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Comparative Anaysis of the Dynamic Behaviour of Coupled and Non-Coupled Shear Walls in Tall Buildings

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ABSTRACT: This study Analysed and compared the Dynamic Behaviour of Coupled and Non-Coupled Shear wall structural form of tall buildings. The wall dimensions for a non-coupled shear wall structural form of ten (10) storey building was assumed and analysed. A unit mass was also assumed and the masses $m_{1,}m_2$, ……. m_{10} were concentrated at the floor level (lump masses). The stiffness properties of this linear structure are characterized by the lateral stiffness $k_{1,}k_2$, ……. k_{10} of individual stories, The matrix stiffness method was applied to generate the element stiffness matrix equation of the structure and the mass matrix equation was also generated. These mass and stiffness matrices equations which gave a symmetric matrices where applied to generate the dynamic equilibrium equation for the ten(10) degree of freedom system. The expansion of this equilibrium equation leads to a frequency equation which was solved for natural frequencies w. The Stodola Iteration Method was used to determine the natural frequencies and the corresponding mode shapes of the structures. Rayleigh damping method was applied to estimate the damping inherent in the structures. It was discovered that the average percentage difference of coefficient of damping inherent in coupled shear wall structure exceeds that of non-coupled shear walls by 45.8% while the natural period of damping for non-coupled shear wall exceeds the coupled shear wall by 85.14%. These show that coupled shear wall structural forms have high potential to resist dynamic effect compared to Non-Coupled shear wall structures and is highly recommended for the construction of tall buildings.

KEY WORDS: Shear Wall, Coupled Shear Wall, Stiffness Method, Stodola Iteration, Multi-Degree of Freedom, Stiffness Matrix, Natural Frequency, Mode Shapes.

I. INTRODUCTION

Tall building from a structural engineer's point of view, can be defined as one that, by virtue of its height, is affected by lateral forces due to wind or earthquake or both to an extent that they play an important role in the structural design (Smith and Coull, 2006)

Dynamic load, especially, lateral forces due to wind or seismic loading must be considered for tall buildings along with gravity forces. High wind pressures on the sides of tall buildings produce base shear and overturning moments. These forces cause lateral displacement in a multi-storey building. This lateral displacement at the top of a building is called drift (Patil and Alandkar, 2016). The resistance to these lateral loads is provided by shear walls, coupled shear wall, rigid frame action between the beams and columns etc.

Shear Walls are concrete or masonry continuous vertical walls that may serve both architecturally as partitions and structurally to carry gravity and lateral loading. Their very high in- plane stiffness and strength

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makes them ideally suited for bracing tall buildings (Nishant and Siddhant, 2014). In a non-coupled shear wall structure, such walls are entirely responsible for the lateral load resistance of the building. They act as vertical cantilevers in the form of separate planar walls, and as non-planar assemblies of connected walls around elevator, stair, and service shafts. (Smith and Coull, 2006).

A coupled shear wall structure is a particular, but very common, form of shear wall structure that consists of two or more shear walls in the same plane, or almost the same plane, connected at the floor levels by beams or stiff slabs. The effect of the shear-resistant connecting members is to cause the set of walls to behave in their plane partly as a composite cantilever, bending about the common centroidal axis of the walls. (Reddy and Eadukondalu, 2018).

Dynamic load include earthquakes, and strong winds like hurricanes and tornadoes, vibration of ground due to bomb blast, explosions, impact loads, vibration effects from compound disc player, vibration from heavy construction equipment etc. Any structure can be subjected to dynamic load. The common effect of all dynamic disturbances is that they generate vibrations in the structures upon which they act. The consequences of vibration include over stressing and collapse of structure, cracking, damage to safety-related equipment, fatigue, distortion in partition and adverse human response (Smith and Coull, 2006).

Several researches have been carried out on the effect of dynamic loads on tall buildings. For instance, (Kameshwari et.al, 2011) analysed the influence of drift and inter storey drift of the structure on various configuration of shear wall panels on high rise structures. (Nanjma et.al, 2012) conducted analytical study on the effects of change in height of shear wall on storey displacement in the dynamic response of building frames. (Eshan et.al, 2012) determined the shear wall configuration on seismic performance of building. (Shahabodin, 2008) conducted comparative investigation on using shear wall and infill to improve seismic performance of existing buildings. However, these researches try to analyse and compare the lateral resistance efficiency of coupled and non-coupled shear wall structural form of tall buildings to dynamic load.

II. METHODOLOGY

This analysis studied the ten degree of freedom system, so for this purpose, ten-story structure of height of 3.5m each with a total height of 35m was idealized. Two change levels A and B, divide the structure into three regions. The masses concentrated at the floor levels are denoted by $m_1, m_2, ... m_{10}$. While the lateral stiffness properties of the structure are denoted by $k_1, k_2 .... k_{10}$ as shown in Fig. 1.

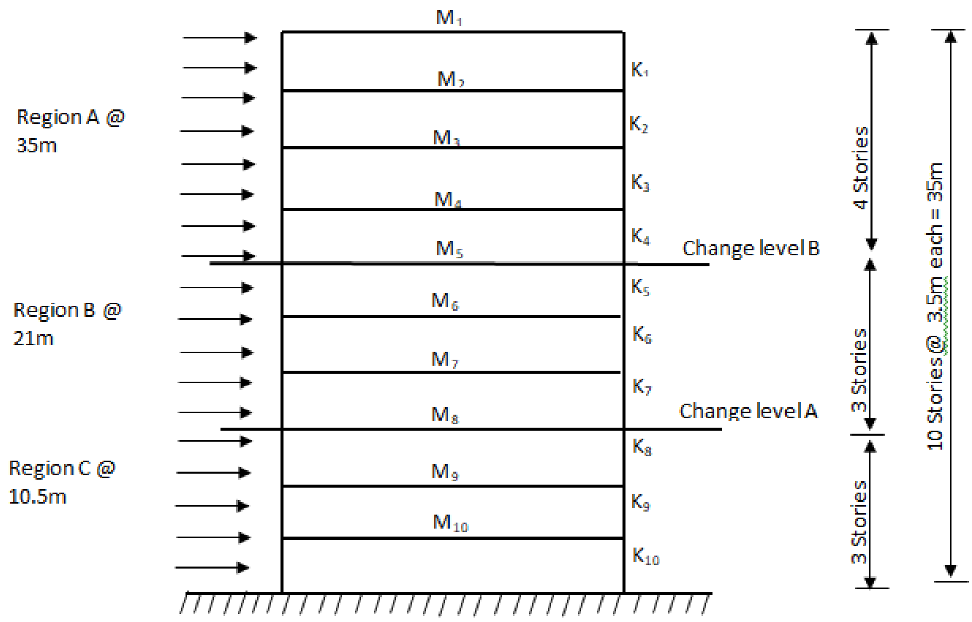


Fig. 1 The Ten Storey shear wall structure subjected to external forces

2.1 Assumption

In this idealization as shown in Fig.1, the following assumptions where made:

- it is assumed that the columns supporting and interconnecting the floor systems are massless and the entire mass of the structure is concentrated at the floor levels.
- the floor systems and beams are rigid whereas the columns are flexible to lateral deformation but rigid in the vertical direction.
- The structure is assumed to be supported on rigid ground
- Unit mass was assumed for each floor in this analysis and the masses were lumped at the floor levels of the structure.
- the joints between the floor slabs and the columns are fixed against rotation.
- Since, the beams are usually built monolithically within the columns, the beam column joint can be assumed to be rigid as without any rotations at joint

If the floor of this structure is displaced laterally through some distance, x, then released and permitted to oscillate freely, the structure will oscillate around its initial equilibrium position. These oscillations would continue forever with the same amplitude x, and the structure would never come to rest. This, of course, is unrealistic. Intuition suggests that an actual structure in free vibration should oscillate with ever decreasing amplitude and eventually come to rest.

In order to incorporate this feature into the dynamics of the structure, an energy absorbing element was introduced in the form of Coupled and non-coupled shear wall structural forms of tall building. These viscous dampers included in the structure were analyzed using Rayleigh damping technique. In damping, the kinetic energy and strain energy of the vibrating system are dissipated by these mechanisms.

2.2 Determination of Mass and Stiffness Matrices for the Shear Wall Structures

The ten storey structure without damping was idealized using spring mass system as shown in fig. 2

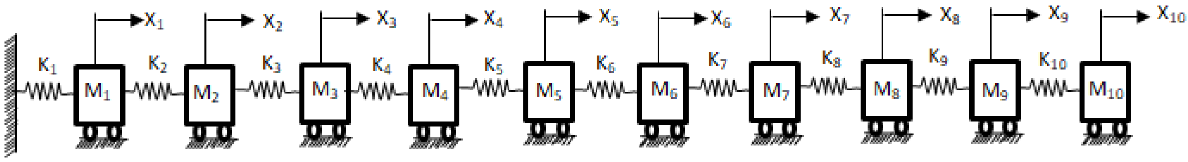
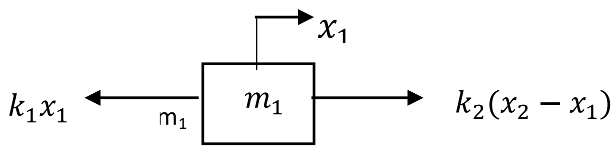


Fig. 2 Idealized ten-story structure without damping

Free body diagram for mass m_1

Fig. 3. Free body diagram o



Considering the equilibrium of the forces acting on the first mass, m_1, the governing differential equation of motion is obtained from the Free body diagram of the mass by applying Newton's second law of motion as shown in Equation (1)

$$m_1\ddot{x}_1 + (k_1 + k_2)x_1 - k_2x_2 = 0 \quad (1)$$

The similar differential equations of motion were generated for m_2.... m_{10} and the equations were rearranged in matrix form and the mass and stiffness matrices were obtained and presented

2.3 Determination of Mass Matrices for the Coupled and Non-Coupled Share Wall Structures

The masses denoted by $m_{1,}m_2$, …….. m_{10} formed a diagonal matrix $[m]$ as presented in Equation (2)

$$[m] = \begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & m_7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{10} \end{bmatrix} \quad (2)$$

2.4 Determination of Stiffness Matrix for the Coupled and Non-Coupled Share Wall Structure

(2)

The stiffness k represents the combined stiffness of two columns for lateral deformation, that is the ‹ restoring force and it stores the potential energy (internal strain energy) due to columns. The hori: members on the floors are infinitely rigid as compared to the columns. That means flexibility of slabs are ignored, masses of columns are ignored. Hence stiffness due to columns and inertia due to slabs are considered. The elements of the stiffness denoted by $\mathrm{k}_{1,}\mathrm{k}_2$, …….. k_{10} formed a diagonal matrix $[k]$as presented in Equation (2).

