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ESTIMATION FOR CHARACTERISTIC VALUE MECHANICAL PROPERTIES OF STRUCTURAL TIMBER

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ABSTRACT

Characteristic value is generally a value that corresponds to a fractile of the statistical distribution of a timber property. For modulus of elasticity, the fractile is the 5-percentile and the mean value is also a characteristic value. Due to the presence of random defects, the testing of samples from a population will result in mechanical properties which can be represented by a statistical distribution. Limit state design codes are based on characteristic values of these properties and are determined as the weighted means of the sample lower 5-percentiles for strength properties and density, whereas the weighted mean of the sample averages (50-percentile) is used for determining modulus of elasticity. To account for safety reasons and strength values of timber, there is very much essential for structural dimensioning, and these are calculated based on the characteristic value of timber, which corresponds to the 5% percentile of a given probability distribution model. The main objective of this study was to estimate the characteristic values of modulus of elasticity and modulus of rupture of timber on best probability distribution model and the subsequent calculation of the characteristic value as indicated by EN 384:2004 allowing to evaluate its accuracy. In the estimation method, Indian standard methods to evaluate the mean strength values and then they are being compared with strength class table for different timber species.

KEYWORDS: *Characteristic Value, Bending Strength, Modulus of Elasticity, Strength Class*

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I.INTRODUCTION

Timber is used as construction material for last many years, but the research field covering the prediction of the strength of structural timber is still under development stage. At present, the common conception is that the determination of strength properties has to be determined for every timber species individually. In India, there are more than 1600 commercially available timber species among which 150 species of timber can be used for engineering purpose. The largest amount of these wood species are hardwoods. These wood species are often used when high strength and high durability are required. At present, timber is increasingly coming from sustainably managed forests. Through forest management process, the forests are preserved and have an economic value for the local population. A result of this approach, more and more unknown wood species in small quantities are coming in the market, the strength properties of which have to be determined that can be used for construction of bridges, houses and high rise buildings. In India, the methods for the determination of strength properties of a timber species is IS 1708 -1986 where grading rule has not been applied. Thus to use the timber in structures, grading rules have to be formulated that are related to the strength properties which can be determined by tests. For machine grading, for example, the density and modulus of elasticity are used. For softwoods species, machine grading is more accurate and gives higher yields in the higher strength classes in comparison with visual grading. But for hardwoods, a major problem for visual grading is that the most important feature for the mechanical properties, the slope of grain, is very difficult to measure in practice.

André L. et al (1) found out the relationships between the characteristic values of the evaluated strength properties and the coefficients obtained of timber during the study were significantly higher when compared to those of the relationships proposed by ABNT NBR 7190 (1997), which implies in more conservative estimates by this document for the evaluated species.

Experimental measurements of shear and compression strength values were performed for 40 hardwood species by Anderson Renato Vobornik Wolenski (2) and the precision of the relation proposed by the Brazilian standard was evaluated using the analysis of variance (ANOVA) method. Linear, exponential, logarithmic, and geometric regression models were used as an alternative to the NBR relation for shear strength estimation. He found that the regression models proposed in the work are an alternative to the equation of the standard. The higher coefficient of determination was found for the geometric model, suggesting that it is the model of best fit and is the most appropriate for estimation of shear strength along the grain from compression strength values. The analyzed tropical wood species, classified as Brazilian hardwood, demonstrate a potential for structural use in civil engineering

Sung-Jun Pang(3) in their study found the condition that would be able to apply the censored data analysis for more precise 5th percentile determination. With the ideal tension test data, the censored data were simulated by reducing constant strengths from randomly selected data. He also found out that the proportion of censored data and the amount of under-measurement were investigated by comparing the precisions of censored data analysis. Lastly he concluded that from a hypothesis, the constant strengths were underestimated when a specimen failed in grip.

Andreas Briggert (4) in their paper showed that in order to guarantee appropriate safety levels of timber structures, there is a need to further develop the grading standards. Presently, there is considerable risk, using grading methods applying a global board property or the lowest local board property along the whole board as IP to strength, that the minimum requirement of 5-percentile characteristic strength given in EN 338 [1] for a graded class are not fulfilled for timber graded in the daily production.

