**Comparing Reinforced Concrete High-rise**

**Structures to the New Developments**

**in Timber Structural High-rises**

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# Introduction

Timber is a pervasive material used since the ancient times for the production of furniture, sculptures and later its utility advanced in the construction of buildings. Timber is the product of nature and time, the complete cross-section of timber trunks and the crown diameter provide support, conduction and storage [[1]](#footnote-1). Cross-laminated timber (CLT) is the plate-like engineered form of timber with quasi-rigid and multi-layered composite. Primarily, it consists of several layers made up of boards that are organized cross-wide at the right angle to each other and have the capacity to bear load in and out of the plane. The huge dimensions and versatility in applications of CLT made its development in the 1990s expand and the timber engineering made its way through mineral based solid construction, architecture, monolithic buildings, and point or line supported elements [[2]](#footnote-2). Glued laminated timber (GLT) or commonly known as glulam is the traditional engineered product of timber that is developed by adding several laminates of dimension lumber held together by robust moisture-resistant glue. The lamination grains are in parallel course to the length of member and can be used as beam in its horizontal application while as column and arches in vertical form [[3]](#footnote-3).

Reinforced concrete structures are the century-old common structural material used for public structures worldwide. These structures comprise of the members like beams, columns, trusses and boards with steel bars and concrete [[4]](#footnote-4). The concrete enwraps the steel bars, but recent studies have stated that the steel corrosion severely deteriorates the durability of the concrete [[5]](#footnote-5).

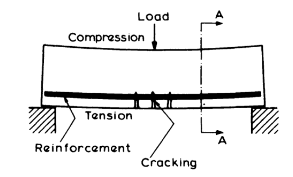
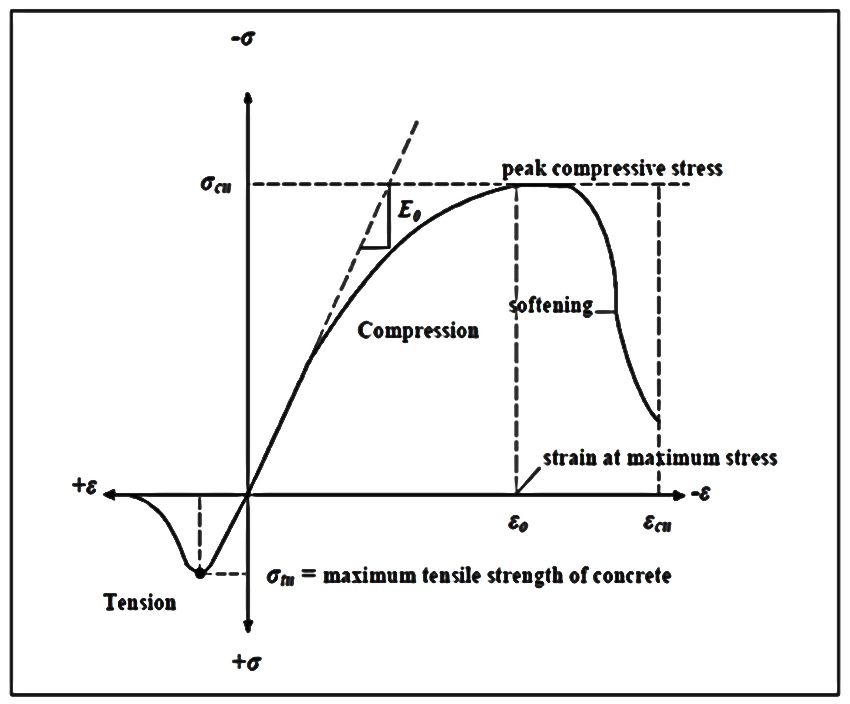
During the development period in the 1900s, the use of reinforced concrete was quite economical and became common while the use of timber for the traditional construction got superseded by mineral-based solid components such as concrete, brick and steel mainly in Europe [[6]](#footnote-6). But in the late twentieth century, timber started gaining prominence in the construction industry and structural components made up of wood increased continuously. Wood products are not only of great ecological importance but high sustainability, the versatility of wood component is manifold. Among all the kinds of building materials, timber is the most inhomogeneity in its characteristics and exhibits extraordinary variations in mechanical properties [[7]](#footnote-7).

# Engineering Properties of Reinforced Concrete

Reinforced concrete is a robust and durable material used in construction and has the adaptability to take various shapes and sizes of columns, arches, or shells. The best engineering properties of reinforced concrete can be attained by conjoining the finest features of both concrete and steel. By the combination of these two elements, the steel provides tensile and shear strength and while on the other hand concrete provides protects the steel and improves durability and fire resistance [[8]](#footnote-8). The reinforced concrete structures are planned on the basis of the tensile strength of concrete which is only 10% of the compressive strength and thus concrete exhibits no resistance against tensile forces. The bonding between the interface of concrete and steel transfer the tensile forces. The composite action of the reinforced steel is due to this bond otherwise the reinforcing bars could slip within concrete. It is imperative to design the concrete such that it is well compacted around the bars and sometimes these bars are twisted for additional mechanical grip. The compatibility of the strains is ensured based on the perfect bond between the strain in reinforcements and strain in the concrete in the adjacent member [[9]](#footnote-9). The differential expansion can be problematic for the bonds as the coefficient for thermal expansion for concrete and steel are sufficiently close.

## Composite Action and Stress-Strain Relation

Concrete has strong compression characteristics and steel has strong tension resilience along with compression properties, but an efficient reinforced concrete design will be comprised of steel in tension withstanding the concrete in compression. As the beam is bent, it is necessary for the steel to be closer to the foot of the beam to take efficiently the higher magnitudes of a load. A concrete cover depth between the bars and the outer concrete surface helps prevent the steel from corrosive reactions. At the event of increased tension, there is an increased probability of cracking to take place, but the stronger reinforcement bonds ensure that the cracks do not open up and the steel embedded in the concrete could be protected from corrosion (Figure 1a). While the shearing forces go beyond the limiting capacity of the concrete, steel reinforcement supplements it to bear the additional load [[10]](#footnote-10). As the load on the structure increases, the stress and strain increase in the concrete and reinforcement bars. The equilibrium in these forces and the compatibility of the members should be considered vitally. The choice of concrete is reliant on the necessity of the strength, magnitude of loading and size and kind of structural members. The well-compacted concrete constitutes high density, low water-to-cement ratio and chemically inert combinations. The curve for the stress-strain ratio in the reinforced concrete is generally linear as per the elasticity up to the extreme tensile strength in tension (Figure 1b). After the breaking point, cracking of the concrete begins and its strength slowly starts to decrease [[11]](#footnote-11). The steel reinforcements are of multiple types such as high-rolled mild steel and high yield, cold-worked high yield and hard-drawn steel wire.