$[K] =$

$$\begin{bmatrix} K_1+K_2 & -k_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -k_2 & K_2+K_3 & -k_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -k_3 & K_3+K_4 & -k_4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -k_4 & K_4+K_5 & -k_5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & --k_5 & K_5+K_6 & -k_6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -k_6 & K_6+K_7 & -k_7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -k_7 & K_7+K_8 & -k_8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -k_8 & K_8+K_9 & -k_9 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_9 & K_9+K_{10} & -k_{10} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{10} & K_{10} \end{bmatrix} \quad (3)$$

The procedure for the determination of natural frequencies will becomes extremely cumbersome in this method as the number of modes increases. For this reason, other procedures have been devised. For this report, Stodola iterative method was adopted and presented.

2.5 Stodola (Matrix Iteration) Method

This is one of the most convenient methods to determine the mode shapes and corresponding natural frequencies of a structure. This iterative method can be applied to extract the highest eigenvalue of either symmetric or unsymmetric matrix of any order. In Stodola method, the initially assumed mode shape is iteratively adjusted until an adequate approximation of the true mode shape has been achieved. Then the frequency of vibration is determined (Okawa et al, (2016).

2.6 Procedure of Stodola Method

The following are the step-by-step procedures on the use of stodola method.

i. Determination of Dynamic Matrix

The mode shape $\{u\}$ for an undamped system in free vibration can be written as shown in Equation (4)

$$[k]\{u\} = w_j^2[m]\{u\} \quad (4)$$

Where $[k] = w_j^2[m]$

Multiplying Equation (4) by the flexibility matrix $[f] = [k]^{-1}$, we have

$$\{u\} = w_j^2[f][m]\{u\}$$

(5)

$$= w_j^2[A]\{u\}$$

(6)

$$\text{Let } A = [f][m] = [k]^{-1}[m]$$

(7)

and A is called dynamic matrix.

ii. Assumption of mode shape of the shear building

Assume the mode shape $\{u\}^{(1)}$ that can be considered to be a close approximation to the first mode, where the amplitude is arbitrary.

iii. Assumption of next mode shape of the shear building

The first mode shape is obtained using Equation (8)

$$\{u_1\}^{(1)} = [A]\{u\}^{(1)} \tag{8}$$

While the second mode shape is obtained using Equation (8)

$$\{u_1\}^{(2)} = \lambda_1\{u\}^{(1)} = \frac{1}{w_j^2}\{u\}^{(1)}. \tag{9}$$

Where λ_1 is an arbitrary constant if λ_1 is chosen to be $\{u\}^{(1)} = \{u\}^{(2)}\lambda_1$, it will eventually converges on $\frac{1}{w_j^2}$.

iv. Repetition of assumed mode shape

Repeat step iii) until the following relation is satisfied

$$\{\hat{u}\}^{(r)} \approx \lambda_1\{u\}^{(r-1)} \tag{10}$$

Then $\{\hat{u}\}^{(r)}$ is the mode shape vector or eigen vector and $\lambda_r = \frac{1}{w_j^2}$ is the eigen value.

$$\text{Therefore, the natural frequency } w_j = \frac{1}{\sqrt{\lambda_j}} \tag{11}$$

Therefore, we can eliminate the higher modes from the first assumption of the mode shape and the contribution of the higher modes can be made as small as is desired by repeating step iii) in i)

$$\text{The reciprocation of the frequency, called the natural period } T_n = \frac{2\pi}{w_n} \tag{12}$$

2.7 Analysis of Higher Modes using Sweeping Technique

In order to calculate the second mode by the matrix iteration method, it is necessary to assume a trial mode shape $\{u_2\}^1$ which contains no first mode component as follows:

An arbitrary assumption of the second mode shape is as shown in Equation (11)

$$\{u_2\}^1 = \{\emptyset_1\}x_1 + \{\emptyset_2\}x_2 + \{\emptyset_3\}x_3 + \cdots \tag{11}$$

Pre – multiplying both sides of Equation (11) by $\{\emptyset_1\}^T[m]$ leads to Equation (12)

$$\begin{aligned}\{\emptyset_1\}^T[m]\{u_2\}^{(1)} &= \{\emptyset_1\}^T[m]\{\emptyset_1\}x_1 + \{\emptyset_1\}^T[m]\{\emptyset_2\}x_2 + \{\emptyset_1\}^T[m]\{\emptyset_3\}x_3 \\ &= \{\emptyset_n\}^T[m]\{\emptyset_n\}x_n\end{aligned} \tag{12}$$

Hence,

$$x_1 = \frac{\{\emptyset_1\}^T[m]\{u_2\}^{(1)}}{\{\emptyset_n\}^T[m]\{\emptyset_n\}} \tag{13}$$

Therefore, if this component is removed from the assumed shape, the vector is to be purified

$$\{\emptyset_2\}^1 = \{u_2\}^{(1)} - \{\emptyset_1\}x_1 \tag{14}$$

This purified vector will now converge towards the second mode shape in the matrix iteration method. Round – off error in the numerical calculations, however, will cause reappearance of the first mode. Therefore, this purification operation is necessary at each cycle of iteration. A convenient means of purification is to use a sweeping matrix. Substituting Equation (13) into Equation (14) yields Equation (15)

$$\{\hat{u}_2\}^{(1)} = \{u_2\}^{(1)} - \frac{\{\emptyset_1\}\{\emptyset_1\}^T[m]\{u_2\}^{(1)}}{\{\emptyset_1\}^T[m]\{\emptyset_1\}} = \left[[1] - \frac{\{\emptyset_1\}\{\emptyset_1\}^T[m]\{u_2\}^{(1)}}{\{\emptyset_1\}^T[m]\{\emptyset_1\}}\right]\{u_2\}^{(1)}$$

$$\{\hat{u}_2\}^{(1)} = [s_1]\{u_2\}^{(1)} \tag{15}$$

Where

$$[s_1] = [1] - \frac{\{\emptyset_1\}\{\emptyset_1\}^T[m]}{\{\emptyset_1\}^T[m]\{\emptyset_1\}} \quad (16)$$

Equation (16) is the sweeping matrix.

Then, the Stodola procedure can now be formulated so that it converges towards the second mode, replacing the dynamic matrix $[A]$ by the product $[A][S]$ of the dynamic matrix and the sweeping matrix.

The third and higher modes can be obtained by the use of the following sweeping matrices

$$[s_2] = [s_1] - \frac{\{\emptyset_2\}\{\emptyset_2\}^T[m]}{\{\emptyset_2\}^T[m]\{\emptyset_2\}} \quad (17)$$

$$[s_3] = [s_2] - \frac{\{\emptyset_3\}\{\emptyset_3\}^T[m]}{\{\emptyset_3\}^T[m]\{\emptyset_3\}} \quad (18)$$

If $\{\emptyset_1\}$ is the normalized eigenvector $\{\emptyset_1\}\{\emptyset_1\}^T[m] = 1$ because of the normalization principle, in that case, dynamic matrix is written as $[A]_2 = [A]_1[S]_1$ where $[S_1]$ is given as in Equation (19)

$$[s_1] = [1] - (\{\emptyset_1\}\{\emptyset_1\}^T[m]) \quad (19)$$

2.8 Rayleigh Damping

Rayleigh damping expresses damping matrix as a linear combination of the mass and stiffness damping (Adhikari and Phani, 2007),

2.8.1 Mass Proportional Damping (MpD)

The damping present in floor of the structure is proportional to the motion of that floor. This is expressed in Equation (20) as $[c] \propto [m]$ (20)

The mass proportional damping is expressed in Equation (20) as: $[c] = \propto [m]$ (21)

And the corresponding damping ration ς_r is as shown in Equation (22)

$$\varsigma_r = \frac{[c]}{2w_r[m]} = \frac{\propto [m]}{2w_r[m]} = \frac{\propto}{2w_r} \quad (22)$$

The coefficient of damping $\propto$ is defined as expressed in Equation (23)

$$\propto = (2\varsigma_r w_r) \quad (23)$$

2.8.2 Stiffness Proportional Damping (SpD)

The damping is related to the interparticle friction that gives energy in form of heat. Therefore, damping is proportional to the stiffness of the structure. This is expressed as shown in Equation (24) as

$$[c] \propto [k], \quad (24)$$

The stiffness proportional damping is expressed in Equation (25) as: $[c] = \beta[k]$ (25)