The advantages of using a probabilistic approach to obtain a more reliable prediction of the reference properties of these timber members in situ has been described by José Saporiti et al (5) in their paper. They presented an approach that combines information from common non-destructive techniques (NDT), such as visual assessment and ultrasounds, and those from semi-destructive tests (SDT), as meso tension specimens and wood cores. An application of this approach to maritime pine (Pinus pinaster Ait.) and chestnut (Castanea sativa Mill.) timber pieces of structural dimension has been presented. They mentioned that the results obtained with the probabilistic approach are promising, given the similarity with the results obtained for the modulus of elasticity and the correlation between the bending strength and the bending modulus of elasticity.

II. MATERIAL AND METHODS

Strength properties ($\overline{E}$, $\overline{f_{mean}}$, $E_{0,mean}$, $\overline{f_{05}}$, $f_{m,k}$, f_k) were obtained using equation mentioned in EN 384:2004 following the assumptions and the test and calculation methods of Indian and European Standards. In order to obtain a greater comprehension of results, four types of timber species named *Dalbergia spp.* designated as Sample A, Sample B, Sample C and Sample D were used being divided into strength classes of the hardwood group mentioned in BS EN 338:2003 (E) with a moisture content close to 12%, which consists of the equilibrium moisture content.

2.1 Grading of Timber for Structural Use

Safety of any timber structure will depend upon different factors like the correct mechanical strengths, good prediction of the structural behavior of the design aspects and good workmanship during the execution of civil construction work. The cross section size of specimens shall be the same within a sample, but different for other samples, reflecting the range of sizes to which the grading rules are applicable. However, if the size effect for the grading rule has been established for a similar species, then fewer sizes may be tested. The below mentioned Fig.1 shows the relationship between the characteristic strength value and the design strength value, where the design strength value is the characteristic value divided by the material factor. It is clear that when the material factor is a fixed value, and Rk is a fixed percentage fractile of the distribution, the variability in timber strength properties influences the reliability of the structure. Two different strength distributions can have the same characteristic value, but different mean and standard deviations. During grading, the structural beams are assigned to three grades (a), (b) and (c). The 5 percentile are indicated with vertical dashed lines as depicted in Fig. 2. The grading has two effects: the 5 percentile of grades (b) and (c) are higher than the 5 percentile of the ungraded population and the variability in strength properties of the three grades is much lower than that of the ungraded material. This results in a more economic use of the timber. For grading timber, settings have to be determined. These are limit values for the prediction values that determine which strength class the timber can be assigned to. The strength values of timber can only be verified on the basis of the properties of a sample that is tested destructively. For small numbers of pieces in a sample, the characteristic values of a strength grade can vary significantly between tested samples. The characteristic strength value of strength properties of timber can be determined irrespective of the number of pieces in a sample. Hence for hardwood timber, the assigned strength classes can be determined in a reliable way and the yield in the higher strength classes can be increased. This will contribute to an economic, safe and sustainable application of timber in structural applications.

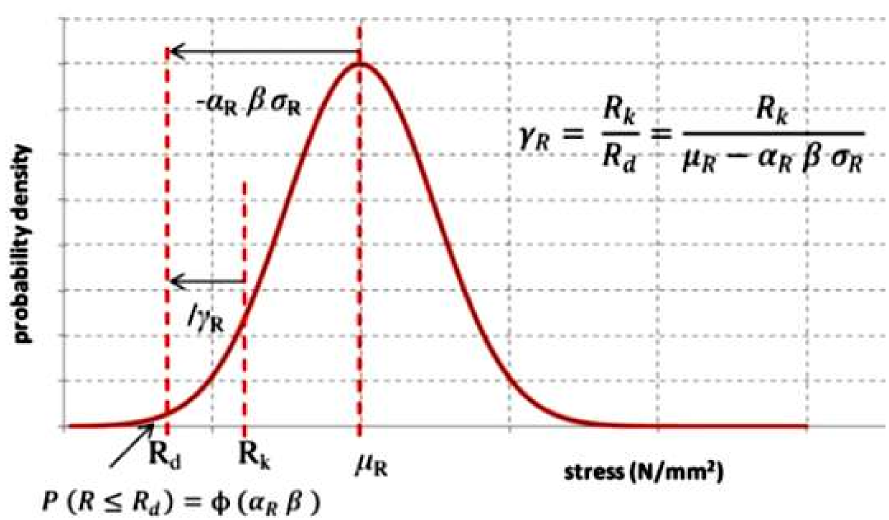

Figure 1: Co-Relation between Characteristic Strength Value and Design Strength.

