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Modeling the stress-strain behavior of Bamboo under cyclic uniaxial loading

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Abstract

This paper presents a series of cyclic uniaxial compressive loading tests carried out on cylindrical samples of bamboo, in order to develop unloading and reloading stress-strain models. Two bamboo species from Congo Basin, the Bambusa vulgaris and Oxytenantera abyssinica were used for these experiments.

It is found from the test results that the unloading and reloading do not essentially change the shape of the envelope curves of the stress-strain relations and that to predict models for an unloading and a reloading path, the plastic strain, the unloading strain, the strain at yield, the unloading stress, the initial tangent modulus and the tangent modulus at zero stress (after specimen is completely unloaded) are the controlling parameters. These controlling parameters were analyzed based on the data obtained from test results to propose empirical relations for the unloading and reloading curves. Two empirical relations, one an exponential type relation and the other a power type relation are proposed to idealize the unloading path while the reloading curve is idealized as a combination of a parabolic curve and a straight line. The proposed unloading and reloading stress-strain models were compared to the tests results and the comparison showed that the predicted unloading and reloading stress-strain relations provide a good agreement with the test data. The empirical relations proposed are adapted from those for plain concrete under similar loading.

***Keywords**: modeling, uniaxial compression, cyclic, bamboo, unloading path, reloading path, plastic strain, empirical relation*

Résumé

Cet article présente une série d'essais de compression axiale cyclique sur les essences de bambou de chine en vue de développer des modèles de contrainte et déformation pour des cycles de charge et de décharge de ce matériau. Deux essences de bambou de la forêt du Bassin du Congo ont été utilisées pour réaliser ces essais. Il s'agit du Bambusa vulgaris et Oxytenantera abyssinica.

Il a été prouvé que la forme de la courbe enveloppe de la relation contrainte-déformation n'est pas influencée par les cycles de charge et de décharge et que pour proposer les modèles pour les trajets différents de charge et de décharge, la déformation plastique, la déformation de contrainte de déchargement, la déformation de limite d'élasticité, la contrainte de déchargement, le module d'Young initial et le module d'Young tangent à la contrainte zéro (lorsque l'échantillon est complètement déchargé) sont des paramètres essentiels. Ces paramètres essentiels ont été analysés suivant les données obtenues des résultats des essais de laboratoire en vue de proposer les relations empiriques pour les courbes de charge et de décharge. Deux relations empiriques, une de forme parabolique et l'autre de forme exponentielle, ont été proposées pour idéaliser la courbe de décharge alors qu'une combinaison d'une relation parabolique et une relation linéaire ont été utilisées pour idéaliser la courbe de recharge. Les modèles proposés pour les relations contrainte-déformation ont été comparés aux résultats des essais et cette comparaison a montré que les modèles proposés s'accordent très bien avec les résultats des essais. Les relations empiriques ont été adaptées des relations utilisées pour modéliser le béton cyclopéen soumis aux mêmes types de chargement uniaxial de compression cyclique.

***Mots clés** : modélisation, compression uniaxial, cyclique, bambou, chemin de décharge, chemin de recharge, déformation plastique, relation empirique.*

1. Introduction

Bamboo is a good construction material for low cost buildings and it is considered as a very safe building material. It has very high flexibility and toughness characteristics as well as very good mechanical characteristics.

It is believed that the mechanical characteristics of bamboo are likely to be at least similar, if not superior to those of structural timber. Bamboo has a very high strength to mass ratio as compared to other building materials such as wood and steel (Janssen, J. J. A, 1985). The tensile strength of some species of bamboo can be as high as 120 MPa and the compressive strength as high as 55 MPa (Bhalla, S). However the drawback of bamboo is that it is susceptible to termite attack. This setback can be improved by suitable treatment.

Its ability to resist seismic loadings and effects of hurricanes is very high; consequently it is a perfect material for earthquake resistant buildings. It is lightweight and its hollow form gives it much stiffness.

Much work has been carried out (Aslani, F et al, 2012, Morris, J. W., et al, 2000, Sima, J.F., et al 2007, Šumaroc, D., et al, 2008) to study the behaviour of materials such as concrete and steel under monotonic as well as cyclic compressive loadings, and several models have been proposed for unloading and reloading hysteresis under compressive cyclic loading for these materials. Also, much work has been carried out to determine the mechanical characteristics of bamboo and the stress strain behaviour of bamboo under various monotonic loading regimes has been determined. However, nothing is available in the literature for the behaviour of Indian bamboo under uniaxial cyclic compressive loadings. The aim of this work is to propose models for the reloading and unloading paths of bamboo under uniaxial cyclic compressive loadings that could be used to predict the behaviour of this material under similar loading. This will help in appreciating the behaviour of the material under cyclic stresses in order to predict the behaviour the material under seismic regions.

The behavioural characteristics of Indian bamboo dominantly depend on the load history. Experimental investigation of Indian bamboo under random cyclic load history was performed in order to study its behaviour under compressive cyclic loading. Through this study, modeling for the stress strain relationship for this material under cyclic random loading is proposed.

The models developed are based on the results of experimental data obtained from laboratory tests performed on specimens of this material. The highly nonlinear nature of the stress strain relationship under cyclic loading cannot be easily described by any mathematical formulae. Through the review of researches carried out on other materials, such as plain concrete under similar loading, it can be suggested that one or more model parameters can be predicted from the experimental stress strain curves.

The real behaviour of bamboo under cyclic loadings has been explained by providing realistic stress-strain material models. The model provided in this research work on the cyclic behaviour of bamboo can be used to predict all the hysteretic characteristics of the material in cyclic loading. The following three categories of models that have been used to model some materials like plain concrete under uniaxial cyclic compression loading can also be used for the development of constitutive models for bamboo. These models are derived from :

- Theory of elasticity;
- Theory of plasticity;
- Fracture and Continuum damaged mechanics.

Also some coupled models based on the association of the theory of plasticity and continuum damaged mechanics have recently been developed.

Two models have been applied to model the behaviour of bamboo under cyclic uniaxial loading. One of the models is based on the theory of plasticity while the other is based on the association of the theory of plasticity and continuum damaged mechanics.

2. Material and Methods

The major objective of this research work is to propose empirical relations to simulate the general stress strain behaviour of Indian bamboo under cyclic loading. Models for the unloading and reloading paths will be proposed. The proposed models are initiated to provide flexibility of mathematical expression and to describe the behaviour of random cycles.

Material

Two bamboo species from the Congo basin rain forest, the *Bambusa vulgaris* and *Oxytenantera abyssinica* were used for these experiments. The *Bambusa vulgaris* is the large and very tall bamboo species whereas *Oxytenantera abyssinica* is the slender bamboo species. The *Bambusa vulgaris* species was obtained from humid soil while the *Oxytenantera abyssinica* is the slender species and it was obtained from dry soil. After harvesting the bamboo culm, the growth bud was carefully trimmed for each species.

Bamboo is the common name for a member of a particular taxonomic group of perennial grass with large woody stem or culm belonging to the family *Poaceae or Graminae* and subfamily *Bambusoideae*. There are about 1200 to 1500 species of bamboo (Chaowana, P., 2013, Chung, K. F. et al, (2002), and Liese, W., 1999). Africa has about 43 species of bamboo covering about 1.5 million hectares of land. The main species of bamboo found in Africa are the Arundinaria alpine, *Bambusa vulgaris* and *Oxytenanthera abyssinia* (Chaowana, P. 2013).

The construction industry is one of the most polluting industries in the world. The production of materials such as steel and cement will emit tons of carbon dioxide in the atmosphere whereas the production of bamboo will consume more carbon dioxide from the atmosphere (Chaowana, P, 2013). Therefore the fast growth rate of bamboo enables it to sequestrate significant quantities of carbon dioxide (CO_2) from the atmosphere in a relatively short time (Bhalla, S., and Janseen, J. J. A, 2000).

Bamboo is the most important non wood species that grows in most tropical and subtropical zones. It has been shown that bamboo is a superior alternate for manufactured wood composites. It is inexpensive, fast growing, easily available, and having comparable physical and mechanical properties to wood (Chaowana, P., 2013).

