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Inferring Strength Of Structural Timbers From Small Clear Specimen Strength Test Data

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Abstract

Despite the existence of diverse timber species in least developed countries such as Uganda, wood has been under-utilized in the construction sector on grounds of its perceived unreliability due to lack of adequate strength data. Attempts have been made to establish strength of small clear specimens but the relationship between MOE and MOR of small clear specimens and structural size tropical timber is not documented. Therefore this research was conducted to compare the flexural strength of small clear to that of structural size specimens; and particularly the effect of knots on MOE and MOR of structural size timber. Small clear tests were conducted in bending, compression and shear parallel to grain using standard procedures of the American Society for Testing and Materials (ASTM), ISO 8905 (1988), and BS 373 (1957). Structural size bending tests were conducted following ASTM ISO 8905 (1988), AS/NZS 2878 (2000); BS 4978; ASTM D198-02; ISO/FDIS 13910:2004 and BS 373 (1957). It was concluded that structural size MOE and MOR can be estimated from small clear MOE and MOR using reduction factors of 40% and 20% respectively. It was recommended that more research into the effect of complex knots, cross-grain and grain angle on timber strength be done for better structural grading of timber.

***Keywords*: MOE, timber, MOR, flexure strength, knots, wood**

1. Introduction

Timber is a natural product of biological origin; hence it is a very variable and heterogeneous material. Unlike other building materials such as metals, plastics, and cement products which are isotropic, wood is an anisotropic material having its properties, having different magnitudes in different directions. Wood may be described as an orthotropic material; with unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. Despite the existence of diverse timber species in Uganda's natural forests and the extensive plantation establishment, wood has been under-utilized as a building material on grounds of its perceived unreliability (Nolan, 1994). Where attempts have been made to use locally available timber as a building material in Uganda, little or no proof of its structural integrity is documented (Kityo and Plumptre, 1997; Zziwa *et al.,* 2006). It should be noted that design of timber structures in Uganda has been based on adopted or adapted foreign standards such as BS 5268:1999 & 1998 on structural use of timber and BS 6399:1996 on loading; prescriptive procedures; and conservative assumptions (Zziwa *et al.,* 2006; Zziwa *et al.,* 2009). In addition, over-exploitation and scarcity of traditional timber species such as, Mahogany and *Milicia excelsa* (Mvule), has led to a diversity of previously unpopular species on the market (Zziwa, 2004) yet there is no strength data to guide their utilisation.

The absence of quick and reliable timber strength assessment techniques has partly led to material wastage at the expense of timber resource sustainability or even under-designing of timber structures which has sometimes led to premature failure of timber structures. Whereas determination of wood strength using small clear specimens is useful, quick and relatively cheap, the values obtained do not directly reflect "actual service" conditions for the structural timber sizes commonly used in construction (Gupta *et al.*, 2004; Branco *et al.*, 2006). This is because full-size timber contains strength-reducing defects, mainly knots that inflict strength reducing effects through replacement of clear wood with harder and denser but weaker knot wood and spiral grain. It has been widely reported that strength properties obtained from small clear specimen testing are generally higher than those obtained from structural size specimen testing but the stiffness values are about the same.

Knots are parts of branches that become incorporated in the trunk during growth. They have long been recognised as a major strength-reducing defect in timber. According to Ishengoma and Nagoda (1991) Knots may be: inter-grown (firmly fixed in surrounding wood; loose (encased knot) or missing (knothole). Knots weaken timber pieces because of the sloping grain surrounding it, which cause loss in strength. Knots decrease most mechanical properties of wood because: they displace clear wood; the fibres around the knot are distorted causing cross grain; and the discontinuity of wood fibres leads to stress concentration in timber pieces. Knots seriously affect wooden members loaded uniformly in tension. For structural use, the effect of knots on strength depends not only on the knot size but also on their location. Knots have maximum effect on the maximum load a beam will sustain when on the tension side (Bannister, *et al.* 2009). Knots on the compression side are less serious. Knots in round timbers such poles and piles have less effect on strength than knots in sawn timbers (Zziwa *et al*., 2011).

