TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS
DEPARTMENT OF CIVIL ENGINEERING

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EXPERIMENTAL TESTING AND CHARACTERIZATION OF BAMBUSA BALCOOA AND BAMBUSA NUTANS FOR ANALYSIS AND DESIGN OF BAMBOO STRUCTURES

Sarowar Poudel

A thesis report submitted in partial fulfillment of the requirements for the MSc degree in Structural Engineering

DEPARTMENT OF CIVIL ENGINEERING
LALITPUR, NEPAL

DECEMBER 2023

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Lalitpur, Nepal

DECEMBER 2023

CERTIFICATION

This report titled **"Experimental Testing and characterization of *Bambusa balcooa* and *Bambusa nutans* for analysis and design of structures"** is prepared and submitted by Mr. Sarowar Poudel and is found satisfactory in terms of scope, quality and presentation as partial fulfillment of the requirement for the MSc degree in Structural Engineering under Department of Civil Engineering, Institute of Engineering, Tribhuvan University.

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Date: November 26, 2023

To Whom It May Concern:

This is to certify that the paper titled "***Study on Relationship of Moisture content and Shear Strength in chemically treated Bambusa nutans culms available in Nepalese market***" (Submission# **679**) submitted by **Sarowar Poudel** as the first author has been accepted after the peer-review process for presentation in the 14th IOE Graduate Conference being held during Nov 29 to Dec 1, 2023. Kindly note that the publication of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon the author's presence for presentation during the conference and timely response to further edits during the publication process.

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Convener,
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ABSTRACT

The purpose of this research/thesis is to investigate and define (for the first time) the mechanical properties of the two natively growing and primarily utilized bamboo species in Nepal, namely: Ban/Dhanu baans (*Bambusa balcooa*) and Maal baans (*Bambusa nutans*). Here bamboo related ISO standards and ASTM D 5764 – 97a (2002) were followed for conducting material tests and analysis. Shaft-bolt arrangement of connections were tested according to the preexisting details used previously in construction in Nepal. While Gusset plate arrangement of connection were designed using material properties of *B. balcooa* with intent of IIIs or IV mode of failure according to yield equations from TR 12 of American Wood Council, then tested. These two typologies of connection were tested from both species, each having two variants namely, confined (with hose-clamps) and unconfined (without hose-clamps). Measurement and Test data were analyzed to compute geometrical imperfection in bamboo culms, characteristic values of mechanical strengths and interpretation of connection tests.

Keywords: bamboo, characterization of mechanical properties, bamboo connections, dowelled connection, yield model

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INTRODUCTION

1.1 Background

Bamboo has been used in human history as early as human have discovered how to use stones and sticks as tools. In Modern history also, people have built lots of shelter, posts and bridges vernacularly using bamboo as primary material. It is evident that bamboo poses good quality as for construction material. Point that it has fascinating strength in tension as well as compression, open a discussion on using bamboo directly as structural elements.
Although preliminary researches on bamboo as a constructional material makes sufficient claim for its usability, we must confirm its mechanical and engineering properties and refer characteristic strengths per individual species. This Thesis deal with the very topic of referring the characteristic strengths of *Bambusa balcooa* and *Bambusa nutans*, so that we may use rational design theories of structural engineering for design of bamboo structures. These two-particular species of bamboo are native to Nepal, and being used on versatile works in the rural communities, and as scaffoldings and form-work supports in urban context too.

1.2 Problem Statement

For designing a structure, an engineer requires characteristic strengths of the materials to be used. For mainstream materials such as concrete and steel there is certain set of values as characteristic strengths depending upon its constituents, by the use of which an engineer may design structures referencing to building codes. But characteristic strength of bamboo has never been derived for any Nepalese species bamboo, thus this study is an effort for finding out various characteristic values for *Bambusa balcooa* such that, on whose basis an engineer may design bamboo structures with confidence in factor of safety.