Figure 1: Composite action and the typical curve between stress and strain in the reinforced concrete **[[12]](#footnote-12)** **[[13]](#footnote-13)**

## Engineering Properties of Timber

Timber has unique engineering properties for high-rise building construction over the centuries. Recent advances in the biological, environmental and engineering fields have brought revolutionary changes in the usage of timber as a building element. Efforts are underway in bringing about the new possibilities for efficient, larger, and viable engineered wood material. Timber constitutes warm and attractive texture and can be modified in various shapes and sizes [[14]](#footnote-14). It is a thermal insulator and has a high strength-to-weight ratio thus can also be used as a amalgamate with steel and concrete. As it is a natural building material, it does not have any controversies with greenhouse emissions and has the aptitude of renewability and recycling. It is an extremely complex material as its properties are dependent on the ecological and loading conditions. It has anisotropic properties that are its strength and stiffness is high parallel to the grain and lower across the perpendicular. The basic properties of the wood are needed to be taken into consideration before the selection. Structural timber can be obtained from both hardwood and softwood, but softwood is commonly available in Europe due to its handiness and cheaper costs [[15]](#footnote-15).

The cross-section of a tree trunk is characterized by the number of annual growth rings. When the growth of the tree is rapid, the growth rings are much wider and result in lower density and increased the strength of the wood. The strength, elasticity modulus, shrinking and swelling characteristics of the wood are different across three orthogonal dimensions. The longitudinal direction is parallel-to-grain while radial and tangential directions are perpendicular to the grain (Figure 2). Structurally wood is sturdier and stiffer in its parallel-to-grain direction. In the engineered timber, the tensile and compression strength is reduced by the effect of knots and defects [[16]](#footnote-16). These characteristics of the wood are significantly lower in the perpendicular-to-grain direction thus, timber structures are designed such that tension stresses across the perpendicular are reduced. However, the compressive stresses across the perpendicular are greater as compared to the parallel-to-grain direction. The modulus of rupture is the most complex property of timber and deals with the bending stress within a flexural element at the failed load strength. The shear strength is based on parallel, perpendicular-to-grain and rolling shear. The duration of load also plays a major role in characterizing the strength and stiffness of timber such that with longer durations of certain magnitude of load, the strength reduces [[17]](#footnote-17).

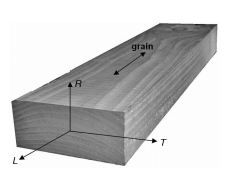


Figure 2: Three orthogonal directions of the timber wood **[[18]](#footnote-18)**

## Current Developments in Timber Applications

The new developments in timber engineered products have made dynamic expansion in the construction industry. Designers and engineers around the world are utilizing the latest techniques and designs for large-scale building capacities. CLT is one of the modified forms of timber which can substitute for slabs of concrete within floors and walls. Glulam is another engineered product that can be used in the capacity of concrete or steel beams and columns. There is high competition among building constructors to build the tallest timber towers [[19]](#footnote-19).



Figure 3: Tallest timber tower in Brisbane, Australia **[[20]](#footnote-20)**

Though increasing the height is still a challenging step but various theoretical designs have been approved and physical testing is underway. The global ecological dilemma has made the plant sciences filed conduct research on the functional properties of the wood and improve the production of natural building materials [[21]](#footnote-21). CLT and Glulam are extensively used in the current modes of construction. However, despite the technological advances, there are limitations in the utility of CLT due to perpendicular-to-grain crushing property in the panels of the floor junctions in buildings more than 10 stories tall 10 stories, 45 meters high tower featuring a hybrid of CLT and Glulam.

## Production of Reinforced Concrete

Reinforced concrete is a compound building material that needs innovative technologies for its production. Concrete is a mixture of three ingredients; 60-70% of the fine aggregates that include sand, stones, rocks and recycled glass, 10-15% of the cement which is mainly calcium silicates and aluminates and 15-20% of the water. The components of the composite can be varied according to the technological needs or apparent characteristics such as finished texture or colour. Aggregates are added in the mixture to enhance its capacity of withstanding extreme weather conditions and fire and water resistance [[22]](#footnote-22). The concrete structures are of the most common building materials because of its strong compression property and ability to hold multitude load. This feature is introduced in the concrete by reinforcing it with steel bars embedded in it primarily in the vertical beams. The wet concrete is cast around the strong steel reinforcements and when the concrete sets and hardens, the newly formed composite material is called the reinforced concrete. The steel provides resistance against bending and stretching by providing the tensile strain while the concrete offers the compressive strength. The reinforced steel bars are designed such that they have ridges on them for firm anchoring inside the concrete to avoid slippage [[23]](#footnote-23).

## Production of Timber

The production of timber as a building material involves several specialized processing operations though these procedures affect the strength and stability of the material. The initial step is the harvesting of small-diameter timber only for construction purposes. During the harvesting process, the external surface of the trunks may get damaged resulting in defects in the aesthetics and the texture of the wood. The preservation and drying of the timber are made possible by the debarking process and after that, the cross-section analysis of the trunk is carried out to measure the apparent properties of the wood. The digital fabrication and connection detailing of the wood are also to be considered for wood selection. The mechanical rounding of the wood reduces the wood's bending strength. Drying of the timbers is a challenging process as the whole timbers take much longer than the sawn timbers to dry due to their larger part of the depth and low surface to volume ratio [[24]](#footnote-24). Timber is vulnerable to the attack by fungus, insects and pests and it causes the loss in strength, stiffness and aesthetic effects. The CLT and glulam are mechanically processed by the laminated glue and an additional layer of charcoal to protect the wood from the ignition. Before using the timber products for the construction purpose is to require certain standards to be fulfilled. CLT and glulam criteria include the quality, design, and load-bearing models for analysing the required characteristics [[25]](#footnote-25).

