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Damage Evaluation of Two Equatorial Hardwoods under Uniaxial Compression: Case of *Entandrophragma cylindricum* (Sapelli) and *Chlorophora exelcia* (Iroko)

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Abstract

This work aims at characterizing the evolution of the damage of two tropical hardwoods. Two species from Cameroon, the Entandrophragma Cylindricum and the Chlorora Exelcia were used for the purpose. Repeated compressive loading has been made on specimens strictly selected along with longitudinal and radial directions of each species. Each cycle was made of one phase of monotonic loading and a phase of elastic release. From data obtained, we determined the variation of Young modulus and plastic deformation during each cycle of loading, and we had deduced the damage of the material. Results show that the damage appears only after a certain threshold of the plastic deformation; that damage then grows exponentially to reach a threshold after which the failure of the material occurs. As well, we noticed that the growth of damage is accompanied by the progressive decrease of the Young modulus; this confirms the deteriorating effect of the damage on the mechanical properties. Elsewhere, the damage failure threshold is less than the theoretical value, and differs from one direction to another. Finally, we noticed that the damage failure threshold of sapelli is greater than that of iroko that allows concluding that iroko gets damaged and fails more rapidly than sapelli.

Keywords

Damage, Wood, Measurement, Cyclic Test, Modulus of Elasticity

1. Introduction

The context of sustainable development and of the respect of environment brought the population to turn their self this last decade towards biologic and renewable materials whose principally woods. Those woods abundantly available on the earth surface, and particularly in the equatorials zones have utility in various domains extended from carpentry to civil engineering. However, the optimal use of those woods implies the perfect knowledge of their physical, and mechanical properties and especially their behavior when they are subjected to a certain type of loading usually found in structures. A good knowledge of the wood's behavior regarding phenomena as plasticity, fatigue and damage is thus necessary for a better valorization of that resource.

Damage is a progressive deterioration conducting to the failure of the material [1]. The process of damage starts by the germination of micro cavities, followed their growth and their coalescence. The coalescence of micro cavities is the final stage of the damage process which corresponds to the creation of micro cracks within the material [2]. The mathematical description of the phenomenon of damage is possible since 1960s when Kachanov [6] defined a variable which describes the evolution of the deterioration of the material. Since then the phenomenon of damage has widely been studied for materials as steels, aluminum, and concrete [1]-[6].

Many studies have been conducted on the determination of physical and viscoelastic properties of wooden material [7], [8], [9], [10] but nevertheless, very few studies have been done on the damage of wooden material. This work aims to describe the damage of some tropical species.

An important stage in the study of the damage of a material is the measurement of that damage. There are several methods of measuring the damage in the literature [11] [12]; however, the pertinence of a method depends on the type of loading on which the material is subjected. In this work, we used a method based on the variation of the modulus of elasticity to measure the damage in the longitudinal and radial direction of sapelli and iroko, subjected to repeated compressive loading.

2. Material

2.1. The Wood

Wood is a biological, anisotropic, heterogeneous and hygroscopic material. In the wood, it is possible to distinguish two main areas: the duramen and the sapwood [13]. The duramen is the central part of the wood made up of died cells and ensure the mechanical support of the tree. The sapwood is located at the periphery under the bark and is made of living cells and ensure the conduction of the sap. Wood presents a large variability according to the species, the area of growth, and the age. Two tropical species were the subject of this study:

- The sapelli (Entendrophragma Cylindricum) found essentially in Africa, notably in west Africa, central Africa and east Africa. It is widely used as wood for carpentry; naval construction, bridge, framework [14], [15];

– Iroko (Chlorophora Exelcia) also found in Africa, especially in central Africa, west Africa and East Africa, it is widely used as wood for carpentry, parts of wooden structures, naval construction [14] [16].

2.2. Specimens

Specimens were extracted in the duramen of each species (**Figure 1(a)**) following the longitudinal and radial direction and were stored in the laboratory during a period of two months (sixty days) under an average ambient temperature of 23˚C, this to ensure the drying and the drying and the equilibrium with the environment. They were extracted following the standard NFB 51-003 for the specimens in compression. Dimension of tests tubes is (**Figure 1(b)**) 30 mm × 30 mm × 90 mm.

3. Methods

3.1. Determination of Moisture Content

The moisture content is determined following the standard NFB 51-004 which consist in determining the mass of wood with moisture, and the mass of wood in an anhydrous state after a dehydration in a climatic enclosure.

