# Significance of Density in Structural Timber Engineering and Density Profile of Bhutanese Softwood Timber

Tshewang Nidup[1*], Andrea Frangi[2]

[1]Department of Civil Engineering, Royal University of Bhutan
[2] Institute of Structural Engineering, ETH Zurich
E-mail: *tnidup.cst@rub.edu.bt

*Received: 14 April 2025; Revised: 9 June 2025; Accepted: 10 July 2025, Published:17 August 2025*

**Abstract**

Given its favorable structural and environmental attributes, timber is witnessing a renaissance as a viable modern structural material. A vital property influencing the use of timber as a structural material is its density. Density not only dictates the self-weight of structures but is one of the key characterizing parameters for timber strength. Structural softwood species in Europe are graded into strength class ranging from C14 to C50 according to the requirement established in EN338. A C14 strength class, for instance, must have a characteristic density value of 290kg/m$^3$ and a mean density value of 350kg/m$^3$ at 12% moisture content. More significantly, the strength of fasteners used for connections in timber structures is greatly influenced by density. The embedment and withdrawal strength of fasteners which affect the connection's ultimate capacity and behavior are very much a function of timber density. Further, the ease and cost of processing and fabrication and the charring rate of timber during fire are also dependent on its density. Timber, however, exhibits significant inter and intra species variability in its density. The Joint committee for Structural Safety (JCSS) recommends a probabilistic model for density variability for graded softwood in Europe with a normal distribution variation and a coefficient of variation (COV) of 0.1. Currently models to represent the density variability for native timber species in Bhutan is nonexistent. This paper discusses the importance of density in timber structures and presents the density profile recorded till date within the overall framework of developing the probabilistic model to represent the density variation in Bhutanese conifer timber species.

***Keywords:*** *Timber Strength, Characteristic Density, Strength Class, Embedment and Withdrawal Strength, Probabilistic Model, Distribution and Coefficient of Variation*

## 1. INTRODUCTION

Timber, a natural renewable material, is witnessing a renaissance as a viable building material in modern construction. Advances in engineered timber products and technology along with the growing emphasis to decarbonize the building sector have positioned timber as a viable alternative to steel and concrete in a wide range of structural applications. It is widely hailed as the building material of the future in view of its favorable structural and environmental attributes (Smith & Snow 2008, Wegener & Zimmer 2008). A comparison of its environmental credentials in terms of emission and embodied energy with concrete and steel is given in Table 1 (Gonzalez, 2006).

***Table 1:*** *Embodied Energy and Emission Comparison*

| Material | Wood(Natural) | Concrete | Steel |
|---|---|---|---|
| Embodied Energy: $MJ/kg$ | 1.20 | 12 | 32.0 |
| Emission: $kgCO_2/kg$ | 0.0000 | 0.0194 | 0.5168 |

## 2. IT'S ALL ABOUT DENSITY

Wood density depends on several factors and varies with the amount of water it contains. It is thus required to cite the moisture content at which its density is measured. The densities of the timber when dry usually refer to a moisture content of 12 per cent (Harding, 1988).

The single most important property influencing the mechanical performance of timber is its density (Dinwoodie 1996). It not only dictates the self-weight of structures but is one of the key characterizing parameters for timber strength. Structural softwood species in Europe are graded into strength class ranging from C14 to C50 according to the threshold established in EN338. A C14 strength class, for instance, must have a characteristic density ( taken as the 5$^{th}$ percentile value) of 290kg/m$^3$ and a mean density value of 350kg/m$^3$ at 12% moisture content in addition to similar limiting values for strength and stiffness. The mean and characteristic density threshold for each softwood strength class as per EN 338 is given in Table 2.

