The Nigeria Journal of Forestry

July & December 2010

Published by
The Forestry Association of Nigeria

EFFECTS OF WOOD PROPERTIES ON INCIDENTAL DAMAGES TO FELLED TREES IN SOME SELECTED NIGERIAN HARDWOOD SPECIES

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Omole A.O. Effects of Wood Properties on Incidental Damages to Felled Trees in Some Selected Nigerian Hardwood Species. *Nigerian Journal of Forestry 40(1):17-25*

ABSTRACT
Tropical timbers are usually heavily crowned and bulky. Felling of a mature tree of any such species is always accompanied by considerable impact resulting in heavy dynamic stresses being set up within the felled tree. These stresses cause much damage to wood fibres in particular and to a larger extent, to the amorphous middle lamella. This study was carried out to investigate the influences wood properties on the magnitude of the induced stress and associated incidental damage in nine matured tropical timbers grown in Nigerian low land rain forest. Data were collected on tree characteristics with the aid of a checklist using time study and work analysis. During felling, duration of impact was estimated experimentally. Data collected were analyzed using a combination of multiple linear regression and correlation analyses to assess the extent of association and relationship as well as the level of predictability among the evaluated properties. Results showed that the average moisture of green wood ranged between 108% and 147% while the average density of green wood ranged from 939.91kg/m³ and 1845kg/m³ for all the species. Observed average maximum dynamic stress ranged between $8.38 \times 10^6 N/m^2$ and $18.75 \times 10^6 N/m^2$. Of the 27 fitted models for the study species per variable and on the basis of coefficient of multiple determination (R^2), standard error (SE) value and significance of the regression model, 3 models were selected were selected for damages and 7 for maximum dynamic stress. Significant relationship was established between maximum dynamic stress, damage volume, tree species, tree height, tree mass stem diameter and angular velocity at $P < 0.05$. The magnitude of the dynamic stresses (9.08×10^6 N/m² – $18.75 \times 10^6 N/m^2$) and force generated at impact (1.498 x 10 Ns – 7.588x 10^6Ns) are considerably high and these are dictated by species, tree /height, tree diameter, tree mass and angular velocity. Regression models showed that these factors can be responsible for as high as 71% of the MDS induced in the wood of the felled tree as in the case of Terminalia superba.The use of regression models to study the dynamic stresses induced in wood and the associated mechanical damages during felling is offers a valuable contribution to existing knowledge in logging industries in the tropical rain forest.

Key words: Incidental damages, wood properties, dynamic stresses, tropical timbers

INTRODUCTION

Wood of different tree species is characteristically different in terms of their structural composition and mechanical properties. The woods of some tree species break into pieces on landing while some are able to absorb the shock with little damage. In effect, the response of wood in a falling tree to dynamically applied stress does not only depend on the magnitude of the stress but also depend on species attributes such as tree height, density of the tree, and the crown shape among others (Lucas, 1997; Omole, 2000 & 2010). Hearmon (1952) suggested that a piece of wood should be better considered as a layered polymeric fibre-composite. The arrangement of the cells influences the transfer of stress along the radial direction (Dinwoodie 1989). The strength properties of wood are higher in directions parallel to the grain than the directions perpendicular to the grain. This is because of the tubular shape of the cells and the arrangement of the micro-fibrils of the wood. Along the longitudinal axis, the micro-fibrils are held together by primary bond which requires more energy to break compared to the perpendicular direction which is held by secondary bond (Garden and Blackwell 1974). As a tree reaches the ground when it falls, stresses are set up and failure may occur even at an angle where the stress developed is less than that elsewhere in the wood, because of the orthotropic nature of wood. It has been established that there is a relationship between angular dependence of wood properties (the slope of the grain) and the ultimate stress (Lucas 1997 and Omole 2010).

The angular variation as put up by Hankinson's equation shows that the strength of wood at an angle è to the grain lies between a maximum value, (P_L) when è = O (parallel to the grain) and minimum (P_T) when è = 90°. Hankinson's equation, according to Kim (1986) is written as:

$$PQ = \frac{P_L P_T}{P_L Sin^2\theta + P_T Cos^2\theta} \qquad (1)$$

Where PQ= tensile strength properties of wood. P_L = strength parallel to the grain, P_T = strength perpendicular to the grain.

