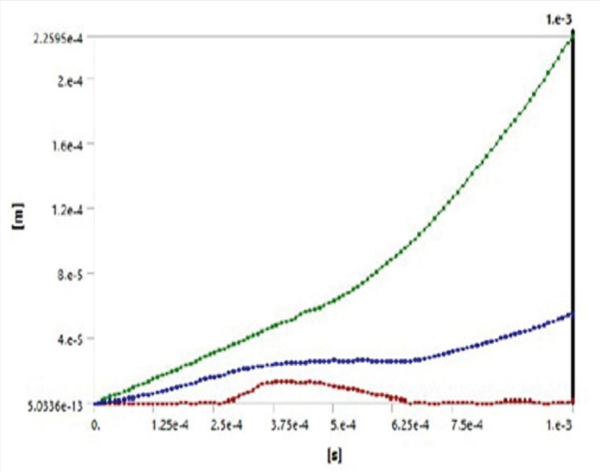

Figure 3.4: 4-DOF Undamped Transient Vibration Response at Time (t) = 0.001 sec.

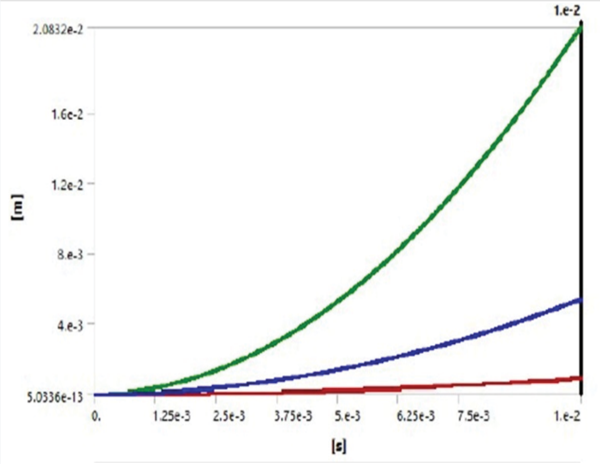

Figure 3.5: 4- DOF Undamped Transient Response at Time (t) = 0.01 sec.

Table 2: Min. & Avg. Transient Response of MDOF forced vibration of Undamped system

Time	Minimum	Average
0.001 sec	0.0000012076 m	0.000054574 m
0.01 sec	0.00084015 m	0.005345 m

Table 2.1: MDOF forced vibration of Undamped system Maximum displacement over time (t) =0.01 sec

Time	Maximum
0.01 sec	0.020832 m

Where c = damping & ω_n = natural damping in rad/sec

Provide damping for maximum frequency i.e. ω_n = 2.65Hz =16.65 rad/sec.

Taking Damping value $c_1 = c_2 = c_3$ = 924075 N-s/m for 1st, 2nd, and 3rd storey & c_4 =462037.5 N-s/m for 4th storey.

Check 1st, 2nd, & 3rd storey damping:

Damping ratio (ρ) = $\frac{c}{2m\omega_n}$ = $\frac{924075}{2\times 55500\times 16.65}$ = 0.5 < 1 Hence 1st, 2nd, & 3rd storey is underdamped.

Check 3rd storey damping:

Damping ratio (ρ) = $\frac{c}{2m\omega_n}$ = $\frac{462037.5}{2\times 27750\times 16.65} = 0.5$ < 1 Hence 3rd storey is underdamped.

Equivalent Spring-mass system for underdamped of forced system: Equivalent spring-mass system for 4-storey building in the underdamped condition.

4-DOF Transient Vibration Response graph for underdamped of Forced System obtained by ANSYS: The 4-DOF Transient Vibration Response for (t) = 0.001 sec, (t) = 0.01 sec, initial time is 0.000001 sec.

