# Dynamic Performance of Tall Mass-Timber Buildings

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**Abstract- The construction materials used in the building tall structures are responsible for extremely high carbon emissions. Therefore, to address this issue building designers are constantly looking at alternative sustainable construction materials. A new type of timber called Mass-Timber as a material for construction is now attracting the building designers because of its sustainability advantages. Mass-timber is an innovative type of engineered timber with improved structural properties making it suitable for the construction of tall and heavy structures. This paper is intended to study the performance of tall mass-timber buildings under the most severe dynamic loading conditions of India. Three models of mass-timber buildings are analyzed in ETABS under the seismic and wind loads according to the demands of most severe earthquake zone-V and one of the windiest regions at Bhuj, India. It is observed that the mass participation during seismic activities is considerably low and the wind loads are considerably higher than the seismic loads. It is concluded that with a suitable lateral load resisting structural system mass-timber buildings can perform adequately.**

**Keywords- Mass-Timber, CLT, GLT, core wall, Time-Historey analysis, ETABS.**

## 1. INTRODUCTION

Timber or lumber is a type of wood which has been processed into useful structural shapes such as beams, columns or planks etc. The inherent properties of timber such as high strength to weight ratio, durability, insulation, sustainability and natural availability, make it one of the best performing structural material. Recently, timber is gaining attention of designers and engineers as a choice of structural material for the construction of tall buildings around the world, mainly due to a new structural timber called Mass-Timber and its sustainability advantages. A few centuries ago, timber was mostly

used structural material in India. But, with the popular construction materials such as concrete and steel the growth of structural timber is left behind.[1]

### 1.1 SUSTAINABILITY

In the past, energy efficient design was considered as a solution on climate change, but the focus has been now increased towards sustainable materials. Since, energy efficiency in operation is considered secondary to energy consumption in production, mass-timber is emerging as a practicable option for sustainable construction material. This is mainly due to the inherent ability of timber to absorb and store carbon dioxide within itself.[2] While other construction materials such as steel and concrete have high carbon footprint, timber on the other hand causes no carbon emissions during its production owing to its natural availability and negligible emissions due to energy use are caused during its crafting. Overall, the use of timber as a construction material creates a reduction in atmospheric carbon dioxide by trapping it inside its volume.

### 1.2 MASS-TIMBER

The mass-timber products are heavy wood structural elements used for applications such as heavy timber beams, columns, floors, wall panels etc. With their ability to bear larger loads within permissible deformation limits, it is now possible to construct taller buildings by using timber. These mass-timber products are prefabricated in workshops with the help of CNC cutting machines with high precision and accuracy, then transported to the site for assembly. The openings for doors and windows can already be made and the finished product in required sizes can directly be installed on-site. This makes the construction site very clean and silent therefore, it is a calm workplace as compared to RC construction site. Furthermore, this procedure reduces the construction time by a large extent.[3] These products are manufactured by laminating pieces of wood like small dimension lumber, sliced thin wood veneers or strands

of wood, by using a strong structural moisture resistant adhesive, nails or wooden dowel type connectors. The glued products are kept in compression to form a final rigid member.

The mass-timber products are classified according to their base material and lamination geometry as Cross Laminated Timber (CLT), Glue Laminated timber (GLT), Nail Laminated Timber (NLT), Laminated Strand Lumber (LSL), Laminated Veneer Lumber (LVL) and other large dimensioned Structural Composite Lumber (SCL).[4] The lamination procedures enable to overcome the anisotropic nature of wood and provides engineered material strength in different directions. Amongst all these materials CLT and GLT are used popularly in tall mass-timber buildings due to their exceptional strength, dimensional stability and rigidity. CLT consists of layers of small dimension lumber (in odd numbers, typically three, five, or seven to avoid warping) oriented perpendicular to one another and then glued together with moisture resistant adhesives. Therefore, CLT panels are more suited as floors, partition walls and structural walls. GLT is composed of individual wood lumbers and bonded together with moisture resistant adhesives such that, the grains of all the laminations are parallel to the length of member. Thus, GLTs are suitable for axial and flexural members such as columns, struts and beams. Additionally, GLT or Glulam members can be fabricated into different shapes such as curved beams and arches for aesthetic and economical designs.[5]

## 1.3 MASS-TIMBER STRUCTURAL SYSTEMS

Building codes in many countries currently limit wood structures to no more than 4 or 6-stories. However, the technical design limits of mass-timber construction have increased up to 40-stories and more due to recent innovations. In response, tall wood building constructions are rising all over the world.[6]

Timber framing systems can be differentiated as Light and Heavy timber framing. Light timber frame systems are suitable for low rise houses with moderate lateral load resisting capacity.[7] Heavy timber buildings can be classifies into three categories in terms of lateral load resistance capacity. Firstly as low rise buildings dominated by wind, secondly the hybrid structures including lateral load resisting system made of another material such as reinforced concrete or masonry shear wall and braced steel frame and thirdly the moment resisting heavy timber GLT beam and post frame or panelised CLT systems.[8]

In this paper three models of mass-timber structures are analyzed for dynamic loading. These includes a Beam and Post framing model, and two similar models first with CLT (Cross Laminated Timber) shear wall core and second with a reinforced concrete shear wall core. Custom orthotropic material properties of mostly used commercially available Mass-Timber products are used for analysis to obtain accurate results. Linear time history method is used to access the seismic performance of the structures.