Bamboo is a composite material with long and parallel cellulose fibers in its structure. Its growth rate is very high with most of the growth occurring during the first year and growth ceasing by the fifth year (Amada, S. et al 2001). The strength of bamboo increases with age. The maximum strength occurs at the age of about 3-4 years (Amada, S. et al. 2001) and after this age, the strength begins to decrease.

The major morphological characteristic of bamboo is divided into the rhizome and the culm. The rhizome or the subterranean stem is the underground part of the bamboo while the culm is the upper ground part that contains the wood material. The culm is straight, hollow and cylindrical in shape having nodes and internodes. The function of the nodes is to prevent buckling. In the internodes, the cells are strongly oriented axially with no radial cell elements; therefore the transversal interconnection is provided only by the nodes.

The bamboo culm is made up of tiny countless fibers known as cellulose embedded in a lignin matrix (Chaowana, P., 2013, Janseen, J. J. A. 2000 and Liese, W 1999). The cellulose fibers run the length of the culm, carrying nutrients between the roots and the leaves (Naik, N.K 2004). The cellulose fibers act as the reinforcing steel in reinforced concrete or glass fibers in fiber reinforced plastics (Janseen, J. J. A. 1985). The lignin is the thermoplastic resin in that fills the spaces between the cellulose fibers The distribution of the cellulose fibers increases from the inside to the outside (Janseen, J. J. A. 1985 and Naik, N.K 2004). Generally, the cellulose fiber is stronger than lignin. About 70% of the fibers in bamboo is cellulose and in most bamboo species, the fibers constitute about 60% on the outside and 10% on the inside (Janseen, J. J. A. 1985).

Bamboo is an orthotropic material, having particular mechanical characteristics in the three directions; that is along the longitudinal, the transverse and the radial directions. Also, bamboo is a biological material, therefore the mechanical characteristics are affected by conditions such as soil conditions, species, age, environmental conditions and position of the culm within the bamboo (Naik, N.K 2004).

Bamboo is one of the oldest building materials used by mankind in the tropical and subtropical zones. The bamboo culms have been widely used in building applications such as flooring, ceilings, walls, windows, roof trusses, structural materials for bridges and scaffoldings for the construction of high rising buildings.

The length of the specimens from *Bambusa vulgaris* varied from 88mm to 91.5mm while that of *Oxytenantera abyssinica* varied from 185mm to 195mm. The external diameters varied from 86mm to 92mm for *Bambusa vulgaris* and from 31mm to 40mm for *Oxytenantera abyssinica*. The wall thickness varied from 14mm to 19mm for *Bambusa vulgaris* and from 4.5mm for the top specimens to 21mm for the bottom specimens for *Oxytenantera abyssinica* as shown on table 1.

The green bamboo was left in the laboratory for five (5) months for seasoning. After air drying, some specimens were oven dried at a temperature of 120^{0}C for twenty four (24) hours as shown on picture 1a while others were soaked in water for forty three (43) days as shown on picture 1b before testing.

The moisture contents of some of the samples used for experiments are found on table 2

Table 1: Geometrical characteristics of the *Oxytenantera abyssinica* specimens used

Nº	Specimen	Diameter (mm)		Length (mm)	Remarks
		External (d1)	Internal (d2)		
01	T2 Bottom with node (Fig.3a)	39.5	19.5	188	**Samples soaked in water for 43 days before testing.**
02	T10 Bottom without node (Fig.3b)	37	16.5	185	
03	T6 Middle without node (Fig.3c)	36.25	27.25	188	
04	T10 Middle without node (Fig.4a)	40.5	33.25	187	**Samples oven dried at 120°C for 24hrs**
05	T7 Middle without node (Fig.4b)	36	30.5	189	
06	T8 Bottom with node (Fig.4c)	38.1	32.05	190	
07	T9 Bottom without node (Fig.4d)	40.05	34.3	193	
08	T9 Top without node (Fig.5a)	38	32.9	190	**Samples air dried before testing**
09	T4 Bottom with node (Fig.5b)	34.25	24.65	184	
10	T4 Middle with node (Fig.5c)	33.3	26.3	184	
11	T6 Bottom without node (Fig.5d)	38.5	32.75	186	
12	T1 middle (Fig.5e)	36.45	27.6	184	

Table 2 : Moisture contents

Nº	Specimen	Moisture content (%)
1	T2 Bottom	107.5
2	T10 Bottom	87.5
3	T6 Middle	101.25
4	T9 Top	16.39
5	T4 Bottom	17.14
6	T1 Middle	15.98
7	T4 Middle	15.07
8	T6 Bottom	16.42

Methods (Experimental Program) :

The purpose of the experimental program in this paper is to investigate the behaviour of Indian bamboo under cyclic compressive uniaxial loading. The stress strain curves obtained for various specimens are presented and analyzed to calibrate the analytical model. To investigate the behaviour of Indian bamboo under cyclic loading, two different loading regimes are employed as follows:

- Monotonic loading.
- Cycles to the envelope curves.

After cutting the specimens from the culm, the ends were sanded to make them smooth. Each specimen was placed in the testing machine and the compression load applied parallel to the grain.

For the monotonic loading, the specimens were loaded continuously until they were completely damaged while for the cyclic compression loading, the specimens were loaded till the first crack and then unloaded to zero load, then reloaded again. Reloading and unloading cycling was continued until the specimen was completely damaged.

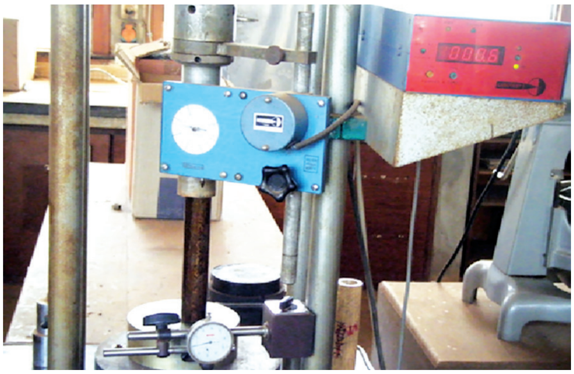
Two testing machines were used. The 5000kN universal press with adjustable speed was used for the *Bambusa vulgaris* specimens while the 50kN CBR press with a minimum speed of 1.27mm/s and an incorporated digital micrometer, was used for the *Oxytenantera abyssinica* specimens. The deformations were monitored using the digital micrometer and loads were read after every 0.2mm of deformations. The test set up is shown on pictures 2a and 2b.

The stresses and strains were calculated using the original specimen dimensions and using the conventional expressions for these quantities. The bamboo culm was modeled as a hollow cylinder as shown on figure 1. Stress-strain diagrams were plotted as shown on the diagrams from figures 2 to 5e .