## Strength to Reinforced Concrete and Timber

The strength of both reinforced concrete designs and timber structures is dependent on the structural components and their absolute properties. The composite of concrete and reinforced steel bars and their design eventually after the casting and drying upstarts exhibiting strength when a certain load is applied to it. The concrete gains its strength at around 7 days of casting but it takes almost 5 years to completely settle and each grain attains its maximum strength. The concrete ingredients and the steel bars are selected for the reinforced structure construction such that they are compatible, and their thermal expansion coefficient is directly proportional. The bending of the bars and the cracking in the concrete takes places upon excessive heat, both components don not expand simultaneously. The tensile and compression strength decides the flexural ductility and shearing capacities of the reinforced concrete [[26]](#footnote-26). Moreover, the constituents of the composite are selected based on the requirement of the structure.

On the other hand, the strength of the CLT shear walls is assessed based on its stiffness load-carrying capacity. In order to determine the deformations, different contributions are considered to analyse the structure. These factors include translational, rotational, panel shear and panel bending contributions. The equilibrium equations, shear wall geometry and the connection properties define the strength of the CLT structures [[27]](#footnote-27). The quantity and width of the lamella on the embedment strength in Glulam and CLT also influence the strength of the structure. In CLT, the thinner crossed layers are responsible for the strength of the embedment. Within the large dowel displacement settings, the densification and hardening effect affect the stresses and strength. However, the thickness of the embedment and its strength are particularly high in the Glulam structure models [[28]](#footnote-28). It is important to analyse the factors involved in the strength and stiffness of the models to achieve efficient results for the CLT and Glulam applications in the building industry.

## Australian Standards

In Australia, each construction project needs to be approved by the building codes on the uses of CLT and it is specific project-by-project. The relevant building surveyor must pass a permit application that analyses if the supporting documentation for the alternative solutions complies with the requirements under Australian building acts and regulations. The Australian fire codes are formulated to design the structure that provides protection and timely escape before the building collapses or inhabitants are succumbed to smoke inhalation. The regulatory measures have prescribed how a building of timber is more secure from fire and takes longer to ignite as compared to reinforced concrete. Even if the CLT building catches fire, the charcoal coating over it provides an additional layer. The main reason behind CLT improved performance in fire is subjective to variable properties of timber such as wood type, density, adhesiveness and also the nature of fire and protection coating over timber according to the standards AS 1720.4-2006. Similarly, the reinforced concrete structures have specified key standards defined by Australian codes and regulatory bodies such as AS 3600 and AS 3735-2001 [[29]](#footnote-29). They provide certain design requirements that ensure stability and strength of the building along with-it serviceability and durability. It also provides safety standards for thermal insulation, fire resistance and earthquakes.

# Construction Management

## Availability of Timber

In Australia, timber planation was quite common in States of South Australia, Victoria, New South Wales and Western Australia in the last two centuries. Primarily, shortfall of local softwood was the reason for the rapid growth of these even-aged stands of unusual pines but later on, hardwood eucalypt plantations became more environmentally friendly and economically acceptable. The timber industry is prominent economically in majority of the developed rainfall regions of Victoria. Employment in timber industry is approximately around 10,000 and the state gets the benefit of over $AUS32 annually from sovereigns and regulatory organisations [[30]](#footnote-30).

Conventionally, the timber wood in Acacia and Eucalyptus forests in western Queensland are considered as fence-post element and an obstacle to grassland development. Conceivably, the condition of trees is not quite preferable, as they have small stem diameters, the occurrence of timber deficiencies results in reduced commercial products and additional processing costs. The inaccessibility of main timber markets and high-quality timber and building hardwoods from eastern Queensland is also a cause of lower utility. Eventually, as landowners have resisted to increase the production of their timber plantations, most of the supply has been destroyed and burnt. The maintaining practice was typically foreseen by the government until late twentieth century. The poor implementation of western Queensland hardwoods is a rare illustration of the worldwide issues of market growth and marketing of timber species that are not well studied yet [[31]](#footnote-31).

Timber products from Australia and international manufacturers pay extremely high prices for smaller quantities of timber from tropical savannahs of Northern Australia. Timber for its unique properties such as high density and hardness is admired in the construction industry [[32]](#footnote-32). Many investors have shown interest in the assessment of economic viability of small-scale timber production. Nonetheless, it is not yet fully known if the demand can be increased from providing high-quality timber to permit large-scale production of timber as compared to current rate in the construction industry.

## Availability of Reinforced Concrete

Many developing economies are reportedly looking forward to improving the worth of the construction materials and boosting the output of the industry with better consumption of mechanisation, prefabrication technology and upgrading the worker’s competencies. Diverse strengthened concrete building settings had been established in the early 1970s by the construction enterprises in Europe and the United States to meet the growing demand for housing. In Australia, reinforced concrete construction is said to be the most popular and conventional method of building high-rises [[33]](#footnote-33). Almost eighty per cent of high-rises, especially those over twenty storeys have been constructed using same structural designs. This method is considered as the most economical and sustainable practice of construction for medium to high-rise buildings in Australia.

## Cost Comparison of Reinforced Concrete and CLT

According to the surveys conducted from contractors involved in CLT construction, the costs of building were estimated while excluding the costs for acoustical reducing and fire resistance. The frame of the structure in CLT was approximately $48 to $56 per gross square foot. Whereas acoustical and fire resistance costs were predicted to be from $2 to $6 per square foot. On the other hand, the cost of the frame in reinforced concrete structures was expected to vary from $42 to $46 per gross square foot. In this method, the added cost for acoustical dulling may be expected to range from $1 to $2 per square foot. Recent studies show that the cost of the structural frame in CLT buildings is around 16 to 29% greater than that of the cast-in-place in the reinforced concrete buildings [[34]](#footnote-34). Therefore, it can be stated that CLT structures cost considerably high than reinforced concrete structures [[35]](#footnote-35).

## Construction Time Comparison among CLT and Reinforced Structures

In the construction industry, the time that goes into the construction of a project is a significant factor for client that determines the type of construction material, method and the structural system that is going to put into use so that they project can be carried into the seamless manner. A construction project of any kind almost always requires a considerable amount of time, resources, efforts and financial investment in order to complete. The time required for the construction of a project depends on the owner of the project since it the time period and the demands on the client in this regard which decides the cost requirement. Here, time is always of the essence, while anything else comes secondary to the matter. In order to complete a project, timely construction of a building is key towards quick, efficient and on-time completion of the project. Here, the time required of to complete every step of the project needs to be closely look at and managed so that the construction process can be carried out at different schedule, based on how time consuming an aspect can be. This, way not only does the project remains on schedule but the various aspects are carried out in a timely and well-managed manner.