The damping constant of each mode of vibration is as expressed in Equation (26)

$$C_r = \beta k_r = \beta w_r^2 m_r \quad (26)$$

And the corresponding damping ration ς_r is as shown in Equation (27)

$$\varsigma_r = \frac{[c]}{2w_r[m]} = \frac{\beta w_r^2[m]}{2w_r[m]} = \frac{\beta w_r}{2} \quad (27)$$

Using the result for the Mass Proportional Damping (MpD) and Stiffness Proportional Damping (SpD) as obtained in Equations (22) and (27) respectively, Rayleigh damping ratio ς_r which is the summation mass and stiffness damping, yields Equation (28)

$$\varsigma_r = \frac{\propto}{2w_r} + \frac{\beta w_r}{2} = \frac{\propto}{2}.\frac{\mathbf{1}}{w_r} + \frac{\beta}{2}w_r = \frac{1}{2}\left(\frac{\propto}{w_r} + \beta w_r\right) \quad (28)$$

Rayleigh damping is therefore defined for an MDOF system by specifying for two different unequal frequencies of vibration and solving by simultaneous solution of the equation (29)

$$\varsigma_r = \frac{1}{2}\left(\frac{\propto}{w_r} + \beta w_r\right) \quad (29)$$

ie

$$\varsigma_1 = \frac{1}{2}\left(\frac{\propto}{w_1} + \beta w_1\right) \quad (30)$$

$$\varsigma_2 = \frac{1}{2}\left(\frac{\propto}{w_2} + \beta w_2\right) \quad (31)$$

2.9 Dynamic Analysis of Shear Wall Structural Form of Tall Building

The structure which consists of 10 stories buildings of height of 3.5m each with a total height of 35m was considered. The four shear walls include two symmetrical pairs (types 1 and 2) and two change levels A and B, divide the structures into 3 regions. The wall dimensions for the coupled and non-coupled shear wall structures were shown below and inertia were estimated.

2.9.1 The Wall Dimensions for Non-Coupled Shear Wall Structural Form of Tall Building

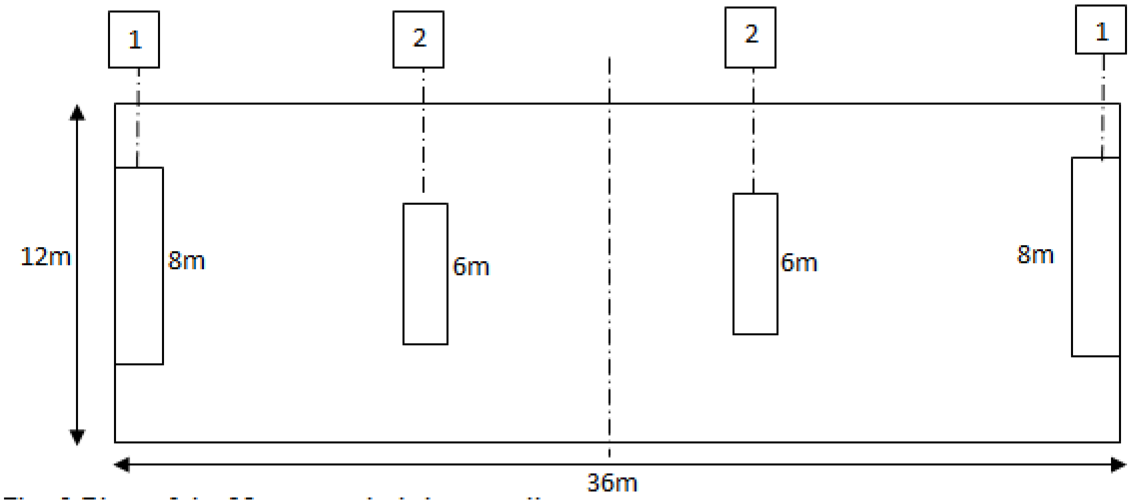


Fig. 3 Plan of the Non- coupled shear wall structure

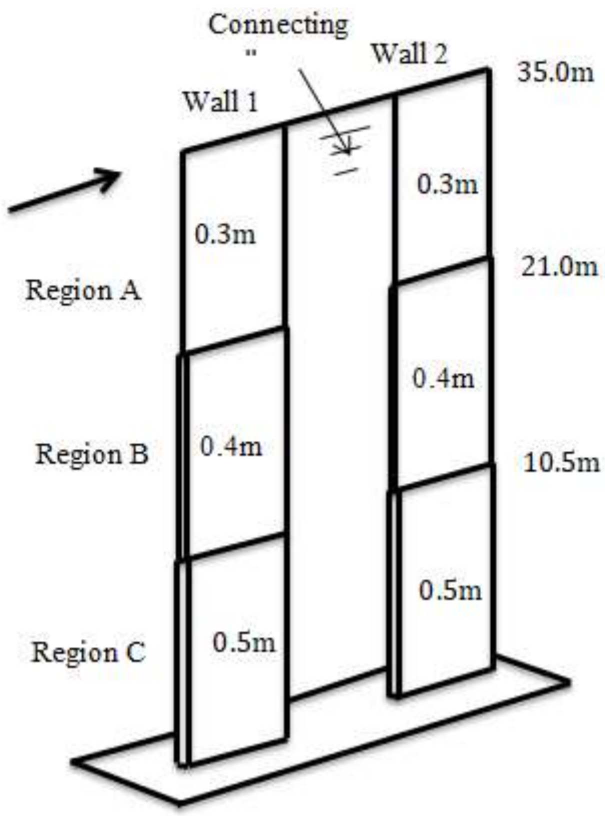


Fig. 4 End View of the Non- coupled shear wall structure

2.9.2 The Wall Dimensions for Coupled Shear Wall Structural Form of Tall Building

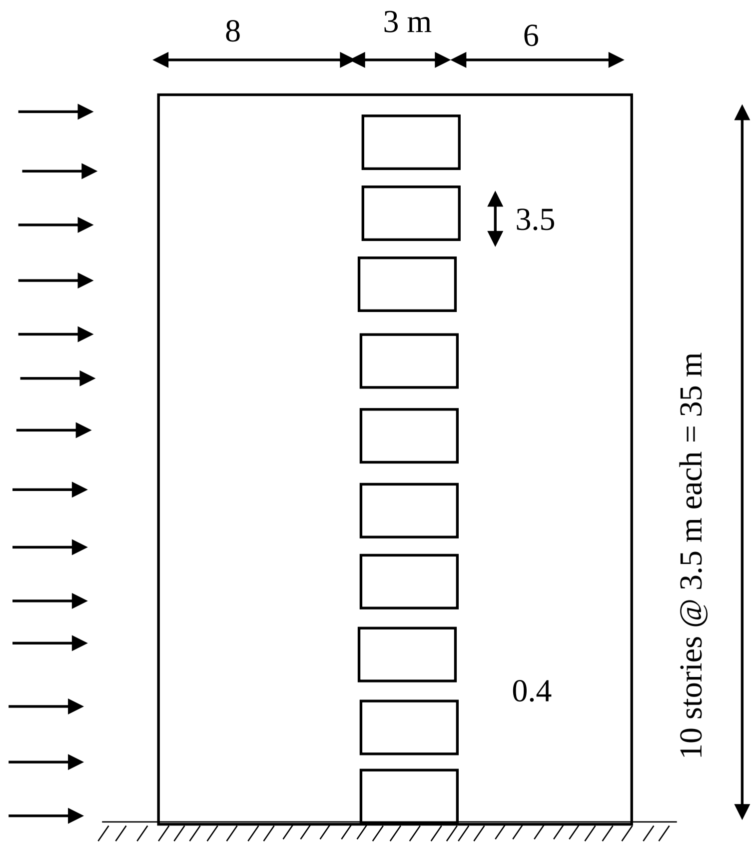


Fig 5: End View of the coupled shear wall structure

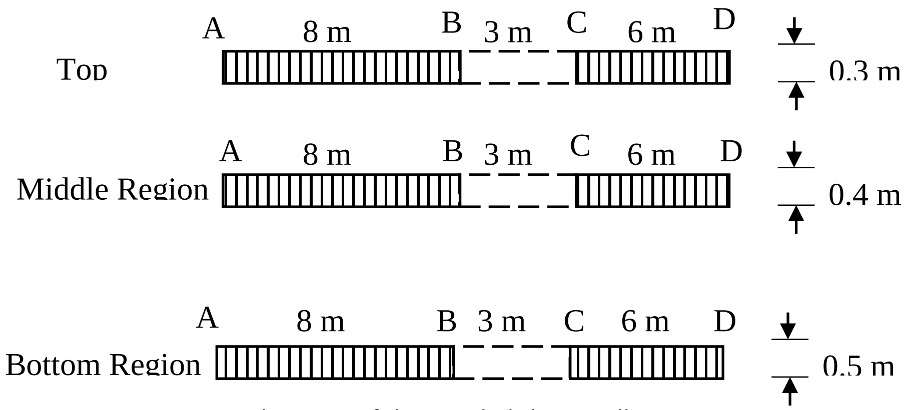


Fig. 6: Plan view of the coupled shear wall structure

III. Results

The results of the analysis for the Coupled and Non-Coupled shear wall structural form of tall buildings are presented in this section

3.1 The Stiffness and Mass Matrices for the Shear Wall Structural Form of Tall Buildings: The results of the stiffness and mass matrices for the Coupled and Non-Coupled shear wall are presented in this section