Picture. 1a Specimen in an oven

Picture. 1b Specimen soaked in water

Picture 1 : Preparation of specimens



Picture. 2a Specimen under the press

Picture. 2b Wet Specimen under the press

Pictures 2: Specimens under the press for testing

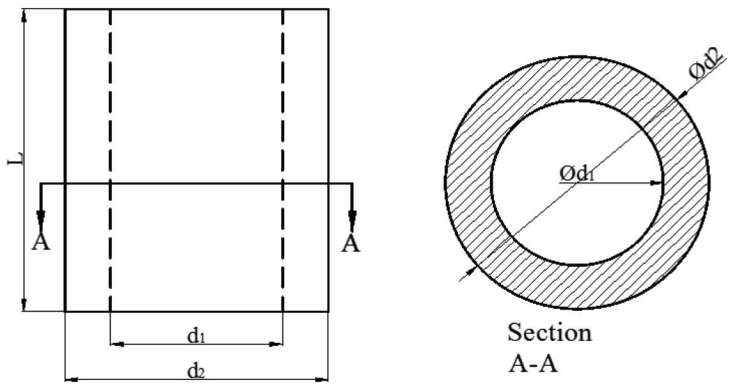


Fig 1: Typical bamboo culm

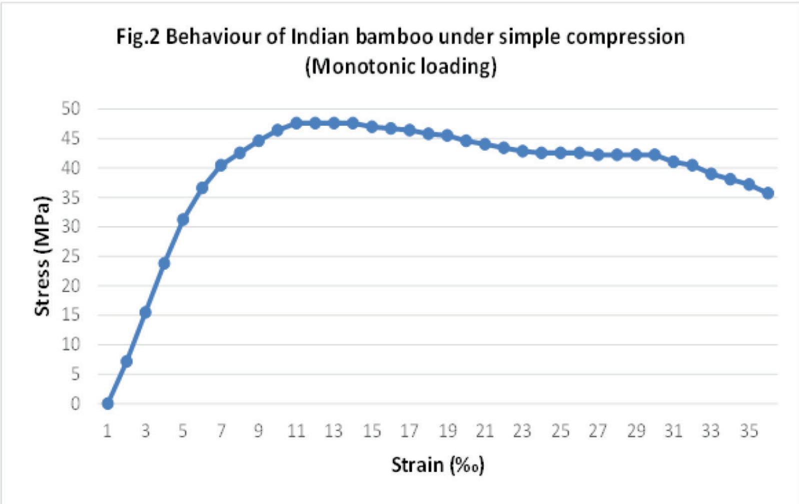
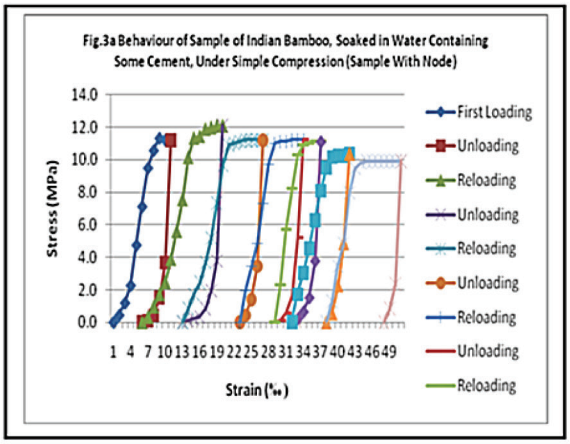
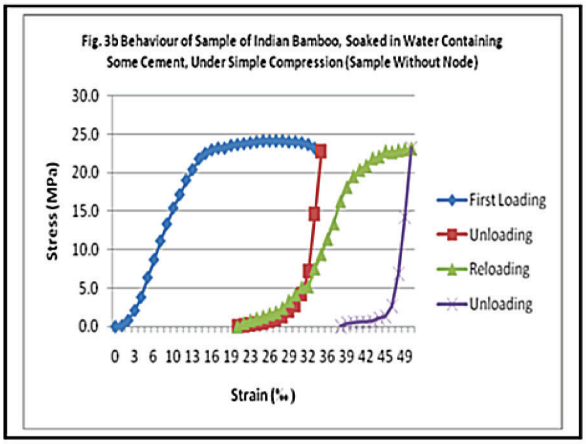


Fig. 2 Typical stress-strain diagram (Monotonic loading)





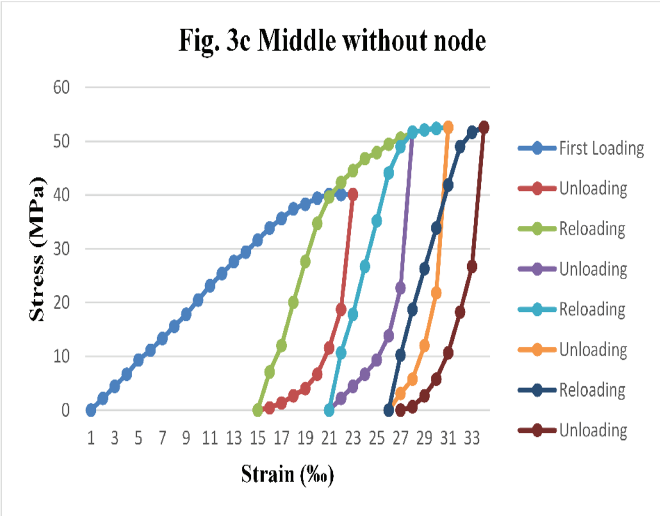


Fig. 3 Samples of *Oxytenantera abyssinica* soaked in water

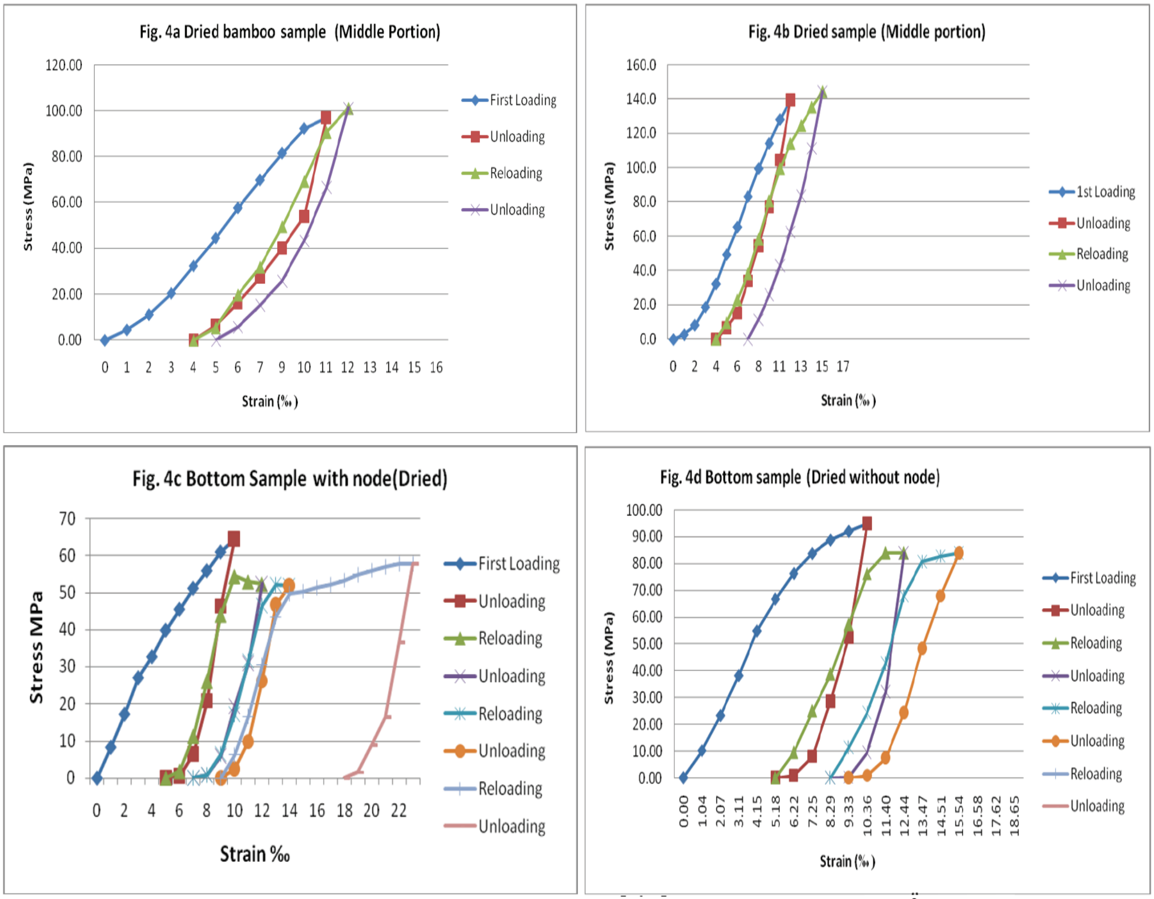


Fig.4 Samples of *Oxytenantera abyssinica* oven dried at a temperature of 120^{0}C for 24 hours.