Xu (2002) noted that knots have a negative influence on MOE even though knotty wood is stiffer than clear wood in the longitudinal direction. Nguedjio (1999) found that the existence of knots changes the ratio between edgewise and flat-wise MOE of timber in bending. Lam *et al.,* (2005) reported that the effect of knots is to reduce the difference between the fibre stress at elastic limit and the modulus of rupture of beams. It was also reported by Faherty and Williamson (1998) that there are also localised areas of low stiffness that are often associated with knots. However, such zones generally comprise a small portion of timber while overall timber stiffness reflects the character of all parts. According to Phillips *et al.* (1981) and Bannister, *et al.* (2009) knots have the most severe effect on tensile strength, modulus of rupture, compression strength parallel to grain, and modulus of elasticity in that order. As a result knotty timber is weaker compared to clear wood. Knots in dimensional timber are treated as holes for the purpose of determining allowable strength values according to ASTM D245 (ASTM, 2002). The material inhomogeneity associated with the knot induces a stress concentration further reducing capacity while the resulting grain angle distortion provides an opportunity for tensile stresses perpendicular to the grain to develop and splits to form (Dinwoodie, 1981; Cramer *et al*., 1996; Buchanan, 2007). When a log is sawed, the obscure pattern of interlocking fibres around knots is destroyed leading to discontinuity of fibres, unsupported fibres, differential shrinkage and lower strength values (Madsen, 1992).

The effect of a knot on strength depends on the proportion of timber occupied by the knot, their number, nature, size and distribution both along the length of a piece of timber and across its section (Andreu and Rinnhofer, 2003; Rais *et al*., 2010). Dead knots result in larger reductions in stiffness than green knots; large knots are more critical than small ones; clustered knots have more significant effect on strength than evenly distributed knots of similar size; while knots on the top and bottom edge of a beam are more significant than those in the centre (Rajput *et al.* 1980; Grant *et al.* 1984; Faherty and Williamson, 1998; Thelandersson and Larsen, 2003; Gupta *et al*., 2004; Rais *et al.,* 2010). It is therefore recommended to avoid timbers with many knots particularly along the edges of structural timber subjected to complex stresses.

The effect of knots on timber strength explains why visual timber grading is based on identification of the single most severe strength-reducing defect, the knots (Cramer *et al*., 1996). The presence of knots in solid sawn timber is unavoidable, and knots can be a major factor in reducing the ultimate failure strength of structural timber. Visual strength grading of timber is always based on the knot area ratio (KAR), which is the ratio of the size of the knot to the width of the face or edge in which it occurs. There is a correlation between the strength of a wooden member and its knot ratio. In members subjected to bending, the precise influence of knots depends also largely on the position of the knot in relation to the stress distribution in the beam. Thus in formulating grading rules it is often permissible to allow larger knots at the centre of the face than at its outer edges because of the difference in bending stresses at these points. Lam *et al* (2005) studied the influence of knots on wood stiffness using knot area ratio and established that the bigger the ratio the less the stiffness. Serious knots such as edge knots affect the elastic limit of beams and consequently affect the stiffness (MOE) of structural timber (Nguedjio, 1999; Rais *et al.,* 2010). Divos and Kiss (2010) also demonstrated the possibility of timber grading by incorporating the effect of knots and their concentration in measured MOE values using the concentrated knot diameter ratio (CKDR).

While the influence of knots on strength properties has been widely reported in literature, the relationship between MOE and MOR of small clear specimens and structural size tropical timber has not been ascertained. Therefore a research was conducted to compare the flexural strength of small clear specimens to that of structural size specimens; and to particularly analyse the effect of knots on MOE and MOR of structural size timber. The results of the study would then be used to establish adjustment factors to enable more reliable extrapolation of small clear timber strength data to predict structural size timber strength in the building construction industry.

Materials and Methods

An investigation of the relationship between structural size and small clear timber strength and the effect of knots on MOE and MOR of timber was conducted. There is no clear documented information in literature on whether the strength-reducing effects of knots on timber strength are more severe in some species than others but what is clear in literature is the fact that there is general reduction in timber strength of any species with occurrence of knots. Therefore, to avoid bias two timber species namely Pine (*Pinus caribaea*) and Kalitunsi (*Eucalyptus grandis*) were investigated.