The moisture content is given by the relation

$$H = \frac{m_H - m_0}{m_0} \times 100 \tag{1}$$

where:

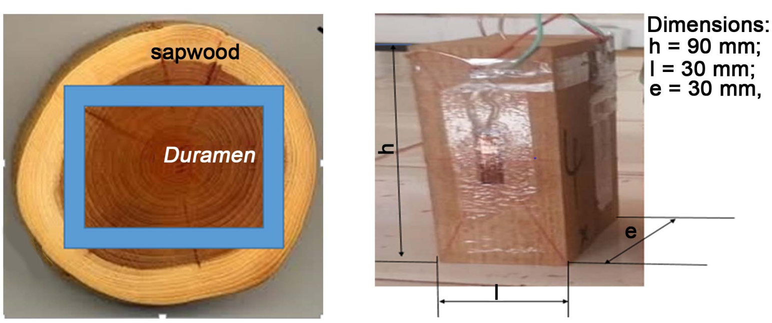
– H is the moisture content of the specimen;

– m_0 is the mass of wood in an anhydrous state;

– m_H is the mass of wood with moisture H.

3.2. Determination of Mechanical Properties

The determination of the maximum stress has been done following the standard NFB 51-007. The maximum stress C_H thus obtained corresponds to a precise moisture content H. That maximum stress would be converted to a maximum stress at a moisture content of 12% using the relation [7].



(a) (b)

Figure 1. Zone of extraction of specimen (a) and dimensions of specimen (b).

$$C_{12} = C_H \left[1 + c \left(H - 12 \right) \right] \quad (2)$$

where:

C_{12} is the maximum stress at 12%;

H is the moisture content;

C is the upkeep moisture coefficient in axial compression.

For the determination of the modulus of elasticity, test of monotonic loading at low velocity has been carried out on specimen. Strains, where recorded at each increment of the stress and the modulus of elasticity, have been deduced after plotting the graph stress-strain using the Hooke's Law.

3.3. Measurement of the Damage

The method of measurement that we used to measure the damage is an indirect and destructive method based on the variation of the modulus of elasticity of a material as effect of the damage. The principle of the method consists in determining the modulus of elasticity of the damaged material and then using the effect of the damage on an undamaged material, the damage is deduced by the relation [2].

$$D = 1 - \frac{\tilde{E}}{E} \quad (3)$$

where:

D is Damage;

$\tilde{E}$ is the modulus of elasticity of the damaged material;

E is the modulus of elasticity of the undamaged material.

For the determination of the damage of our species, repeated compressive loading tests were made. For each cycle of loading, the stress has been increased by steps of 2.5 Mpa from zero at a low velocity. For the first cycle, the phase of loading was conducted with the increase of the stress till a value lightly less than 30% of the maximum stress; then a quick unloading has followed, bringing back the stress to 0 Mpa. For the following cycles, the same procedure of loading was reproduced, but making sure that the ultimate stress for the cycle is greater than that of the previous cycle by a value of 2.5 Mpa. Tests tubes in longitudinal direction were subjected to 05 cycles of loading and unloading, while those in radial direction were subjected to 03 cycles.

3.4. The Testing Machine

The machine used (**Figure 2**) is a modern compression-tension machine of type DMY. The machine is made of a hydraulic jack (3 - 4) activated by an engine (8) which develop a power of 1.5 Kw. The engine is started by power supply. Oil circulates from the oil vat through the pipes and arrives under pressure in the cylinder (4). This pressure involves the displacement of the piston (3) which, once in contact with the test-tube, gradually compresses it (adjustment of the race by the operator). The pressure and the shortening are simultaneously