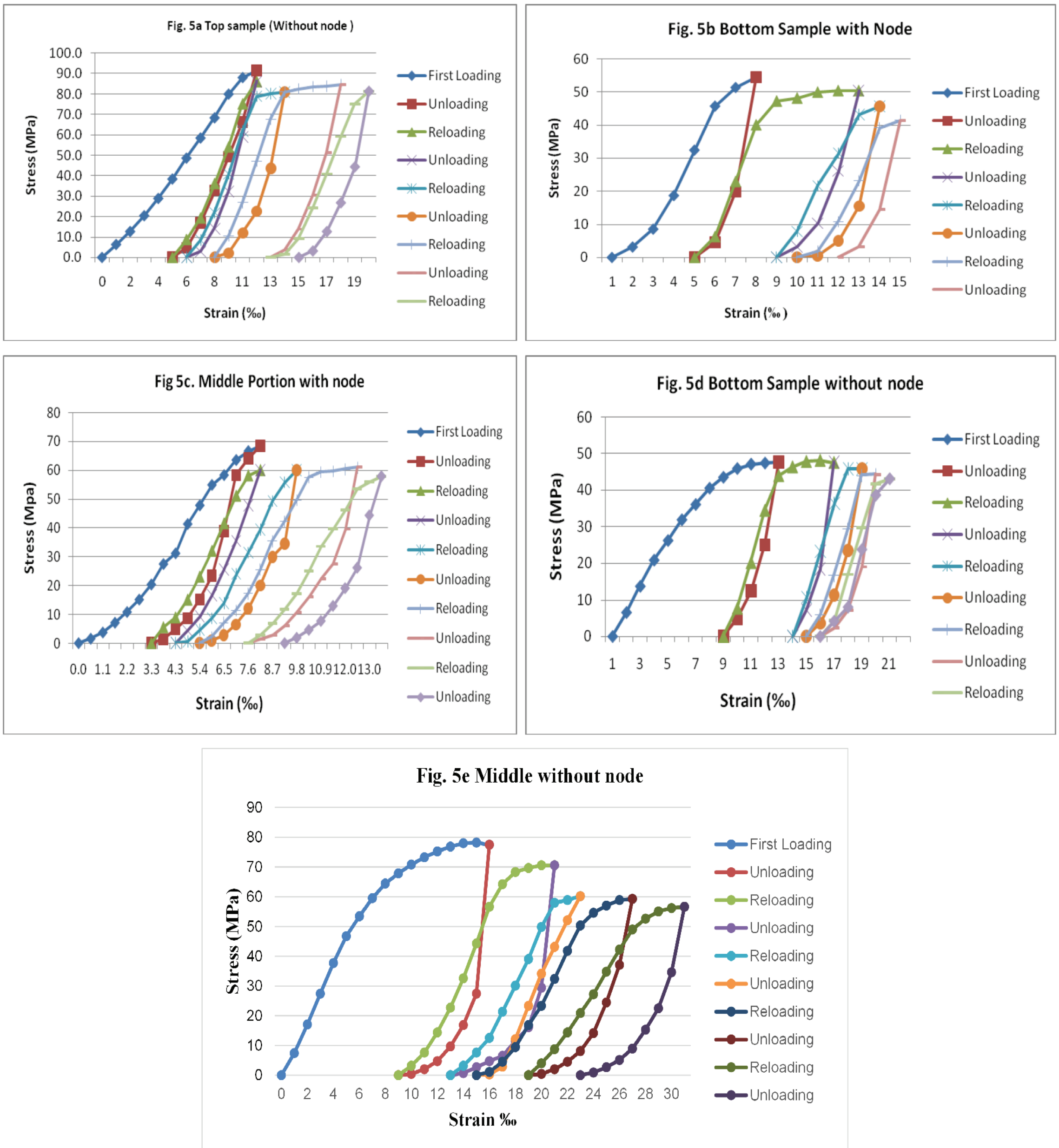


Fig.5 Samples of *Oxytenantera abyssinica* air dried

The stress strain diagrams shown in figures 3a to 5e and used for this study were obtained from tests carried out on specimens of bamboo by the authors of the article. In the literature, no models are available for modeling the behaviour of this material under cyclic uniaxial compressive loads. Therefore models used in these studies are models adapted from those used for plain concrete under similar loading. Several specimens were tested but the results of only twelve (12) specimens are shown on the graphs above. Pictures on 3 below show some of the samples that were tested.

Picture 3a Tested wet specimen

Picture 3b other specimens tested

Pictures 3 Specimens tested

Modeling of the cyclic behavior

The curve shown in figure 6 is a typical curve showing the results of a cyclic uniaxial unloading and reloading test on a specimen of bamboo.

The parameters shown in this figure are important parameters from the test data that are used to predict the unloading and reloading paths of the curves. These parameters are:

- the residual plastic strain (known as the plastic strain) ε_{pl} represented on figure 6 by e_{pl};
- the value of the stress at the peak of the previous loading cycle (known as the unloading stress)
- σ_{un} represented on figure 6 by $S_{n;}$
- the value of the strain at the peak of the previous loading cycle (known as the unloading strain) ε_{un}
- the strain at yield ε_0
- the tangent modulus, E_{pl} at zero stress (when the material is completely unloaded).

The residual (or non-recoverable) strains also known as the plastic strains are the strains corresponding to zero stress level on the reloading or unloading stress-strain curves.

Unloading-Reloading Curves

As it has been observed, when a bamboo specimen is monotonically loaded up to a certain strain level and then unloaded to a zero stress level in a typical cyclic test, the unloading curve is concave from the unloading point and is characterized by a high stiff stiffness at the beginning as can be seen from figures 7a to 7d. The stiffness gradually decreases and becomes very flat at low stress levels, and the

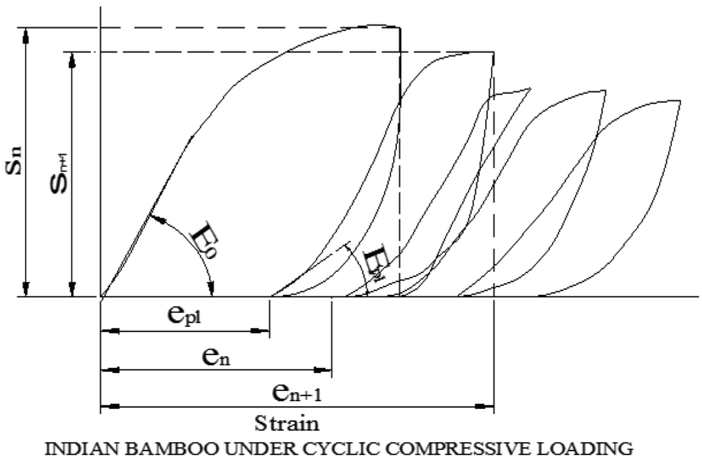


Fig. 6 Indian Bamboo under cyclic compressive loading

residual plastic strains are considerably reduced. When reloading is performed from zero stress up to the envelope curve, the reloading curve is rather flat in almost all of its length as can be seen from figures 8a to 8d. Depending on the compression damage level, a great amount of energy may be dissipated in a complete cycle. Modeling the unloading and reloading curves permit us to determine the energy dissipation of the material due to cyclic loading.

Modeling the Unloading and Reloading Curves

Mathematical modeling of engineering materials is important in the design of engineering structures. The model should be able to explain, in the best way, the mechanical behaviour of the material and should be as simple as possible to facilitate its use.

In this section, analytical expressions for stress strain relations for bamboo subjected to cyclic uniaxial compression are developed. The models developed are based on constants which are functions of the strength of the bamboo species and they can be acquired from experimental results. Models are proposed for the unloading and the reloading paths.

Reloading and unloading curves also depend on the point (or the stress) on the envelope curve where unloading starts (for the unloading curve) or where reloading ends (for the reloading curve) and the common points. The strains at the intersection of the unloading curve and the envelope curve as well as the intersection of the reloading curve and the envelope curve are also important.

It is assumed that the envelope, reloading and the unloading curves passing through a point in the stress-strain domain are unique (that is they are independent of the previous loading history).

Modeling the Unloading Path

Two empirical relations, one an exponential type relation and the other a power type relation are proposed to idealize the unloading path. These empirical relations consider the boundary conditions at the onset of unloading and at zero stress.

Exponential type equations

The equations proposed for the unloading branch include parameters of the unloading curves obtained experimentally such as the unloading strain-plastic strain ratio, the stiffness at the end of the unloading curve, E_{pl} , the unloading stress, the initial modulus of elasticity, and the compressive damage at the unloading stress.

The proposed model for the unloading curve is given by the following series of equations:

$$\sigma = Be^{(C\beta\rho)} E_0 \left(\varepsilon - \varepsilon_{pl}\right) -------- Eq.1$$

where

$$B = \left(\frac{r(1-\delta_{un})}{r-1} \right) ------------- Eq.2$$

$$C = Log\left(\frac{R(1-\delta_{un})(r-1)}{r} \right) ------- Eq.3$$

$$\beta = \left(1 - \frac{(\varepsilon - \varepsilon_{pl})}{(\varepsilon_{un} - \varepsilon_{pl})} \right) ----------- Eq.4$$

$$r = \frac{\varepsilon_{un}}{\varepsilon_{pl}} ------------------ Eq.5$$

$$R = \frac{E_{pl}}{E_0} ------------------ Eq.6$$

The parameter ρ is an unloading parameter that depends on the level of damage and the type of material that is studied. The values of this parameter for the four specimens modeled are found on table 3.