Graph for underdamped system at time (t) = 0.001 sec

Graph for underdamped system at time (t) = 0.01 sec

Result for MDOF Underdamped Transient Response:

- Result for Max. & Min. Underdamped Transient Response of MDOF forced vibration of damped system at three different time stages, i.e. $(t)_1$ = 0.001sec, $(t)_2$ = 0.01 sec, presented in table 4.1
- Underdamped Maximum displacement over time (t) =0.01 sec presented in table 4.2

For critically damped of forced vibration system

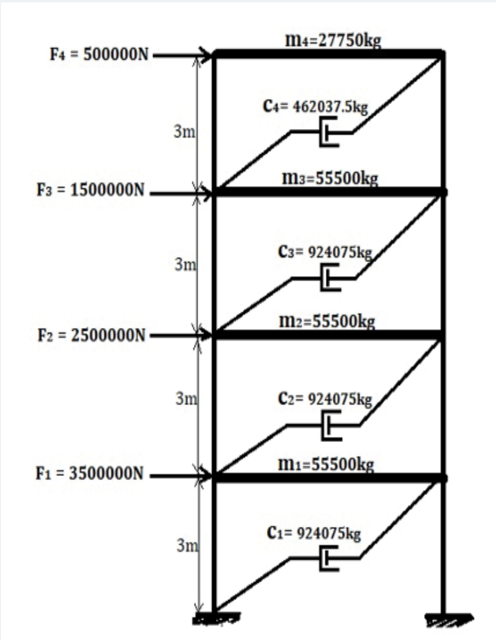

Figure 4.1: 4-storey underdamped of forced system.

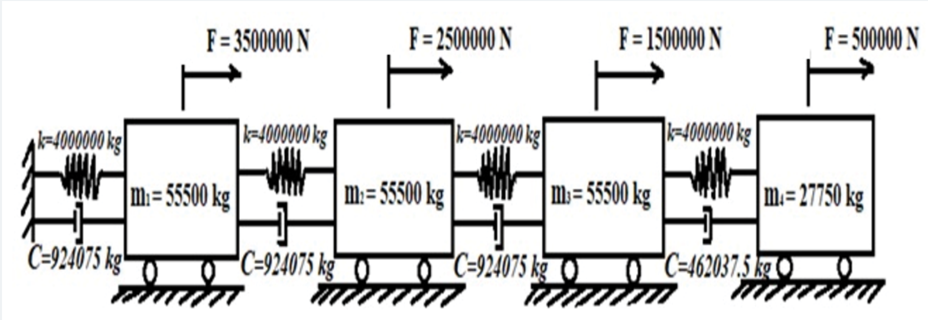

Figure 4.2: Equivalent Spring-mass system for 4-storey building underdamped system.

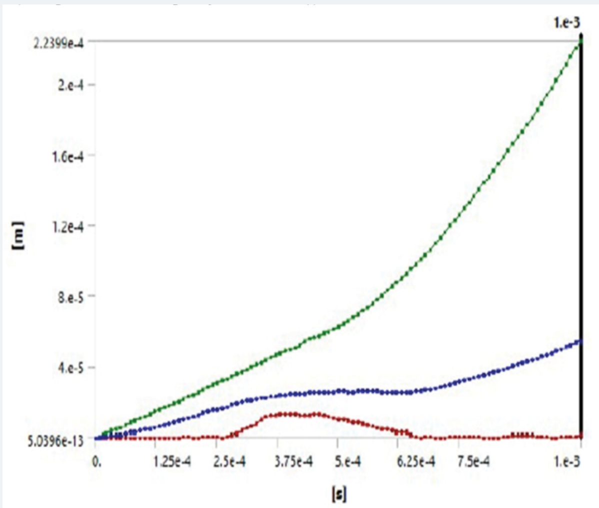

Figure 4.3: Graph for 4-DOF underdamped Transient Response at time (t) = 0.001 sec.