## 1.4 TALL MASS-TIMBER BUILDING INITIATIVE

Between 2008 and 2019, the heights of modern timber buildings using engineered timber were seen to be growing. From 9-storey Stadthaus building in London and the 17-storey Brock Commons building in Vancouver, Canada in the year 2017.[9] And finally 18-storey tall Mjøstårnet completed in March 2019 in Norway which is regarded as tallest timber building in the world to date.[10] While it is uncertain what heights of tall buildings constructed using timber might eventually reach, a very significant increases in the height of such buildings may be possible in the coming years.[11]

Skidmore, Owings, and Merrill (SOM) published a study, "Timber Tower Research Project" intending to develop a conceptual structural system for sustainable tall mass-timber building which is cost competitive with other building techniques. The Concrete Jointed Timber Frame system consisting of solid mass-timber as primary structural elements connected with steel bar reinforcement with concrete joints was suggested. Mass-Timber was primarily used for floors, columns and shear walls. The lateral load resisting system consisted of solid CLT shear wall core located at the centre of building plan forming a large tube. Supplementary shear wall extending from central core to perimeter with reducing height were provided to control uplift forced due to winds. The research concluded mass-timber as a capable structural material for use in high rise structures

suggested the use of composite structural systems for economy.[12]

Another study called "The Case for Tall Wood" conducted by Equilibrium Consultants and MGA Architects demonstrated the possibility of mass-timber building up to 30 stories. The design was primarily made from CLT, LSL and LVL panels linked together with ductile wide flange steel beams. For lateral load resisting system (LLRS), three options were suggested for different storey heights such that, 12 storey building with core only, 20 storey building having core with interior shear walls or perimeter moment frame of and lastly 30 storey building having core and both interior shear walls and perimeter moment frames. The perimeter frame was made of GLT beam and post members whereas the core and shear walls were entirely CLT panels. Using the strength of solid vertical CLT panels as strong columns, the strong column-weak beam type framing was provided. The weak beams of wide flange steel members were used to provide controlled ductility in the system as per the principle of capacity design and their reliable overstrength capacity. Reduced beam sections were provided to achieve desired hinge locations. In result, all the of three LLRS options provided moderate to high ductility. It was concluded that the buildings of height 30 storey or more can practically constructed economically with a combination of lateral load resisting system.[13]

Most of the mass-timber buildings are constructed over a reinforced concrete podium deck and the foundations. The light-weight of timber creates considerable reduction in the load on the foundation. Therefore, the cost of the foundation is further reduced in construction.[14]

## 2. AIM

To demonstrate the ability of timber structures and hybrid timber structures as a tall building and effective lateral load resisting system.

## 3. OBJECTIVES-
- To create computer-based 3D models of timber structures using different structural systems.
- Calculate its performance under seismic and wind loading according to IS:1893 and IS 875 within

permissible deformation limits in the most severe loading conditions in India.
- Demonstrate the structural performance in terms of maximum displacements, base shear and storey drifts and roof acceleration.
- Compare the results of different models and showcase the feasibility of structural systems under considerations.
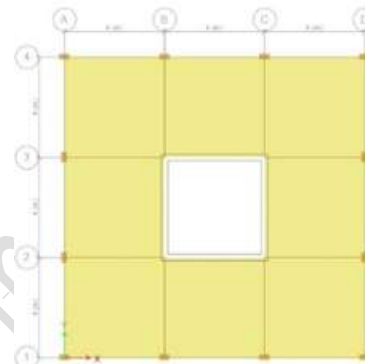
## 4. METHODOLOGY

### 4.1 MODELLING OF THE BUILDING



Figure 1Core wall model plan

A simple 12m X 12m plan was adopted and 3D models were prepared for different structural systems as shown in figure 1 by using ETABS. It is a powerful tool used for analysis and design of buildings and all the calculations are based on finite element modelling. All the plans under consideration for this study are symmetrical having bay width 4m and the floor to floor height of 3m. There are G+10 stories and 3 bays. The material properties of steel, rebar and concrete are built in ETABS but the timber properties are not readily available therefore custom orthotropic material properties of timber products were created.