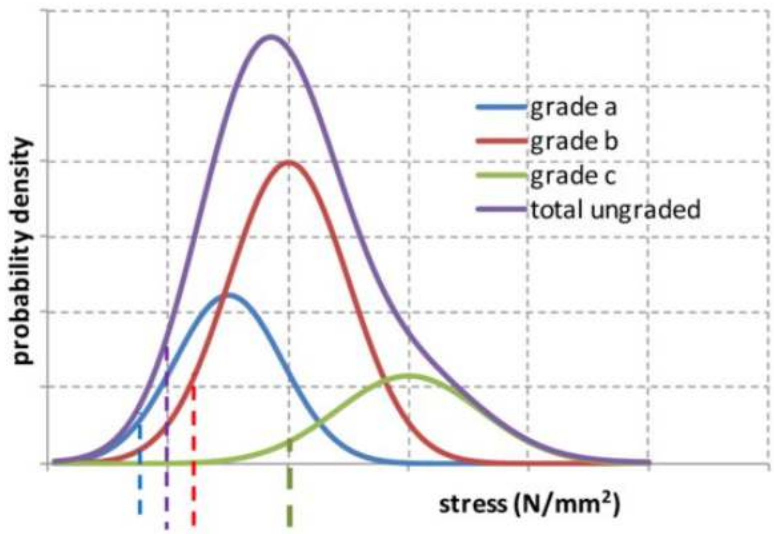

Figure 2: Effect of Strength Grading of Structural Timber.

2.2. Determination of Mechanical Properties of Structural Timber

In India, there standard test methods are available to determine the mechanical properties of timber as per IS 1708-1986 (RA 2015). These tests are normally performed on timber which has been conditioned to about 12% moisture content. The size of the specimens and the rate of loading are mentioned the test protocols. Bending properties like modulus of elasticity and modulus of rupture are normally determined by symmetrically loading a specimen at two points. The distance between points of supports i.e span length shall be 90 cm in case of 5cm x 5 cm cross-section test peice. This method is referred to as 'Two-point' bending test and the intent is to create a zone of constant moment with no shear of the beam under test. The modulus of elasticity is determined from the slope of the load-midspan deflection curve and the bending strength or modulus of rupture is determined from the maximum load that it sustains. The load shall be applied continuously throughout the test such that the movable head of the testing machine moves at a constant rate of 3 mm per minute. Deflection of neutral axis shall be measured at the mid span between two points equidistant from mid span to an accuracy of 0.01 mm by suitable Universal Testing Machine having deflectometer. The gauge length shall be kept as 40 cm. The deflection shall be measured at suitable load intervals up to limit of proportionality and continued up to maximum load.

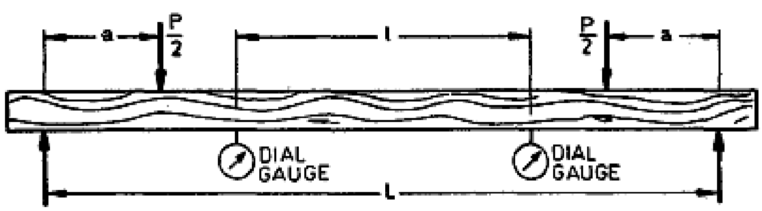

Figure 3: Timber Sample Under Two Point Static Bending.