3.1.1 Non-Coupled Shear Wall Structural Form of Tall Building The results of the stiffness and mass matrices for the ten storey Non-coupled shear wall structural form of tall building as presented in Figure 3 and 4 was analysed and the results were presented as follows

ii) The Mass Matrix for the Non-Coupled Shear Wall Structure:

$$[m] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (32)$$

i) The Stiffness Matrix for the Non-Coupled Shear Wall Structure

$$[K] = \begin{bmatrix} 33.96 & -16.98 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -16.98 & 33.96 & -16.98 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -16.98 & 30.56 & -13.58 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -13.58 & 27.17 & -13.58 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -13.58 & 27.17 & -13.58 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -13.58 & 23.77 & -10.19 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -10.19 & 20.38 & -10.19 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -10.19 & 20.38 & -10.19 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -10.19 & 20.38 & -10.19 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -10.19 & 10.19 \end{bmatrix} \quad (33)$$

3.1.2 Coupled Shear Wall Structural Form of Tall Building

The results of the stiffness and mass matrices for the ten storey Coupled shear wall structural form of tall building was analysed and the results were presented as follows

ii) The Mass Matrix for the Coupled Shear Wall Structure

$$[m] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (34)$$

i) The Stiffness Matrix for the Coupled Shear Wall Structure

$$[K] = \begin{bmatrix} 90.34 & -45.17 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -45.17 & 90.34 & -45.17 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -45.17 & 90.34 & -45.17 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -45.17 & 90.34 & -45.17 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -45.17 & 90.34 & -45.17 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -45.17 & 90.34 & -45.17 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -45.17 & 90.34 & -45.17 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -45.17 & 90.34 & -45.17 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -45.17 & 90.34 & -45.17 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -45.17 & 45.17 \end{bmatrix} \quad (35)$$

3.2 The Result of the Dynamic and Sweeping Matrices for the Shear Wall Structure: The result of the first dynamic matrix [A] and sweeping matrix [S] of the coupled and non-coupled shear wall structural form of tall building structure considered in this research is presented as shown

3.2.1 Non-Coupled Shear Wall Structural Form of Tall Building

i) Dynamic Matrix for Non-Coupled Shear Wall Structural Form of Tall Building

$$[A] = \begin{bmatrix} 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 & 0.059 \\ 0.059 & 0.118 & 0.118 & 0.118 & 0.118 & 0.118 & 0.118 & 0.118 & 0.118 & 0.118 \\ 0.059 & 0.118 & 0.177 & 0.177 & 0.177 & 0.177 & 0.177 & 0.177 & 0.177 & 0.177 \\ 0.059 & 0.118 & 0.177 & 0.250 & 0.250 & 0.250 & 0.250 & 0.250 & 0.250 & 0.250 \\ 0.059 & 0.118 & 0.177 & 0.250 & 0.324 & 0.324 & 0.324 & 0.324 & 0.324 & 0.324 \\ 0.059 & 0.118 & 0.177 & 0.250 & 0.324 & 0.398 & 0.398 & 0.398 & 0.398 & 0.398 \\ 0.059 & 0.118 & 0.177 & 0.250 & 0.324 & 0.398 & 0.496 & 0.496 & 0.496 & 0.496 \\ 0.059 & 0.118 & 0.177 & 0.250 & 0.324 & 0.398 & 0.496 & 0.594 & 0.594 & 0.594 \\ 0.059 & 0.118 & 0.177 & 0.250 & 0.324 & 0.398 & 0.496 & 0.594 & 0.692 & 0.692 \\ 0.059 & 0.118 & 0.177 & 0.250 & 0.324 & 0.398 & 0.496 & 0.594 & 0.692 & 0.790 \end{bmatrix} \quad (36)$$

i) Sweeping Matrix for Non-Coupled Shear Wall Structural Form of Tall Building

$$[S_1] = \begin{bmatrix} 0.997 & -0.006 & -0.009 & -0.012 & -0.015 & -0.018 & -0.020 & -0.023 & -0.024 & -0.025 \\ -0.006 & 0.988 & -0.017 & -0.024 & -0.030 & -0.035 & -0.041 & -0.045 & -0.048 & -0.050 \\ -0.009 & -0.017 & 0.975 & -0.035 & -0.044 & -0.051 & -0.060 & -0.067 & -0.071 & -0.074 \\ -0.012 & -0.024 & -0.035 & 0.952 & -0.060 & -0.071 & -0.083 & -0.092 & -0.098 & -0.101 \\ -0.015 & -0.030 & -0.044 & -0.060 & 0.925 & -0.088 & -0.103 & -0.115 & -0.123 & -0.127 \\ -0.018 & -0.035 & -0.051 & -0.071 & -0.088 & 0.896 & -0.122 & -0.135 & -0.145 & -0.149 \\ -0.020 & -0.041 & -0.060 & -0.083 & -0.103 & -0.122 & 0.858 & -0.158 & -0.169 & -0.174 \\ -0.023 & -0.045 & -0.067 & -0.092 & -0.115 & -0.135 & -0.158 & 0.824 & -0.188 & -0.194 \\ -0.024 & -0.048 & -0.071 & -0.098 & -0.123 & -0.145 & -0.169 & -0.188 & 0.799 & -0.208 \\ -0.025 & -0.050 & -0.074 & -0.101 & -0.127 & -0.149 & -0.174 & -0.194 & -0.208 & 0.786 \end{bmatrix} \quad (37)$$

3.2.2 Coupled Shear Wall Structural Form of Tall Building

i) Dynamic matrix [A] for coupled shear wall structural form of tall building

$$[A_1] = \begin{bmatrix} 0.022 & 0.022 & 0.022 & 0.022 & 0.022 & 0.022 & 0.022 & 0.022 & 0.022 & 0.022 \\ 0.022 & 0.044 & 0.044 & 0.044 & 0.044 & 0.044 & 0.044 & 0.044 & 0.044 & 0.044 \\ 0.022 & 0.044 & 0.066 & 0.066 & 0.066 & 0.066 & 0.066 & 0.066 & -0.066 & 0.066 \\ 0.022 & 0.044 & 0.066 & 0.089 & 0.089 & -0.089 & 0.089 & 0.089 & -0.089 & 0.089 \\ 0.022 & 0.044 & 0.066 & 0.089 & 0.111 & 0.111 & 0.111 & 0.111 & 0.111 & 0.111 \\ 0.022 & 0.044 & 0.066 & 0.089 & 0.111 & 0.133 & 0.133 & 0.133 & 0.133 & 0.133 \\ 0.022 & 0.044 & 0.066 & 0.089 & 0.111 & 0.133 & 0.155 & 0.155 & 0.155 & 0.155 \\ 0.022 & 0.044 & 0.066 & 0.089 & 0.111 & 0.133 & 0.155 & 0.177 & 0.177 & 0.177 \\ 0.022 & 0.044 & 0.066 & 0.089 & 0.111 & 0.133 & 0.155 & 0.177 & 0.199 & 0.199 \\ 0.022 & 0.044 & 0.066 & 0.089 & 0.111 & 0.133 & 0.155 & 0.177 & 0.199 & 0.221 \end{bmatrix} \quad (38)$$

ii) Sweeping Matrix for Coupled Shear Wall Structural Form of Tall Building

$$[S_1] = \begin{bmatrix} 0.996 & -0.008 & -0.012 & -0.016 & -0.019 & -0.022 & -0.025 & -0.026 & -0.028 & -0.028 \\ -0.008 & 0.983 & -0.024 & -0.032 & -0.038 & -0.044 & -0.049 & -0.052 & -0.055 & -0.056 \\ -0.012 & -0.024 & 0.964 & -0.047 & -0.056 & -0.065 & -0.072 & -0.077 & -0.081 & -0.082 \\ -0.016 & -0.032 & -0.047 & 0.940 & -0.073 & -0.084 & -0.093 & -0.100 & -0.105 & -0.107 \\ -0.019 & -0.038 & -0.056 & -0.073 & 0.912 & -0.101 & -0.112 & -0.121 & -0.126 & -0.129 \\ -0.022 & -0.044 & -0.065 & -0.084 & -0.101 & 0.884 & -0.129 & -0.139 & -0.145 & -0.149 \\ -0.025 & -0.049 & -0.072 & -0.093 & -0.112 & -0.129 & 0.857 & -0.154 & -0.161 & -0.164 \\ -0.026 & -0.052 & -0.077 & -0.100 & -0.121 & -0.139 & -0.154 & 0.835 & -0.173 & -0.177 \\ -0.028 & -0.055 & -0.081 & -0.105 & -0.126 & -0.145 & -0.161 & -0.173 & 0.819 & -0.185 \\ -0.028 & -0.056 & -0.082 & -0.107 & -0.129 & -0.149 & -0.164 & -0.177 & -0.185 & 0.811 \end{bmatrix} \quad (39)$$

3.3 The results of other dynamic properties for coupled and non-coupled shear wall structures

This section presents the results of other dynamic properties for coupled and non-coupled shear wall structural form of tall building tn this analysis

3.3.1 Non-Coupled Shear Wall Structural Form of Tall Building

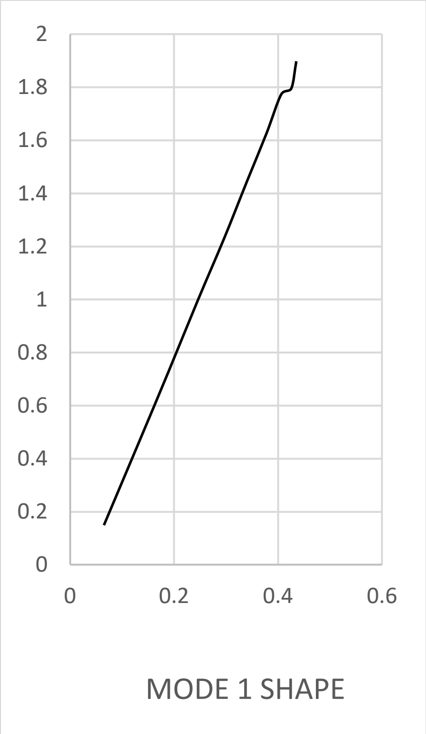
Table 1: The summary sheet showing the natural frequencies w_n, the generalized mass M and the mode shapes for non- coupled shear wall structures