The use of this formula, according to Dinwoodie (1989) includes determination of tensile strength, compression strength, elastic modulus and toughness of wood.

Visco-elasticity of Wood

The response of wood to applied stress has been extensively discussed by many scholars (Hearmon, 1952; Pierce *et al* 1985;, Dinwoodie, 1989; and Lucas, 1997) Their submissions are that wood as a load-bearing material combines both elastic and viscous properties. This is the reason why the response of wood to applied stress does not only depend on the type of stress but also on mode of application and duration. According to Dinwoodie (1981) and Lucas (1997) stress application to a visco-elastic material such as wood leads to instantaneous elastic deformation, which is cut short from causing greater damage as a result of the 'dash-pot' mechanism inbuilt in wood. Subsequently, there is increasing deformation with load duration. According to Caulfield (1985), time dependence strain ª (t) generated in wood is given by the mathematical model:

$$^{a}(t) = {}^{a}_{0+}\ a.t_{m} \qquad (2)$$

Where ª (t) = time dependent strain,
$^{a}_{0}$ = the initial deformation, a and m = constant,
t = elapsed time

Visco-elastic behaviour of wood may be represented by a combination of springs and dash-pots mechanism. The springs act a mechanical analogue of the elastic component of deformation while the dash-pots simulate the viscous component. Visco-elasticity is characterized by the normal strain and time-dependent viscous flow. The simplest mathematical model which best simulates the visco-elastic behaviour of timber under load is the Kelvin's model for linearly visco-elastic material. The viscoelastic properties of wood explain why strain response to stress of wood is very complex. It depends on value of stress, duration of stress and rate of application. This according to Ylinen (1965) is represented by the formula:

$$^{a} = F\ dt \frac{d\delta}{dt} \qquad (3)$$

Where, ª = strain, F = force, ä = stress and t = duration of stress

For a linearly visco-elastic material, when both stress and strain are infinitesimal, wood has been indicated to combine both liquid and solid characteristics. The cell wall of wood especially the cellulose (S2 layer) which constitutes the crystalline region behaves like a spring (elastic) while the lignin or amorphous middle lamella behaves like a dashpot (Pierce *et al.*, 1985 Lucas 1997). Wood being linearly visco-elastic at low stress level, the stress/ strain relationship is time-dependent. This can be represented by the mathematical model developed by Yinen (1965) to predict time-dependent elastic and strength properties of wood by the aid of non-linear visco-elastic rheological model.

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\delta}{dt} + \frac{dt}{\mu} \qquad (4)$$

Where ª = strain, t = time, ä = stress, E = Youngs modulus of elasticity and ì = viscosity

Hearmon (1952) stated that whenever a load is applied on wood, the impact is first felt on the middle lamella which provides the cushion effect but excessive stress will cause the failure of cell wall and subsequent collapse of the bulk structure. The rheological and structural properties have contributed significantly to the ability of the wood in the felled tree to withstand the high dynamic stresses without much damage (Lucas 1997, Omole 2000). Otherwise, the entire wood would have shattered upon the tree striking the ground. Although the structural composition of wood may make it complex and difficult to predict in terms of its rheological behavior and response to applied stress, various theories and mathematical models aforementioned have clearly demonstrated that the behaviour of wood to stress application can be roughly predicted.

Modeling approach as a tool can be employed to solve problems associated with logging decision and have been in use for over four decades (Wang *et al.* 1998) Maltheck and Walther (1991) used computer simulation to study field experiment in the felling of old *Fagus sylvatica* trees growing on slopes and leaning slightly down slope, these usually being highly susceptible to end splitting. Their results showed that the new technique incorporating a key-hole cut was successful in preventing end splitting. Wang *et al.*

(1998) used computer simulation model to evaluate potential interaction of stand type, harvesting method and equipment. Volume or wood loss through damages from trees exploitation was estimated by Atanga (1999). He developed model to predict wastes and damages during exploitation of teak (*Tectona grandis)* in Ago Owu Forest Reserve, Osun State, Nigeria. The conclusions from the above review is that the application of simulation models to study wood harvesting damages and associated problems have been restricted to either homogenous temperate forests or plantations in tropical Africa.