CLT structures, when compared to concrete, can be installed in a relatively shorter amount of time. Furthermore, 15,000 square feet of CLT can be installed in a 24-hour period alone, which can reduce the time required for construction even further. Courtesy of this time deduction, a number of projects made from CLT structure have been made possible in record time. The CLT can be shipped directed to job sites, where panels can be directly lifted and secured into place using steal connectors. It enables the construction of large towers and also enables the assembly of multiple floors that have been constructed on a weekly basis. CLT not only enables faster construction, but it also enables the construction of multiple floors which is often found in the combination of quieter and much safer work sites. Add in the possibilities of improvement courtesy of pre-fabrication, as well as seamless installation, and the site noise is greatly reduced, which allows for the construction in urban areas, along with minimal public disturbances. CLT also enables year around construction, the sort that is inhibited by changes in the weather.

In the present case, the estimated amount of time that was required for construction was no more than 60 working days at most i.e. 12 weeks of dedicated project management using CLT structures. On the other hand, if concrete structures were used, the entire project would have taken 83 days at the very least. Not only is the number of hours required to spent on the project are considerably reduced, but the cost estimation for concreate, steel and optimized CLT would also be vastly different from one another. According to the construction analysis alone, the reduction in construction cost was estimated to be reduced by 3.3% in case of steel building, and 4.6% than concrete building [[36]](#footnote-36).

Table 1: Expected time for construction of above hypothesised buildings using CLT and reinforced concrete

|  |  |
| --- | --- |
| **Material** | **Expected Time** |
| **CLT** | 60 working days |
| **Reinforce Concrete** | 83 working days |

Time ratio of both the processes can be determined as;

Time taken by concrete / Time taken by CLT

83/ 60 =1.38

This means that on average concrete building takes 38% more time than construction of a CLT building of same area measurement.

## Restraining Contractors on Moving to Timber Construction

In construction industry contractors always try to use traditional methods of construction. Due to this reason they are more prone to use the traditional building material as they are trained to do so. Another reason of preferring reinforced concrete over any other building material is because many contractors are not aware about the advantages and properties of the material. Typically, every contractors knows the details regarding the properties of reinforced concrete. Moreover, they also know the cost of using the material, requirement and durability as well so they try to stick to the traditional building material. Contractors and labours are well proficient in their field with all the specialties and skills. They had been following the protocols for generations now. The shift from reinforced concrete to latest engineered technology of timber will take place gradually. However, bulk timber production process has already been started in well developed nations and they are moving towards producing their domestic wood. The forest industry is also likely to bloom along with construction industry. The quality control for timber wood and analysing of the wood properties is also a challenging task [[37]](#footnote-37). The structural health monitoring task project for the whole timber construction has already started in a few developed countries including Australia, United Stated and United Kingdom.

Though timber has been used since the ancient times mainly for the production of furniture and sculptures but its versatility also spread in the construction industry and recently the shift has become more significant. This change will have a direct impact on the common workforce as they will lose their job flow in the conventional construction industry. Moreover, the technology has been focusing on finding novel and efficient ways of improving the reinforced construction and majority of the research and literature is available for this. Nonetheless, with the ecological and sustainability awareness among think tanks has made remarkable research for the importance and utility of CLT and glulam in the mainstream construction industry [[38]](#footnote-38). As more companies are adopting timber construction, there is need to introduce courses and training programs for contractors and labours who are already working in the industry.

## Safety of High-rise Timber Construction

A major safety advantage in timber construction of high-rise buildings is that its structural members, such as CLT, do not rely on additional protection measures, such as drywall, to resist fire. The required structural fire ratings are provided by each member as soon as it is installed. However once the fire reaches above the 10th story it is no use to pour water over it. A lack of familiarity, limited understanding and uncommon usage of the material as well as of the extent of fire testing before the construction and data available to the design community. it cannot be said with complete assurance that the usage of timber is 100 per cent safe and reliable yet. To study the safety of timber construction significant fire test have been carried out in the U.S. as well as Europe and Canada. The results of fire testing are similar, showing that CLT will act in a predictable manner. Fire resistance can be calculated with the help of assumptions on adhesive type, the number and thickness of “plys” which add up to make each panel [[39]](#footnote-39). Wood rotting is another safety concern associated with timber buildings that can and will start when there is at least 20% moisture content in the wood. But rotting of wood through excessive moisture is a slow process where the fungi start to grow and starting to feed on the cellulose present in the wood structure. For wood to start rotting the wood needs to remain wet all the time.

# Sustainability

The Australian construction industry has the competency of moving towards sustainable means by improving operational energy efficiency and decreasing the human force in the building. This objective can only be achieved by choosing the right and sustainable building materials. Australian builders have an awareness about the operating energy issues as the cost of electricity and gas is rising and strict building codes and regulations. Consumers have not enough understanding of the contributions of the embodied energy in creating the carbon footprints of their buildings. Only the residential construction industry's Gross Domestic Product makes up to the 7% while the whole construction sector adds up to 23% of the national carbon emissions [[40]](#footnote-40). The aim of obtaining a sustainable building can be achieved by decreasing the negative impacts of the building materials on the environment while keeping in consideration the strength and other characteristics. In a building made up of reinforced concert, it is essential to evaluate the scope of concrete and reinforced steel bars such that their impact on the environment is more advantageous as compared to negative. Similarly, while building with timber, the positive impacts of using wood should be utilized but with ensured strength and durability of the building [[41]](#footnote-41).

## Environmental Impacts

### Effects of Reinforced Concrete and Timber Buildings on Environment

The environmental benefits of using timber for construction purpose are yet not given much value by the market. After the detailed assessment of the impacts of using both reinforced concrete and timber for construction purposes and life cycle comparative analysis, it has been found out that the operation of the building despite the production of building materials is the main contributor towards lifetime energy consumption and global warming potential. But this phenomenon is decreasing as now building are adopting energy-efficient modern techniques. The energy-saving operation by using timber construction is dominated by lifetime energy saving [[42]](#footnote-42). The Environmental Assessment Tool (EAT) uptakes the use of timber and reinforced concrete as per the legislative requirements of their application in the construction industry of Australia. Its purpose is that it provides relative analysis on the sustainability of buildings by both types of materials.