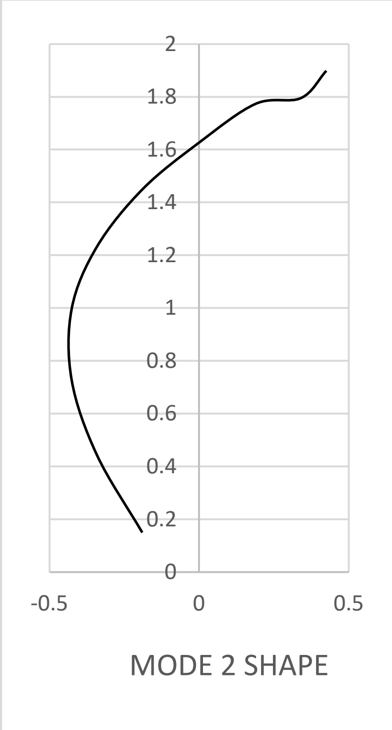
w_n	0.569	1.571	2.598	3.503	4.403	5.116	5.768	6.154	6.873	7.625
M	2.160	2.242	2.435	2.458	3.159	3.241	5.353	5.389	11.605	8.219
Mode	$\emptyset_{1j}$	$\emptyset_{2j}$	$\emptyset_{3j}$	$\emptyset_{4j}$	$\emptyset_{5j}$	$\emptyset_{6j}$	$\emptyset_{7j}$	$\emptyset_{8j}$	$\emptyset_{9j}$	$\emptyset_{10j}$
	0.054	-0.155	0.255	-0.286	0.382	-0.372	0.467	-0.311	0.289	-0.177
	0.108	-0.287	0.407	-0.362	0.292	-0.106	-0.116	0.279	-0.422	0.405
	0.159	-0.378	0.394	-0.173	-0.147	0.335	-0.424	0.050	0.260	-0.421
	0.219	-0.421	0.180	0.223	-0.459	0.184	0.319	-0.329	0.070	0.524
	0.274	-0.389	-0.124	0.417	-0.088	-0.337	0.216	0.300	-0.368	-0.386
	0.323	-0.285	-0.365	0.232	0.395	-0.185	-0.421	0.001	0.434	0.386
	0.377	-0.078	-0.441	-0.297	0.258	0.497	0.128	-0.333	-0.391	-0.061
	0.419	0.148	-0.225	-0.470	-0.355	-0.087	0.243	0.515	0.340	0.181
	0.448	0.338	0.139	-0.079	-0.283	-0.454	-0.391	-0.462	-0.259	0.061
	0.463	0.446	0.411	0.407	0.317	0.309	0.187	0.186	0.086	0.122

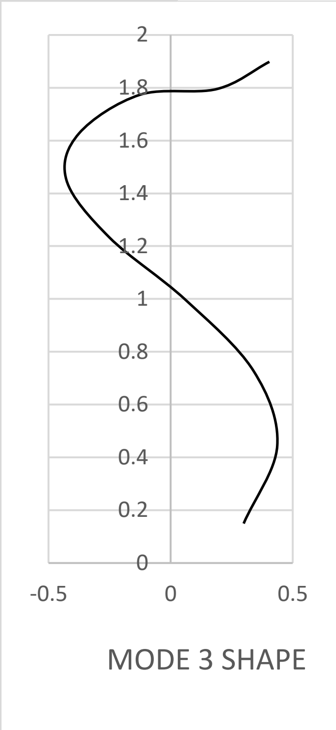
Table 2. The summary sheet showing other dynamic properties such as natural frequencies W_n, generalized mass M, non-dimensional viscous damping coefficient ς, modal damping coefficient C, the damped natural frequency W_d, the natural period T, and the damped period T_d.

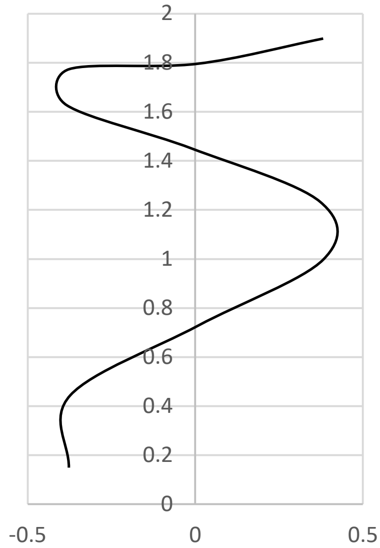
	W_n	M	ς	C	W_d	T	T_d
1	0.569	2.16	0.050	0.057	0.569	11.038	11.052
2	1.571	2.242	0.060	0.189	1.568	4.000	4.007
3	2.598	2.435	0.087	0.451	2.588	2.419	2.428
4	3.503	2.458	0.113	0.790	3.480	1.794	1.806
5	4.403	3.159	0.139	1.227	4.360	1.427	1.441
6	5.116	3.241	0.161	1.644	5.049	1.228	1.245
7	5.768	5.353	0.180	2.080	5.673	1.089	1.108
8	6.154	5.389	0.192	2.363	6.040	1.021	1.040
9	6.873	11.605	0.214	2.937	6.714	0.914	0.936
10	7.625	8.219	0.237	3.607	7.409	0.824	0.848

ii) The corresponding mode shapes for the numerical values of the non-coupled shear wall structures from mode 1 - 10 as presented in table 1 are shown in Figure 7

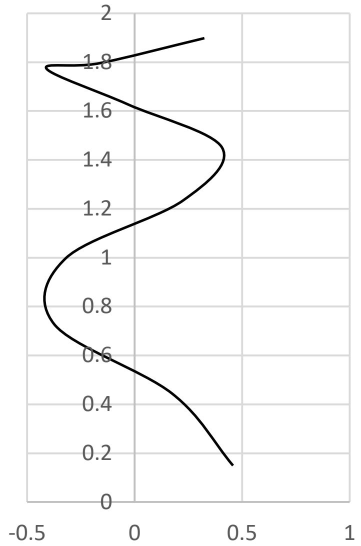

2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
MODE 1 SHAPE


2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.5
0
0.5
MODE 2 SHAPE

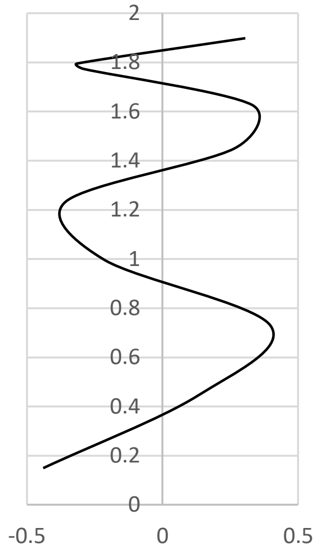

2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.5
0
0.5
MODE 3 SHAPE



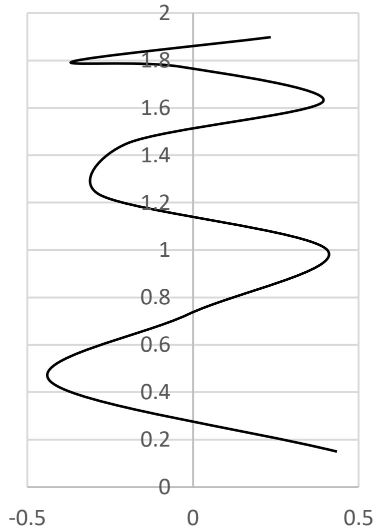
MODE 4 SHAPE



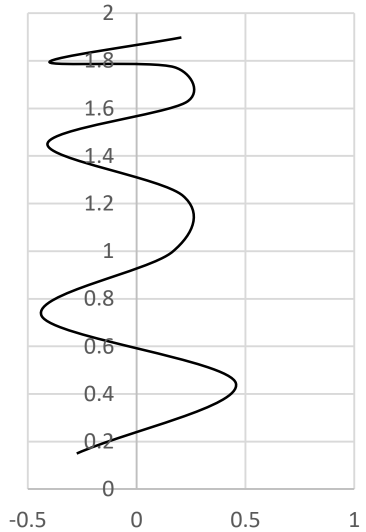
MODE 5 SHAPE



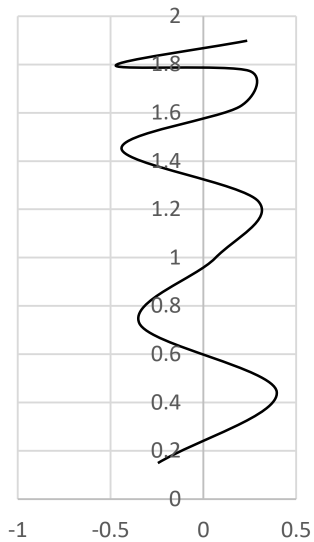
MODE 6 SHAPE



MODE 7 SHAPE



MODE 8 SHAPE



MODE 9 SHAPE

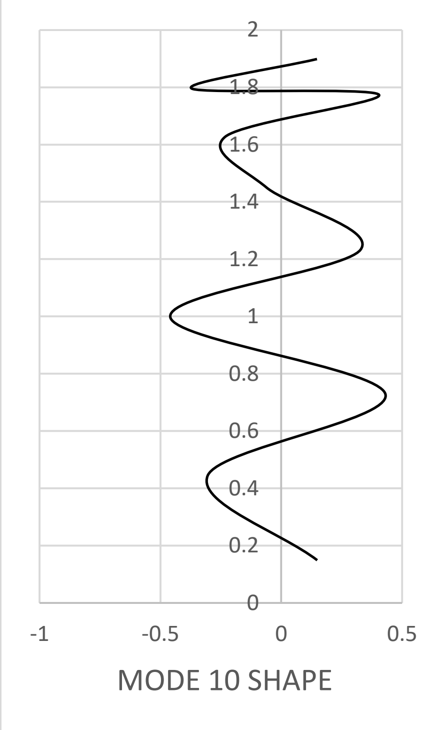


Fig. 7. The normalized mode shapes for mode 1 to 10 of the non-coupled shear wall structures