In spite of the significance on wood utilization of the response of wood to applied stress, and mechanical damages resulting from dynamic stresses in wood as the tree falls, little work has been done on the relationship between the wood properties and associated damages especially with respect to tropical timbers. The objective of the present study is therefore to assess the relationships among trees and wood parameters on dynamic stresses and impact damages in some structural timbers found in lowland rainforest, South-Western Nigeria.

MATERIALS AND METHODS

Study area

The study was carried out in Shasha Forest Reserve (SNFR) which is situated approximately between latitude 7 °-7.3 °N and longitude 4° – 5°E, covering an area of about 310.80km². The Forest Reserve falls within the lowland rain forest region. The forest is characterized by highly deciduous tree species in the upper storey. The reserve is bounded on the South by Omo Forest Reserve, on the West by Ago-Owu Forest Reserve and on the North-west corner by Ife Forest Reserve. The forest is generally well drained by Owena and Shasha rivers. The topography of Shasha Forest Reserve ranged from moderately undulating to flat terrain. The geology of the reserve as being dominated by rocks consisting mainly of granites, gneisses and schist of the basement complex with the rocks occasionally seen exposed in the river beds or as rocks outcrops. The climate is of the equatorial type with two distinct seasons - the rainy and dry seasons with the total annual rainfall ranged from 887 mm to 2180 mm with two peaks in June/ July and September. (Bada 1977 and Kio (1978).

Species Selection

With logging intensity, utilization potentials and economic value as criteria, nine (9) different tree species were selected for the study. The species selected were: *Afzelia africana,* (Apa) *Nauclea diderrichii* (Opepe), *Terminalia superba* (Afara), *Khaya ivorensis (mahogany), Triplochiton scleroxylon* (Obeche), *Entandrophragma angolensis* (Ijebo), *Cordia millenii* (Ọmo), *Mansonia altissima (Mansonia)* and *Milicia excelsa* (Iroko).

Species Characteristics

(i) *Afzelia africana* (Apa): This species is found in both savannah forests of dry areas and dense forests of humid regions. It attains its greatest size in the closed moist deciduous forest with a height of 40m and above. The sapwood is pale, and sharply defined from light-brown heartwood. The wood in the tree is hard, tough and heavy, with density between 830kg/m³ to 910kg/m³ when dry. The uses amongst other include: bridge, doors and window-frames, ships and rails.

(ii) *Cordia millenii* (Omo): This species occurs as a deciduous tree of tropical rain forests in Nigeria. It is a medium sized tree averaging 30m high and 0.9m diameter. The wood is very durable, light and moderately soft, with density of about 480kg/m³ when dry. Its uses include load bearing applications, furniture and joinery, cabinets making and general fittings and canoe making in Nigeria.

iii) *Entandrophragma angolensis* (Ij'ebo): This is a very large tree found in dense virgin forests. It grows to a height of 48m or more and a diameter from 0.75m to 2m. The heartwood is typically a uniform reddish-brown, which darkens on exposure to light. The wood is moderately heavy weighing about 640kg/m³ when dry. The uses include furniture, interior decoration, ship building, cabinets, joineries and fittings.

(iv) *Khaya ivorensis* (Lagos Mahogany): The tree of this species can grow to a height of about 48m and more with a clean bole up to 25m in length above the buttresses and with a diameter of 1 m to 2m or more. The heartwood is distinctly pink when freshly sawn and changes colour when seasoned. The wood has very good strength properties extremely useful in heavy construction works and other uses such as furniture, high quality joineries etc.

(v) *Mansonia altissima* (Mansonia): *Mansonia altissima* is a medium-sized slender tree which reaches a height of 30m and an average girth diameter of 0.75m at maturity. The sapwood is whitish and the heartwood is yellowish-brown to grey brown. It is fairly hard and weighs 610kg/m³ when dried. The wood has a very high strength properties and the durability is very high. The timber is mostly used as a decorative timber, furniture and is a substitute for African walnut.