***Table 2:** EN338 Strength Class and Density Threshold*

| Strength Class | Characteristic Density(kg/m³) | Mean Density (kg/m³) |
|---|---|---|
| C14 | 290 | 350 |
| C16 | 310 | 370 |
| C18 | 320 | 380 |
| C20 | 330 | 390 |
| C22 | 340 | 410 |
| C24 | 350 | 420 |
| C27 | 370 | 440 |
| C30 | 380 | 460 |
| C35 | 400 | 480 |
| C40 | 420 | 500 |
| C45 | 440 | 520 |
| C50 | 460 | 540 |

More significantly, the strength of fasteners used for connections in timber structures is related to density. The embedment and withdrawal strength of fasteners which affect the connection's ultimate load carrying capacity and behavior are dependent on density. Likewise, the ease and cost of processing and fabricating timber products and the charring rate of timber during fire are also influenced by its density. Density, therefore, is a very critical property for ensuring the reliability and safety of timber structures.

## 3. DENSITY AND STRUCTURAL EFFICIENCY

Mechanical performance of structural material is as much influenced by density (ρ) as it is by its Strength and Stiffness (Young's Modulus, E). Specific stiffness, defined as the ratio of Young's Modulus to Density (E/ρ) rather than the absolute Young's Modulus (E), provides a normalized measure of a material's stiffness relative to its weight, and serves as a more meaningful metric of its structural efficiency (Gordon 2003).

The comparison of E, ρ and specific stiffnesses (E/ρ) relevant for flexural member, and compression member as a column and a wall panel made of steel, concrete and wood is made in Table 3.

***Table 3:** Comparison of Efficiency in Different Structural Roles*

| Material | Young's Modulus $E$ (MN/m²) | Specific Gravity $\rho$ | $E/\rho$* | $\sqrt{E}/\rho$** | $\sqrt[3]{E}/\rho$*** |
|---|---|---|---|---|---|
| Steel | 210,000 | 7.8 | 27,000 | 59 | 7.7 |
| Concrete | 22,000 | 2.5 | 9,000 | 59 | 11 |
| Wood (Spruce) | 14,000 | 0.5 | 28,000 | 240 | 48 |
| | | | | High Premium for Low Density | |

* Weight Cost" for Deflection Criteria "Flexural member"

** Weight Cost for Compression Load Criteria in a Column

*** Weight Cost" for a Compression Load Criteria in a Wall Panel

Steel, obviously has a high absolute stiffness, but it is also very heavy with a specific gravity of 7.8 reducing its specific stiffness. In contrast, a well-chosen timber can offer a much lower density with a favorable stiffness, resulting in a high E/ρ value and thus serving as a very efficient structural member. This structural efficiency is a key driver for the growing popularity of engineered wood products (like glulam, CLT and LVL) in sustainable structural design.

## 4. DENSITY (SELF WEIGTH, COST AND LATERAL STABILITY)

Density has a bearing not only the final size of elements and the load path systems in a structure but also the cost and general stability of structures.

### 4.1 Self-Weight and Load Calculations

The self-weight (dead load) of a structure is directly proportional to the material density. Structural members must carry not only live and environmental loads but also their own weight. Thus, especially in long span and tall structures, using lower density material can reduce the overall structural mass, leading to savings in size and cost of foundations, transport and handling, and also lead to lower seismic inertia forces.

### 4.2 Cost Implications

Material density influences the overall cost of structures as well. Denser materials often offer higher strength and stiffness, allowing for smaller cross-sections. However, they can be more expensive per unit volume and more difficult to process or transport. Lower density materials are easier and cheaper to transport, especially over long distances. Balancing structural performance with material efficiency and economic viability is essential.

### 4.3 Lateral Stability

Material density also has a strong bearing on the structure's stability particularly in light-frame and tall structures. Some minimum mass (density) can help improve resistance to both uplift and overturning under wind loading. These effects are accounted for in the design codes via the requirement for load combination considerations. The load combination under wind loading conditions as per IS 800 and EN1990 are given below in Equation 1 and 2

*IS 800*
$$\left.\begin{array}{l} 1.5(DL+WL) \\ 0.9DL+1.5WL \\ 0.9DL-1.5WL \end{array}\right\} \quad (1)$$

*EN1990*
$$\left.\begin{array}{l} 1.35\cdot G_k+1.5\cdot Q_{wind} \\ 0.9\cdot G_k+1.5\cdot Q_{wind} \end{array}\right\} \quad (2)$$

The reduced load factor of 0.9 for deal load ($0.9DL$ in IS 800 and $0.9G_k$ in EN1990) is used for stability check under wind load combination. Density in this regard has a positive impact of ensuring natural stability to structures.