Table 3: The summary sheet correlating natural frequency W_n, the generalized mass M, the damping coefficient C and the natural period of vibration T of the non-coupled shear wall structure

Mode	Natural Frequency w	Generalized Mass M	Coefficient of Damping C	Natural Period of Vibration T
1	0.569	2.160	0.057	11.038
2	1.571	2.242	0.189	4.000
3	2.598	2.435	0.451	2.419
4	3.503	2.458	0.790	1.794
5	4.403	3.159	1.227	1.427
6	5.116	3.241	1.644	1.228
7	5.768	5.353	2.080	1.089
8	6.154	5.389	2.363	1.021
9	6.873	11.605	2.937	0.914
10	7.625	8.219	3.607	0.824

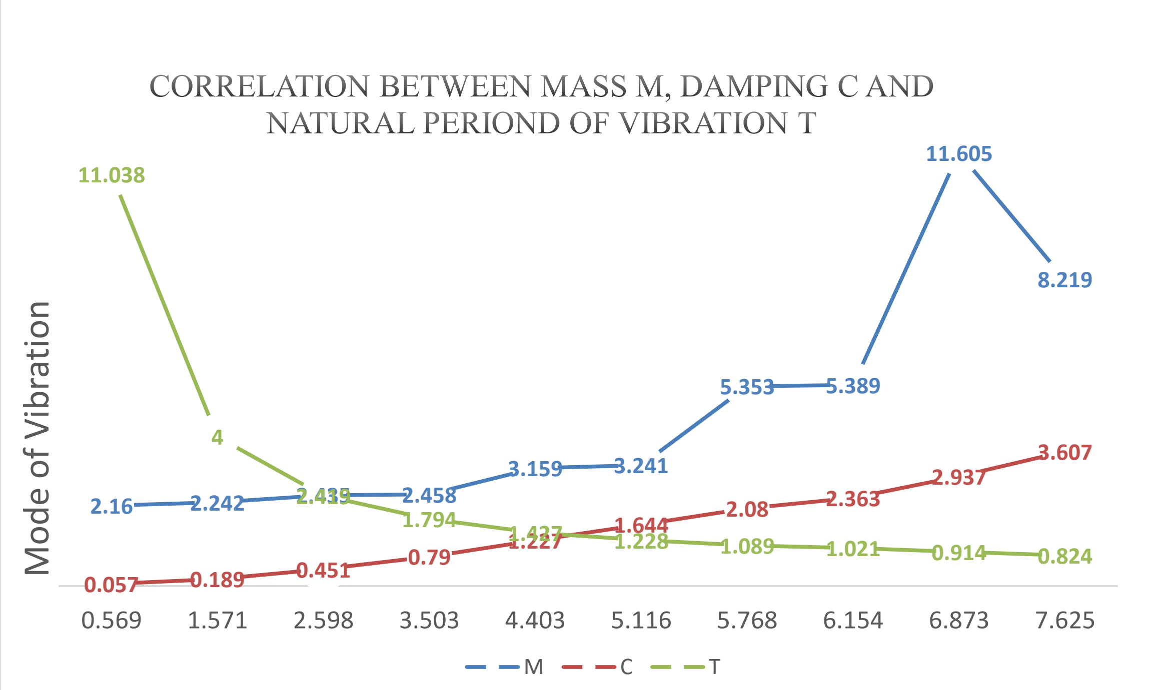


Fig. 8: Graph Correlating the mass, damping and period of vibration for non-coupled shear wall structure

3.3.2 Coupled Shear Wall Structural Form of Tall Building

Table 4: The summary sheet showing the natural frequencies and mode shapes for Coupled Shear Wall Structure.

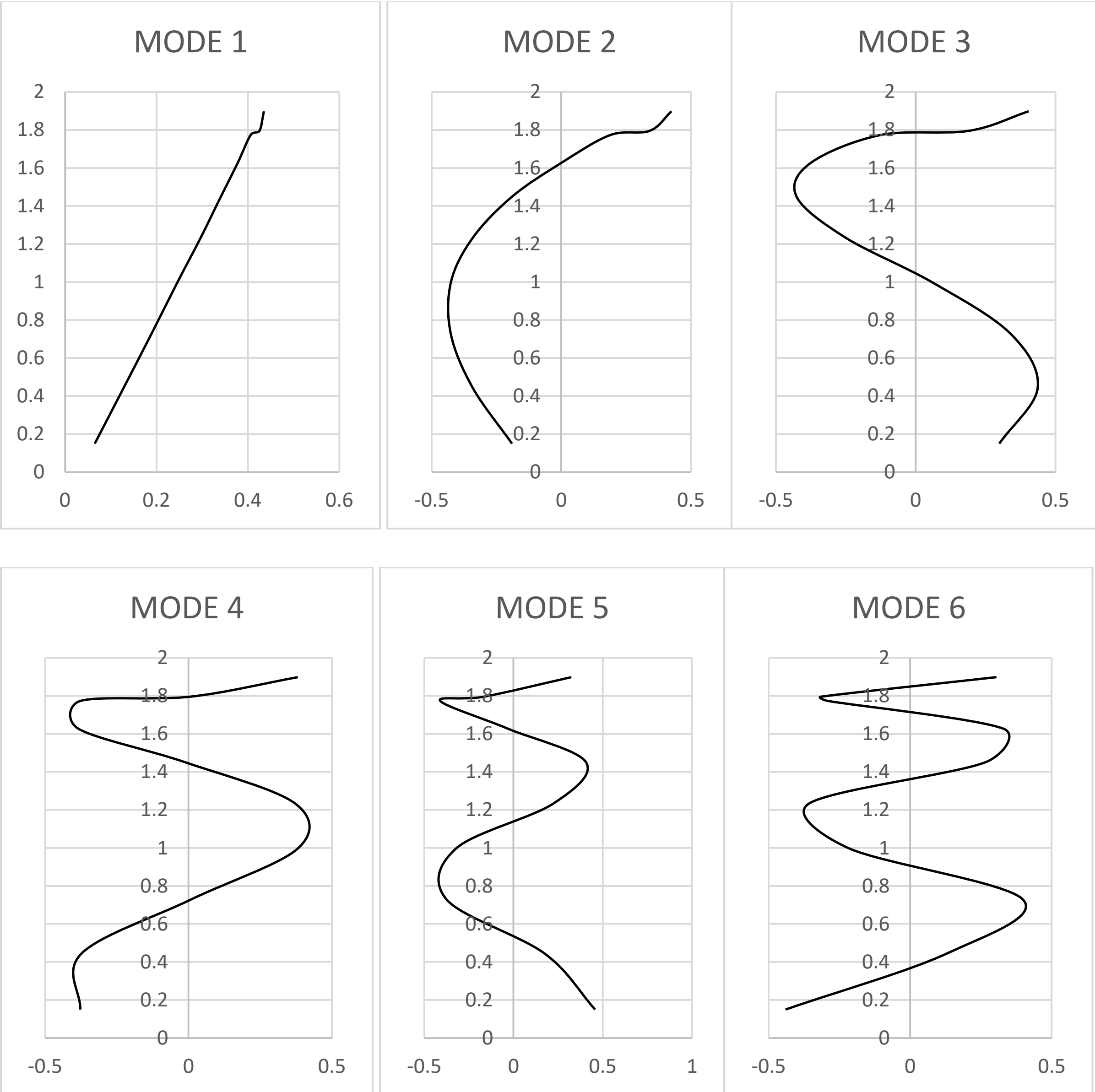
W	1.004	2.988	4.895	6.707	8.287	9.746	10.934	11.918	12.073	6.405
Mode	$\emptyset_{1j}$	$\emptyset_{2j}$	$\emptyset_{3j}$	$\emptyset_{4j}$	$\emptyset_{5j}$	$\emptyset_{6j}$	$\emptyset_{7j}$	$\emptyset_{8j}$	$\emptyset_{9j}$	$\emptyset_{10j}$
1	0.065	-0.190	0.299	-0.377	0.458	-0.440	0.434	-0.273	-0.245	0.170
2	0.129	-0.342	0.437	-0.373	0.174	0.130	-0.430	0.457	0.397	-0.356
3	0.189	-0.426	0.339	0.009	-0.375	0.398	-0.014	-0.437	-0.349	0.446
4	0.246	-0.425	0.060	0.382	-0.320	-0.216	0.407	0.167	0.066	-0.486
5	0.297	-0.341	-0.250	0.372	0.223	-0.357	-0.281	0.215	0.295	0.281
6	0.341	-0.189	-0.426	-0.010	0.407	0.265	-0.199	-0.409	-0.441	-0.069
7	0.378	0.001	-0.375	-0.384	-0.030	0.330	0.393	0.229	0.198	-0.263
8	0.406	0.190	-0.125	-0.376	-0.410	-0.291	-0.037	0.174	0.244	0.337
9	0.425	0.341	0.191	0.005	-0.166	-0.315	-0.363	-0.398	-0.470	-0.367
10	0.435	0.425	0.405	0.381	0.324	0.305	0.234	0.206	0.234	0.092

Table 5: The summary sheet showing other dynamic properties such as natural frequencies W_n, generalized mass M, non-dimensional viscous damping coefficient ς, modal damping coefficient C, the damped natural frequency W_d, the natural period T and the damped period T_d.