(vi) *Nauclea diderrichii* (Opepe): This tree species has a wide distribution across West Africa It is a large tree, well shaped tree from 39m to 48m or more in height and 1m to 2m in diameter at breast height. The tree has a clean bole up to 20m to 30m with very low buttresses or none. The timber is lustrous, very hard and moderately heavy, with density of about 750kg/m^3 when dried. The uses include pilling and decking, general construction, and other structural purposes.

(vii) *Terminate superba* (Afara): *Terminalia superba* is a high forest tree species. It is a very large tree up to 50m high or more with large thin buttresses and a diameter of about 1.8m. The wood is of medium hardness and weighs about 560kg/m^3 when dried to 15% moisture content. Large logs of this tree are susceptible to defective heart rot due to growth stresses. The wood is widely used for face veneers for flush doors, high quality plywood and furniture.

(viii) *Triplochiton scleroxylon* (Obeche): This tree species is found in most West African countries especially Nigeria. It is a very large tree species growing up to 60m high and 6.6m girth. Large tree is characterized by extensive sharp buttresses sometimes up to 6m or more up the trunk Both the heartwood and sapwood are creamy-white to pale yellow in colour. The timber is light weighing about 390kg/m^3 when dried. The timber is used for interior joineries, core veneer, lining of drawers and cupboards and furniture.

(ix) *Milicia excelsa* (Iroko): The species is widely distributed in tropical Africa. It is a very large tree reaching 43m or more in height and up to 2.7m in diameter. The heartwood is distinct yellow in colour which turns golden-brown upon exposure to light and the sapwood is narrow and clearly defined. The timber is heavy weighing an average of 660kg/m^3 when dried. Uses include ship and boat building, light flooring, interior and exterior joinery, and harbour works. Tree parameters such as species, total height, diameter at 3 levels (stump, middle and top), initial lean position and defects were collected.

Felling Operation

Tree felling operations were carried out by experienced chain saw operators using the conventional felling method. Tree felling commenced by first making a notch cut at the direction of lean with the aid of powered saw. This is done to make easy the control of the tree fall and to reduce the risk of accident. After the notch cut, a back cut is then given to the trees taking into cognizance the hinge which is the gap between the two cuts. This hinge is normally used in controlling the rate of falling of the timber. During falling, landing time per tree and duration of impact were determined. The manner of fall, the nature of damage and the magnitude of the damages were assessed to be able to qualify and quantify the damages.

Data Analysis

Data collected were analyzed using a combination of descriptive and inferential statistics

Tree Volume Estimation

The volume of each tree was estimated before felling using Newton's formula which states thus:

$$V = \frac{\pi H}{24} (A_b + 4A_m + A_t) \qquad (5)$$

where V = Volume of tree (m^3), H = Height of tree (m), A_b = cross-sectional area at the base of the tree (m^2), A_m = cross-sectional area at the middle of the tree (m^2), A_t = cross-sectional area at the top of the tree (m^2).

Density and Moisture Content of Wood from the Felled Tree

Test samples of 20mm x 20mm x 20mm were collected from the felled trees at the base, middle and top for determination of moisture content and density of green samples using oven dry method at temperature 101 ± 2^{0}C.

Volume of Damaged Portions The volume of damaged portions due to landing impact expressed as a percentage of the whole tree was estimated by subtracting the volume of undamaged wood from the total volume, using the formula: The formula used is:

$$V_d = V_T - V_G \qquad (8)$$

Where, V_d = volume of damaged portion (m^3),
V_T = Total volume of tree (m^3)
V_G = Volume of good quality wood ((m^3)

Physically broken parts of the merchantable logs that were not useful as solid lumber are categorized as wastage.

Maximum Dynamic Stress (MDS) Induced

Angular velocity, angular acceleration, momentum, force generated at impact and the dynamic stress induced were calculated mathematically and the duration of impact determined experimentally with the aid of a stop watch. Stress is equal to force per unit area, the cross-sectional area of the top was used for dynamic stress estimation because the stress will be highest at the top.