The compressive damage at the unloading point δ_{un} can be determined from the following equation :

$$\delta = \left(1 - \left(\frac{\varepsilon_0}{\varepsilon} \right)(1-A) - Ae^{\mu} \right) ---------- Eq.7$$

where

$$\mu = \frac{(\varepsilon_0 - \varepsilon)}{\varepsilon_{un}} ------------------ Eq.8$$

$$A = \frac{(\sigma_{un} - \varepsilon_0 E_0)}{E_0(\varepsilon_{un} e^{\gamma} - \varepsilon_0)} --------------- Eq.9$$

$$\gamma = \frac{(\varepsilon_0 - \varepsilon_{un})}{\varepsilon_{un}} ----------------- Eq.10$$

Power type equations

The power type function used to idealize the unloading curve is given by the relation:

$$\sigma = \left(\frac{(1-\bar{\varepsilon})}{(1+\alpha\bar{\varepsilon})} \right)^{\alpha} \sigma_{un} ------------ Eq.11$$

Where σ_{un} is the measured unloading stress obtained from the test data, α is a constant that depends on the specimen used and its values are found on table 4 ; while is the normalized strain given by the relation:

$$\bar{\varepsilon} = \frac{(\varepsilon - \varepsilon_{un})}{(\varepsilon_{pl} - \varepsilon_{un})} --------------- Eq.12$$

Modeling the Reloading Path

In this study, the reloading path is idealized as combination of power curve and a straight line. The equations for this idealization are given below as:

$$\sigma = \begin{cases} \alpha_1 \sigma_{un,(n+1)} (\bar{\varepsilon})^{\eta} & 0 \le \bar{\varepsilon} < \bar{\varepsilon}_1 \\ E_{rl}(\varepsilon - \varepsilon_{un,(n+1)}) + \sigma_{un,(n+1)} & \bar{\varepsilon}_1 \le \bar{\varepsilon} \le 1 \end{cases} ---- Eq.13$$

Where $\bar{\varepsilon}$ is the normalized strain given by equation 15 below and $\bar{\varepsilon}_1$ is the maximum normalized strain for which the equation can be used. Its value varies from 0.375 to 0.800.

$$\bar{\varepsilon} = \frac{(\varepsilon - \varepsilon_{pl,n})}{(\varepsilon_{un,n+1} - \varepsilon_{pl,n})} --------------- Eq.14$$

$$E_{rl} = \frac{(\sigma_{un,(n+1)} - \alpha_2 \sigma_{un,n})}{(\beta(\varepsilon_{un,(n+1)} - \varepsilon_{pl;n}))} ------------ Eq.15$$

$\sigma_{un,(n+1)}$ is the unloading stress for the (n+1)th unloading path, $\varepsilon_{un,(n+1)}$ is the strain corresponding to the unloading stress for the (n+1)th unloading path, $\varepsilon_{pl,n}$ is the plastic strain at the end of the nth unloading path while η is a constant.

Table 3: Parameters used for the unloading paths (exponential type equations)

Cycle N°	B	r	ρ	γ	A	R	C	E_{pl}
	Specimen T1 Middle (E_0= 8617.879 MPa.)							
1	1.185	1.778	2.07	-0.688	1.081	0.048	-1.962	414.321
2	0.944	1.615	2.1	-0.762	0.531	0.0721	-2.005	621.481
3	0.805	1.533	0.2	-0.783	0.261	0.0240	-2.630	207.161
4	0.793	1.421	1.0	-0.815	0.194	0.048	-2.475	414.321
5	0.759	1.348	1.03	-0.837	0.126	0.096	-2.314	828.642
Specimen T4 Bottom (E_0= 10068.003 MPa.)								
1	1.66	1.75	1.98	-0.429	1.749	0.412	-0.902	4143.211
2	1.153	1.5	1.13	-0.667	0.282	0.288	-1.433	2900.248
3	1.044	1.444	1.98	-0.692	0.0706	0.288	-1.545	414.321
4	1.262	1.273	1.2	-0.714	-0.075	0.288	-1.778	2900.248
Specimen T6 Middle (E_0= 6218.387 MPa.)								
1	1.818	1.5	1.6	-0.667	1.514	0.727	-0.833	4522.464
2	2.424	1.23	1.35	-0.75	0.919	1.091	-1.032	6783.695
3	1.75	1.286	1.100	-0.778	0.703	0.546	-1.327	3391.848
4	1.693	1.267	1.350	-0.789	0.599	0.364	-1.564	2261.232
5	1.318	1.333	0.750	-0.800	0.520	0.364	-1.523	2261.232
Specimen T9 Top (E_0= 7932.875 MPa.)								
1	1.827	2.200	2.8	-0.364	6.136	1.027	-0.253	8148.745
2	2.066	1.714	1.45	-0.417	3.657	0.337	-0.917	2676.15
3	1.94	1.625	1.65	-0.462	2.260	0.253	-1.139	2007
4	2.024	1.417	1.25	-0.588	1.279	0.422	-1.132	3245.188
5	1.948	1.357	1.25	-0.632	0.883	0.380	-1.291	3010.669

Table 4: Values of α used for the unloading paths (power type equations)

Specimen	Cycle N°				
	1	2	3	4	5
T1 Middle	1.9	1.9	0.88	1.5	1.5
T4 Bottom	1.35	1.25	1.7	1.4	
T6 Middle	1.15	1.2	1.2	1.45	1.1
T9 Top	0.95	1.15	1.32	1.2	1.2

Table 5: Parameters used for the reloading paths

Cycle N°	α_1	α_2	β	η	E_{r1}
	Sample T1 Middle				
1	1.40	0.90	0.65	1.35	929.567
2	1.35	0.50	1.50	1.45	1532.988
3	1.54	0.50	1.50	1.53	1496.595
4	1.52	0.50	1.98	1.34	1046.265
Specimen T4 Bottom					
1	2.45	0.75	2.00	1.16	550.271
2	1.23	0.50	2.00	1.12	1885.161
3	1.50	0.50	2.00	1.98	1709.074
Specimen T6 Middle					
1	2.50	0.70	2.55	1.25	665.068
2	1.50	0.85	1.95	1.20	521.823
3	1.35	0.85	1.95	1.36	521.823
4	1.30	0.85	1.95	1.30	531.969
Specimen T9 Top					
1	1.15	0.50	0.65	1.45	9864.017
2	1.50	0.50	2.50	2.05	2054.901
3	2.00	0.80	2.50	1.23	832.58
4	1.35	0.65	0.50	1.75	7168.261

Table 6 : Stress deteriorating ratios

Specimen	Cycle			
	1	2	3	4
T1 Middle	0.9101	0.8535	0.9851	0.9545
T4 Bottom	0.9256	0.9063	0.9064	
T6 Middle	1.0000	0.9625	0.9675	0.9732
T9 Top	0.9423	0.9388	1.0434	0.9625

Stress Deteriorating Ratio

The deterioration of the stress at an unloading strain ε_{un} after unloading and reloading can be evaluated using the stress deteriorating ratio λ given by:

$$\lambda = \frac{\sigma_{un,(n+1)}}{\sigma_{un}} ---------------- Eq.16$$

The stress deteriorating ratios for the specimens modelled are found on table 6.

3. Results

Cyclic uniaxial compression was carried out on several cylindrical specimens of bamboo. Several cycles of unloading and reloading were performed until material failure. Axial compressive forces were recorded against corresponding deformations. The axial compressive stresses and strains were calculated using the original dimensions of the specimens and using the conventional expressions for these quantities. Stress-strain diagrams were plotted and mathematical models were provided to predict the cyclic behaviour of the material. Expressions were adapted from those used for plain concrete to model the unloading and reloading paths.