(a) Determination of Mean of Modulus of Elasticity

The mean modulus of elasticity $\bar{E}$ can be calculated by testing minimum five test specimens in each sample by using the formulae after the sample is conditioned in a conditioning chamber ($27^0 \pm 2^0$C and 65±5% RH)

$$\bar{E} = \frac{3\,Pal^2}{4\,bh^3\Delta}$$

Where,

P = Load in N at limit of proportionality,

b = Breath of sample in mm,

h = Depth of sample in mm,

Δ = Deflection in mm at the limit of proportionality,

a = Distance between points of application of load and support in mm

l = Gauge length in mm

(b). Determination of Mean Bending Strength

The mean Bending Strength (modulus of rupture) $\overline{f_{mean}}$ can be calculated by testing minimum five test specimens in each sample by using the formulae after sample is conditioned in a conditioning chamber ($27^0 \pm 2^0$C and 65±5% RH)

$$\overline{f_{mean}} = \frac{3P'a}{bh^2}$$

Where,

P' = Maximum Load in N,

a = Distance between points of application of load and support in mm

b = Breath of sample in mm,

h = Depth of sample in mm,

2.3. Characteristic values of Strength

For each sample, the 5-percentile strength value, $\overline{f_{05}}$ is found by ranking all the test values for a sample in ascending order and finding the value below which 5% of the values fall. A larger test sample will usually give a much more reliable estimation of the5-percentile value and a variety of statistical methods are employed to fit the data distribution, with a log normal analysis being one of the more popular that is used.

(a) Characteristic Value of Modulus of Elasticity (MoE)

After adjusting the value of $\overline{E}$ for each sample (minimum five specimen) the characteristic value of bending strength $E_{0,mean}$can be calculated from the equation as per EN 384:2004

$$E_{0,mean} = \frac{\sum \bar{E}_j n_j}{\sum n_j}$$

Where,

n_j = Number of specimen in sample j

$\overline{E_j}$ = Is the mean value of bending strength for sample j expressed in N/mm^2

5-percentile characteristic value of MoE parallel to grain $E_{0,05}$ expressed in N/mm^2

a) For softwoods $E_{0,05} = 0.67\ E_{0,mean}$

b) For hardwoods $E_{0,05} = 0.84 E_{0,mean}$

5-percentile characteristic value of Modulus of Elasticity perpendicular to grain $E_{90,mean}$ (in N/mm^2)

a) for softwoods $E_{90,mean} = \frac{E_{0,mean}}{30}$

b) for hardwoods $E_{90,mean} = \frac{E_{0,mean}}{15}$

(b) Characteristic value of Bending Strength

The characteristic bending compressive strength is defined as the bending strength below which not more than 5% of the test results are expected to fall. From the normal or the Gaussian Distribution curve, the 5th percentile corresponds to 1.65 standard deviations below the mean. The bending strength of the samples although exhibit variations, when plotted on a histogram are found to follow the shape of a bell shape curve, as shown below in Fig 4.

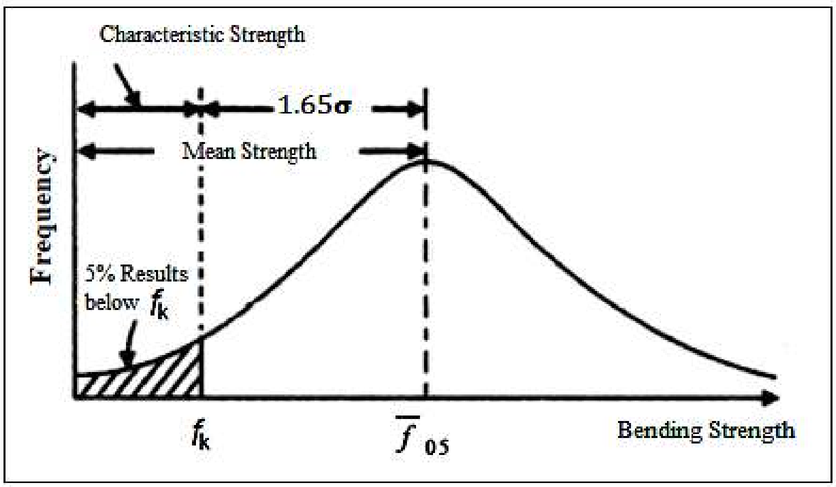

Figure 4: Normal Distribution Curve

The 5- percentile bending strength $\overline{f_{05}}$ can be calculated from the equation:

$$\overline{f_{05}} = \overline{f_{mean}} - 1.65 * sd)$$

Where,

$\overline{f_{mean}}$ = Mean bending strength (MOR) in N/mm^2

sd= Standard Deviation of the sample specimen

The characteristic values of samples can be selected as per sampling plan. Any suspected difference in the mechanical properties of the population distribution may be due to growth regions, sawmills, tree size or method of conversion that should be represented within the number of samples selected, by a similar proportion to their frequency in the population. This should be the major influence in determining the number and size of samples.

After adjusting the value of $\overline{f_{mean}}$ for each sample (minimum five specimen) the characteristic value of bending strength $f_{m,k}$ can be calculated from the equation.

$$f_{m,k} = \frac{\Sigma f_j n_j}{\Sigma n_j}$$

Where,

n_j = Number of specimen in sample j

f_j = Is the mean bending strength for sample j expressed in N/mm^2

The characteristic value of bending strength f_k to be calculated from the equation as per EN 384:2004:

$$f_k = \overline{f_{05}} * k_s * k_v$$

Where,

$\overline{f_{05}}$ = The 5- percentile bending strength of the adjusted (f_{05}) for each sample weighted according to number of pieces in each sample, N/mm^2

k_s = is a factor to adjust for the number of samples and their size and shall be obtained from Fig 5.

k_v = is a factor to allow for the lower variability of $\overline{f_{05}}$ values between samples for machine grades in comparison with visual grades;

For machine grades with $f_{m,k}$ greater than 30 N/mm^2, and all visual grades, k_v=1.0

For machine grades with $f_{m,k}$ greater than 30 N/mm^2, and all visual grades, k_v=1.1

Factors ks and kv shall not be used to calculate characteristic values of shear, tension perpendicular to grain and compression perpendicular to grain strengths.

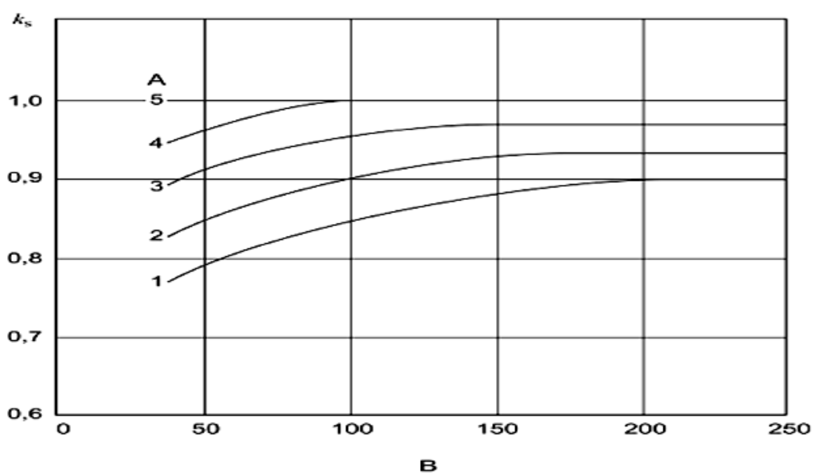

Figure 5: Effects of Number of Samples and Their Size on the Factor ks.

2.4 Allocation of Strength Classes –Characteristic Values

The European standard BS EN 338:2003 (E) strength class system assigns structural timber to grades or strength classes with defined properties. It comprises twelve classes for poplar and softwood species, namely and six classes for hardwood species mentioned in Table 1. In the table, the letters C and D refer to coniferous and deciduous respectively while the numerical values represent the characteristic bending strength in MPa for the strength class. Timber populations are assigned to a strength class if the characteristic values of bending strength and density of the population are equal to or greater than the values for the strength class and if the characteristic mean modulus of elasticity in bending equals or exceeds 95% of the value for the strength class. All the properties tabulated in the table are compatible with timber at a moisture content consistent with temperature of 20^0C and RH of 65%.