Models, Specification and Choice of Functional Forms

For the nine study tree species, the specified regression model for damage volume and maximum dynamic stress are:

i) Volume of Damaged Portion (model 1)

$$V_d = f(H,V,W) \qquad (10)$$

where V_d *= damaged volume* (m^3), *H = tree height (m), V= tree volume* (m^3)*and W= tree weight (N)*

(ii) Maximum Dynamic Stress (model 2)

$$S_m = f(H,Ds,M,A) \qquad (11)$$

Where, S_m *= Maximum dynamic stress* (N/m^2)*, H = tree height (m), Ds = tree diameter (m), M = mass (kg), A = angular velocity of the tree* (ω)*.*

For each species and the two models three functional regression forms were tried. These are linear, semi-log function and double log function. These are as stated below:

Model 1

Linear: $V_d = ß_0 + ß_1H + ß_2V + ß_3W + E$

Where V_d = volume of damaged portion, $ß_0$ = Constant, $ß_1$, $ß_2$ and $ß_3$ = regression constant, E = residual or error term, while B,V, and W are as earlier stated.

Semi logarithm: $V_d = Lnß_0 + Ln\,ß_1H + Lnß_2V + Lnß_3W + LnE$

Double logarithm: $LnV_d = Lnß_0 + Ln\,ß_1H + Lnß_2V + Lnß_3W + LnE$

Model 2

Linear: $S_m = ß_0 + ß_1H + ß_2Ds + ß_3M + ß_4A + E$

Where: S_m, $ß_0$, $ß_1$, $ß_2$, $ß_3$, $ß_4$, H, Ds, M, A and E are as earlier defined.

Semi-logarithm: $S_m = Ln\,ß_0 + Lnß_1H + Lnß_2Ds + Lnß_3M + Lnß_4A + LnE$

Double logarithm: $LnS_m = Ln\,ß_0 + Lnß_1H + Lnß_2Ds + Lnß_3M + Lnß_4A + LnE$

The three functional models were tried for each of the 9 species, for damaged volume and maximum dynamic stress (MDS).

Selection of the Lead Equation

The models were selected based on the co-efficient of determination (R^2) value, root mean square error (RMSE) and F-ratio. After this analysis, if it is discovered that the calculated value of F is greater than the tabulated value, then the regression equation is significant at the tested level of probability. It can then be inferred that at least one of the independent variables contribute significantly to the dependent variable. Therefore t-test was used to identify how many of the independent variables are responsible for the magnitude of change in the dependent variable.

RESULT AND DISCUSSION

The result of this work indicated that *Afzelia africana* has the highest frequency of about 18% of the total number of the study species followed by *Nauclea diderrichii* which represents 15.5% (table 1). The least values were recorded for *Mansonia altissima* and *Entandrophrama angolensis* which constitute 4.8% and 4.5% respectively. In all the sites, *Afzelia africana and Nauclea diderrichii* were the most cropped because the species enjoys heavy export market. *Obeche* is also being heavily cropped because of its domestic use for veneer production and other light structural applications. There is a wide variation between and within species in terms of height (Table 1). Most of the species (83.8%) have the average total height of about 50m indicating that most of the sampled trees are very tall. This observation is line with existing reports for the mature trees in tropical rain forests. Pires and Prance (1977) and Richard (1996) reported an average height of taller tree in a rain forest of between 48-58m with individual sometimes above 60m. The average volume of tree for the study species ranged between 13.68 m^3 for *Mansonia altissima* and 46.25 m^3 for *Entandrophragma angolensis.* The high values of the calculated volumes are indications of the massiveness of the study species. The average density of green wood recorded ranged from 936.91 kg/m^3 for *Cordia millenii* and 1845 kg/m^3 for *Nauclea diderrichii.* The observed densities of green wood were higher than the nominal density (sometimes double the value) due to high moisture content. The average moisture content (on dry basis) for all the species is more than 100% with *Nauclea diderrichii* having the highest average moisture content of 147.05%. Tree and wood properties evaluation in Table 1 show that the study species are characteristically different in height, volume, density and moisture content and are in line with previous studies reported in literature (Cown *et al.*,1991; Richard, 1996; Lucas, 1997; Omole, 2000 and 2010).