The first model (Fig.1.a) consists of post and beam system with GLT beams and columns with CLT floors. Second and third models (Fig.1.b) are similar to the first having an RCC core and CLT core respectively for lateral load resistance.

### 4.2 MATERIAL PROPERTIES

The material property of mass-timber depends upon the species of wood used and the method of lamination. For this study properties of commercially available CLT panels were adopted from 'Katerra' assigned according to the

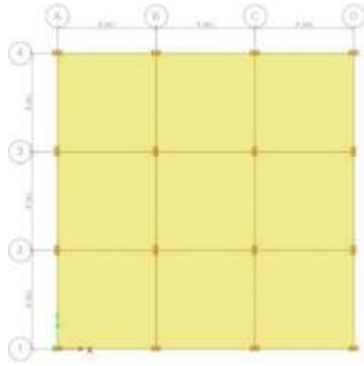| Modulus of Elasticity parallel to grain | 12400 |
|---|---|
| Modulus of Elasticity perpendicular to grain | 385 |
| Shear Modulus parallel to grain | 690 |
| Shear Modulus perpendicular to grain | 50 |



Figure 2Plan of Beam and Post mode

specifications of the manufacturer.[15] These panels are manufactured according to the widely recognized National Design Specifications (NDS) in America and CSA-086 requirements in Canada.[16] Thickness of panels is 5.4 inches (i.e. 137 mm) and it is a 5 ply panel.

The columns and Beams in the 3D model are constructed using GLT. Unlike CLT panels the GLT products are commonly available and usually customized according to the project requirements. Therefore, beams and columns of custom sizes can be used. The properties of GLT are taken from CSA-086 (2014). The floor slabs and the Shear walls are made of CLT panels of different thickness, their material properties are taken from Katerra design Manual.[15] Specific gravity of both the materials is 0.5 and Poisson's ratio is 0.3.

For the third model, a hybrid combination of concrete core and a beam and post of mass-timber is considered. The concrete grade used for analysis is M30 and the steel required is designed in ETABS according to IS 456-2000.

Table 1. Material properties of GLT

| Property | Magnitude (N/mm$^2$) |
|---|---|
| Tension Parallel to grain | 30.2 |
| Compression parallel to grain | 20.4 |

Table 2. Material properties of CLT panels

| Property | Longitudinal (N/mm$^2$) | Transverse (N/mm$^2$) |
|---|---|---|
| Tension Parallel to grain | 3.1 | 1.7 |
| Compression parallel to grain | 8 | 5 |
| Compression perpendicular to grain | 3 | 3 |
| Bending at Extreme Fibre | 6 | 3.45 |
| Shear Modulus parallel to grain | 1 | 1 |
| Modulus of Elasticity parallel to grain | 9650 | 8270 |

## 4.3 LOAD CALCULATIONS

The dead loads in the structure are calculated automatically by ETABS from provided material density. According to the manufacturer's specifications available specific gravity of 0.5 is considered. This building is planned for commercial use therefore the live loads are taken as 5 kN/m2 according to IS:875 Part-II. Floor finish load of 1 kN/m2 is assumed and mentioned as super dead load in ETABS. Wall loads on beams is calculated according to material density of 500kg/m3 (i.e. 5kN/m3 approx.). Therefore, for 5.4-inch-thick walls, wall load = 5 x 0.137 x (3-0.3) = 1.85 kN/m

## 4.4 BUILDING FRAME DESIGN

The building is assumed to be located in Bhuj region which is the most severe, earthquake zone-V in addition to one of the highest basic wind speeds in India. Rectangular GLT beam and columns of size 230x300mm and 230x400mm are provided

respectively. CLT floor sections are manufactured by cross laminating individual wood lumbers of 1.08-inch thickness in 5 layers are used. The odd number of layers reduces warping of the panels. Therefore, 5.4-inch-thick floor panels are provided according to manufacturer specifications. In case of models with shear wall core, for CLT core wall 6-inch (i.e. nearly 150mm) CLT panel was considered whereas RCC shear wall core of 150mm was tested.

### 4.5 LINEAR TIME-HISTOREY ANALYSIS

Timber is a linear elastic material, having mostly brittle nature of failure. Therefore, to get the seismic analysis of the structure linear time history is the most accurate method.[7]

### 4.6 SELECTION OF TIME HISTOREY RECORDS

In this analysis seven time history record were used. All seven records were scaled to the design spectrum provided in IS:1893-2016 using ETABS. The accelerograms were selected from the PEER Strong Ground Motion Database and USGS Centre for Strong Motion Data for this study. Accelerograms within the magnitude of 6.5 to 7 were chosen. The details of the earthquake records used are given below.