The environmental profits of timber are immense as it is a natural building material. Trees absorb carbon dioxide from the atmosphere, store it and then release oxygen into the atmosphere. Whereas reinforced concrete is responsible for carbon emissions and eventually increasing the greenhouse gases in the atmosphere. Timber wood creates a carbon sink which is an exclusive characteristic for a manufacturing material. Timber is reaped from trees and when used in buildings, it stores immense carbon which is only released into the atmosphere upon wood-decaying and burning [[43]](#footnote-43). When the life cycle of timber is near the end, much of its material can be recycled and used in construction or production of panels. Wood waste from the manufacturing of timber and destruction of buildings can be used as fossil fuels. The production and transportation of timber require comparatively fewer energy resources than reinforced concrete. Reinforced concrete production requires a huge amount of energy and advanced heavy machinery. The comparison in the embodied energy and carbon dioxide emissions of different materials is expressed in Table 1.

Table 1: Embodied energy and carbon dioxide emissions by various building materials **[[44]](#footnote-44)**

|  |  |  |
| --- | --- | --- |
| **Material** | **Embodied Energy**  **(MJ/kg)** | **Carbon Dioxide Emissions**  **(kgCO2/kg)** |
| Timber | 1.20 | 0.00 |
| Reinforced Concrete | 12.0 | 0.0194 |
| Steel | 32.0 | 0.5168 |

### Benefits of Reinforced Concrete and Timber

Reinforced concrete has its benefits based on sustainability, resilience, environmental and social point of view. As reinforced concrete has high density and ability to store heat and cold, it can be used as a source of thermal energy. It also has efficient acoustic properties as it effectively reduces the transmission of low frequency sounds through concrete elements. In contrast to timber structures, reinforced concrete provides additional fire and climatic resistance. It has high durability and low maintenance requirements. As the ingredients and quantities of elements in reinforced concrete are variable, it is possible to use materials with a decreased amount of embodied energy and carbon dioxide emissions. After the demolition of buildings or the excess concrete can be recycled and reused as collective substitutes [[45]](#footnote-45). It has long term durability as compared to timber because it can resist the harsh environmental conditions and fewer damages are caused in case of disasters. Better quality reinforced concrete materials can be attained at less cost as compared to timber. It also has greater flexibility options as concrete technology allows modifying the elements in almost any shape. The timber, on the other hand, has its benefits based on its environmental and aesthetic characteristics. It is an environmentally friendly and reusable building material that requires less production and transportation energy. Timber stores carbon dioxide and offers significant insulation. Another benefit of using timber is that there is a vast land area covered with forests and have large quantities of timber trees. The wood quality of timber for added strength and stiffness, molecular plant genetics technologies can be applied for the production of modified wood with desired traits [[46]](#footnote-46).

### Cross-laminated Timber and Carbon Storage

The construction industry is largely dependent on concrete and steel at the cost of environmental safety. Concrete adds up to 4-8% of carbon dioxide emissions of the world. On the contrary, wood naturally stores carbon instead of emitting it. Traditionally, a cubic meter of wood stores up to a tonne of carbon dioxide. Wood not only removes carbon dioxides by absorbing it but is also capable of replacing steel and concrete which are carbon-intensive materials. CLT is now becoming a primary building material and can be seen in many new construction sites. CLT is an inch-thick plank of wood, supplied with knots and splinters and added aesthetic features. The strength of planks is increased by adding multiple layers and gluing them with each other perpendicularly. Recently, due to climate concerns, construction regulations have moved to a sustainable and ecological approach. For this purpose, there is a recent call for tree plantation on a huge level to absorb carbon dioxide and curb climate change. Many states have also started investing in CLT projects to participate in saving the climate mission. Using wood materials for structures is easier and time-saving as well. Since 2017, there is a sudden take up in using CLT as a building material in Japan, Latvia, Canada, France and Australia. According to a report from Ledinek Engineering, around 500 trees equate 1000 cubic meters of CLT thus, factories that process 50,000 cubic meters of CLT are trapping the carbon of around 25,000 trees annually. Carbon is stored in wood as long as it holds the building or is reused otherwise if it rots or burnt, all the stored carbon releases. Extended research work on this issue was conducted in 2014 suggested that almost 50% of the timber for construction ends up in landfills, 36% timber is recycled while the remaining 14% is burnt for biomass energy [[47]](#footnote-47).

### Energy Required in Creating the Components for Reinforced Concrete High-rises

Technological advances have made it possible to calculate the large volumes of material and energy studies in a diverse structural engineering system. Buildings consume only operating energy out of total energy utilization. The embodied energy of any construction structure includes accessing raw material, transportation, manufacturing, distribution and construction on site. In order to quantify the embodied energy and carbon dioxide emissions of any building material, it is necessary to overview the whole manufacturing and application process. The embodied energy of the total life-cycle energy varies from country to country ranging from 5% to 40%. In the building materials for reinforced concrete mix, the amount of carbon emission and embodied energy is relatively low per unit volume. Though concrete is the most commonly consumed material in the building industry, its total value in reinforced concrete structures is significantly high. Concrete cannot be recycled or reused in the majority of the structures. In reinforced concrete structures, the carbon dioxide footprint and embodied energy can be reduced not merely by the use of new construction elements like low carbon blocks of cement, residues and recycling the substitutes but also by minimizing the carbon dioxide footprint by optimization of reinforced concrete structural designs. Currently, the total cost and total weight are mainly optimized for improved structural designs. Optimized designs are also desirable for sustainability, strength and durability of the building structures. The minimizing programs of carbon dioxide footprint are achieved by adjusting the structural design to attain minimum carbon emissions in contrast to the optimized design for achieving minimum cost is of the ratio of 5% to 15% depending on the factors being assessed during calculations. This minimization can be lower for low-rise building structures having primarily tension-controlled members. On the contrary, for high-rise buildings, in which the members attain large compressive forces, the minimization can be significant. The same strategy may also be true for pre and post-stressed concrete structures [[48]](#footnote-48).

### Sustaining Timber High-rises without Effecting the Environment through Deforestation

As the awareness increases among general masses about the climate and environmental issues, the consumption patterns change accordingly, and new ways are opening up for the forest and wood construction industry. Recently, new functional green technologies are providing opportunities to fulfil consumer's needs while minimizing their effects on the environment. Recent data has suggested that by the end of the year 2022, worldwide utilization of timber will enhance by 45% that is estimated the amount of timber will rise to 2.3 billion cubic meters. Timber is a renewable and sustainable product and its continuous use may create significant environmental impacts from the time of its harvesting till product disposal. Its impacts on the environment other than deforestation are consumption access energy to produce the finished product and the greenhouse gases emission all the while timber undergoes processing. The energy utilized in transportation of timber has impacts on the environment as it is the cause of gaseous emissions and ultimately affects global warming, eutrophication and acidification. The disposal of timber has negative impacts on urbanization as urban wood waste after processing activities and demolition.