Table 1: Average Tree and Wood Properties of the Selected Species

Tree Species	No. of Selected trees	Percentage (%)	Height (m) (m^3)	Volume (kg/m^3)	Density	Moisture Content* (%)
A. africana	53	18.3	51.23	30.72	1765.81	133.77
N. didemchii	33	11.4	49.90	32.29	1845.95	147.05
T. superba	13	4.5	54.78	37.82	1167.00	126.27
K. ivorensis	33	11.4	56.61	42.88	1263.48	129.39
M. excelsa	25	8.6	50.64	35.75	936.91	129.44
C. millenii	14	4.8	42.11	21.21	936.91	108.09
T. scleroxylon	45	15.5	54.78	40.79	882.27	116.39
M. altissima	41	14.1	40.39	13.68	1268.57	110.64
E. angolensis	33	11.4	56.38	46.25	1612.62	137.62

*Moisture contents were calculated on dry basis.

Table 2: Average force and stress induced on study species during felling

Tree Species	Impulse (Value = x 10^5 Ns) Minimum	Maximum	Average	Dynamic stress (x $10^6 N/m^2$) Minimum	Maximum	Average
A. africana	11.57	102.35	53.74	6.50	29.90	18.18
N. didemchii	21.81	108.70	58.18	11.54	31.05	18.75
T. superba	25.50	72.11	44.65	8.22	34.34	14.29
K. ivorensis	25.52	77.34	55.47	9.09	20.59	13.46
M. excelsa	13.93	84.89	55.09	5.16	12.23	12.66
C. millenii	6.05	30.38	17.73	5.61	12.24	8.38
T. scleroxylon	19.61	55.04	36.22	4.65	17.01	10.01
M. altissima	9.41	20.70	14.98	6.72	16.50	9.08
E. angolensis	35.03	111.8	75.88	14.90	21.38	17.84

Table 3: Summary of Regression Model Performance for Felling Induced Mechanical Damages in the study species.

Species	R^2 linear	S-log	d-log	Sum of squares Linear	S-log	D-log	Standard error Linear	S-log	D-log
Apa	0.797	0.778	0.793	0.007	0.046	0.002	0.083	0.214	0.016
Opepe	0.767	0.785	0.776	0.018	0.011	0.006	0.135	0.107	0.025
Afara	0.694	0.697	0.692	0.002*	0.001*	0.001*	0.049	0.009	0.003
Mahogany	0.762	0.747	0.789	0.024	0.003*	0.001	0.153	0.057	0.015
Ijebo	0.665	0.695	0.691	0.035	0.035	0.001	0.187	0.186	0.231
Mansonia	0.829	0.818	0.832	0.001*	0.300*	0.101	0.002	0.012	0.318
Iroko	0.641	0.673	0.673	0.030	0.016	0.030	0.174	0.128	0.034
Obeche	0.872	0.847	0.870	0.284	0.348	0.003	0.533	0.590	0.055
Omo	0.657	0.676	0.663	0.033	0.064	0.001	0.183	0.254	0.022

*significant at P = 0.05

Table 4: Results of regression analyses of mechanical damages in the study species

Species	Dep. variable	Independent variable	Model equation	R^2	SE	F-ratio
Mahogany	Vd	Ht, M, D, Av	Vd=-02.3723-5.4460LnH+ 5.9753LnW	0.762	0.057	289
Afara	Vd	Ht, M, D, Av	$LnVd = -.4731 - 0.3219LnW + 4089LnV_a$	0.692	0.003	930
Mansonia	Vd	Ht, M, D, Av	Vd= -1.8189 –0.00225W + 0.1948V + 0.0151H	0.829	0.002	656

Table 5: Summary of the regression models performance for MDS in the study species.