	W_n	M	ς	C	W_d	T	T_d
1	1.004	2.298	0.046	0.093	1.003	6.257	6.264
2	2.988	2.352	0.120	0.719	2.966	2.103	2.119
3	4.895	2.47	0.195	1.908	4.801	1.284	1.309
4	6.707	2.623	0.266	3.571	6.465	0.937	0.972
5	8.287	3.083	0.329	5.446	7.827	0.758	0.803
6	9.746	3.28	0.386	7.526	8.990	0.645	0.699

7	10.935	4.269	0.433	9.471	9.856	0.575	0.638
8	11.920	4.852	0.472	11.252	10.509	0.527	0.598
9	12.066	4.277	0.478	11.530	10.600	0.521	0.593
10	12.759	10.898	0.505	12.890	11.011	0.493	0.571

ii) The corresponding mode shapes for the numerical values of the non-coupled shear wall structures from mode 1 - 10 as presented in table 4 are shown in Figure 9



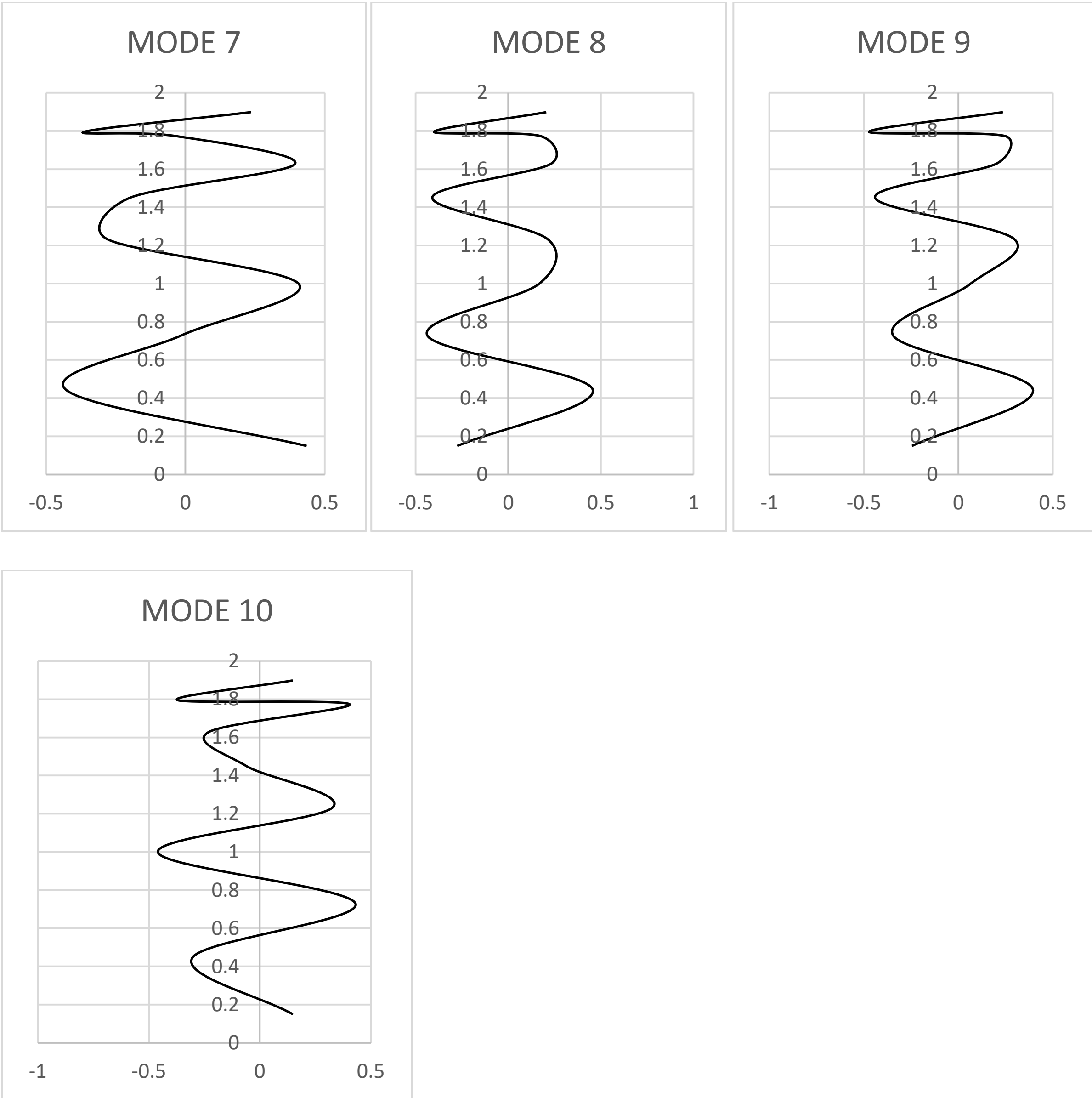


Fig. 9 Graph showing the mode shapes of the structure from mode 1 to 10 for the coupled shear wall structures

Table 6: The summary sheet correlating natural frequency, the mass, the damping and the period of vibration of the non-coupled shear wall structure

Mode	Natural Frequency w	Generalized Mass M	Coefficient of Damping C	Natural Period of Vibration T
1	1.004	2.298	0.093	6.257
2	2.988	2.352	0.719	2.103
3	4.895	2.47	1.908	1.284
4	6.707	2.623	3.571	0.937
5	8.287	3.083	5.446	0.758
6	9.746	3.28	7.526	0.645
7	10.935	4.269	9.471	0.575
8	11.92	4.852	11.252	0.527

9	12.066	4.277	11.53	0.521
10	12.759	10.898	12.89	0.493

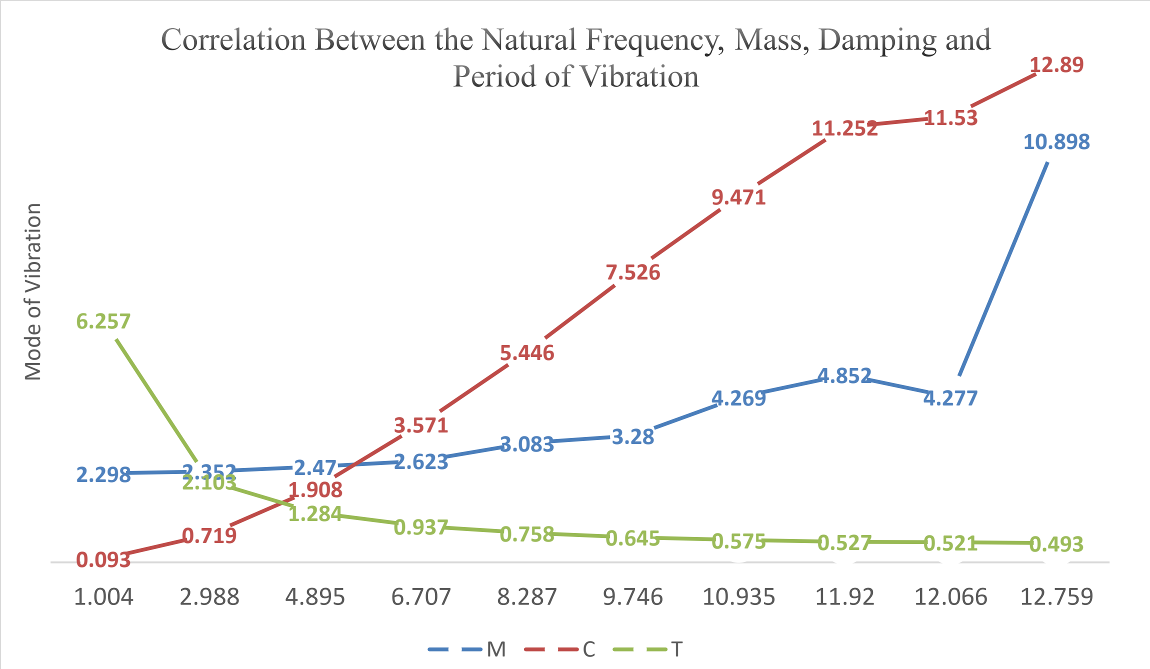


Fig 10. Graph Correlating the natural frequency, mass, damping and period of vibration for non-coupled shear wall structure

3.4 Results of the comparative analysis between the dynamic properties of coupled and non-coupled shear wall structural form of tall building

Table 7. Results of the comparative dynamic analysis between the coupled and non-coupled shear wall structural form of tall building

Natural frequency for non-coupled shear wall structures W(rad/s)	Natural frequency for coupled shear wall structures W(rad/s)	Coefficient of damping for non-coupled shear wall structures C	Coefficient of damping for Coupled shear wall structures C	Natural Period for non-coupled shear wall structures T(s)	Natural Period for Coupled shear wall structures T(s)	Percentage Difference in Natural frequency between non-coupled shear wall and Coupled shear wall structures w%	Percentage Difference in Coefficient of damping between non-coupled shear wall and Coupled shear wall structures C %	Percentage Difference in Natural Period between shear wall and Coupled shear wall structures T%
0.569	1.004	0.057	0.093	11.038	6.257	43.314%	38.806%	-76.412%
1.571	2.988	0.189	0.719	4.000	2.103	47.415%	73.785%	-90.169%
2.598	4.895	0.451	1.908	2.419	1.284	46.923%	76.345%	-88.406%
3.503	6.707	0.790	3.571	1.794	0.937	47.772%	77.869%	-91.469%
4.403	8.287	1.227	5.446	1.427	0.758	46.876%	77.468%	-88.241%
5.116	9.746	1.644	7.526	1.228	0.645	47.511%	78.160%	-90.515%
5.768	10.935	2.080	9.471	1.089	0.575	47.254%	78.043%	-89.586%
6.154	11.920	2.363	11.252	1.021	0.527	48.370%	79.004%	-93.685%