Table 1: Strength Classes- Characteristic Values of Timber

Type of Timber Species	Strength Classes	Bending Strength, $f_{m,k}$	Mean Modulus of Elasticity (Parallel to the grain), $E_{0,mean}$	5% Modulus of Elasticity (Parallel to grain), $E_{0,05}$	Mean Modulus of Elasticity (Perpendicular to grain), $E_{90,mean}$
		N/mm^2	kN/mm^2	kN/mm^2	kN/mm^2
Soft Wood Species	C14	*14*	*7*	*4.7*	*0.23*
	C16	*16*	*8*	*5.4*	*0.27*
	C18	*18*	*9*	*6.0*	*0.30*
	C20	*20*	*9.5*	*6.4*	*0.32*
	C22	*22*	*10*	*6.7*	*0.33*
	C24	*24*	*11*	*7.4*	*0.37*
	C27	*27*	*11.5*	*7.7*	*0.38*
	C30	*30*	*12*	*8.0*	*0.40*
	C35	*35*	*13*	*8.7*	*0.43*
	C40	*40*	*14*	*9.4*	*0.47*
	C45	*45*	*15*	*10.0*	*0.50*
	C50	*50*	*16*	*10.7*	*0.53*
Hard Wood Species	D30	*30*	*10*	*8.0*	*0.64*
	D35	*35*	*10*	*8.7*	*0.69*
	D40	*40*	*11*	*9.4*	*0.75*
	D50	*50*	*14*	*11.8*	*0.93*
	D60	*60*	*17*	*14.3*	*1.13*
	D70	*70*	*20*	*16.8*	*1.33*

III. RESULTS AND DISCUSSION

Figure 1 shows the average values of modulus of elasticity parallel to grain ($E_{0,mean}$), 5- percentile characteristic values of modulus of elasticity parallel to grain ($E_{0,05}$), mean value of bending strength (f_{mean}) and characteristic values of bending strength ($f_{m,k}$) of different timber samples of species named *Dalbergia spp.* with designated as Sample A, Sample B, Sample C, and Sample D and were compared with strength classes of the hardwood group mentioned in BS EN 338:2003 (E).

Table 2: Results of Mean and Characteristic obtained from Timber Samples

Sample Designation	$E_{0,mean}$ (N/mm^2)	$E_{0,05}$ (N/mm^2)	$\overline{(f_{mean})}$ (N/mm^2)	$f_{m,k}$ (N/mm^2)
Sample A	16423	13795	93.30	83.97
Sample B	16693	14022	114.84	103.35
Sample C	11980	10063	109.66	98.69
Sample D	11722	9846	86.10	77.49