Species	R^2 linear	S-log	D-log	Sum of squares Linear	S-log	D-log	Standard error Linear	S-log	D-log
Apa	0.368	0.411	0.430	1.701*	0.598*	0.579*	0.000	0.112	0.110
Opepe	0.210	0.172	0.101	8.855	0.675	0.732*	0.001	0.130	0.135
Afara	0.710	0.649	0.660	2.449*	0.203*	0.231	0.001	0.075	0.060
Mahogany	0.323	0.315	0.258	1.617*	0.157*	0.171*	0.000	0.076	0.080
Ijebo	0.114	0.059	0.258	1.204*	0.141*	0.111*	0.001	0.125	0.111
Mansonia	0.206	0.216	0.269	8.128*	0.135*	0.126*	0.000	0.123	0.119
Iroko	0.412	0.470	0.512	1.883*	0.211*	0.198*	0.000	0.103	0.099
Obeche	0.606	0.637	0.639	3.156*	0.081*	0.081*	0.000	.0537	0.0536
Omo	0.653	0.613	0.652	6.411*	0.149*	0.134*	0.001	.0730	0.069

*significant at P = 0.05
S-log = semi log, D-log = double log

Table 6: Results of regression analyses of MDS in the study species

Species	Dependent variable	Independent variable	Model equations	R^2	SE	F- ratio
Apa	S_m	Ht, D, M, A_v	$LnS_m = 12.7398 - 0.0452LnH + 7.0x10^{-6} LnM - 2.1731LnA_v$	40.03	0.110	9.06
Mahogany	S_m	Ht, D, M, A_v	$LnS_m = 3.2525 + 1.08 \times 10^{-5}M_a$	31.54	0.080	3.11
Opepe	S_m	Ht, D, M, A_v	$LnS_m = 6.6057 - 0.326D_s + 6.5 \times 10^{-6} M$	17.16	0.130	2.07
Iroko	S_m	Ht, D, M, A_v	$LnS_m = 3.1512 + 0.6679LnM$	51.18	0.100	5.24
Afara	S_m	Ht, D, M, A_v	$LnS_m = 1324 + 1.6619LnH - 1.3844LnD_s + 0.8242LnM + 2.4341LnA_v$	66.01	0.061	13.50
Obeche	S_m	Ht, D, M, A_v	$LnS_m = .6351 - 1.2145LnD_s + 1.0774L_nM_a$	63.86	0.053	12.38
Omo	S_m	Ht, D, M, A_v	$LnS_m = 24.9032 - 1.4147LnD_s + 0.8021LnM_a$	65.15	0.069	13.09

In all the study species as shown in table 2, the average impulse and dynamic stresses induced in the wood during felling operations are considerably high and varies from one species to the other depending on tree volume with the average force generated at impact ranging between 1.498 x 10^6N for *Mansonia* and 7.589 x 10^6N *Ijebo*. The mean dynamic stress induced in the species ranged from 8.38 x 10^6N/m² in *Obeche* and 18.75 x 10^6N/m² in *Opepe*. The maximum dynamic stresses induced in the trees impact were all well above the ultimate stresses in static loading.

Models performances for incidental damages and MDS in the study species

Shown in table 3 are results of the regression analyses carried out to determine the factors responsible for the magnitude of the incidental damages in tropical hardwoods during felling. Of the 27 fitted models for the nine species and on the basic of coefficient of multiple determination (R^2) standard error (SE) value and significance of the regression model, only 3 models for 3 species were selected. These species are *Terminalia africana, Khaya ivorensis* and *Mansonia altissima* and the equations are as shown in table 4.