The MOE and MOR of small clear specimens of *E. grandis* and *P. caribaea* were determined in a static bending test on specimens measuring 300 mm × 20 mm × 20 mm using a Testometric AX M500 – 25KN Universal Testing Machine at a loading rate of 6.6 mm per minute. Thirty small clear specimens were tested for Pine whereas 30 specimens were tested for *E. grandis*. Specimens were loaded to failure in three-point loading over a span of 280 mm. To determine the MOE and MOR of structural size specimens of the two species, structural size tests were conducted according to BS 4978; ASTM D198-02 and ISO/FDIS 13910:2004(E). Timbers with nominal dimensions of 100mm by 50mm were randomly selected from 3 timber yards in Kampala for preparation of uniform structural size specimens according to (ASTM D 198-02). For each species, samples were divided into two groups; those with visible knots and those without visible knots. The Pine sample consisted of 19 specimens with knots and 26 specimens without while the Eucalyptus sample consisted of 23 specimens with knots and 23 specimens without visible knots. These sample sizes were considered adequate given the scope of the study and resource limitations. Specimens with visible knots were prepared in way that majority of the knots were located within the middle third (Figures 1 – 3) to enable clear monitoring of failure modes during experimentation. The knots were fully described by their number, size and location. Measurement of extent and dimension of knots was made on the surface of the specimen in question to derive the knot area ratio. This was based on the fact that the KAR is the percentage of the cross-section that is taken up with knots (BS 4978, 2007).

Figure 1: Structural size specimens for Eucalyptus grandis and Pinus caribaea

Figure 2: Pinus caribaea specimens with visible knots

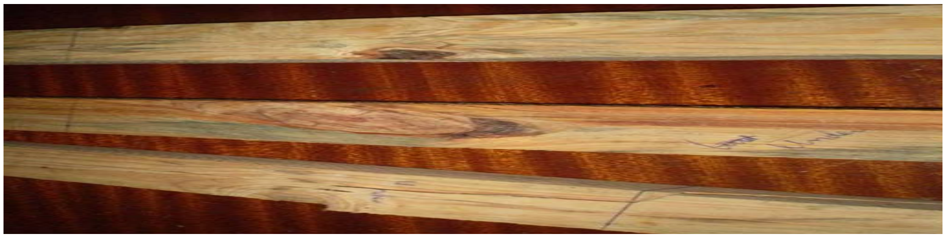


Figure 3: ***Eucalyptus grandis*** **Specimens with visible knots**

Solid wood beams of span 18d were loaded at third points by loads equal to $\frac{F}{2}$ in a four-point bending test (Figure 4).

The span was determined from the beam depth, the distance between load points as well as the type and orientation of the material in the beam (ASTM D198-02). The total length of specimens was 20d (ISO/FDIS 13910:2004. The beam span intended primarily for evaluation of flexural properties was such that the shear span was relatively long. Structural size specimens of uniform rectangular cross-section having a:d ratios ranging from 5:1 to 12:1 (where, d is beam depth, and a, is the distance from support to nearest load point) are recommended (ASTM D 198-02). In this study d was = 50mm and a=300mm, giving a:d=6:1. Hence specimens measuring 50 mm × 40 mm (depth, d = 50 mm, width, b = 40 mm) and 1.0 m span were prepared. The specimen length was based on the allowable span of the UTM.

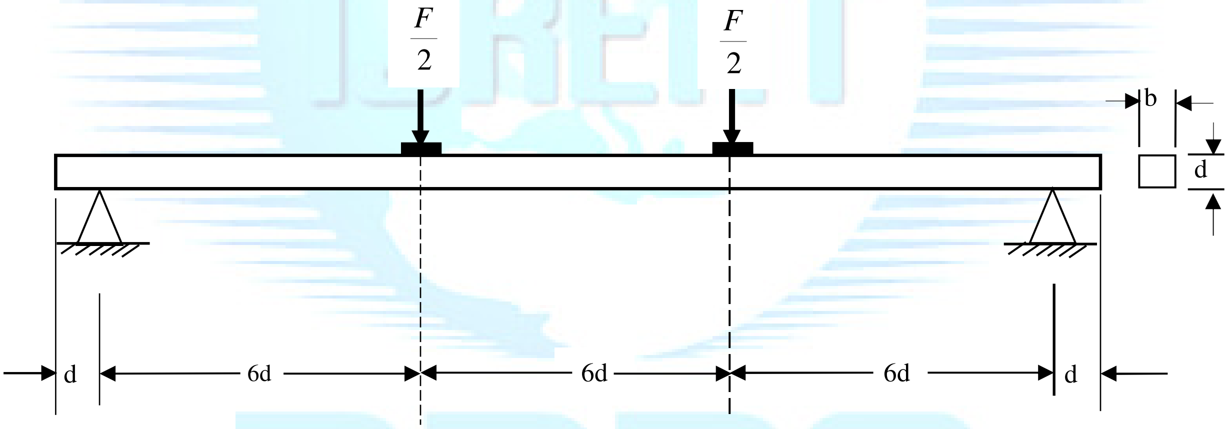


Figure 4: Configuration for Measurement of MOR and MOE for of Structural-Size Timber

Test procedures in accordance with ASTM D198 standard methods of static tests of timber in structural sizes were used. Specimens were loaded flat-wise and tests were conducted at a loading rate of 4.4 mm/minute using a UTM with a capacity of 50KN. The static bending test configuration used was as shown in Figure 5. The duration of each test, t, in minutes was 5≤ t ≤10. MOE and MOR test results were obtained directly from the computer data.