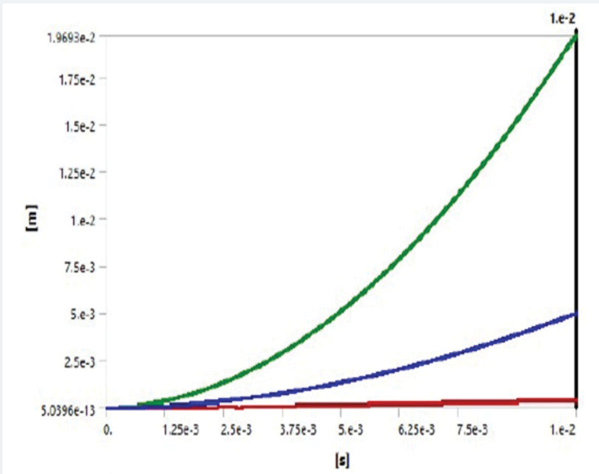

Figure 4.4: Graph for 4-DOF underdamped Trasnsient Response system at (t) = 0.01sec.

Table 4.1: Min. & Avg. Underdamped Transient Response of MDOF forced vibration of damped system.

Time(t)	Minimum	Average
0.001 sec	0.0000011683 m	0.000054081 m
0.01 sec	0.00034632 m	0.0049398 m

Table 4.2: MDOF forced vibration of Underdamped system Maximum displacement over time (t) =0.01 sec.

Time(t)	Maximum
0.01	0.019693 m

Provide damping for maximum frequency i.e. ω_n =2.65Hz =16.65 rad/sec

If the damping ratio (ρ) = $\frac{c}{c_c}$ = $\frac{c}{2m\omega_n}$ = 1.0 then it is called critically damped system

Take Damping for 1st, 2nd, 3rd storey $c_1 = c_2 = c_3$ = 1848150 N-s/m

Damping ratio (ρ) = $\frac{c}{c_c}$ = $\frac{c}{2m\omega_n}$ = $\frac{1848150}{2\times 55500\times 16.65}$ = 1

Hence it is critically damped

Take damping for 4th storey $c_4 = 924075$ N-s/m

Damping ratio (ρ) = $\frac{c}{c_c} = \frac{c}{2m\omega_n} = \frac{924075}{2\times 27750\times 16.65} = 1$

Hence it is critically damped.

Equivalent critically damped spring-mass system:

Equivalent critically damped spring-mass system for 4-storey building without any external force shown.

Transient Vibration Response graph for critically damped of Forced vibration System:

Initial time is 0.000001 sec.

Graph at time (t) = 0.001 sec

Graph at time (t) = 0.01 sec

Result for MDOF Critically Transient Response:

- Result for Max. & Min. Critically Transient Response of MDOF forced vibration of the damped system at two different time stages, i.e. (t)1 = 0.001 sec, (t)2 = 0.01 sec, with initial time 0.000001 sec presented in table 4.3
- Critically Maximum displacement overtime (t) = 0.01 sec presented in table 4.4

Over damped forced transient vibration response

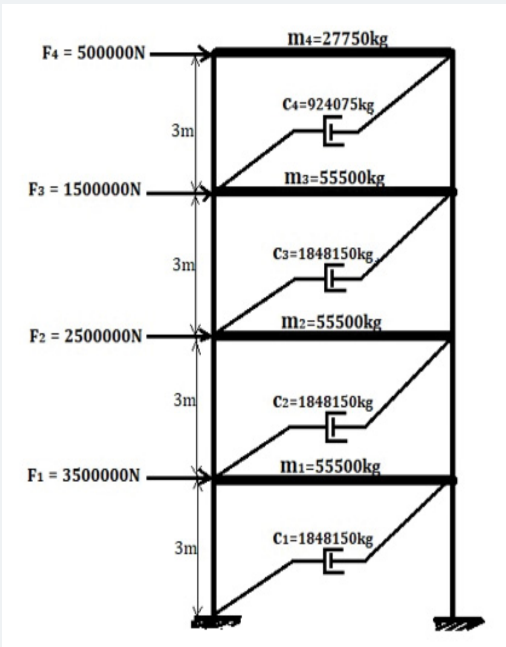

Figure 4.5: 4-storey critically damped system.