## Social Impacts

### Societal Perception of Moving from Reinforced Concrete to Timber

The growing need for residential apartment construction with the recent engineered timber applications has offered the ability to move from conventional means of construction including reinforced concrete to timber. However, there are certain barriers in the adoption of timber, especially in residential sectors. These include common misperceptions, lack of education and historical beliefs about the poor performance of timber in contrast to concrete and steel. The Environmental Assessment Tools (ETA) is also responsible for not delivering the proper information and setting up incentives for the use of timber. These reasons for the slow uptake in the usage of timber as construction material require utmost attention from the concerned authorities. The engineers and architects avoid the use of timber on the basis of their own beliefs and convince the consumers on these false perceptions too [[49]](#footnote-49). People believe that timber is a highly degradable material is likely to be destroyed in time due to moisture, pests attack and weathering. There is also an ongoing misbelief that heavy floors and walls made up of reinforced concrete are durable and economically efficient. Homebuilders in Australia have been marketing homes built of concrete and bricks thus limiting the timber designing for new homes. Thermal performance and structural capacities, acoustics and fire resistance capabilities of timber are still not well known by the local folks [[50]](#footnote-50).

### Impact of the shorter lifespan of Timber Buildings

For construction around the world, Timber is an important product. In a foreseeable future, it is possible to use timber in the construction of larger buildings and skyscrapers. But many elements effect the use of timber as a construction product. The most important factor is the lifespan of the material. Durability is the capability to perform a function over a specified period people tend to build especially the bigger ones from good materials. But buildings are just like everything else also depreciate with time and needs to be maintained regularly and periodically renovated. And the natural durability of wood can be enhanced through different treatments like coal tar, oil paints, chemical slats, and creosote oil. Brushing, spraying, injecting under pressure, dipping and stepping are some methods used for wood preservation [[51]](#footnote-51). According to a recent colloquium at Getty centre in California, the average life of building wood and masonry is about 120 years but Building Code of Australia (BCA) suggest durability design life is normally from 15 to 50 years. According to lifecycle analyses that durability of timber is same as other construction materials and this assumption is justified by the study of demolition contractors be the Athena Institute, Pennsylvania that buildings are not damaged due to the degradation of timber main structure rather design of timber plays an important role in limiting the exposure to degradation such as the 16th century Spreuer bridge in Lucerne.

Durability or lifespan of timber used for buildings is affected by many environmental components that include environmental agents such as temperature, radiations, humidity, rain, wind, soil types, pollutants, biological and biochemical agents. Besides there are certain conditions that are important to be considered before choosing any material such as thermal expansion, tensile strength, cyclic changes, abrasion, maintenance, ground contact, intended use, performance criteria, expected environment conditions and composition [[52]](#footnote-52). Through increasing durability of building timber, the trend of construction with timber can be increased. But the hardest part is to change the perspective and mind of people to move to conventional timber construction with using the modern methods of preservation, durability and protection of wood. Another issue that hold the people for moving towards timber construction is the lack of a proper understanding of how elements that the wood is made of contributing at a macro scale level in the environment, in the long run [[53]](#footnote-53). The skyscrapers and mega buildings built with timber require additional analytical studies about some elements properties that are not well studied and exist in timber. Proper architectural and engineering designs can improve the association between structural wood and construction material and maximize the lifespan of timber. However, it is also necessary to know that the construction method of steel or concrete buildings might be different from the structural construction of timber buildings.

### The Shift of Employment Aspects and Disciplines:

Europe is only 17% of the total area of land but consists of 25% or the world's forests and the quantity of timber in these forests in increasing with each year. The Western Europe forests are privately owned, and Eastern Europe forests are mainly owned by the state. USA, Canada, Russia, Germany and Sweden produce the largest amounts of sawn timber, but it is not addressed to the construction industry. While the marketplace of reinforced concrete is widely spread and is highly related to the construction industry. It is a traditional and standardized building material and the majority of the labour workforce, contractors, supply chain and producers are linked with reinforced concrete industry. In developing countries like India, China and even South Africa which has largest resources of wood use concrete for construction purposes [[54]](#footnote-54). Thus, shifting from concrete to timber will bring a drastic change in the construction industry and people associated with this industry will face huge economic losses. The concrete market is much wider and productive as compared to timber market.

### Educating People on the Benefits of CLT Structural High-rises:

Timber represents the history of civilizations where it was mainly used for conventional medicine and as well as for construction purposes. Wood is environmentally friendly, renewable and can be regrown. Timber can be used as alternative construction product especially in urban infill developments and is also ecological and sustainable material. According to Forest and Wood Products Australia (FWPA), the major reason for repulsion of living in multi-storey CLT building is that instead of logical thinking people rely on norms, culture social beliefs and past events in the society. These beliefs are rooted deep in society and require good knowledge about understanding the attitude and behaviour of consumers, due to which it is a very complicated process to change the particular behaviour[[55]](#footnote-55). The facilitation of introduction of modern timber construction technology is required. Also, the awareness is required on a large scale not only in society but on consumer, industrial and government level.

According to Grattan Institute resources restriction, social, economic changes and environmental changes are the major challenges in way of a proper introduction of timber construction in Australia. Attitude and values play an important role in the life of people. In order to solve an issue first, the behavioural construction toward certain value and attitude are studied and observed very carefully. To overcome the barriers and hurdle in the way of solving the introduction of timber. Systematic change in attitude towards environmental issue is required to motivate people toward wood construction. Marketing strategies like ‘value mode' is one of the approaches to motivate people toward timber construction in which the behaviour and attitude of a specific person is targeted based on his mode of attraction toward specific thing [[56]](#footnote-56). Common cause model is another method to motivate people in which the targeted interest is fulfilled by acquiring the relative object. For example, environment loving people will try and adopt CLT technology because of its eco-friendly impact. Thus, achieving the main target of timber used in the production of building indirectly. Positive and supportive contextual factors can motivate people with less or no interest in achieving a certain goal.