1.3 Objective of Study

The holistic objective of Research is to authenticate the bamboo structures as timber design and the very first step for this is to characterize the properties of bamboos native to Nepal which have more potential to be used in construction industry. For this characterization, a method can be 'material testing' and 'structural element' testing in the laboratory.
The specific objective of this study is to provide experimental data needed for engineered analysis and design using full-culm bamboo as the primary structural material. *Bambusa nutans* is the one of the most used and cultivated species of bamboo in Nepal, while *Bambusa balcooa*,is also widely used in the construction industry for scaffolding and temporary structures. The objective is fulfilled through three key tasks.

Task 1 involves experimental testing and characterization to gain an understanding of the material behavior of the bamboo species.

Task 2 test shaft-bolt connections as well as dowelled connection (Gusset-plate) systems for joining bamboo members.

Task 3 run analysis from data and refer characteristic values from each test.

1.4 Scope of Study

Following will be scope of this study:

1. Acquire basic material property of a Nepalese bamboo species.
2. Perform physical grading so as to quantify irregularities of the bamboo culms
3. Analyze these data for assessment of characteristic values
4. Assessment of performance of two types of bamboo connections

1.5 Limitation of Study

The study will be limited on reaching the goal of finding material and mechanical properties of this bamboo species. By following international codes for testing this type of material ISO is exactly referred while ASTM codes are modified to some extent (for example, using wood/ timber related codes for bamboo properties assessment. Two types of joints will also be tested for their performance. The thesis work will be concluded by referring various characteristic properties and strengths for *B. balcooa* and *B. nutans* following ASTM/ ISO standards.

1.6 Organization of Thesis

The overall thesis work is categorized into two types of work:

1. Physical Work
2. Desk Work

Physical works deal with all the works for preparing specimen and then getting tested. While the Desk work comprises all the work relating to analysis of data, evaluating characteristic values and then writing of the thesis report.

This Thesis report is divided into five chapters, first is this 'Introduction', which discusses in the need of this work. Second chapter is 'Literature Review', which basically is summarization of various literatures found relevant to this subject matter in Bamboo domain. Third is the methodology which describes the procedure for achieving our objectives. 'Results and Discussions' constitutes several data and their analytics. Last chapter 'Conclusion and Recommendation' for making summary of chapter 4 relevant in structural engineering diaspora and discusses in some of the prospects of future research in bamboo structures.

2
LITERATURE REVIEW

2.1 Overview

Bamboo is an orthotropic, functionally graded material [18], its properties dependent on the moisture content [19], age of harvest [4]. Its considerable variability in mechanical and geometric properties [7] can be controlled by grading [5] and use of multiple culms [6]. Though, note that multiple culm members do not exhibit composite behavior [16]. Under flexure, bamboo exhibits bi-modulus behavior [8]. While the short elements are shear critical [15], the failure moments of long-span members occurs as the minimum [13] of Brazier moment [14], tensile/compressive failure in the longitudinal direction, splitting induced by shear, splitting induced by circumferential tension. The bamboo culms owing to their slender profile and geometric/material imperfections are particularly susceptible to buckling. The buckling phenomenon has received a considerable attention, and several methods can analytically predict this peculiarity with accuracy [2] [9] [12]. Another important issues concerning bamboo is its durability, though not addressed in this research specifically, is achieved through a combination of treatment of green bamboo [3] and durability by design process [12].

Traditional connections in the form of lashing [20], plug-in joints and fish-mouth connections [21] rely on the skill and expertise of the craftsmen. These systems are difficult to analyze and design, and their mechanical behavior is poorly documented. In this context, the proposed research focuses on the dowelled connection systems for connecting bamboo culms [22]. The bolted or dowel connections present numerous advantages: (a) they are ubiquitous, versatile, and simple to design and construct, (b) they offer easy combination of multiple bamboo culms into a single structural element while accommodating substantial geometric variability [28] [29], (d) they exhibit predictable and ductile mechanical behavior, (e) through means of radial confinement, they are resistant to premature failure by longitudinal splitting [26] [27], and (f) their yielding can be predicted with accuracy using analytical expressions [6] [24] [25]. In accordance with the principle of capacity-based design, the dowelled connections are designed to fail before other components of the bamboo axial member. As a result, their failure is characterized by high predictably and ductility. A peculiarity of dowelled connections for bamboo structures is that the axial deformation of the bamboo members become concentrated at the connection zones [23].