Figure 5: The Universal Testing Machine, computer and test specimen

Figure 6: Structural size bending test – *Pinus caribaea*

The moisture content of the samples was not controlled; but rather the samples were kept in air-dry condition. After each structural size test the MC of each specimen was determined using an electrical moisture meter and the average moisture content was taken as the representative moisture content for the species under investigation.

To ascertain the relationship between small clear strength and structural size strength; means of MOE and MOR for structural size and small clear strength data were compared for the two species. Emphasis was on establishing how the mean MOR and MOE of the data sets compared. Basing on the trends in the two species, common factors of safety in form of percentages were suggested to enable prediction of structural size MOE and MOR using the small clear MOE and MOR respectively. To analyse the effect of knots on MOE and MOR of structural size timber, means of MOE and MOR for structural size specimens with visible knots were compared with those from a sample batch without visible defects.

2. Results and Discussion

Table 1 shows the Mean MOE and MOR for small clear and structural size specimens whereas Table 2 shows the mean MOE and MOR for structural size specimens with and without knots.

Table 1: Mean MOE and MOR for Small Clear and Structural Size Specimens

Species	**Specimen**	**Means (N/mm^2)**	
		MOR	**MOE**
Pine	Structural Size	25.3 (5.70)	4928 (806)
	Small Clear	28.7 (6.70)	7640 (1394)
Eucalyptus	Structural Size	30.8 (6.65)	5667 (1431)
	Small Clear	38.8 (15.11)	9154 (2768)

The italicised values in parenthesis are standard deviations.

Table 2: Mean MOE and MOR for Structural Size Specimens with and without Knots

Species	**Specimen**	**Means (N/mm^2)**	
		MOR	**MOE**
Pine	With visible knots	23.4 (*6.34*)	5146 (*1091*)
	Without visible knots	33.6 (*6.33*)	5965 (*1365*)
Eucalyptus	With visible knots	30.7 (*6.68*)	5979 (*1624*)
	Without visible knots	35.0 (*7.22*)	6176 (*1671*)

The italicised values in parenthesis are standard deviations.

For Pine, the mean MOE of SSS was 65% of the mean for SCS whereas the MOR of SSS was 88% of the mean for SCS. For Eucalyptus, the mean MOE of SSS was 62% of the mean for SCS whereas the MOR of SSS was 80% of the mean for SCS. The ratios of the mean MOE and MOR indicate that SCS MOE can be approximated to SSS MOE using a conservative reduction factor of 40% while for MOR a reduction factor of 20% is required. The ratios of the mean MOE and MOR indicate that SCS MOE can be approximated to SSS MOE using a conservative reduction factor of 40% while for MOR a reduction factor of 20% is required. This concurs with Green and Shelley (2006) who noted that small clear test results can be used to derive the allowable timber properties. The findings imply factors of safety of 1.25 and 1.7 for MOR and MOE respectively. The factor of safety for MOR is in close range with a reduction factor, F=2.65 for tropical timbers, which incorporates allowances for specimen size, rate of loading and safety considerations (Mettem, 1986).

The observed low MOE and MOR of SSS compared to SCS could be attributed to factors such as specimen size, loading rate, and knots (Wolfe and Moseley, 2000). For the two species tested, mean trends suggest that the MOE and MOR of SSS were lower than values for SCS. This was in agreement with (Leicester, 2010, personal communication) who noted that MOE of structural timber is slightly less than that of small clear specimens cut from the timber. The lower means of MOE and MOR of SSS with knots compared to those without knots was an indication that knots have a strength reducing effect in full-size timber. The significant difference between MOR of SSS with and without visible knots for both species further confirmed that knots have a negative effect on the bending strength of wood and hence should be considered in timber structural designs. This finding further justifies why timber bending strength (MOR) is the most common property that is evaluated for full-size structural members.