Social norms and cultural standards also play a role in the achieving of certain targets as fear or pressure of society and reward or punishment work as motivation. Proper information and awareness regarding cost efficiency can also attract people toward timber construction. The role of government is also important as it can motivate people by providing financial benefits to consumers. Bank financing is also necessary for producers and industries to support timber building products and also can provide loans to consumers on easy instalments for buying timber houses. Moreover, the main factors that influence the construction of timber are building tradition, environmental concerns and considerable structural benefits of wood. The negative perception of wood degradation and decaying can be reduced by providing proper awareness and proofs by architects and structural engineers. Building Information Modelling (BIM) and other related technologies may provide a piece of better knowledge and understanding of wood building and can promote timber construction. Introduction of Computer Numerical Control (CNC) cutting and new 3D software introduction will soon offer opportunities for timber construction in the market.

## Economic Impacts

### Viability of Timber Structures

Cross-laminated timber structures are becoming major players in sustainable construction shortly. Since the first CLT building in Australia in 2012, knowledge about the environmental impacts and strength of the building structures has been well received by the Australian people. This improvement will help in making the CLT structures a viable alternative to reinforced concrete designs in buildings. Australian Building Codes Board has modified the national construction code that will enhance the use of timber as a building element. According to the environmental and economic concerns, if timber takes uphold of the construction industry in the 21st century, Australia has to put in significant efforts to make timber a viable construction alternative [[57]](#footnote-57). Meanwhile, the literature is full of the opportunities and advantages of the use of timber in construction, there is also a need to study the barriers reported in the industry. The main viability barrier to the broader use of timber is the uncertainties about the materials used in construction. Though their strength and other properties have been well studied, there are still worries over an issue like its performance under extreme climatic conditions, fires and the durability of the buildings [[58]](#footnote-58). However, the opportunities assessed for timber use include its carbon reserving properties that not only help reduce the carbon emissions but provide an alternative approach for buildings. Timber also has the ability to be used on various kinds of lands, for instance, unstable brownfield and over service tunnels in lending the strength with urban densification. The cost of the timber is comparable to the traditional methods of construction with quality material offset by decreased foundations and time of construction. Timber buildings are provided special insurance costs as incentives [[59]](#footnote-59). However, the overall price of the product increases when the transportation charges from central Europe are added to it. This, as a result, motivates the domestic production of timber in other countries.

### Viability of Reinforced Concrete Structures

Reinforced concrete is the conventional construction material in the majority of the nations and even in Australia till date. The properties and mechanization of the concrete and the reinforcing bars make it prioritized user choice. The characteristics and building sustainability that comes with it has made it stay this far in the industry. Not only using the conventional means of construction has become a societal norm but architects and engineers still rely on the old reinforced concrete structural designs. However, the climatic change with higher wind speeds, earthquakes and floods pose a detrimental threat to the buildings and if the design standards are maintained like in the recent times, damage in the future will inevitably be manifolds. The inadequate design and structural material increase the economic risk for newer construction projects subject to natural disaster as well as corrosion of the reinforced steel bars and cracking of the concrete. These risks are chronological and spatially dependent. Since the period 1967-2005, extreme storms have caused the yearly insured loss of around $300 million in the states of Queensland, New South Wales and Victoria [[60]](#footnote-60). Nonetheless, construction projects that utilize the traditional reinforced concrete material are more often acceptable in the society being considered as time-saving, safer and cheaper. Though, the recent case studies comparing the costs of building both the methods in Melbourne has suggested that engineered timber structures are much faster and cheaper as compared to reinforced concrete with almost 50% time saving and 10% cost saving potential [[61]](#footnote-61). However, there are more economically and environmentally viable options for construction with reinforced concrete by engineering and modifying the technology such as fibre reinforced and crumbed rubber concrete.

### Effect of Building with Timber on Construction Industry

The construction industry today is the long process of evolution and developments. The earlier construction material was wood and then with the advent of technology, the modern industry adopted other means of construction including concrete, steel and bricks. However, in the efforts to reduce the carbon emissions and saving the climate, Australia has planned to shift its construction industry that relies on reinforced concrete to timber buildings. The Australian Building Code has also made amendments in the regulations of high-rises and residential buildings that can now utilize timber. Many research departments in Australia including the Centre for Future Timber Structures are researching the potential of timber, mainly its use in taller buildings [[62]](#footnote-62). This evolution in the industry will change many attributes such as the economic potential of the industry, processing and manufacturing sections, architects and engineers, labour workforce and the social conceptions. The parts of the industry that are only associated with reinforced concrete will have to face a drastic decline in the consumer product sale on extensive levels [[63]](#footnote-63). However, this change will be quite slow, and the old concrete buildings will still look forward to this industry as adaptation measures. Meanwhile, the timber industry grows, it is a chance for the conventional industry to be prepared for the new shift.

### Effect of Growing Timber Industry on Economy

The Australian construction industry has made commitments to adapt timber as a building material and increase the area of timber plantations in recent years. In Queensland, the interest in long rotation hardwood plantation is increasing and the investments in the sawn timber production are reaching new highs though currently these investments are proclaimed not financially viable. Conversely, in the long run, the ecosystem and plantation industry are expected to make a cost-effective and socio-economically desirable future. The economic models to study the impacts of timber on the economy include the quantification of carbon sequestration, salinity amelioration and ecological impacts of the hardwood plantation [[64]](#footnote-64). Though the financial returns of the timber production maybe not so positive for quite many years, the plantation forestry will help boost up the economy of the country. The economic framework of the timber industry can be derived in terms of supply and demand basis, price elasticities, efficient pricing and resource allocation. The current timber industry situation is same such as an infant industry with prices likely to increase as the supply increases [[65]](#footnote-65).

### Effect of Timber Industry on Employments

The Australian plan of forestry industry 2040 aims at two-thirds of Australia's timber production instead of native forestry. The purpose of timber production is not merely influenced by construction but also focused on bioenergy projects. Thus, the timber used will not only be limited to the infrastructure but electricity production. The metal products will also be replaced by timber same as reinforced concrete will be surpassed by timber buildings [[66]](#footnote-66). The formal timber industry employs more than 13.2 million people and is utilized in making more than 5000 types of wood-based products [[67]](#footnote-67). Timber industry’s economic contribution is increasing significantly as the need for wood is immensely increasing due to environmental changes. As the shift of construction industry will move from concrete and steel, the timber production, processing and transportation sectors will grow and provide opportunities for investments and increase the employment ratio starting from forests to finished good. However, employees in the concrete and steel industry will face complications as timber will replace their industry. The transition period will be hard for the current construction industry but will benefit the ecosystem and the economy of the country in the long run.