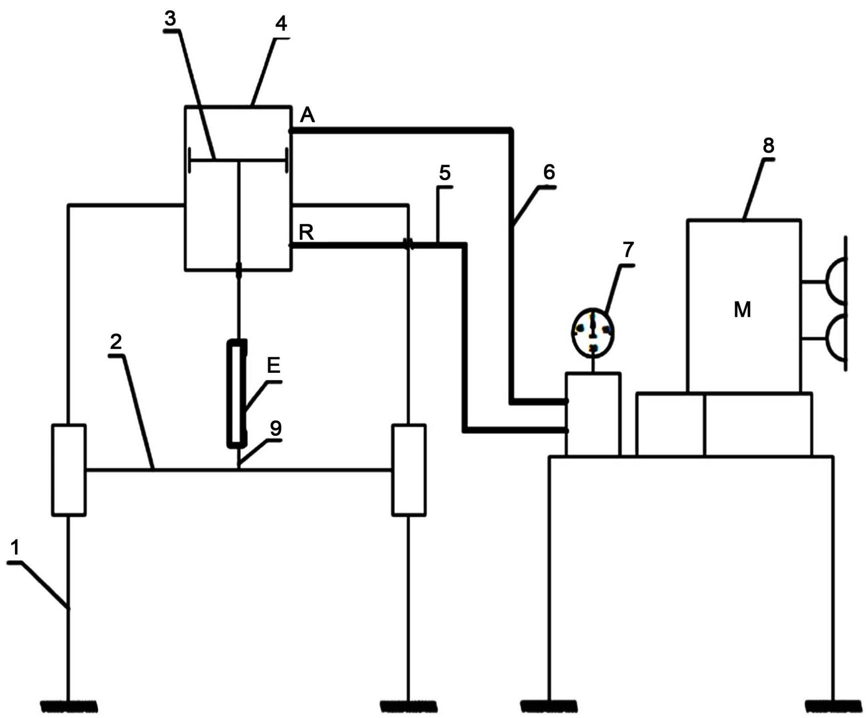


Figure 2. Kinematic diagram of the testing machine.

recorded. A handle regulates the quantity of fluid going in the jack (6) and the quantity living the jack. A manometer fixed on the handle indicates the pressure of the fluid.

1) A base plate in UPN on which rests the four uprights.

2) Two longitudinal members adjustable in the vertical.

3) A piston whose linear displacement of the rod causes the extension or the compression of the sample.

4) A cylinder body, in which houses the control piston.

5) A driving pipe for the injection of the oil.

6) Another piping allowing the aspiration of the oil.

7) A manometer to evaluate the intensity of the effort applied.

8) An electric motor powered by a D_C socket, a box containing oil, filter elements and oil pumping.

4. Results and Discussions

4.1. Moisture Content

Table 1 and Table 2 show the variation of the moisture content of sapelli and iroko dried in the laboratory. Tests tubes were stored in the laboratory during a period of sixty days at the average ambient temperature of 23˚C and the air moisture content of 70%. It follows from tables that the moisture content of sapelli during our test is 19.31% and 15.82% for iroko. Those moisture content are greater than 8% and lower than 25% and thus are satisfactory to guarantee the validity of our various results [7].

Table 1. Moisture content of the sapelli during the experiment.

Test-tubes	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mass M_H	51.96	52.1	53.53	51.32	51.99	50.35	50.54	52.25	52.18	49.11	50.15	51.17	50.24	50.10
Mass M_0	40.04	42.32	44.38	43.26	44.08	44.29	42.88	43.99	42.62	42.16	43.17	42.26	42.16	42.05
Moisture content H (%)	20.72	23.10	20.61	18.63	17.26	17.38	17.42	14.88	22.59	23.76	13.49	18.67	21.37	19.47
Average H (%)	**19.31**													

Table 2. Moisture content of the iroko during the experiment.

Test-tubes	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mass M_H	44.29	46.5	44.36	45.96	42.25	44.29	42.24	44.22	43.99	44.59	48.98	44.76	43.24	42.17
Mass M_0	36.37	40.17	38.24	39.55	36.43	38.99	36.46	38.85	38.23	39.25	39.2	38.15	37.26	37.15
Moisture content H (%)	21.77	15.75	16.00	17.90	15.97	15.89	15.85	13.60	17.89	17.41	13.34	13.17	13.40	11.25
Average H (%)	**15.82**													

4.2. Maximum Stress of Species during the Experiment

It came from **Table 3** and **Table 4** that the average maximum stress of sapelli at a moisture content oh 19.31% is 47.98 Mpa and that of iroko at a moisture content of 15.82% is 45.80 Mpa. Those maximum stress converted to 12% of moisture content using Equation (2) gives 62.86 Mpa for sapelli and 53.05 Mpa for iroko. Maximum stress found in the literature is 62 Mpa for sapelli and 52 Mpa for iroko [14], [15], [16] The proximity of our results to those of literature therefore, allow us to confirm the reliability of our equipment and the validity of our results.

4.3. The Damage

Repeated compressive loading tests till failure were made on a series of 06 specimens in the longitudinal and 05 specimens in the radial direction of each species. During each cycle of loading, strain and stress have been recorded and the graph stress-strain have been plotted. On that graph, the slope of the linear part with the correlation factor greater to 0.99 represents the modulus of elasticity. For the first cycle, the slope represents the modulus of elasticity of the undamaged material, while for the other cycles, the slope represents the modulus of elasticity of the damaged material. The damage is deduced whit the relation of Equation (2). **Tables 5-8** show results for each direction.