Table 3. Earthquake records considered for the seismic analysis

| Sr. No. | Location, Year, Magnitude | Station | PGA (g) |
|---|---|---|---|
| 1. | Bhuj, 2001, 7 ML | Ahmedabad | 0.105 |
| 2. | India-Burma Border, 1988,7.2 Ms | Bokajan | 0.150 |
| 3. | Chamoli, 19991 6.6 Mw | Gopeshwar | 0.358 |
| 4. | Uttarkashi, 1991, 7 Ms | Bhatwari | 0.252 |
| 5. | El Centro, 1940, 6.95 Mw | El Centro Arrey | 0.178 |
| 6. | Northridge, 1994, 6.7 Mw | Saticoy | 0.800 |
| 7. | Kobe Japan, 1995, 6.9 Mw | Kobe University | 0.508 |

### 4.7 WIND LOADS

Wind load is most critical lateral load in case of tall timber structures since the property of being light-weight helps in reducing earthquake load but not wind load. Wind load largely depends on the exposure area and not on the mass of the building. Therefore, unlike seismic loads wind loads are independent of construction materials used. For the purpose of this study the location of building is assumed at Bhuj, India as it is zone-V region of earthquake and has one of the highest wind speeds in India. A Class B building having height 33m is considered with terrain category 1 and basic wind speed of 50 m/sec according to the location.

### 5. ANALYSIS

Linear time historey analysis was carried out by using ETABS. In this study the joints and supports of the structure are assumed to be perfectly elastic as the timber properties dictate and the nonlinear links are not considered. Such condition can be achieved by providing excessive number of fasteners while assembling the building components and thus the links formed will not heavily loaded for nonlinear behaviour. The maximum permissible drift as per IS:1893-2016 is 0.4% of the building height at the roof level. In this case the building height is 33m therefore, the maximum permissible deflection is 132mm. P-delta effect was considered in dynamic seismic analysis and the mass source was defined as total dead load and 0.5 times of the live load according to IS:1893-2016 guidelines.

Different load combinations are considered for wind and earthquake load considering that the probability of both occurring at the same time is extremely low are used in the analysis. Load combinations as follows are considered.
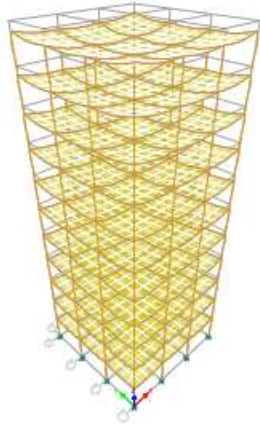
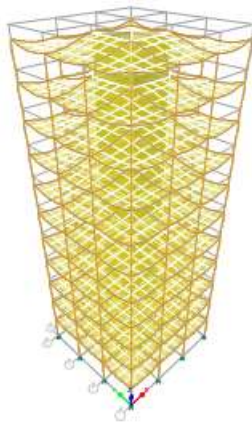Fig. 3. Deformed shape of Post and Beam model
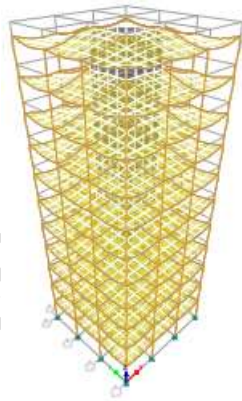


Fig. 4. Deformed shape of CLT core wall model



Fig. 5. Deformed shape of RCC core wall model

A)  For Earthquake Load
1)  1.5(DL + LL)
2)  1.2(DL + LL ± EQ-X)
3)  1.2(DL + LL ± EQ-Y)
4)  1.5(DL ± EQ-X)
5)  1.5(DL ± EQ-Y)

6)  0.9DL ± 1.5EQ-X
7)  0.9DL ± 1.5EQ-Y

B)  For Wind Load
1)  1.5(DL + LL)
2)  1.2(DL + LL ± WL)
3)  1.5(DL ± WL)
4)  0.9DL ± 1.5WL

The results including maximum base shear, roof accelerations, storey drifts and displacements for the most severe load combinations are discussed in 6.0. In the load combinations EQ load is by time historey records and simulation results obtained in ETABS analysis.

## 6.    RESULTS AND DISCUSSION

Performance of the building during dynamic loading in this study is demonstrated by various parameters such as acceleration at roof level, maximum lateral displacement, inter-storey drift, mode shapes and roof drift. The results attained through the three different models and mainly earthquake and wind loadings as a form of dynamic loads are presented. The results obtained from three different structural framing systems in the time history analysis are presented below.