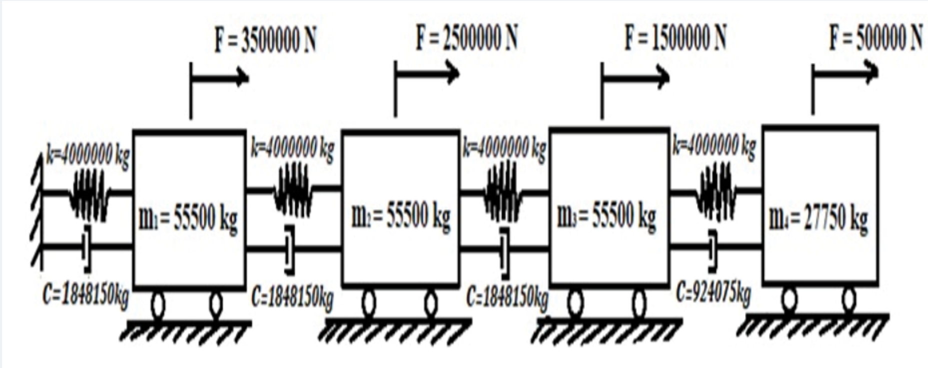

Figure 4.6: Equivalent critically damped spring-mass system with external force.

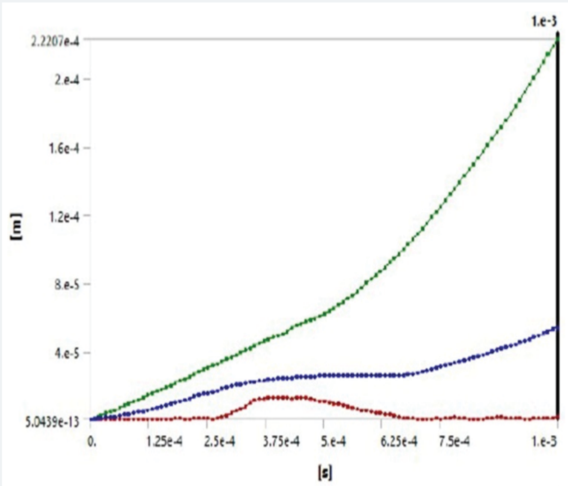

Figure 4.7: 4-DOF critically damped Transient response at time (t) = 0.001 sec.

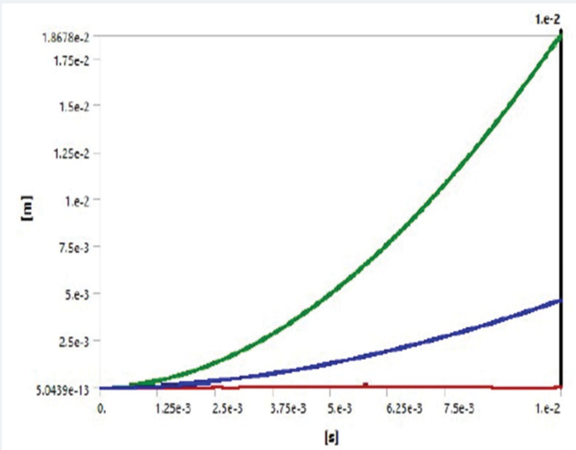

Figure 4.8: 4-DOF critically damped Transient vibration response at (t) = 0.01 sec.

Table 4.3: Min & Avg. Critically Transient Response of MDOF forced vibration of damped system.

Time(t)	Minimum	Average
0.001 sec	0.0000011479 m	0.000053598 m
0.01 sec	0.000036736 m	0.0046033 m

Table 4.4: MDOF forced vibration of critically damped system Maximum displacement over time (t) = 0.01 sec.

Time(t)	Maximum
0.01 sec	0.018678 m

Provide damping for maximum frequency i.e. ω_n =2.65Hz =16.65 rad/sec

If the damping ratio $(\rho = \frac{c}{2m\omega_n}$ >1.0 then it is called overdamped system.