Bamboo has a unique fiber texture, consisting of long, slender fibers with thick cell walls, and a high degree of fiber alignment. This results in a mechanical graded structure, where the outer layers of the culm are stiffer and stronger than the inner layers and this graded structure contributes to the high strength and stiffness of bamboo [18]. The compressive strength of bamboo is the most important mechanical property for the design of bamboo scaffolding [19].

The experiment carried out by subjecting the bamboo columns to axial compressive loads until failure showed that the buckling resistance of bamboo columns decreased with increasing slenderness ratio, column length and even presence of nodes also had a significant effect on the buckling behavior of the bamboo columns [2]. (Correal D. et al., 2010) focuses on the mechanical properties of Guadua *angustifolia* bamboo and investigates how the mechanical properties vary with age and height position in the culm. "*Based on the experimental results, it was found that the top portion (sobrebasa) showed the maximum strength and modulus of elasticity compared to the other portions, since this portion of bamboo has higher density, density of Guadua a.k. culm has more influence in modulus of rupture in bending, than in any of the other studied mechanical properties. Guadua angustifolia kunt is reached between 3 and 4 years old, because the mechanical properties at those ages were the highest and remained almost constant, whereas the mechanical properties of the culms at the age of 5 were the lowest."* [4] The compression strength of the bamboo is influenced by the length-to-diameter ratio of the specimens, and shorter specimens showed higher compression strength than longer ones [5]. The critical buckling load of bamboo culms was significantly be affected by the culm diameter, wall thickness, and slenderness ratio also; The strength of bamboo was affected by its moisture content, with the wet culms exhibiting higher buckling strength than dry culms. [7]. The results suggested that the design of bamboo structures must consider these factors to ensure structural stability and optimal performance.

[8] presents a bimodulus bending model for bamboo poles with different material properties of inner and outer layer of bamboo culms and found that it provided accurate predictions of the bending behavior of bamboo poles which could be useful for design of structures particularly where culm geometry is complex or material properties are unknown. Further investigation on the buckling behavior of four different bamboo species under axial compressive loads test results showed that the critical buckling load is significantly influenced by the aspect ratio along with slenderness ratio of the bamboo culm which came in good agreement with the theoretical model purposed by authors [9].

Bamboo culms exhibit a nonlinear and asymmetrical bending behavior, with the tensile side of the culm experiencing higher strains and stresses than the compressive side and also the bending stiffness of bamboo culms is affected by both their diameter and wall thickness, with larger and thicker culms exhibiting higher stiffness values [13]. The radial gradation has a significant effect on the mechanical properties of bamboo, especially on the shear modulus and strength also the stiffness and strength of bamboo decrease as the distance from the outer surface of the culm increases [17]. [23] did simulation and experimental verification of a full-scale bamboo truss, experiment ran numerical modeling to simulate the truss's behavior under different loading conditions and compared the results with experimental tests conducted on a physical prototype of the truss. The study showed that numerical simulations can provide accurate predictions of the truss's behavior, and the results were validated by experiments.

2.2 Engineering Application

Load Table provided data on strength and stiffness of bamboo culms including the maximum bending moment and axial load capacity [15]. [16] García-Aladín et al. (2018) conducted a theoretical and experimental analysis of two-culm bamboo beams. The authors investigated the behavior of the beams under flexural loads, and compared the experimental results with those predicted by a finite element model. The study found that the beams exhibited good performance, with high load carrying capacity and stiffness. The authors also found that the bending stiffness of the beams was influenced by the inter-culm connection details and the orientation of the culms in the cross-section of the beam.

2.3 ISO Standards

ISO 19624:2018 specifies the basic principles and procedures for the grading of bamboo culms, considering their characteristics and properties. It provides a classification system for the determination of the quality of bamboo culms, based on visual grading and non-destructive testing. This standard also describes the procedures for the sampling, testing, and inspection of bamboo culms. The standard aims to provide a reliable and consistent method for grading bamboo culms that can be used by manufacturers, designers, and users of bamboo structures.