The results of statistical analysis of maximum dynamic stress are as presented in Table 5. Based on the significant of the equation, high coefficient of determination and low standard error, only seven models of seven species were selected. The equations for the selected models are summarized in table 6. The results show that the seven (7) species exhibit significant relationship between the dependent variable (MDS) and the independent variables (Height, diameter, mass and angular velocity) while only two species (*Mansonia altissima* and *Entandrophragma angolensis* did not. The response to dynamic loading is expected to vary because species with lower strength properties are more sensitive to dynamically applied load than species with higher strength. This explains

Table 7: Correlation Matrix of the investigated tree parameters of the Selected Nine Species

Species	x	a_1	a_2	a_3	a_4
Afzelia Africana	a_1	1.00			
	a_2	0.657	1.00		
	a_3	0.780	0.819	1.00	
	a_4	-0.987	0.669	-0.780	1.00
Nauclea diderrichii	a_1	1.00			
	a_2	0.681	1.00		
	a_3	0.881	0.841	1.00	
	a_4	-0.987	0.654	0.842	1.00
Terminalia superba	a_1	1.00			
	a_2	0.365	1.00		
	a_3	0.393	0.531	1.00	
	a_4	0.171	-0.120	-0.568	1.00
Khaya ivorensis	a_1	1.00			
	a_2	0.739	1.00		
	a_3	0.919	0.752	1.00	
	a_4	-0.993	-0.738	-0.905	1.00
Meliacia excelsa	a_1	1.00			
	a_2	0.872	1.00		
	a_3	0.866	0.871	1.00	
	a_4	-0.986	-0.840	-0.861	1.00
Cordial millenii	a_1	1.00			
	a_2	0.754	1.00		
	a_3	0.701	0.807	1.00	
	a_4	-0.992	0.733	0.694	1.00
Entandropharama angolensis	a_1	1.00			
	a_2	0.849	1.00		
	a_3	0.857	0.986	1.00	
	a_4	-0.997	-0.842	-0.855	1.00
Triplochiton scleroxylon	a_1	1.00			
	a_2	0.100	1.00		
	a_3	0.571	0.764	1.00	
	a_4	-0.996	-0.101	-0.566	1.00
Mansonia altissima	a_1	1.00			
	a_2	0.706	1.00		
	a_3	0.616	0.745	1.00	
	a_4	0.996	-0.717	-0.6 25	1.00

*Note: a_1= *Tree Height*, a_2= *Stump diameter*, a_3= *Tree Mass* a_4=*Angular velocity*

why the damages observed in *Obeche* (10.79%) and *Afara* (12.66%) were higher than *Opepe* of 7.68% with the maximum dynamic stress of 18.75x10⁶N/m². A detailed discussion of micro-mechanical failure mechanism in wood according to Mark (1967) is that initial failure in the cell wall is mostly likely to occur in S_1 layer or S_1/S_2 interface. He also hypothesized that inter-laminar shear stresses are the most likely cause of failure in wood. Hence the observed failure in the wood can be inferred to have resulted from excessive shear stress which is dynamic in nature. The magnitude will even be more compounded due to high moisture content of green wood of the study species From the models it was discovered that MDS induced in tropical timbers during felling operation is dictated by the height of the falling tree, the mass of the falling tree and in certain instances the angular velocity at the time of landing.

The correlation matrix presented on Table 7 for the independent variables equally showed a significant relationship. From the various correlation matrices for the independent variables in the nine selected species, the height of the tree is positively correlated with both the stump diameter and the total mass of the tree. This is expected because a taller tree with the same stump diameter should weight higher when compared to a shorter tree. Also in a heterogeneous forest stand, the girth diameter of trees could be a function of the age of the tree and bigger trees expectedly are normally very tall. The mass and the stump diameter are positively correlated with almost perfect correlation. On the other hand, the height is negatively correlated with the angular velocity. This invariably means that the taller a tree is the smaller the value of the angular velocity.

CONCLUSIONS

There are wide variations between and within species in both the tree and wood characteristics. These properties have influenced both dynamic stresses and the mechanical damages induced on the wood in tree during felling operation. For example, the damage model indicated that the magnitude of the damage portion is influenced by tree height, volume and weight. The magnitude of the dynamic stresses and force generated at impact are considerably high and these are related to species, tree height, tree diameter, tree mass and angular velocity. In spite of the very high dynamic stresses induced in wood of the felled trees, the wood is able to absorb the stresses. This unique performance is attributed to its cellular, polymeric and fibre-composite nature. The linear regression models developed allowed the factors involved in determining the impact force and the dynamic stresses on the felled tree to be established without recourse to extensive full scale mechanical testing.

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