### 6.1  BASE SHEAR

Base shear is a horizontal reaction at the base of building mainly due to lateral loading. From the following data it can be seen that CLT core wall model exhibit maximum base shear in both lateral directions. This is mainly due to increase in seismic mass participation and excess deformations, while stiffness remained less. Providing additional CLT shear walls for this model can increase overall stiffness and therefore reduce the deformations and lateral base reactions accordingly. From the following graph it can be seen that CLT core wall exhibits maximum base shear. This is mainly due to lower stiffness than the RCC core wall model and high deformation levels. Additionally, the ductile behavior of the steel reinforcement in RCC shear walls aids in reducing base shear by energy dissipation.
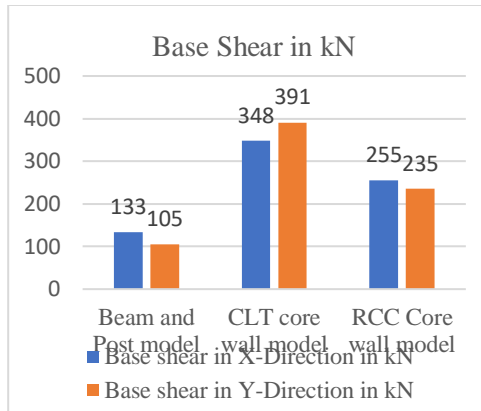
Fig. 6. Graph of Base shear due to seismic loading

## 6.2 Natural Period Of The Building

Natural periods of buildings depend on the distribution of mass and stiffness along the building in all directions. Natural periods of buildings reduce with increase in stiffness and increase with increase in mass.[17] Following data represents the period first three modes in the models studied. It can be seen that the natural period of the buildings reduces with increase in the lateral stiffness. Therefore, the contribution of mass in the change of natural period is far more less than the stiffness. This is primarily due to high strength to weight ratio of timber and higher stiffness of concrete core used in the third model.
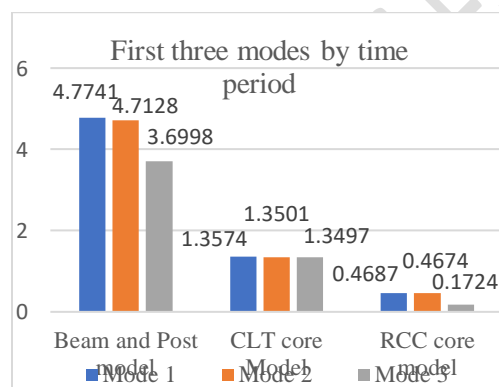


Fig. 7. Graph of first three modes by their time period

## 6.3 ROOF ACCELERATION

The inertia forces in a building are influenced by the accelerations at storey levels. In the fundamental mode of a building, least resistance is offered to deformation, therefore higher accelerations can be attained.[17]
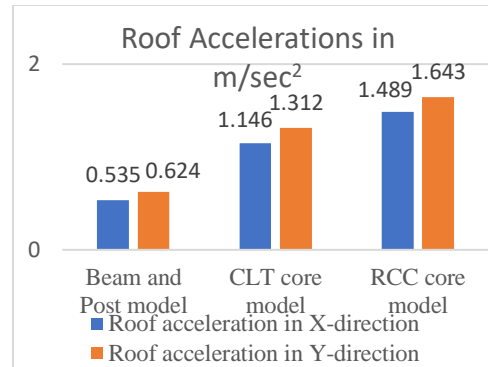


Fig. 8. Graph of roof acceleration in X and Y directions

Furthermore, higher acceleration is not desired since it causes discomfort to the occupants of the buildings and causes damage to the non-structural elements. Increase in stiffness of structures can result in reduction of time period and accordingly increased acceleration. Therefore, while designing the structures for higher stiffness, a care must be taken that roof accelerations are controlled. The chart given below shows the maximum roof acceleration attained in the seismic analysis.

## 6.4 STOREY DRIFTS AND DISPLACEMENTS

The maximum storey drift shall not exceed 0.004 times the storey height, according to IS:1893-2016. Therefore, for the models under consideration that permissible storey drift is 0.132. Following figures show the drift values in the respective models.
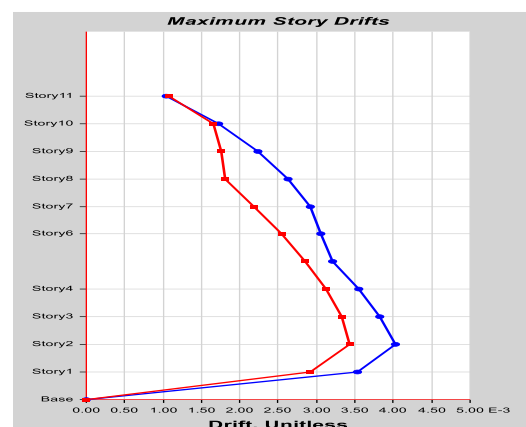