ISO 22157:2019 provides test methods for the determination of physical and mechanical properties of bamboo culms, including density, moisture content, modulus of elasticity, compressive strength, tensile strength, and shear strength. It provides detailed procedures for conducting these tests and specifies the required equipment and specimen preparation. The standard aims to provide a standardized method for evaluating the properties of bamboo culms, which is important for the design and construction of safe and efficient bamboo structures.

ISO 22156:2021 provides guidelines for the structural design of bamboo culms used in construction, including both traditional and modern engineered bamboo structures. The standard covers topics such as material properties, load-carrying capacity, design criteria for various types of structural elements (e.g. beams, columns, trusses), connections, and overall structural stability. It also provides recommendations for safety factors, testing, and quality control measures.

2.4 *Bambusa balcooa*

In a study by [2], the compressive strength of *Bambusa balcooa* was tested using a Universal Testing Machine. The authors found that the average compressive strength of the bamboo was 44.4 MPa, which is comparable to other common construction materials like timber and concrete. 3] conducted a study on the shear strength of bamboo species including *Bambusa balcooa* . The authors used a shear test apparatus to determine the shear strength of the bamboo samples. They found that the shear strength of *Bambusa balcooa* was in the range of 5.5-12.5 MPa, which is relatively high compared to other natural fibers like sisal and jute. Four-point bending tests were conducted on bamboo species including *Bambusa balcooa* in a study by [4]. The authors note that four-point bending tests are commonly used to evaluate the flexural properties of materials. They found that *Bambusa balcooa* had a flexural strength of 91.3 MPa, which is comparable to other construction materials like timber. . In a study by [5], the authors investigated the joint performance of bamboo species including *Bambusa balcooa* using a dowel embedment test. The dowel embedment test is commonly used to evaluate the strength of joints in wood and bamboo materials. The authors found that the joint strength of *Bambusa balcooa* was dependent on factors like the diameter of the dowel and the depth of embedment.

2.5 Connections

[22] presents detailed discussion on the different types of joints used in bamboo construction, along with their advantages and limitations covering both traditional and modern methods of bamboo jointing, including lashing, mortise and tenon joints, scarf joints, and bamboo connector systems and emphasizing on joint design for improving the structural integrity and durability of bamboo structures.

[6] Pradhan and Dimitrakopoulos (2021) conducted a pilot study on the capacity-based design of multi-culm bamboo axial members with dowel-type connections. They highlighted the importance of understanding the behavior of bamboo connections under various loads to design safe and effective bamboo structures. Their study focused on the use of dowel-type connections, which are commonly used in bamboo structures, and proposed a capacity-based design approach for multi-culm axial members. They concluded that the proposed design approach can be used to design safe and effective bamboo structures with dowel-type connections.

The study presented in [24] investigates the load-carrying capacity of dowel-type bolted bamboo joints through experimental and numerical methods. The authors conducted laboratory tests on six bamboo specimens with different joint configurations to determine their ultimate failure load and failure mode. They also developed numerical models using the finite element method to simulate the experimental results.

The results show that the load-carrying capacity of the dowel-type bolted bamboo joints is affected by several factors, including the number and diameter of the bolts, the length of the dowels, and the orientation of the bamboo culms. The failure mode of the joints varied between shear and splitting failure, and was dependent on the specific configuration of the joint. The authors also found that the numerical models developed in this study were able to accurately predict the failure load and mode of the joints, indicating their potential use in the design and analysis of bamboo structures. Overall, this study contributes to the understanding of the mechanical behavior of bamboo joints and provides valuable information for the design and construction of bamboo structures with dowel-type bolted joints.

This study in [25] investigated the bearing capacity of bolted-mortar infill connections in bamboo and developed a yield model formulation. The study also explored the effect of different variables, such as bolt diameter, bolt edge distance, and mortar compressive strength, on the bearing capacity of these connections.

The quasi-static reversed cyclic testing of multi-culm bamboo members with steel connectors investigated the seismic behavior and performance of multi-culm bamboo members connected by steel connectors subjected to quasi-static reversed cyclic loading [26].