The observed insignificant difference between the MOE of Eucalyptus SSS with and without knots was an indication that MOE is not affected to the same degree by knots as MOR. The effect of knots on MOE heavily depends on the location of knot location as there are knots in extreme locations with minimal bending stresses that have almost insignificant impact on the integrity of a timber beam. For *P. caribaea*, the mean MOE of SSS with visible knots was about 86% of mean for SSS without visible knots whereas the MOR of SSS with visible knots was about 70% of mean for SSS without visible knots. For *E.grandis*, the mean MOE of SSS with visible knots was about 97% of mean for SSS without visible knots whereas the MOR of SSS with visible knots was about 88% of mean for SSS without visible knots. In both cases the MOR was more affected by knots than MOE. This concurred with the earlier finding by Phillips *et al.,* (1981) that MOR is affected more by defects than MOE. This is explained by the fact that MOR relates more to ultimate strength.

Majority of SSS had moisture content above 15%; the average moisture content for Pine structural size specimens was 16.7% where as the average for Eucalyptus was 17.2%. Results for structural size specimens were not adjusted to 12% moisture content because one of the aims was to show service conditions of structural size timber. The mean MOE and MOR of SSS were lower than those for small clear specimens (SCS) for both Pine and Eucalyptus (Table 2). The mean MOE and MOR of structural size specimens with visible knots were also lower than the mean MOE and MOR for specimens without visible knots for both Pine and Eucalyptus (Table 1). ANOVA showed significant differences (P<0.05) between the MOR of SSS with and without visible knots for both Pine and Eucalyptus. ANOVA also showed significant differences (P<0.05) between the MOE of SSS with and without visible knots for Pine but not for

Eucalyptus. The mean MOE for SSS with knots was lower than that for SSS without visible knots. ANOVA showed significant differences ($P<0.05$) between the MOE and MOR of SCS and SSS for both species. The fact that there were significant differences in MOE and MOR of timber with and without knots points to the importance of knots as strength reducing defects and highlights the need to avoid knotty timber in building construction applications subjected to bending loads.

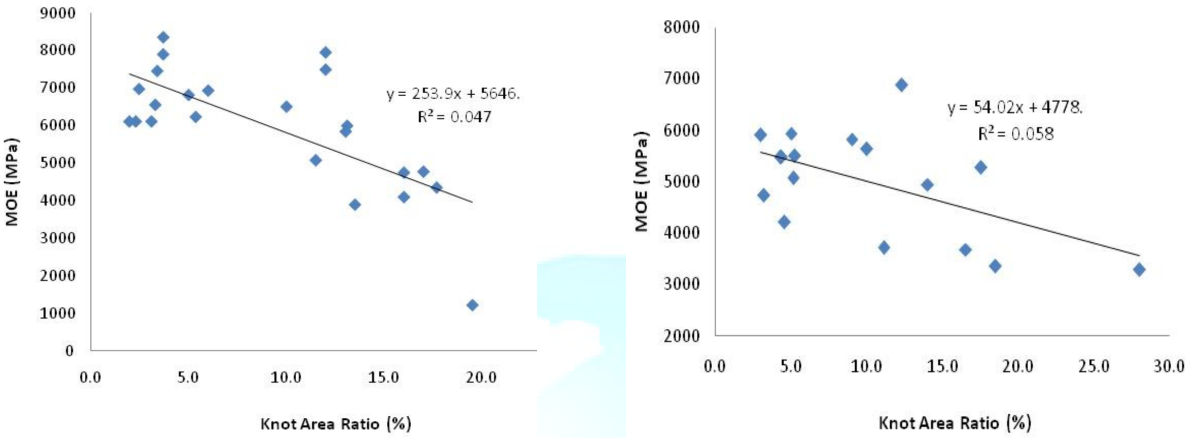
Structural size specimens exhibited fairly linear stress strain curves up to two-thirds of the ultimate load. Majority of specimens failed due to bending stresses within 100 mm of mid-span (Figure 7 & 8). It was observed that the MOR and MOE of a number of specimens with larger knots were far less than those of specimens with smaller knots. A few of the specimens (10%) with multiple but small knots in the middle third exhibited higher MOE and MOR compared to specimens without visible knots. No common mode of failure was identified for specimens with multiple but small knots rather than the normal bending failure mode. For specimens with large visible knots, knots played a big role in defining the specimen capacity, as most of the premature failures generally began at these knot positions, but still within the middle third. This was in agreement with (Wolfe and Moseley, 2000; Rais *et al.,* 2010) who reported a similar effect of knot size and location on the capacity of timber in bending.