## 5. DENSITY AND CONNECTION STRENGTH

Dowel-type fasteners such as bolts, nails, and screws are commonly used to form mechanical connections in timber structures (Blass & Sandhaas, 2017). The performance and capacity of these connections are very much a function of timber density. The embedment strength and the withdrawal capacity of dowel-type fasteners which directly affect the overall strength and reliability of timber joints are dependent on the density. The embedding of the fasteners into the wood and the withdrawal of the fasteners from the wood is depicted in a nailed connection at near failure stage in Figure 1 (Thelandersson 2003).

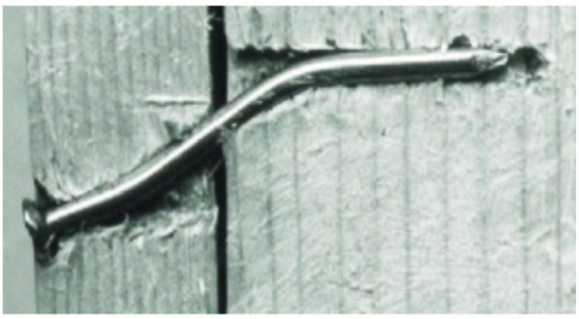

***Fig. 1:*** *A nail fastener connection near ultimate capacity (Blass and Sandhaas 2007).*

### 5.1 Embedment, Withdrawal Strength and Wood Density

The embedment strength refers to the resistance of timber when being crushed under the action of a stiff straight dowel (Porteous & Kermani, 2013). Eurocode 5 expression for the characteristic embedment strength of pre-drilled nails of diameter less than 8mm and screws of diameter less than 6mm is given in Equation 3:

$$f_{h,k} = 0.082\cdot(1-0.01d)\cdot\rho_k \quad \text{(in MPa)} \qquad (3)$$

$d$ = dowel diameter (in mm),

$\rho_k$ = characteristic density of the timber (in kg/m³).

The withdrawal strength governs the resistance of a fastener to being pulled out of the timber. Eurocode 5 relation for characteristic axial withdrawal capacity of fasteners to density is given in Equation 4.

$$f_{ax,k} = k_{ax}\cdot\rho_k^{\alpha} \qquad (4)$$

$f_{ax,k}$ = characteristic withdrawal strength,

$k_{ax}$, $\alpha$ = empirical constants depending on the fastener type and penetration depth,

$\rho_k$ = characteristic density of timber.

The relation between density and embedment and withdrawal capacity is illustrated in *Fig. 2*.

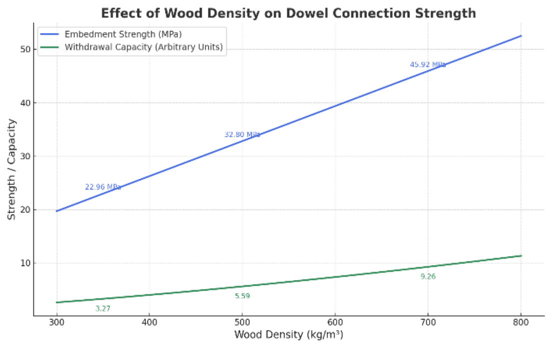


***Fig. 2****: Relation between density and connection strength.*

### 5.2 Behavioral Implications

Wood density also affects the ductility and failure mode of dowel connections. Higher density woods tend to produce more ductile failure modes (via yielding of the dowel with timber crushing), which are favorable for structural performance and energy dissipation.

## 6. DENSITY VALUES AND VARIATION

Wood exhibits substantial natural variability in density both between and within species.

### 6.1. Inter and Intra Species Variation

Different wood species exhibit varying ranges of density, often reflective of their growth patterns and cellular structure. According to the FPL Wood Handbook (USDA, 2021), basic density (oven-dry mass/green volume) can range from less than 300 kg/m³ for lightweight hardwood like balsa to over 1,000 kg/m³ for dense hardwoods such as lignum vitae. Figure 3 shows the typical value of density of some common softwood and hardwood at 12% moisture content.