Steel Connection in bamboo: exhibited satisfactory load-carrying capacity and deformation capacity and chief concern is that it showed a ductile behavior with post-peak load-carrying capacity due to the formation of plastic hinges in the steel members [27]. Here the failure mode was due to yielding of steel elements and crushing of bamboo culms near steel plates.

2.6 Treatment of Bamboo culms

Treatment process recommended by the National Mission on Bamboo Applications, Government of India, includes the use of borax and boric acid as preservatives. These preservatives are said to be economically feasible and have been found to be effective in preventing decay and insect attacks in bamboo [4].

As per [3] TM 05 (2006), the following are the economically feasible bamboo treatment processes:

1. Boucherie process: Involves treating the bamboo with a solution of copper sulphate and other chemicals. This process is effective and widely used but can be costly.

2. Acetic acid treatment: Involves soaking the bamboo in a solution of acetic acid and other chemicals. This process is relatively inexpensive and can be done locally.

3. Boric acid treatment: Involves treating the bamboo with a solution of boric acid and other chemicals. This process is also relatively inexpensive and can be done locally.

4. Heat treatment: Involves subjecting the bamboo to high temperatures to remove moisture and kill insects. This process is relatively inexpensive and environmentally friendly but can result in a loss of strength and stiffness in the bamboo.

5. Smoke treatment: Involves smoking the bamboo over a fire to remove moisture and kill insects. This process is relatively inexpensive and can be done locally but may not be effective against all types of insects.

Overall, the acetic acid and boric acid treatments are considered to be the most economically feasible methods of bamboo preservation.

3
METHODOLOGY

3.1 Overview

This chapter explains the experimental setup and methodology used for conducting the tests to determine the physical properties of a bamboo species according to ISO 22157:2019.

The methodology can be divided into 3 parts:

- Grading and preparation of specimens
- Laboratory Testing
- Analysis of data

Sample preparation:

The bamboo culms were collected from the forest and transported to the laboratory for testing. The culms were selected based on their straightness and uniformity. The bamboo culms were then cut into smaller sections of uniform length and diameter using a saw. The nodes were removed using a knife to obtain straight sections for testing.

Testing apparatus:

The apparatus used for conducting the tests included a universal testing machine (UTM) and a measuring tape. The UTM was equipped with a load cell of 1000 kN capacity and a displacement sensor with an accuracy of ±0.01 mm. The UTM was used to apply axial compressive load on the bamboo specimens until failure. The measuring tape was used to measure the length and diameter of the bamboo specimens before testing.

Test procedure:

The test specimens were conditioned in a controlled environment with a temperature of 27±2°C and a relative humidity of 65±5% for 14 days before testing. The specimens were then weighed and their dimensions got measured using a measuring tape. The specimens were then placed in the UTM and loaded at a rate of 2 mm/min until failure occurred. The load and displacement data were recorded continuously during the test.

Data analysis:

The load-displacement data obtained from the tests were used to calculate the mechanical properties of the bamboo specimens according to the ISO 22157:2019 standard. The mechanical properties determined included the compressive strength, modulus of elasticity, and compressive strain at maximum stress. The data were also used to create stress-strain curves for each specimen.

Materials

Material level tests:

Borax-boric acid treated bamboo culms are procured from well-established supplier of Nepalese market. *Bambusa balcooa* culms are procured from treatment facility of Abari Nepal in Chitwan, Nepal, while *Bambusa nutans* culms were delivered to the heavy lab of Pulchowk campus from treatment facility known as 'Sahara Nepal' in Jhapa, Nepal. Here, it is to be noted that these culms were not guaranteed about their age, moisture content or their position in bamboo plant, which actually affects the mechanical properties of the sample taken. Species of these bamboo is the only specification that is guaranteed. Thus, these culms are the paradigmatic sample culms found in supply chain of treated bamboo in Nepalese market.

Bambusa balcooa originated in Madi were treated using bore-hole of approximately 4mm diameter which more-or-less goes in transverse axis of the culms (positioned near node), while *B. nutans* originated in Jhapa were treated using bore-hole of approximately 6mm (positioned near node) which runs obliquely piercing the node and exiting to another side of consecutive internode.