Take Damping for 1st, 2nd, 3rd storey $c_1 = c_2 = c_3$ = 3696300 N-s/m

Damping ratio (ρ) = $\frac{c}{2m\omega_n}$ = $c_1 = c_2 = c_3$ = 2

Hence it is overdamped..

Take damping for 4th storey $c_4 = 1848150$ N-s/m

Damping ratio (ρ) = $\frac{c}{2m\omega_n}$ = $\frac{3696300}{2\times 55500\times 16.65}$ Hence it is overdamped.

Equivalent Overdamped spring-mass system:

Transient Vibration Response graph for Overdamped of Forced vibration System:

The initial time is 0.000001 sec.

Overdamped forced vibration graph for time (t) = 0.001 sec

Overdamped forced vibration graph for time (t) = 0.01 sec

Result for MDOF Overdamped Transient Response:

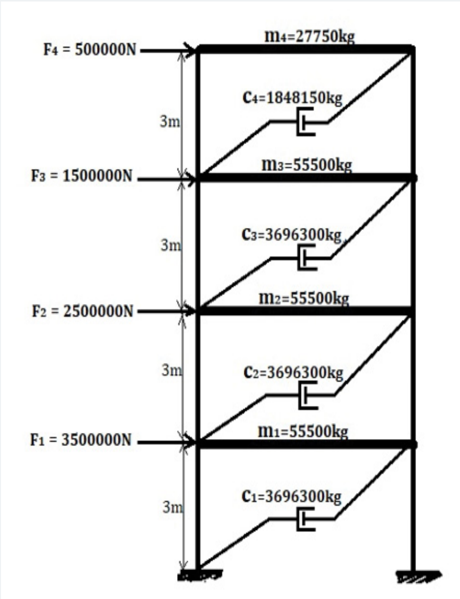

Figure 4.9: 4-storey Overdamped building system.

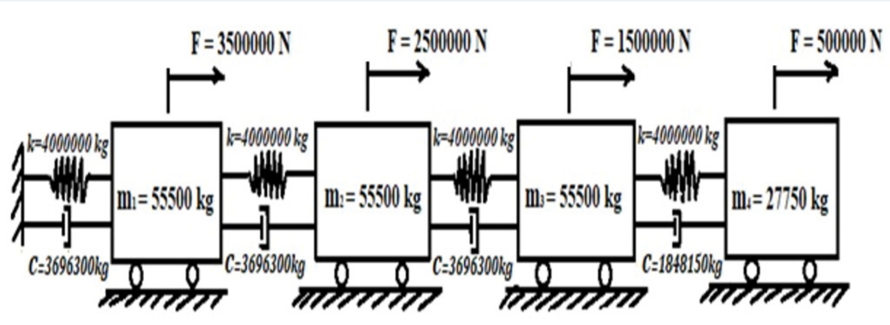

Figure 4.10: Overdamped spring-mass system.

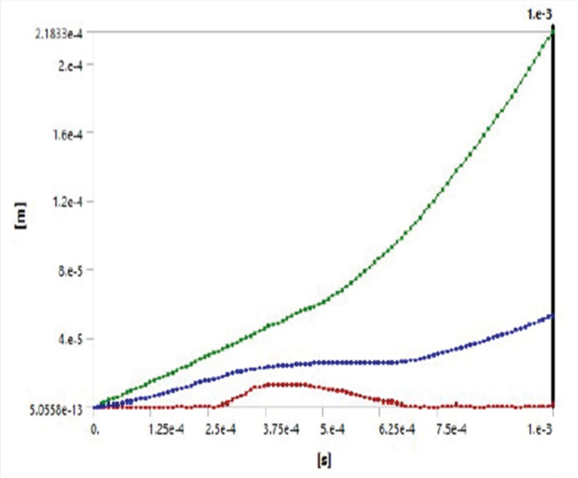

Figure 4.11: Overdamped (MDOF) Free Transient response graph at the time (t) =0.001 sec.