The results are shown on the graphs from figures 7 to 9. Figures 7 and 8 show the experimental stress strain curves compared to the those obtained from the models proposed for the unloading and reloading paths respectively for four samples of *Oxytenantera abyssinica* while figures 9 show the measured and calculated unloading and reloading paths combined together to show the cyclic behaviour of four samples of *Oxytenantera abyssinica* under cyclic uniaxial compression.

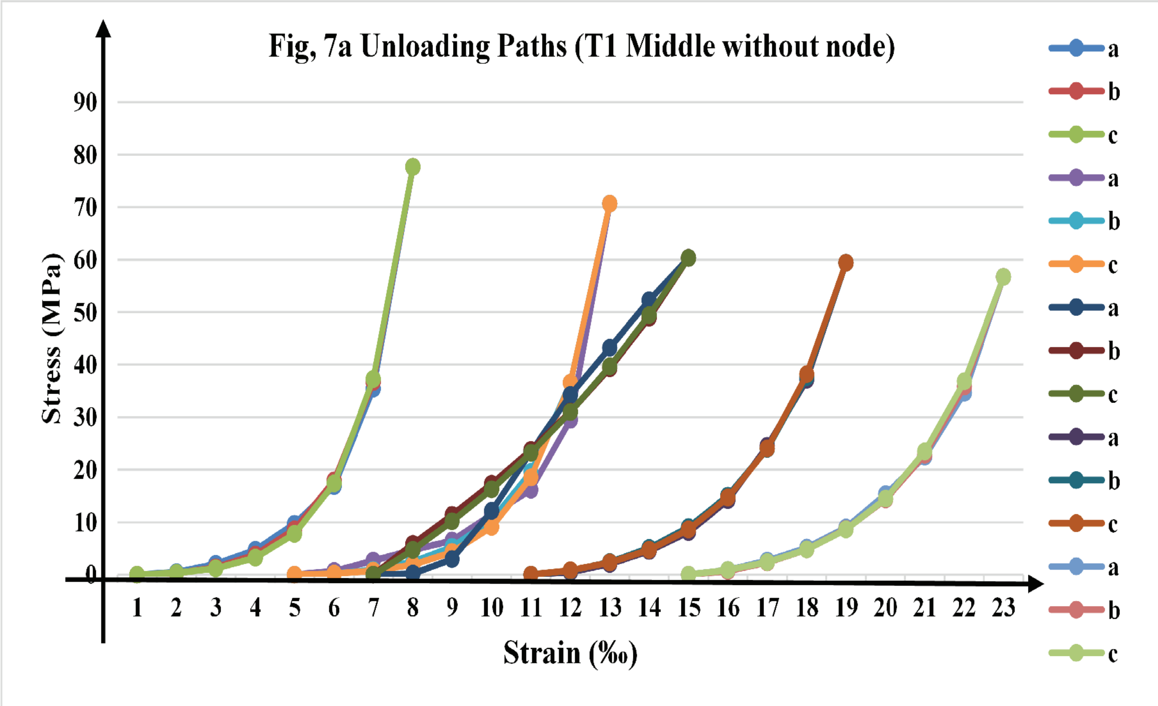
It should be noted that:

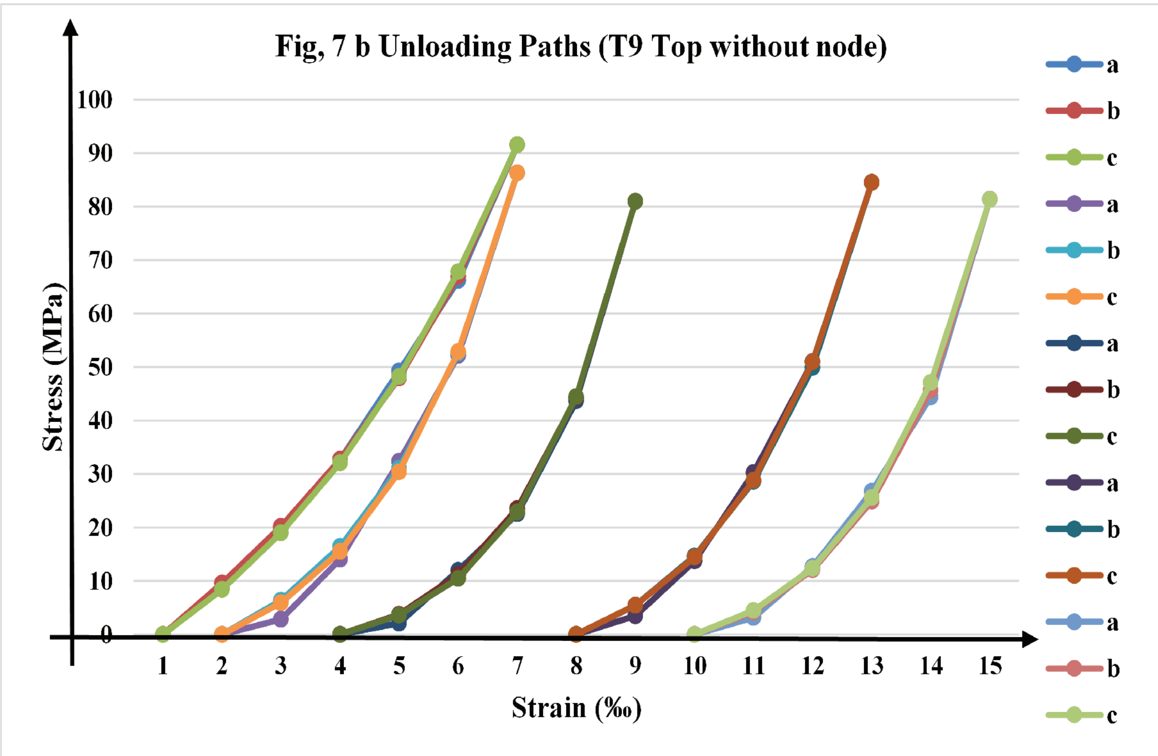
I. In figures 7

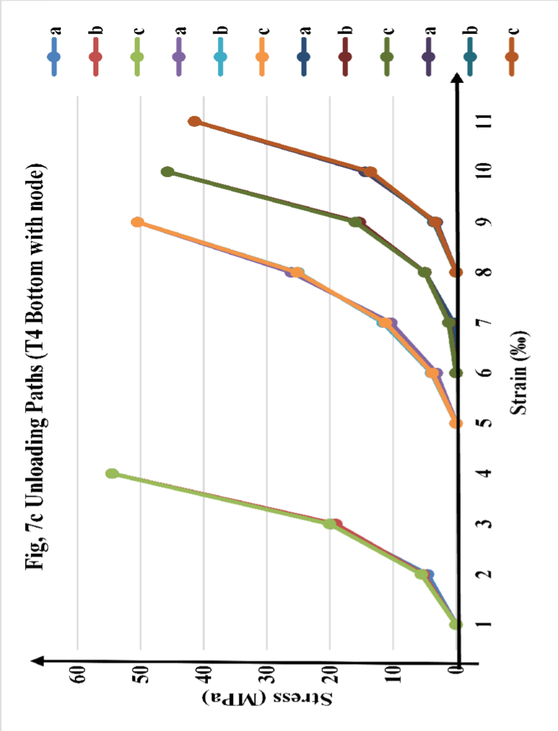
a- represents the graphs obtained from measured data while;

b- represents the graphs obtained from the proposed power type equation;

c- represents graphs obtained from the proposed exponential type equation.