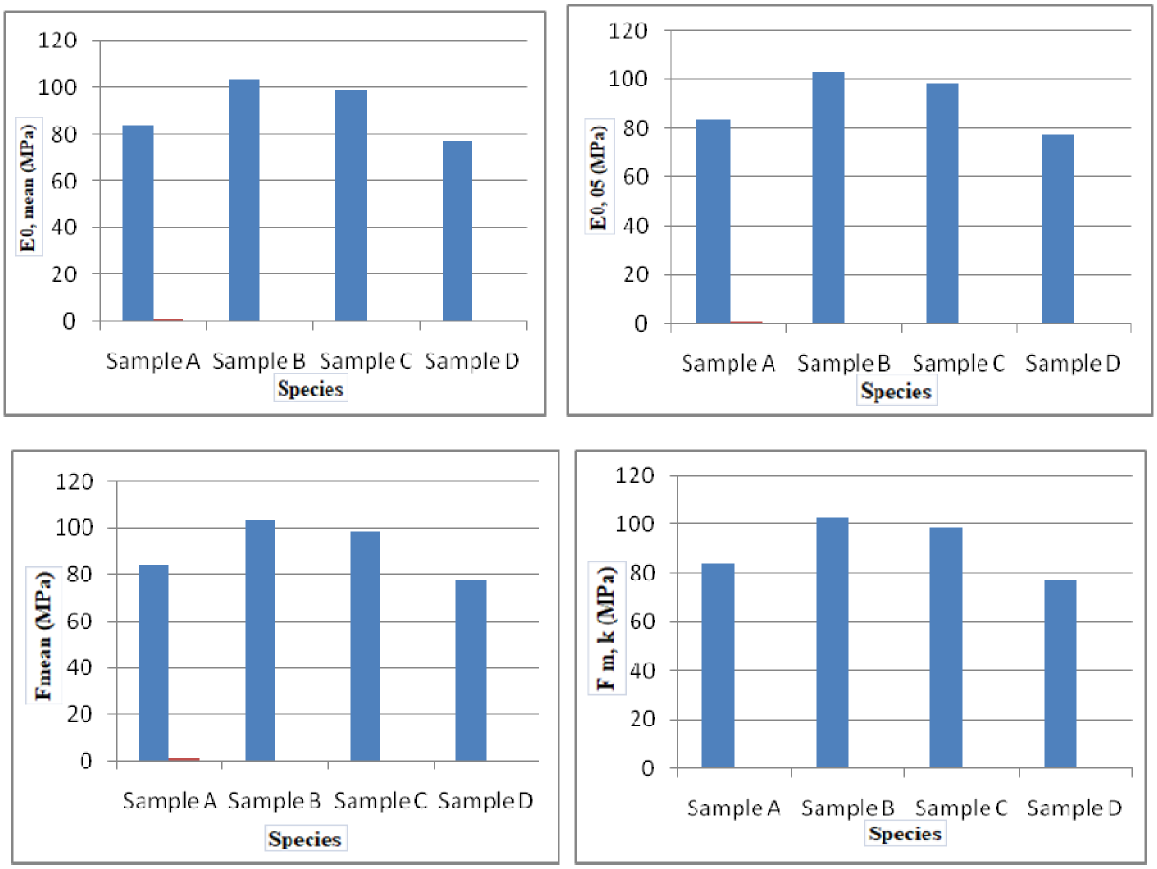

Figure 6: Comparison of Mean and Characteristic Strength of Designated Timber Species.

From Table 2, it is seen that samples designated as sample A and sample B can be categorized as D50 of the strength class belonging to hardwood species whereas sample C and sample D can be categorized as D40 of the strength class belonging to hardwood species mentioned in Table 1 as per European standard BS EN 338:2003 (E) strength class system. Fig. 6 shows strength wise difference of the different designated timber samples of same species where sample B shows highest values of modulus of elasticity parallel to grain, 5- percentile characteristic values of modulus of elasticity parallel to grain, mean value of bending strength and characteristic values of bending strength. Now the timber belonging to sample B, the grading machine may be set to grade the directly to the strength class D50 and its stiffness values and thus marked accordingly. So in this case it can easily be said that Sample A and B and much more tougher than sample C and D in terms of timber properties.

IV.CONCLUSION

Structural design using hardwoods is little different in principle from using softwoods. The strength properties of individual hardwood species may be higher than those for the strength class to which the species belongs. In civil engineering, Load and Resistance Factor Design abbreviated as LFRD is a philosophy under which engineering structures are designed keeping in mind that the probability that a number of performance criteria are exceeded is deemed to be acceptable during the functional lifetime of the engineering structure. Structural engineers must make calculations to ensure that a particular design doesn’t collapse in future and is stiff enough. They must choose an appropriate value of material strength of timber to use it in calculation during using the structural timber in mass timber, bridges, decks, girders.

In India, the design codes using this material strength based around a characteristic value is lacking. Characteristic material properties are divided by structural timber partial safety factors of to arrive at certain design values, which structural or civil engineers can use it in their calculations. The test results obtained are useful for indicating suitability of the different timber species in India for different structural applications and design to relevant codes. We are therefore using statistically rather extreme values for the properties of timbers design of buildings. Since tested timber species is having high strength to weight ratio when compared with other conventional structural materials such as steel and concrete, the timber species become an effective structural material in structural use where its self weight constitutes a large share of the load to be carried. But there is a need for more research work where fire resistance, lateral stability in high rise buildings are required and where here timber may not be the material of choice due to its inherent properties which have been studied in this above work.

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