6.873	12.066	2.937	11.530	0.914	0.521	43.042%	74.525%	-75.568%
7.625	12.759	3.607	12.890	0.824	0.493	40.237%	72.017%	-67.328%
Average Percentage Difference %						45.871%	72.602%	-85.138%

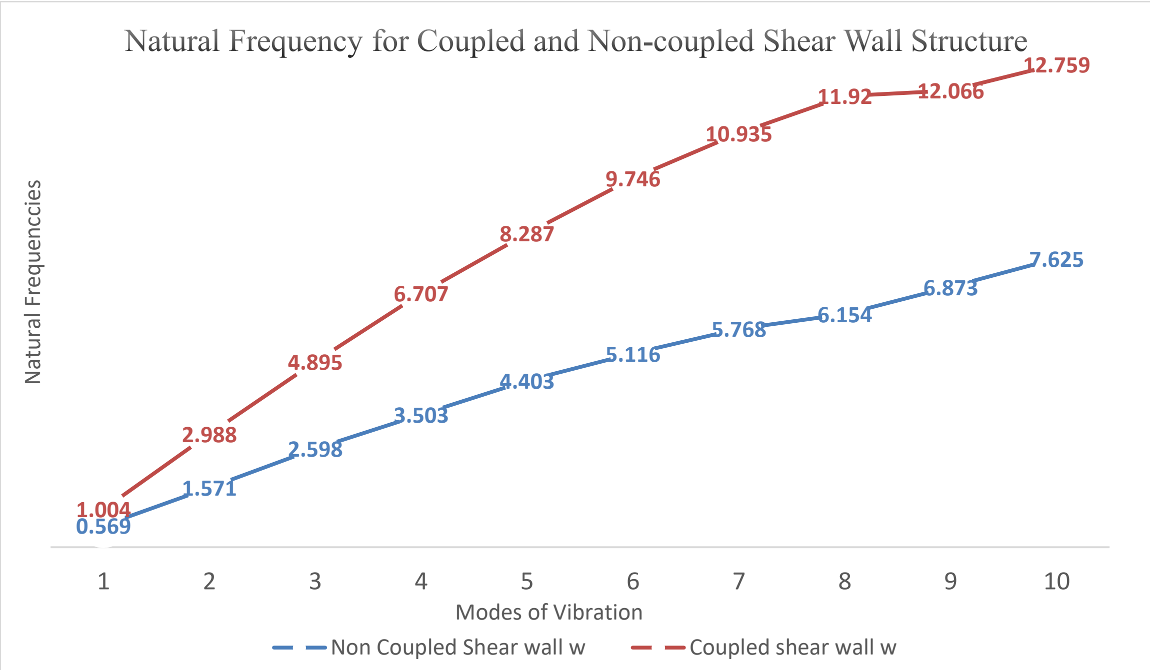


Fig 11. Graph comparing the natural frequencies for coupled and non-coupled shear wall structure

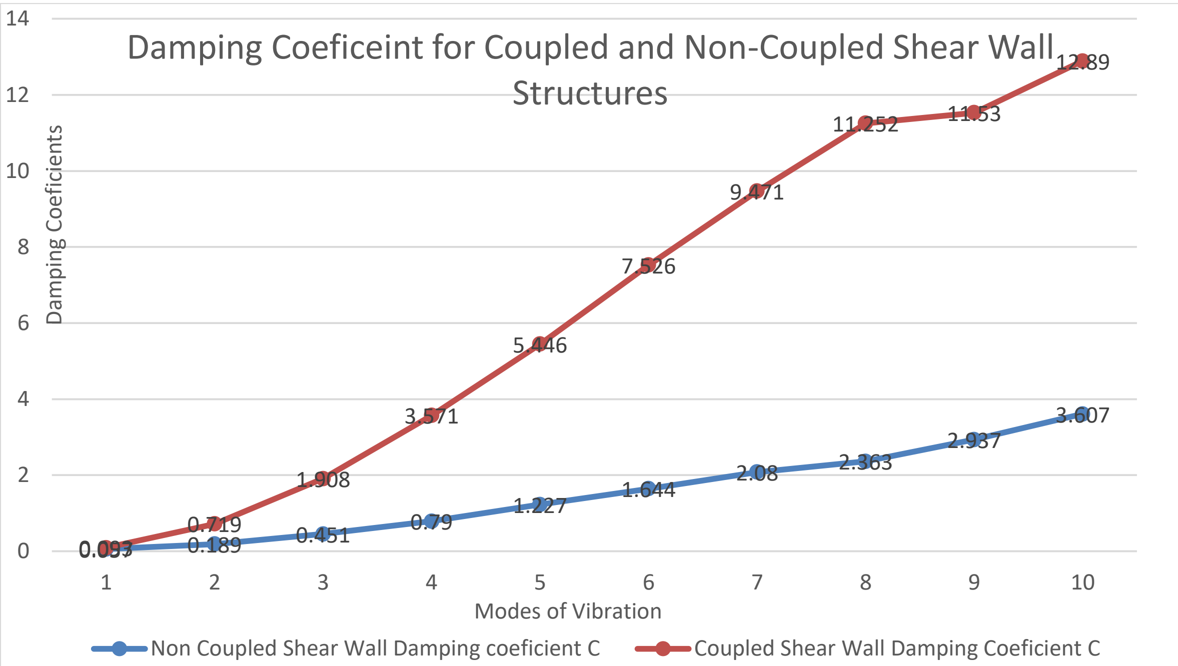


Fig 12. Graph comparing the damping coefficient between the coupled and non-coupled shear wall structure

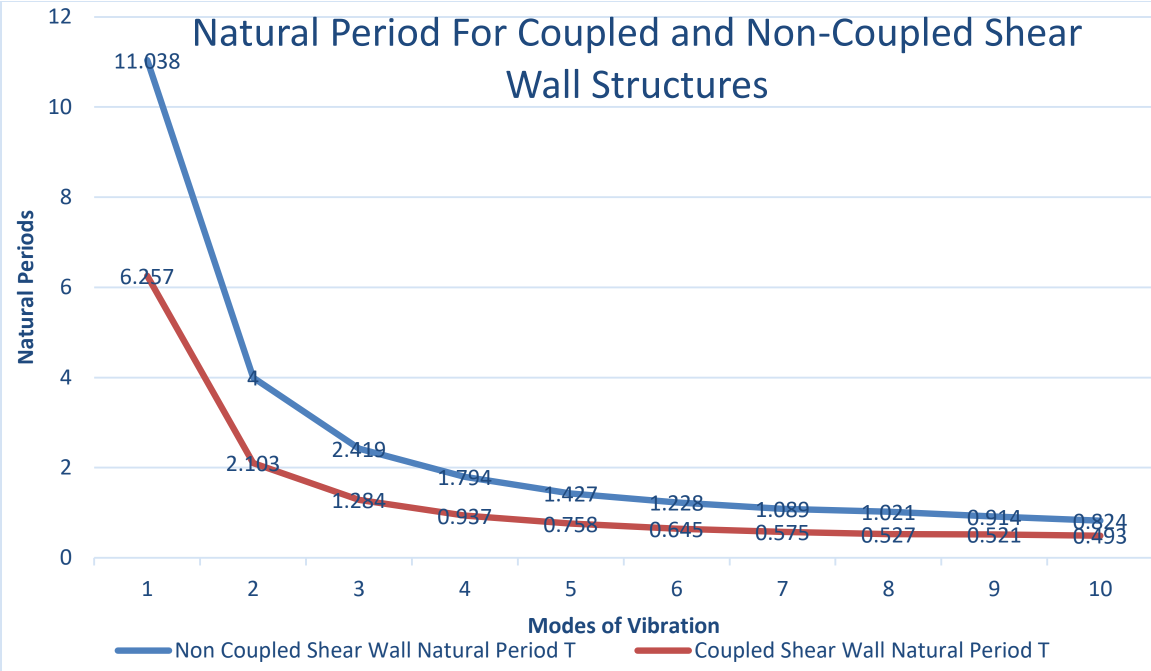


Fig 13 Graph comparing the natural period between the coupled and non-coupled shear wall structure

3.5 Conclusion

This Comparative Analysis of the Dynamic Behaviour of Coupled and Non-Coupled Shear Walls in Tall Buildings was presented. The matrix stiffness method, Stodola Iteration Method and improved Reyleigh's method were used in the analysis. A wall dimensions for a non-coupled shear wall structural form of ten (10) storey building was assumed and analysed, the results were compared with the result of the same wall dimensions but arranged in the coupled shear wall form. A unit mass was assumed and the masses were concentrated at the floor level (lump masses). The matrix stiffness method was applied to generate the element stiffness matrix, and the mass matrix was also generated. The Stodola Iteration Method was used to determine the mode shapes and the corresponding natural frequencies of the structures. Rayleigh damping method was applied to estimate the damping inherent in the structures. It was discovered that the average percentage difference in coefficient of damping inherent in coupled shear wall structure exceeds that of non-coupled shear walls by 45.8% while the time required for the structure to undergo one complete cycle oscillation in non-coupled shear wall structural form of tall building is almost 85.14% greater than what it takes the coupled shear wall to complete one cycle of oscillation. These show that coupled shear wall structural forms have high potential to resist dynamic effect compared to Non-Coupled shear wall structures and is highly recommended for the construction of tall buildings.

IV. References

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