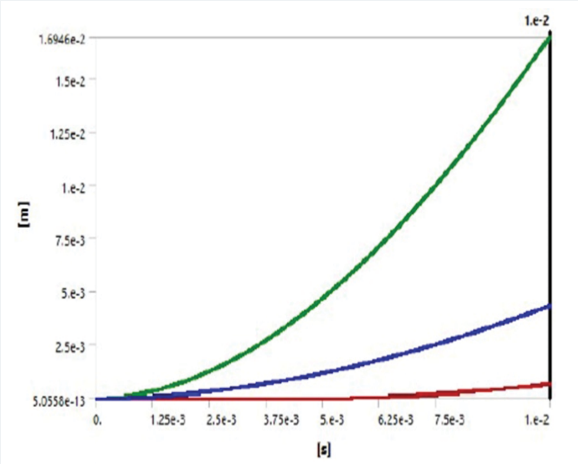

Figure 4.12: Overdamped (MDOF) Free Transient response graph at the time (t) =0.01 sec.

Result for Max. & Min. Overdamped Transient Response of MDOF forced vibration of the damped system at two different time stages, i.e. $(t)_1$ = 0.001 sec, $(t)_2$ = 0.01 sec, and initial time is 0.000001 sec, presented in table 4.5

Overdamped Maximum displacement over time (t) =0.01 sec presented in table 4.6

Conclusion

The Transient vibration response has done on ANSYS it gives sufficient results and graph between time and displacements also gives peak value of displacements for both undamped and damped systems of MDOF systems.

In the case of the damped system worked on all three conditions that are underdamped, critically damped and overdamped systems. According time-history graph and table can select the approximate damping value to the structures.

The time-displacement or deformation graph obtained for two different time stages. The natural frequency is achieved by both theoretical calculations and ANSYS. It is necessary for transient vibration response analysis is and it is easily determined by ANSYS. The whole study of transient vibration response makes possible to predict the damping values which resist any type of sudden impact or force vibration like blast, Earthquake and Tsunami etc. The ANSYS is the modelling and simulation software is used to perform the transient vibration response. The Mode Superposition method is

Table 4.5: Min. & Avg. Overdamped Transient Response of MDOF forced vibration of the damped system.

Time(t)	Minimum(m)	Average
0.001 sec	0.0000011629 m	0.000052661 m
0.01 sec	0.00063868 m	0.0043121 m

Table 4.6: MDOF forced vibration of overdamped system Maximum displacement over time (t) = 0.01 sec

Time(t)	Maximum
0.01 sec	0.016946 m

used by ANSYS to calculate the structure response. The 4-DOF undamped & damped average value has shown below.

The 4-DOF undamped & damped maximum value has shown below.

The 4-DOF undamped & damped average value for two different time stages, i.e. 0.001 sec, 0.01 sec has shown below.

Time	4-DOF average displacement at Undamped system	4-DOF average displacement at Underdamped system	4-DOF average displacement at Critically damped System	4-DOF avgerage displacement at Overdamped system
0.001 sec	0.000054574 m	0.000054081 m	0.000053598 m	0.000052661 m
0.01 sec	0.005345 m	0.0049398 m	0.0046033 m	0.0043121 m

The 4-DOF undamped & damped maximum value for two different time stages, i.e. 0.001 sec, 0.01 sec has shown below.

Time	4-DOF max. displacement at Undamped System	4-DOF max. displacement at Underdamped system	4-DOF max. displacement at Critically damped System	4-DOF max. displacement at Overdamped system
0.01 sec	0.020832 m	0.019693 m	0.018678 m	0.016946 m

The experiment shows that the value of damped transient displacement is less in comparison to the undamped transient displacement values. 4-DOF maximum undamped transient value is 0.020832 m and underdamped, critically and overdamped value is 0.019693m, 0.018678 and 0.016946 m. Therefore, this value shows that the damped transient displacement is less than the undamped transient displacement.

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