# Case Study on Timber Structural High-rises

In the course of recent studies, it has been suggested that reinforced concrete structures are not environment-friendly and have adverse impacts from its production until the end of life. However, timber as a building material is a more sustainable material and has shown its potential in replacing the concrete without conceding the resilience of the building structure. The main focus of these studies is on the carbon footprints, embodied energy values and structural requirements. This case study is based on a hypothetical 43-storey high-rise in a state of Australia and its design is compared with the existing literature studies. The parameters that were considered in this study included the effects of elements, size and shape of elements on the overall performance of the building. A high-rise building was made from CLT walls and concrete core and the outrigger system and it was rectangular with 43 stores and 142 meters height. It was particularly designed to meet the maximum deflection requirements which were 1/500 of the total height of the building. The analysis suggested that building can reduce carbon emissions by 50,000 tonnes in its life cycle. The embodied energy was calculated by considering all the factors from resource extraction till consumption by using the equation;

EE = ∑materiali Quantity materiali × EE factor materiali

And the results expressed embodied energy of CLT as 8MJ/kg and steel bars in the reinforced concrete as 24.6MJ/kg. While the embodied carbon was calculated by the equation;

EC = ∑materiali Quantity materiali × EC factor materiali

And the results shockingly suggested that the embodied carbon in the units of kgC/m3 for CLT was -678.3, concrete 333.6 and for steel, it was 12207. However, the building material timber in terms of volume was higher than reinforced concrete that can be used for the same size of building due to the strength capacity of timber is lower than reinforced concrete. So to meet the structural requirements, a larger volume of timber is needed. Overall studies stated that using timber for the construction of internal parts of a high-rise building can provide substantial solution for achieving both structural and environmental outcomes [[68]](#footnote-68).

# Case Study on Reinforced Concrete High-rises

Australia being low-to-moderate seismic region has to consider the reinforced concrete columns and the structural walls for improved strength and safety of the high-rise buildings. The columns in the high-density buildings have widely spaced and minimum transverse reinforcements for proving extra shear strength to the building but is not involved in the confinement of concrete or longitudinal steel bars. These specially designed structures are considered to possess low lateral load and drift capacity in a traditional setting. Studies have suggested that during earthquakes, the majority of the reinforced concrete high-rise buildings collapse because of loss of vertical load-carrying capacity as the excessive drift leads to the catastrophic collapse of vertical beams. The lateral load drift behaviour and maximum drift capacity of reinforced concrete columns can be defined on four parameters; axial load ratio, transverse and longitudinal reinforcement ratio and aspect ratio. The axial load ratio and longitudinal reinforcement ratio enhances the flexural strength and significantly decreases the drift capacity while the transverse reinforcement ratio increases the lateral drift capacity and increases the flexural strength. However, the aspect ratio has a remarkable effect on the collapse behaviour and transfer the failure mode from shear to a flexural mode [[69]](#footnote-69).

The strength of the detailed wall model depends on three stages which can be calculated to estimate the tolerance ratio of the building [[70]](#footnote-70). The cracking lateral strength can be calculated as;

Fcr = Mcr / Hw

γcr = Mcr Hw / 3EcIg

where Mcr is the bending moment to start the cracking of the concrete based on flexural tensile strength. Hw is the effective height of the wall. Ec is the Young’s modulus of concrete and Ig is the gross second moment of inertia. The yield strength Fy is calculated via the equation;

Fy = My / Hw = ϕ Fu

The yield drift is calculated by using either yield curvature or effective stiffness. For lightly reinforced concrete squat walls, the recommended approach is effective stiffness that is expressed by the equation;

γy = My Hw / 3 Ec Ieff

However, the ultimate strength Fu is calculated by conventional methods of assuming reinforced concrete ultimate strength in a linear strain;

Fu = Mu / Hw

Thus, the ultimate drift γm can be calculated by aggregating yield drift and the plastic yield drift;

γm = γy +γpl

After analyzing the figures in these equations from 14 different reinforced concrete walls, the calculations suggest that the yield drift of all walls vary from 0.1 – 0.7% and the ultimate drift ranges between 1.3 – 3.2%. Research proposes that majority of the designers understand and consider the strength properties of the reinforced concrete columns and walls but the drift behaviour is often ignored which should be an essential characteristic in evaluating the performance of high-rise building structures during the earthquake [[71]](#footnote-71).

# Conclusion

The traditional Australian industry had been relying on the use of reinforced concrete structures for centuries. It involves the concrete matrix embedded around the reinforced steel bars that have been specially made such that they avoid slippage in the mix. Globally, it had been the most common building material in most of the Western countries and still is used in the emerging nations in Asia and Africa. However, with the emergence of construction sciences and the recent studies that the concrete does not protect the steel bars from corrosion. Moreover, the recent global concerns for climate change and protecting the environment have shifted the flow of construction material selection from reinforced concrete to timber products including CLT and glulam. However, there the societal perceptions and economical restraints are keeping people from moving towards timber construction. The skyscrapers and residential buildings require additional analytical information to study the ingredients, quantities and properties of the materials. Suitable architecture and construction designs can improve the relationship between structural wood and artificial building materials and maximize the lifespan of high-rises. It is imperative to calculate the tensile and shear strength and evaluate other properties of the building material to ensure the safety of buildings especially high-rises from the climatic effects and natural disasters like seismic incidents. The site of the building should also be studied well before designing a building plan to measure the exact characteristics of the building material be it any engineered form of timber; CLT or glulam or reinforced concrete elements.

The shift of the construction industry from conventional reinforced concrete to timber will have a significant impact on the social, environmental as well economical situations of a country. Australian building standards have now made it evident that its efforts in moving the trend are not only on the public level but the private construction companies must also follow the same patterns. Before choosing any building material, builders will not only have to calculate the cost values but also the embodied energy and carbon emissions. This move is extraordinary in its practicality as many nations are now competing with each other for the construction of tallest timber tower. It will help in achieving the sustainable goals for newly constructed buildings and will motivate nations to improve their domestic timber production. Both reinforced concrete and timber structures have their benefits and limitations but the need of the hour is to adopt a more sustainable option that is not only economically or environmentally viable but is graciously accepted by the general masses. It is also necessary to create awareness among people about the utility of different building elements. The future prospects of construction industry seem to be moving towards timber usage and thus contributing in saving the planet directly and indirectly.

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