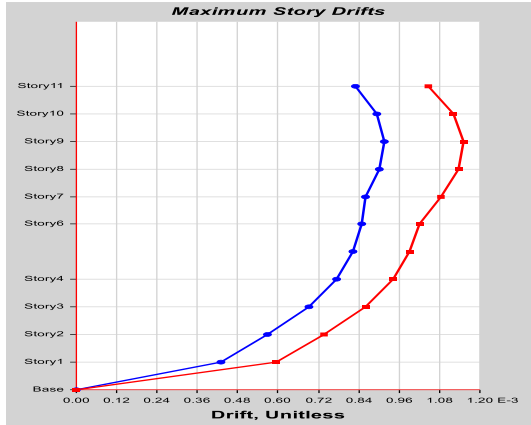Fig. 9. Maximum Storey drift for Beam and Post model

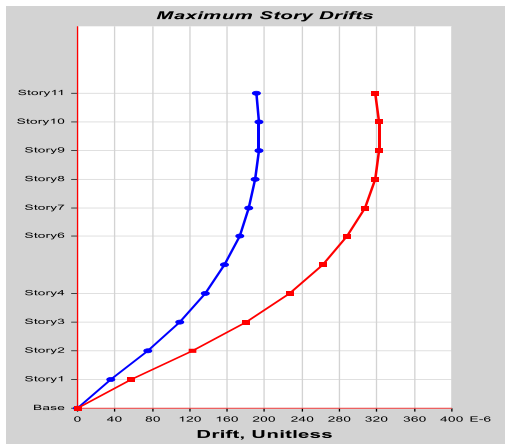Fig. 10. Maximum Storey drift for CLT core wall model



Fig. 11 Maximum storey drift for RCC core wall model

Table 4. Maximum storey drifts due to seismic loading

| Model Type | Maximum Storey Drift |
|---|---|
| Beam and Post model | 0.004033 |
| CLT core wall Model | 0.00115 |
| RCC core wall model | 0.000323 |

It can be seen that all the models have storey drift levels within permissible limits. Moreover, it is observed that the maximum storey drift values are reduced with the stiffer structural systems.

Following data represents the maximum storey displacements or maximum joint displacement when subjected to seismic loading which is measured with reference to the base of the structure. Joint displacement is desired for energy dissipation in a controlled way to avoid structural damage. From the data presented below it can be observed that the maximum displacements in a structure can be controlled by providing shear wall core as a lateral load resisting system.
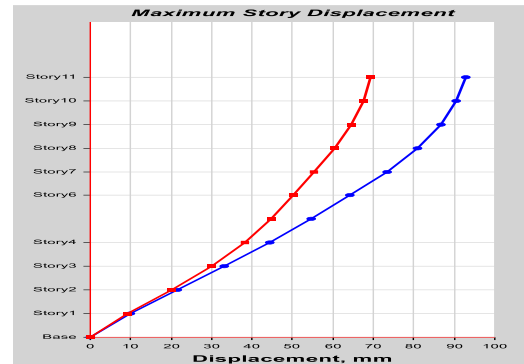


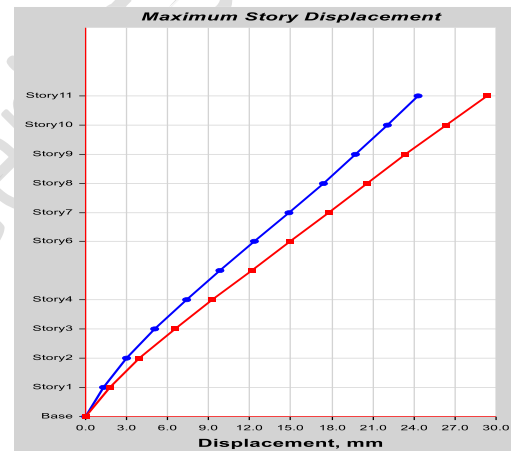Fig 12 Maximum joint displacement of Beam & Post model
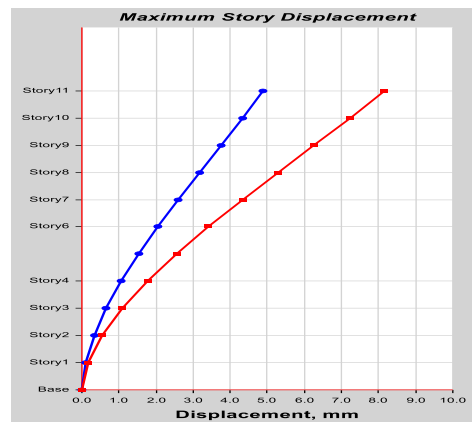


Fig 13 Maximum joint displacement of CLT core wall model



Fig. 14. Maximum joint displacement of RCC core wall model

Table 5. Maximum roof displacement due to seismic loading

| Model Type | Maximum Roof Displacement |
|---|---|
| Beam and Post model | 94 mm |
| CLT core wall Model | 29 mm |
| RCC core wall model | 8 mm |