3.1 Grading and Imperfections of bamboo

ISO 19624:2018 was followed while grading the bamboo culms. Imperfections in the culms were also expressed in-terms of external-taper, internal-taper, bow and ovality according to the same standards.

3.1.1 External Taper

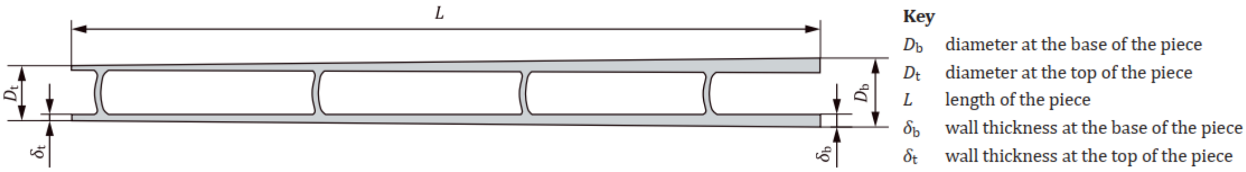


Figure 3.1 parameters of external and internal taper in longitudnal section of bamboo (source: ISO 19624:2018)

3.1.2 External taper (α_e)

External taper for round bamboo is calculated using following expression:

$$\alpha_e = \frac{D_b - D_t}{L}$$

3.1.3 Internal Taper (α_i)

Internal taper for round bamboo is calculated using following expression

$$\alpha_i = \frac{D_b - D_t - 2(\delta_b - \delta_t)}{L}$$

3.1.4 Bow (b_o)

Bow for round bamboo is calculated using following expression:

$$b_o = b_{max}/L_{ref}$$

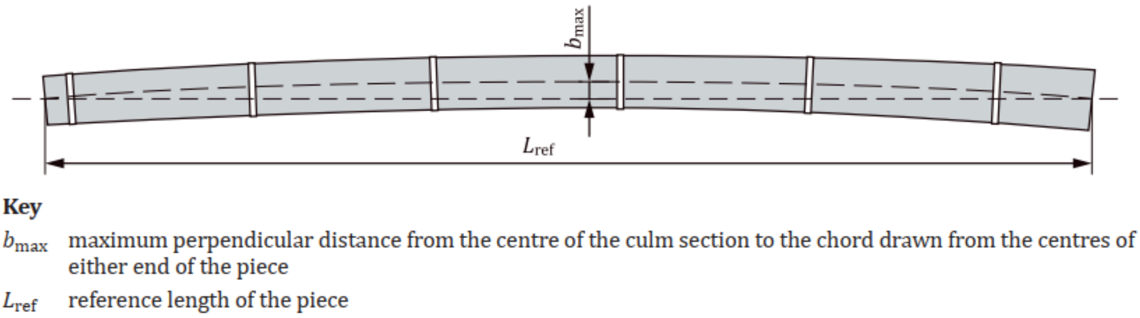


Figure 3.2 elevation of a bamboo culms

3.1.5 Ovality (d_o)

Ovality for round bamboo is calculated using following expression:

$$d_o = 2(D_{max} - D_{\min})/(D_{max} + D_{\min})$$

3.2 Physical Properties: Moisture Content and Density

$$w = \left[\frac{m_i - m_o}{m_o}\right] x100$$

$$\rho = \frac{m_o}{V_o}$$

$$\rho_{12} = \rho_{test} * \frac{1.12}{1 + w}$$

$$\rho_{test} = \frac{m_e}{V}$$

Where,
ρ = basic density
ρ_{12}= density at 12% moisture content
ρ_{test}= density at time of test
m_o = oven dry mass of the test specimen in gm
m_e = mass of the test piece in grams
V = volume of the test piece in mm^3
V_o = volume of the green test piece in mm^3
w = moisture content in decimal

3.3 Mechanical Properties

3.3.1 Compression Test

Compression parallel to fiber is measured as per ISO

$$f_{c,0} = F_{ult} / A$$

where

F_{ult} is the maximum load at which the specimen fails, in Newton (N);

A is the cross-sectional area defined in in square millimeters (mm^2).