The theoretical evolution of the damage variable is between 0 and 1. The value zero corresponds to initial state of undamaged material and value 1 correspond to the failure of the material [11]. For our specimens, we observe that the failure occurs when the value of the damage is less than 1. This shows that the threshold value of the damage for failure of our species is less than 1 in both directions. This observation has also been made concerning another specie [17]. Elsewhere,

Table 3. Maximum stress of sapelli during the experiment.

Tests tubes	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Maximum stress at 19% (Mpa)	46.18	46.18	49.17	49.60	46.18	47.89	47.89	47.89	46.18	49.60	47.89	49.60	49.60	47.89
Average (Mpa)	**47.98**													
Maximum stress at 12%	62.29	66.70	62.09	62.75	55.90	56.12	58.27	53.42	68.18	67.91	52.57	60.66	49.60	49.60
Average	**61.86**													
Root means square	5.54													

Table 4. Maximum stress of iroko during the experiment.

Tests tubes	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Maximum stress at 15.82% (Mpa)	46.18	44.47	47.89	46.18	42.76	46.18	47.89	44.47	46.18	49.60	44.67	42.76	46.18	46.18
Average (Mpa)	**45.80**													
Maximum stress at 12% (Mpa)	64.24	51.15	55.56	88.49	53.52	32.32	53.29	41.52	35.03	49.14	75.19	54.10	45.05	48.35
Average (Mpa)	**53.05**													
Root means square	14.36													

Table 5. Evaluation of damage following the longitudinal direction of sapelli.

	SAP L01		SAP L02		SAP L03		SAP L04		SAP L05		SAP L06	
	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D
Cycle 1	10482.38	0	9392.17	0	9506.12	0	9506.12	0	13584.54	0	12919.52	0
Cycle 2	9366.24	0.1064	9388.93	0.0003	9111.53	0.0415	9474.06	0.0033	12273.73	0.0964	12777.02	0.0110
Clycle 3	9173.90	0.1248	9154.37	0.0253	9066.65	0.0462	9169.63	0.0364	12190.68	0.1026	12715.82	0.0157
Clycle 4	9159.33	0.1262	9026.73	0.0389	8966.41	0.0567	9168.65	0.0365	11948.22	0.1204	12283.93	0.0491
Clycle 5	8899.97	0.1509	9019.44	0.0393	8947.17	0.0587	9034.03	0.0496	11452.20	0.1569	11968.61	0.0736

Table 6. Evaluation of damage following the radial direction of sapelli.

	SAP R01		SAP R02		SAP R03		SAP R04		SAP R05	
	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D
Clycle 1	1424.50	0	1485.28	0	1592.15	0	1339.33	0	1321.76	0
Clycle 2	1252.62	0.1206	1476.81	0.0057	1448.40	0.0902	1124.05	0.0116	1262.40	0.0449
Clycle 3	1078.23	0.2430	1458.05	0.0183	1436.61	0.0976	1021.96	0.2369	1230.58	0.0689

we observe a difference between those threshold values of damage of failure. The threshold value differs from one specimen to another, from one direction to another and especially from one specie to another. This shows that the evolution of the damage in wooden material depends on mechanical and physical properties of the specimen. We also observe a progressive decrease of the modulus of elasticity with the increase of the damage. This shows the deterioration of mechanical properties of a material as an effect of damage. **Figure 3** shows the graph stress-strain and damage-plastic strain for some tests tube.

Table 7. Evaluation of damage following the longitudinal direction of iroko.

	IROK L1		IROK L2		IROK L3		IROK L4		IROK L5		IROK L6	
	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D
Clycle 1	6042.88	0	8068.25	0	9784.42	0	8002.97	0	9725.26	0	10862.97	0
Clycle 2	5994.50	0.0080	7815.88	0.0312	9442.00	0.0349	7530.987	0.0589	9539.05	0.0191	10493.73	0.0339
Clycle 3	5973.81	0.0114	7331.81	0.0912	9195.17	0.0602	7135.71	0.1083	9439.09	0.0294	10400.77	0.0425
Clycle 4	5469.07	0.0949	7240.91	0.1025	7964.50	0.1860	6900.53	0.1377	9363.32	0.0372	10045.24	0.0752
Clycle 5	5447.80	0.0984	7041.29	0.1272	7898.06	0.1927	6480.01	0.1902	9362.74	0.0372	9929.55	0.0859

Table 8. Evaluation of damage following the longitudinal direction of iroko.