Premature and brittle failures were dominant amongst a few structural size specimens with large knots within the middle third section. Figures 7 and 8 show some of the modes of failure for structural size tests for the two species.

Figure 7: Failure Modes during Structural Size bending test – *E. grandis*

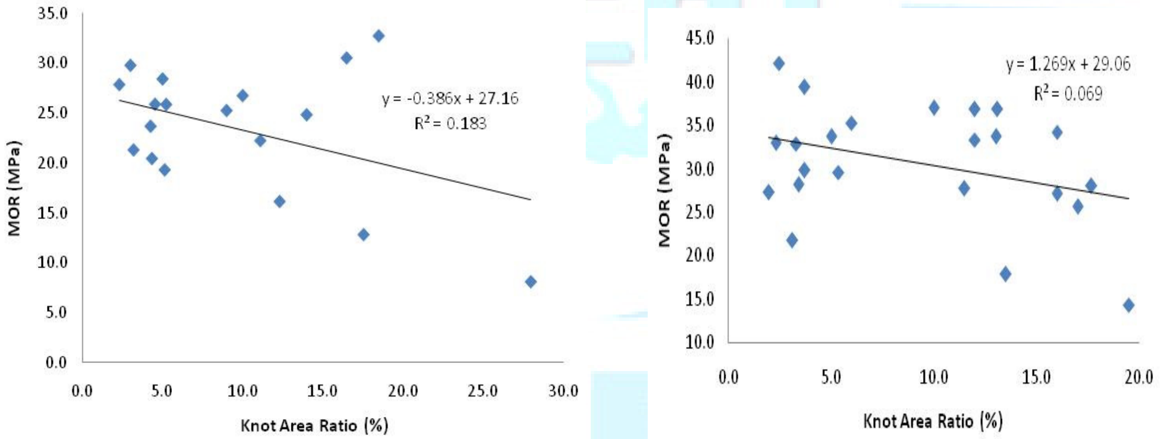
Figure 8: Failure Modes during Structural Size bending test – *P. Caribaea*

The scatter plots in Figures 9 and10 show the MOE versus Knot Area Ratio and MOR versus Knot Area Ratio for Eucalyptus and Pine.



(a) Eucalyptus (*Eucalyptus grandis*) (b) Pine (*Pinus caribaea*)

Figure 9: Relationship between MOE and Knot Area Ratio



(a) Eucalyptus (*Eucalyptus grandis*) (b) Pine (*Pinus caribaea*)

Figure 10: Relationship between MOR and Knot Area Ratio

It was further observed that poor correlation illustrates one of the problems of using visual grading as a stand-alone method of predicting timber strength. The low correlations between knot area ratio and bending strength properties suggest that visual grading cannot alone ensure efficient timber grading. The low correlations are an indication that there are other structural timber strength-reducing factors other than knots. However, the poor correlations between knot area ratio and MOE and MOR could also be attributed to the fact that the tested knot ratio was smaller than the knot value of the entire board; as it is only knots in the middle third that were considered. The relatively low sample sizes could have also contributed to the low correlations. Much as there were low correlations between knot area ratio and static bending strength, the linear regression graphs indicated that there was an inverse relationship between knot area ratio and MOE and MOR. This was a clear testimony that knots have a negative influence on MOE and MOR.

3. Conclusions

It was concluded that the mean MOE and MOR of small clear specimens were higher than the MOE and MOR for structural size specimens; structural size MOE and MOR can be estimated from small clear strength data using conservative reduction factors of 40% and 20% respectively. This is very useful information to structural designers who can from now on make a few small clear tests and use these conservation factors to ascertain the structural size strength values.

It was further concluded that structural size timber specimens with visible knots had lower MOE and MOR than structural size specimens without visible knots and that MOR is affected more than MOE by the presence of knots. It was also found out that the low correlations between Knot Area Ratio and bending strength reaffirmed the weakness of visual timber grading approaches. The study has also provided justifiable evidence that visual grading based on visible knots cannot serve as stand-alone method of predicting timber strength quality. This is critical information, at least in Uganda's case, since it has been a common practice to disregard or select timber on the basis of the visible knots without any empirical evidence. The low correlations between knot area ratio and flexural strength showed the weakness of visual grading as a stand-alone method of predicting timber strength quality. It is recommended that there is need to investigate the flexural behaviour of timber using modelling techniques. There is also need to examine the effect of knots on timber strength using finite element modelling techniques and extensive research studies into the effect of other defects on timber strength is needed.

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