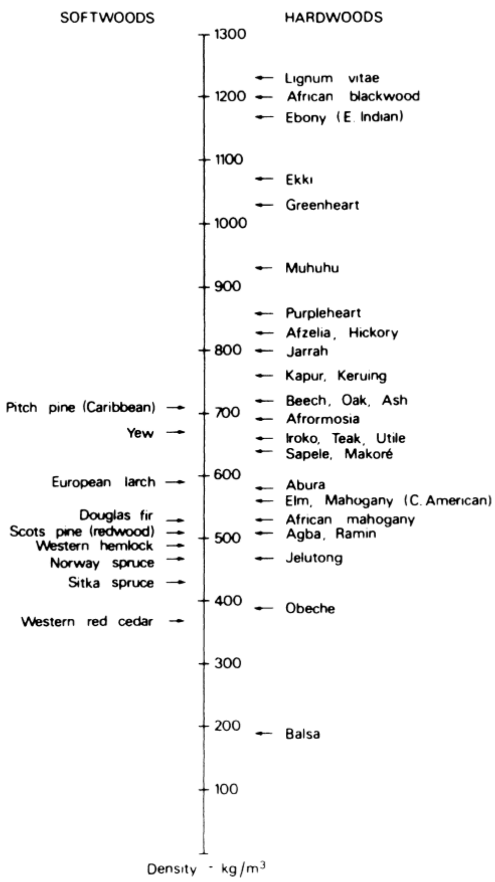


***Fig 3:*** *Density value at 12% moisture content (Building Research Establishment UK)*

Fig. 4 shows the frequency scale of oven dried density of some common species illustrating the variability, both between and within species (Niemz 1993).

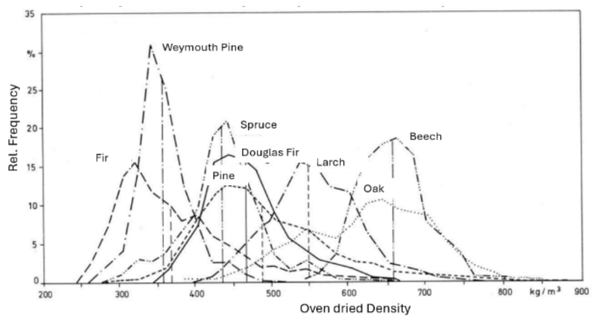


***Fig. 4**: Oven dried density frequency of common wood species (Niemz, 1993).*

### 6.2. Probabilistic Model for Density

Given this inherent variability it is essential to account for material property uncertainty in the design process**.** The Joint Committee on Structural Safety (JCSS) recommends a normally distributed random variable with a coefficient of variation (COV) of 0.1 to model the variability of density for graded softwood in Europe. Figure 5 depicts this model for an arbitrary timber with a mean density of 450kg/m$^3$ for illustration purpose. Such probabilistic models make it possible to incorporate uncertainty in material properties during the design process and for assessing the probability of failure and conducting sensitivity analysis.

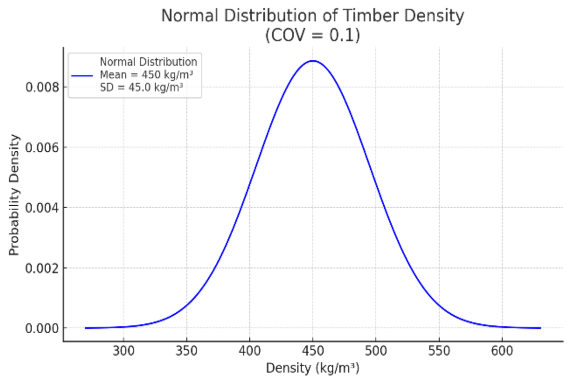


***Fig. 5**: JCSS model for timber density*

## 7. DENSITY PROFILE OF NATIVE BHUTANESE CONIFER SPECIES

The mechanical properties of native timber species in Bhutan have never been investigated. There is a complete lack of data and knowledge on the strength and other key properties necessary for the structural application of native timber species. As such, models like the one recommended by the JCSS for graded softwood in Europe are currently nonexistent. Within the scope of a study to strength grade local timber species, the variability of density of some common softwood species is being studied to formulate a probabilistic model for density variation and determine the mean and characteristic density values. Figure 6 shows the green, oven dried (ODD) density and density as 12% moisture content for three softwood species growing in the western part of the country.