The modulus of elasticity in compression parallel to the fibers, $E_{c,0}$, shall be calculated as the secant between stress and strain pairs at 20 % and 60 % of F_{ult}. $E_{c,0}$ is calculated from Formula (8):

$$E_{c,0} = \frac{F_{60} - F_{20}}{A(\varepsilon_{60} - \varepsilon_{20})}$$

Where,

F_{60}, $F_{20}$are the applied load, in Newton (N), at 60 % and 20 % of F_{ult}, respectively;

$\varepsilon_{60}, \varepsilon_{20}$ are the mean of the strain gauge readings obtained at 20 % and 60 % of F_{ult}, respectively.

3.3.2 Shear Test

Expression for shear strength as per ISO 22157:2019

$$fv = \frac{F_{max}}{4 \times Avg(L) \times t}$$

Fmax = is the maximum load at which the specimen fails in Newtons(N);
Avg(L)=Average height of the specimen measured in 3 random direction.
Σδ= sum of the measured wall thickness
fv = Lower bound strength

3.3.3 Dowel Embedment

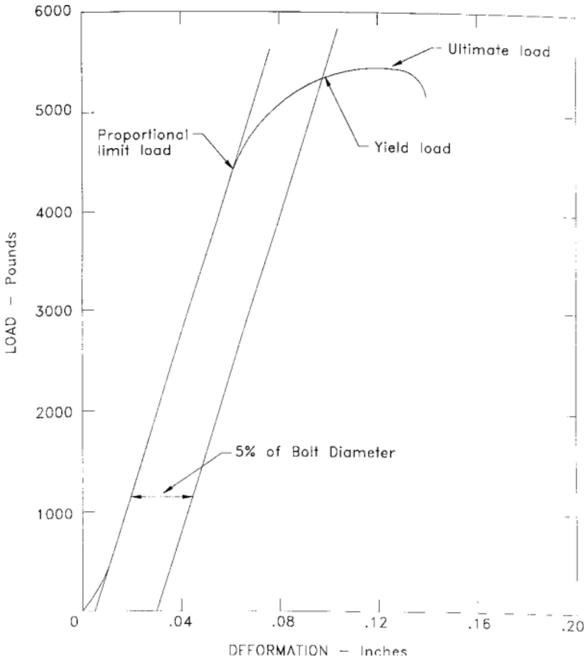


Figure 3.3 definition of yield load for dowel-embedment test (ASTM D 5764 – 97a (2002))

For dowel embedment, a linear equation is fitted in the elastic portion of the force displacement curve. Then, another equation is found by offsetting 5% of the bolt diameter from the original equation. Then, the intersection of this new line with the force displacement curve gives us yield load, as shown in figure.

Dowel embedment strength is given by,

$$DE = \frac{F_y}{2 \times t \times d_b}$$

Where, F_y is the yield load,

t is the average wall thickness,
d_b is the diameter of the bolt.

3.4 Connection Details:

There are two types of connection to test as in scope of thesis. First one is Gusset Plate connection and second one is Shaft-bolt connection.

3.4.1 Gusset Plate connection

After dowel embedment strength and geometrical properties are characterized for a species of bamboo, we proceed using those values to design connection with required mode of failure as in European Yield Model (EYM). The desired mode of failure being Mode III and Mode IV.in double shear connections.