Fig, 7a Unloading Paths (T1 Middle without node)
Stress (MPa)
0
10
20
30
40
50
60
70
80
90
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Strain (‰)
a
b
c
a
b
c
a
b
c
a
b
c
a
b
c


Fig, 7 b Unloading Paths (T9 Top without node)
Stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Strain (‰)
a
b
c
a
b
c
a
b
c
a
b
c
a
b
c



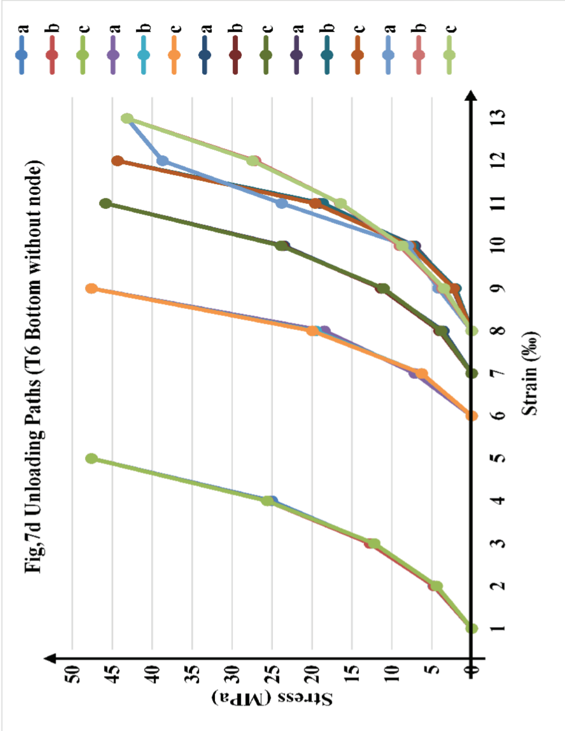
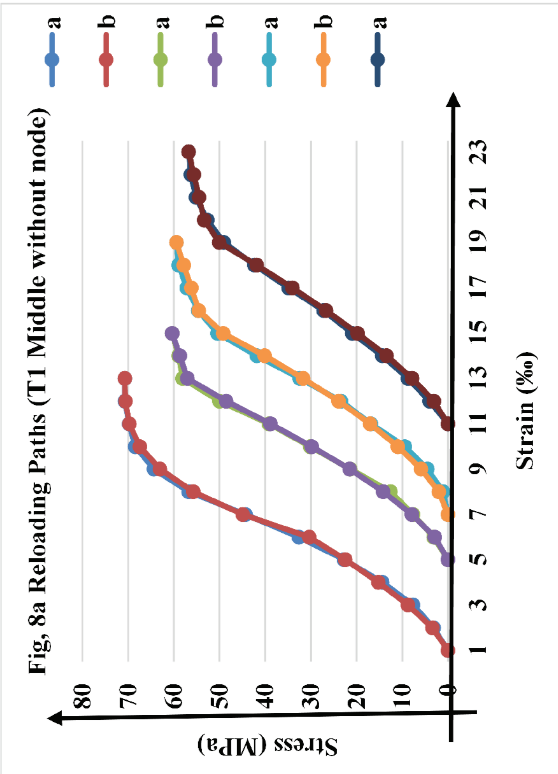
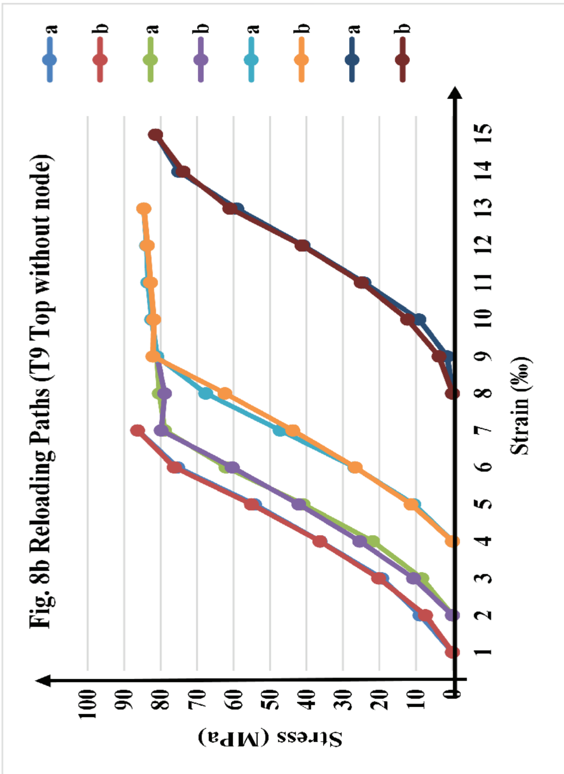


Fig. 7 Unloading Paths for *Oxytenantera abyssinica* (Measured and Calculated Data Compared)





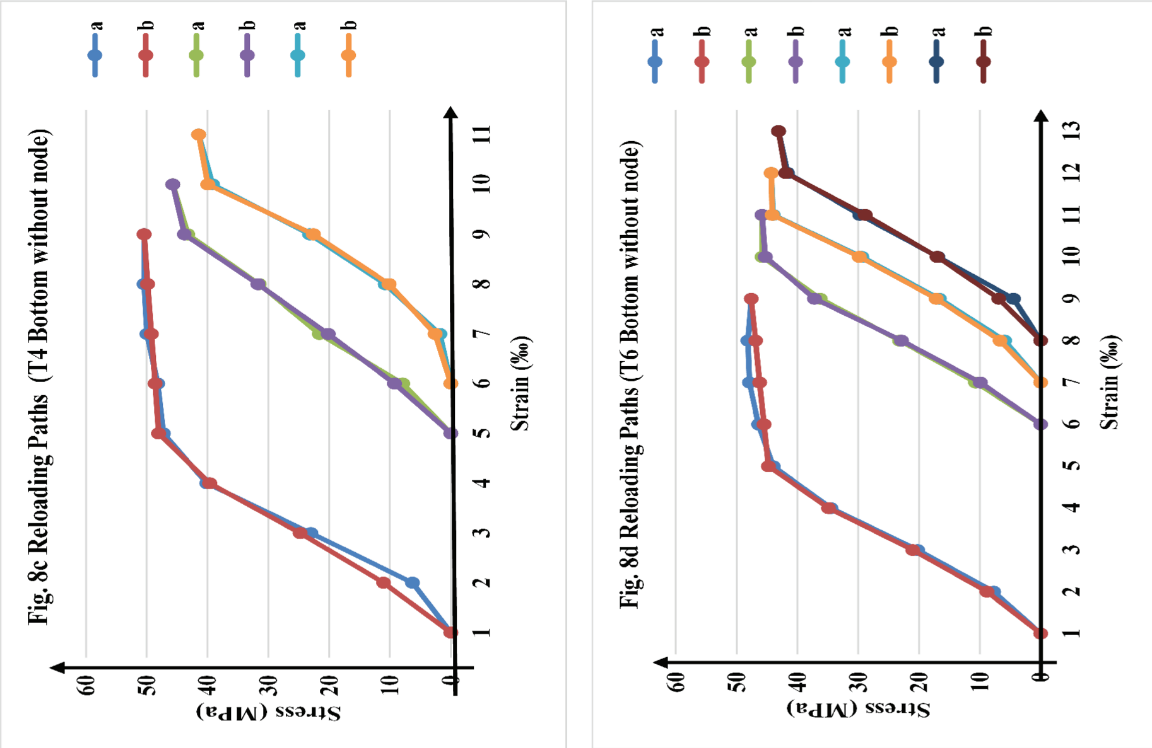
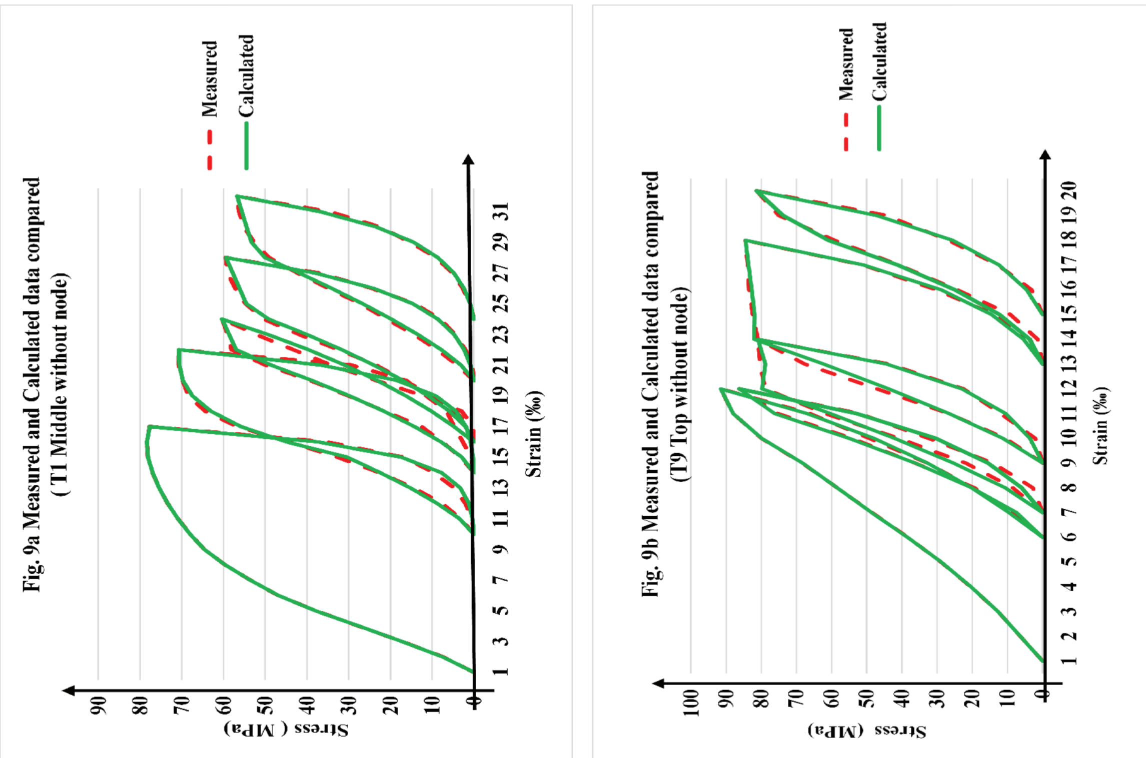
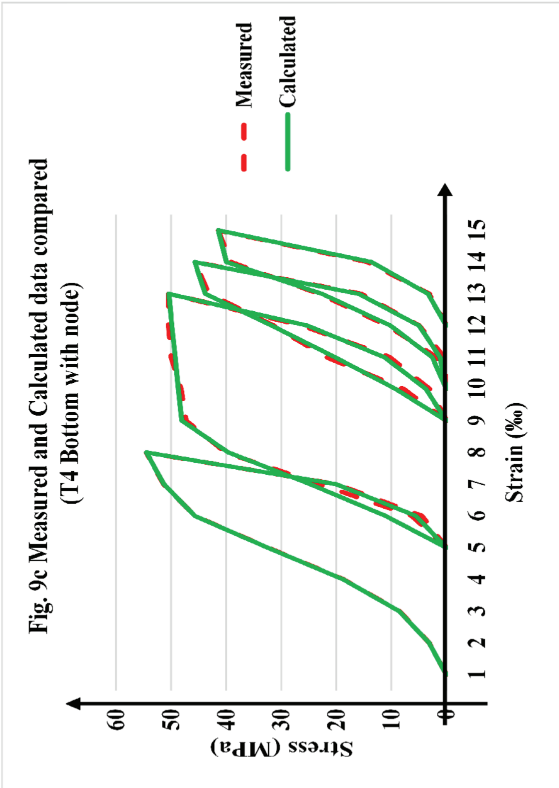