### 6.5 WIND LOAD RESULTS

### 1. BASE SHEAR

Timber being a light-weight material its mass participation in seismic loading is comparatively less than that of other heavy materials such as steel or concrete. In this case wind load is independent of mass of the material and only dependent of the exposure area, terrain category, basic wind speeds the and height of the buildings, it can be said that the wind loads are independent of material. Therefore, for the case of timber structures no significant reduction in wind loads is seen.
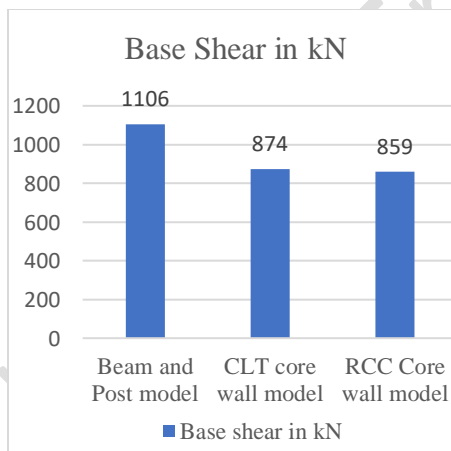


Fig. 15. Maximum base shear due to wind loading

Fig.14 represents maximum storey shear due to wind loads. It can be detected that the most flexible type of structure (Beam and post model) has maximum base shear because of absence of any special lateral load resisting system. On the other hand, both the models with core walls have approximately same maximum storey shear. This indicates the role of geometry in case of wind loads than that of the material type.

### 2. STOREY DRIFTS AND DISPLACEMENTS

From the figures given below it can be seen that all the storey drifts occurred due to wind loading are within permissible limit of 0.132. It can be observed that the storey drifts are considerably reduced in the CLT core model and further reduced in RCC core model. This can be attributed to the stiffness contributed by these models.
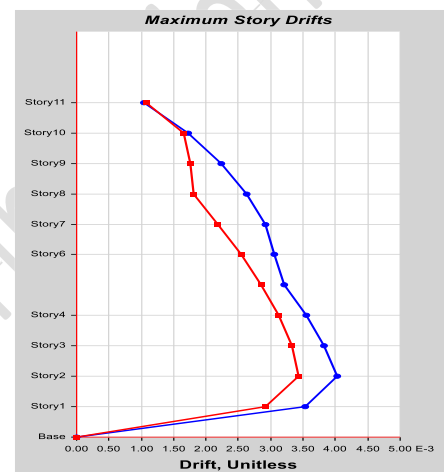


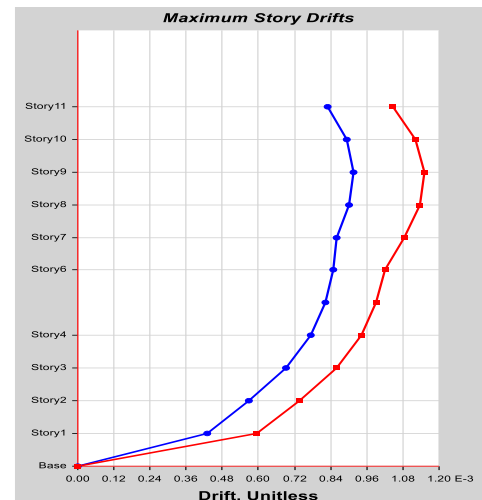Fig. 16. Maximum Storey drifts in Beam and post model due to Wind loads



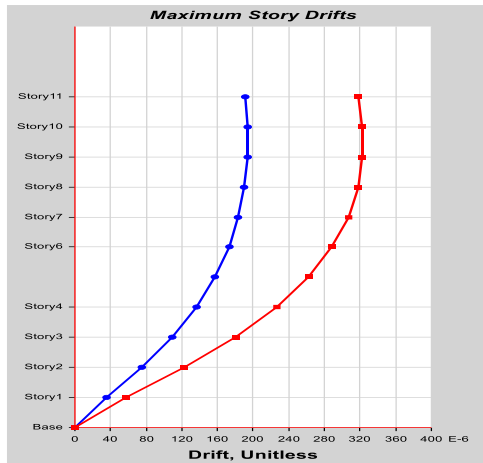Fig. 17. Maximum Storey drift due in CLT core wall model due to wind loads

Fig. 18. Maximum Storey drifts in RCC core wall model due to wind loads

Table 6. Maximum storey drifts due to wind loads

| Model Type | Maximum Storey Drift by wind loads |
|---|---|
| Beam and Post model | 0.033455 |
| CLT core wall Model | 0.002213 |
| RCC core wall model | 0.000570 |