	IROK R01		IROK R02		IROK R03		IROK R04		IROK R05	
	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D	E (Mpa)	D
Clycle 1	1227.35	0	1531.48	0	739.67	0	1474.80	0	1058.14	0
Clycle 2	1195.46	0.0259	1410.11	0.0792	704.81	0.0471	1375.56	0.0672	1026.14	0.0311
Clycle 3	1171.72	0.0445	1354.03	0.1158	666.24	0.0992	1096.24	0.2566	929.02	0.1228

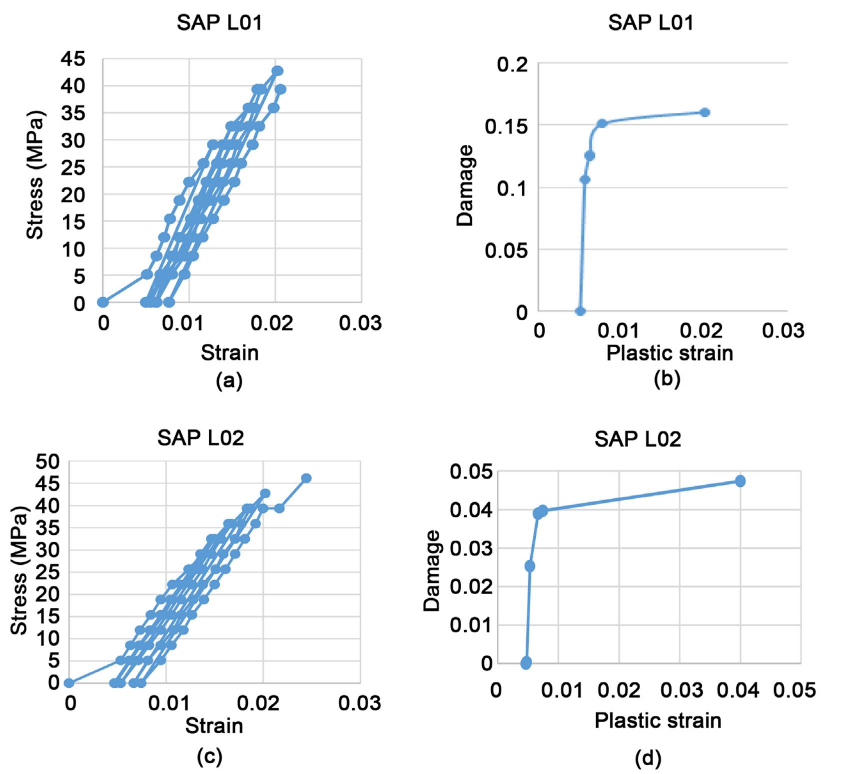


Figure 3. Stress-strain diagram ((a), (c)) and damage-plastic strain ((b), (d)) in longitudinal direction.

From figures, we remark that the graph showing the damage as function of plastic strain has two distinct zones which are:

– A first zone where the damage grows promptly from the value zero to a threshold value;

– A second zone where the damage, over the threshold value grows weakly.

We remark the damage starts only for plastic strain greater than zero and allows us to conclude that the damage occurs only for important plastic strain. Again the value of plastic strain causing the starting of the damage differs from one specimen to another, this difference shows that even if the plastic strain has to be important for the damage to occurs, it has also to reach a certain threshold. That threshold depends on the composition of the specimen, the direction, and the specie.

Elsewhere the quick growth of the damage in the first zone can be explained by the interdependence existing between the damage and the effective stress. The damage reduces the resistant section of the material, and it consequently causes the increase of the effective stress in the specimen.

For the second zone, the stabilization of the evolution of the damage over the threshold value can signify that the threshold value is the maximum value for the damage over which the failure occurs.

5. Conclusion

This work was devoted to the measurement of the damage of some tropical hardwoods. For the purpose, we choose an experimental approach that was a series of repeated compressive loading tests on the longitudinal and radial directions of the species. The variation of Young's modulus allowed to characterize the damage of each specimen. It follows from this work that the damage of a specimen starts after a certain threshold of the plastic strain, then grows exponentially to reach a maximum value over which it remains almost constant. That maximum value is the critical value of the damage and represents a threshold for the failure. The threshold value of damage for the failure for both species and in both directions is lower than the theoretical value. The variation of modulus of elasticity as a function of the damage has allowed to show the deteriorating effect of the damage on the mechanical properties of a material.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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