Fig 8 Reloading Paths for samples of *Oxytenantera abyssinica* (Measured and Calculated Data Compared)





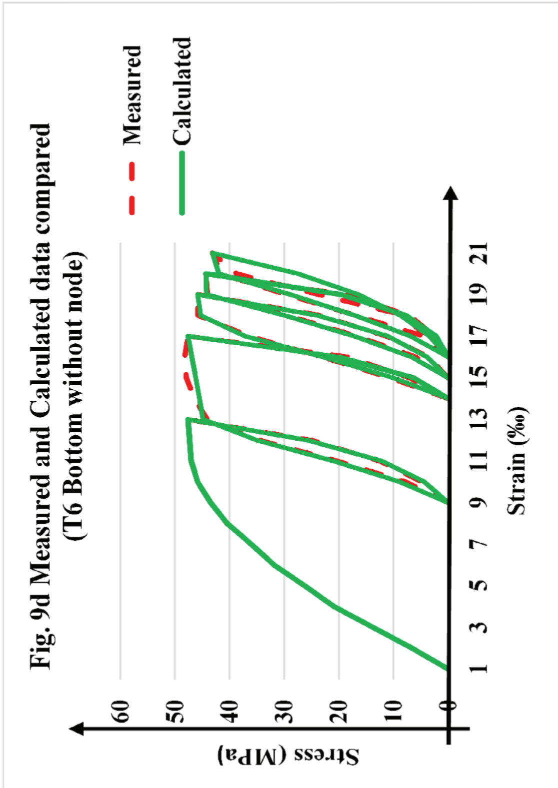


Fig 9 Indian Bamboo under Cyclic Compression Loading for *Oxytenantera abyssinica* (Measured and Calculated data compared for four Samples)

4. Discussion

Comparison of test result and proposed models

From the stress-strain diagrams plotted above, it can be seen that bamboo exhibits hysteretic behaviour, characterized by non-overlapping unloading-reloading curves. Analytical expressions for the behaviour of different materials such as concrete subjected to cyclic uniaxial compression loading have been adapted to model the behaviour of bamboo subjected to similar loadings. The proposed models are compared with experimental results.

Mathematical models have been proposed which can be used to predict the unloading and reloading paths of this hysteretic behaviour of bamboo under cyclic uniaxial loading. The unloading paths are modeled as nonlinear curves. Two mathematical models are proposed to model the unloading paths. These are a power and an exponential curve. The reloading path is modeled as a combination of a linear and a power curve.

The figures above are used to compare the load pattern of cycles to envelope curves. It is observed that the overall stress-strain behaviour of the proposed model and tests results show similar configuration to each as well as fit very well with each other.

Plasticity in Bamboo:

It can be seen from the curves that after the proportional limits, the behavior of Indian bamboo deviates from the linear proportionality behaviour and becomes nonlinear.

Indian bamboo contains a large number of micro cracks even before any load has been applied. This property is very decisive for the mechanical behavior of bamboo. The micro cracks may be caused by thermal expansion and shrinkage during temperature fluctuations. The nonlinear behavior and the s-shape stress-strain curves of bamboo under uniaxial compressive stress can be associated with micro cracks propagation during load and stress- induced plastic flow in the specimen.

Permanent residual strains are produced in the material after the proportional limit. These strains are not lost after the load is removed. The stress at which these permanent strains are produced is known as the yield stress. In this work, the yield stress is taken to be equal to the proportional limit of the material. The value of the yield stress for each specimen tested has been determined.

It is observed from any cycle of stress strain curve that at the end of each cycle, the residual or plastic strain increases as the number of cycles increase. Therefore, the envelope unloading strain is always smaller than the envelope reloading strain. The residual strain is one of the most important parameters that have been used to develop the mathematical models.

Observations

It was observed that the samples soaked in water underwent several cycles before complete failure. Meanwhile the samples tested after drying in an oven were very brittle. Though they had very high resistance than those soaked in water, their failure was very abrupt. They underwent very few cycles before completely splitting. The samples with nodes in the middle have an unusual behavior. No splitting was observed through the whole length of the sample. Only the heads of the samples were observed with cracks. At a certain level of loading, neither the load nor the deformation changed. The arrow indicating the changes in deformations and the device for the measurement of the loads stood fixed at that level.

5. Conclusion

Cyclic constitutive models are proposed to predict the behaviour of Indian bamboo under uniaxial cyclic compression loading. Two species of bamboo found in Cameroon were used to carry out the laboratory tests. These are the *Bambusa vulgaris and the Oxytenantera abyssinica*. The results shown and the models produced are for the *Oxytenantera abyssinica* species. The proposed models are adapted from models used to model the behaviour of plain concrete under similar loading. The test data from experimental investigations were compared to models adapted from the behaviour of other materials subjected to similar loadings.

Two different loading regimes were employed to investigate the behaviour of Indian bamboo under cyclic loading. From the tests results, the major experimental parameters for the proposed analytical expressions were obtained.

From the study, it can be concluded that:

Unloading is nonlinear and can be modeled using a power type or an exponential type equation. Reloading is also nonlinear and is modeled using a combination of a linear type and a power type equation;

When compared with the tests results, the models show satisfactory agreement with the experimental results;

The reloading response does not return to the envelope curve at the previous unloading strain;

The residual or plastic strain at the end of an unloading curve, the unloading strain as well as the reloading strains are important parameters used in producing the models;

The unloading stress and the reloading stresses are also used;

All the input data required for the models are obtained from cyclic compression tests results;

The unloading stress decreases while the plastic strain increases as the number of the unloading paths increases.

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