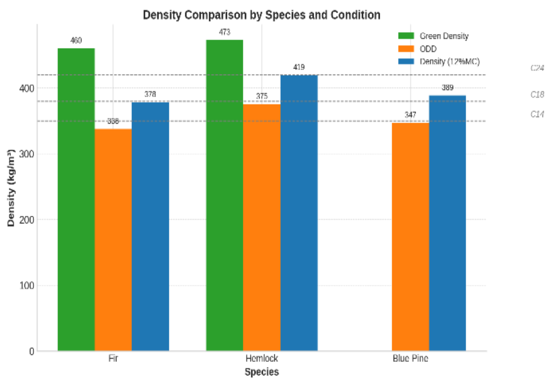


***Fig. 6:** Density at different state of moisture content*

These are initial mean density values from a limited number of samples investigated at the time of the submission of the paper. Based on these preliminary values, Hemlock and Blue pine meet the mean density value of strength class C18. Fir meets the requirement for C16. As the data pool grows and widens, a much more refined and clearer density profile will emerge, resulting in a more representative model for variation and values for the mean and characteristic density.

## 8. CONCLUSION

Material density is like a double-edged sword in structural design. It influences deadload and cost but also plays a vital role in the dynamic performance and stability of the structure. Density is of great relevance for timber structures. It affects both the strength of the timber and the load carrying capacity and behavior of connections. Understanding the variation in wood density is essential for accurate prediction of structural performance and efficient material utilization. Proper characterization of density is thus essential for safe and efficient structural design especially when working with ungraded and/or new-growth timber species as is the case with the native timber species in Bhutan.

### REFERENCES

Bureau of Indian Standards. (2007). *IS 800: General construction in steel – Code of practice*. New Delhi, India: BIS.

Dinwoodie, J. M. (2000). *Timber: Its Nature and Behaviour*. Building Research Establishment, UK.

European Committee for Standardization. (2002). *EN 1990: Eurocode – Basis of structural design*. Brussels, Belgium: CEN.

European Committee for Standardization. (2004). *EN 1995-1-1: Eurocode 5 – Design of timber structures – Part 1-1: General – Common rules and rules for buildings*. Brussels, Belgium: CEN.

European Committee for Standardization. (2016). *EN 338: Eurocode – Structural Timber – Strength Class*. Brussels, Belgium: CEN.

Forest Products Laboratory (2021). *Wood Handbook: Wood as an Engineering Material. General Technical Report* FPL-GTR-282, USDA Forest Service, Madison, WI.

Gerd Wegener and Bernhard Zimmer. *Building with wood is Building for the Future*. In Timber Construction Manual. Basel, 2008

H. E. Desch and J. M. Dinwoodie. *Timber Structure, Properties, Conversion and Use*. Macmillan Education UK, London, 1996

Hans Joachim Blaß and Carmen Sandhaas. *Timber Engineering - Principles for Design*. 2017

Ian Smith and Monica. A Snow. *Timber: An ancient construction material with a bright future*. The Forestry Chronicle, 84(4):504–510, August 2008.

Ingo Burgert, *Wood physics & Wood materials Chapter III Wood density*, ETH Zurich

J. E. Gordon. *Structures, or, Why Things Don't Fall Down*. Da Capo Press, New York, 2nd da capo press ed edition, 2003

Jack Porteous and Abdy Kermani. *Structural Timber Design to Eurocode 5,* Wiley-Blackwell, 2013

Joint Committee on Structural Safety (JCSS) *Probabilistic Model Code*. Zurich, Switzerland, 2001

Sven Thelandersson. *Introduction to Wood as a Construction Material*. In Timber Engineering. John Wiley & Sons Ltd, West Sussex, 2003

T Harding. *British Softwood: Properties and Uses*, Forestry commission bulletin 77, 198