Following data represents the maximum lateral displacement due to wind loads. It can be seen that the wind loads cause heavy lateral displacements than the seismic loads. In case of the Beam and Post model the maximum storey displacement is increased several times than the seismic loading case. This is mainly due to the light-weight property and the excessive flexibility of the first model.
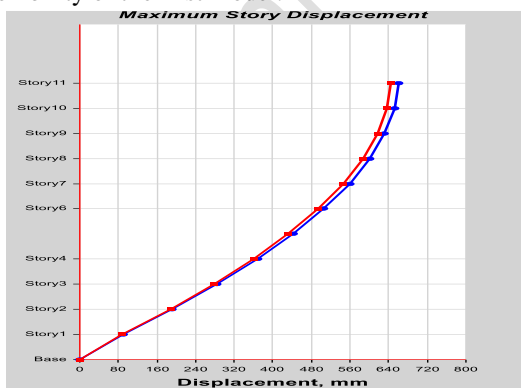


Fig. 19. Maximum lateral displacement in Beam and Post model due to wind loads
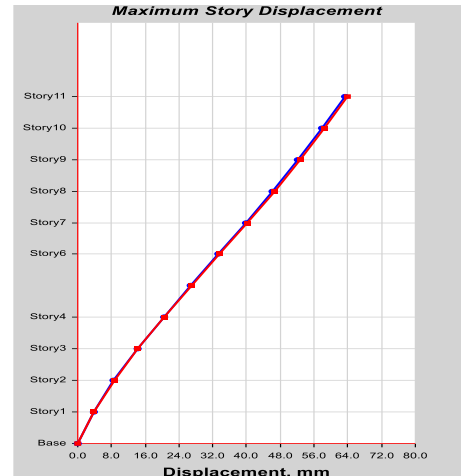


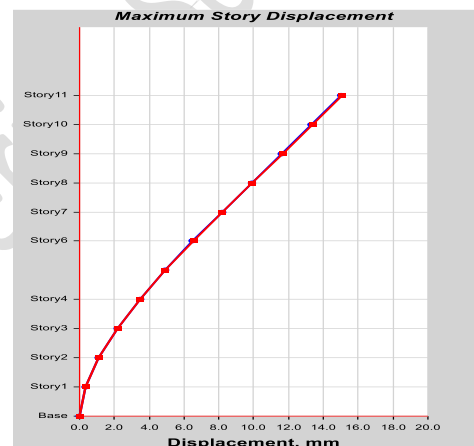Fig. 20. Maximum lateral displacement in CLT core wall model due to wind loads



Fig. 21. Maximum lateral displacement in RCC core wall model due to wind loads

Table 7. Maximum roof displacements due to wind load.

| Model Type | Maximum Roof Displacement by wind loads |
|---|---|
| Beam and Post model | 662 mm |
| CLT core wall Model | 64 mm |
| RCC core wall model | 15 mm |

## 7. CONCLUSION

Three 3D models of mass-timber structures were analyzed in ETABS for lateral seismic loads and wind

loads, including one hybrid structure with RCC core walls. All the frames demonstrated acceptable seismic performance while the addition of core walls as a lateral load resisting system reduced the seismic performance considerably.

In case of the wind loads there are excessive joint displacements observed in the first model (Beam and Post model) which are not feasible for the design. For the given model, these displacements can be reduced by up to 10 times or 40 times by providing central core CLT or RCC walls respectively.

The base shear is affected by the mass participation and for timber structures the mass density is considerably low. Therefore, the base shear values in case of the seismic loading are very low whereas for the wind loads mass participation does not play any significant role and the base shear is seen increasing by 2 to 3 times than the seismic loads.

It is observed that the major wind response is mainly due to the flexibility of Beam and Post structural system. Therefore, it should not be considered suitable for the high-rise structural systems and it may be suitable for low rise buildings.

Mass-timber is a feasible material for the construction of tall buildings provided that the adequate structural systems are used to control its performance under lateral loading. The choice of the lateral loading systems can be made according to height of the structures and its feasibility. From the present study it can be concluded that the second model (i.e. CLT Core wall structural system) can be used as an adequate lateral load resisting system for maximum sustainability benefits.

In case of RCC core wall system reduction is observed in base shear value by 25% to 40% in comparison to the CLT core wall system. This is mainly due to the energy dissipation in steel reinforcement by undergoing plastic deformation. Therefore, it can be concluded that the hybrid timber structural systems are more suitable for heavy seismic activity regions.

In this study the behavior of nonlinear links is not taken into consideration and the structural system is assumed to be functioning within elastic zones of timber. A study concerning the seismic behavior of mass-timber buildings considering the energy dissipation of nonlinear links (fixtures and fasteners) is required to demonstrate more accurate results.

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