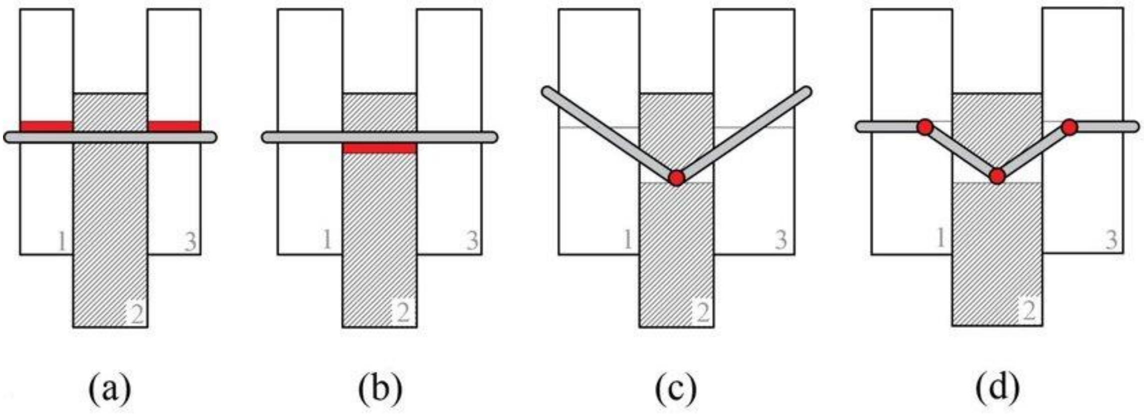


Figure 3.4 modes of failure for timber dowel-type joint in double shear based on Thelanderson & Larsen (2003) (source:Aquino, C. D. (2020)

The characteristic values from *Bambusa balcooa* is used for configuring the dowel of the connection, then same design is implemented on *Bambusa nutans* such that we can have accountability of change of performance of the particular connection in different Nepalese species of bamboo. 9mm bores are drilled through bamboos at each level 70mm apart c/c in each side. Threaded rod going through bamboo and metal plates in between are firmly held with the help of finger-tight-nuts in each side. The metal plates (of 12mm thickness) are then subjected to tension by jaws of UTM for tension.

3.4.2 Shaft-Bolt connection

For the Shaft-bolt connection the configuration of the connection is same as used in the site by Abari Foundation Nepal. The shaft-bolt connection consists of a drill hole of 22mm diameter through bamboo and M.S. shaft of threaded hole drilled transversely at its longitudinal center to fit threaded rod of 10mm, a threaded rod is then fitted into the shaft in each side which is then clamped to jaws of UTM for tension.

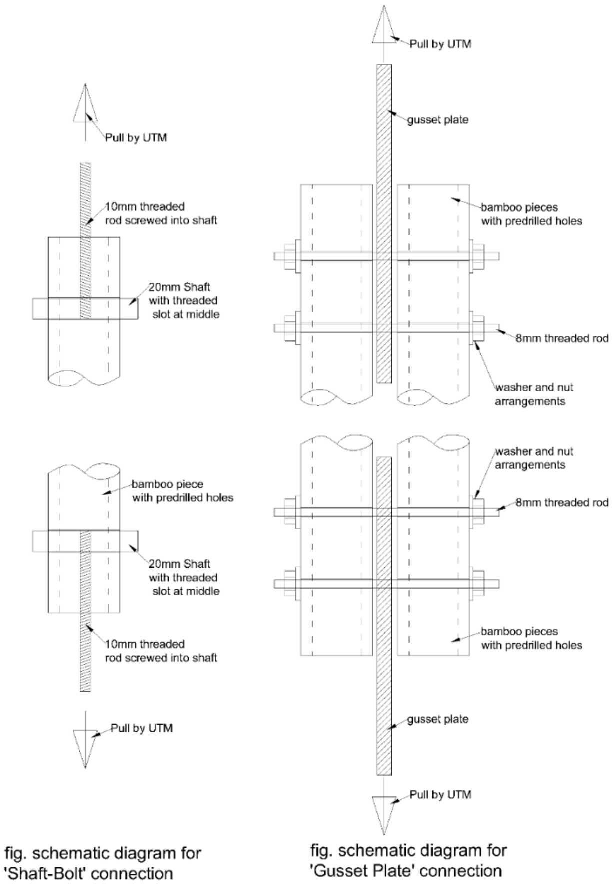
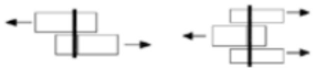
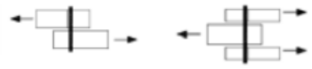
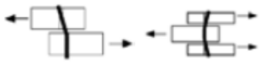
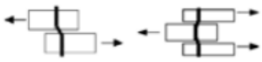


Figure 3.5 schematic diagram for two typologies of connections

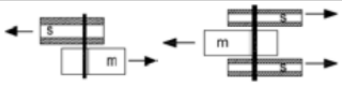
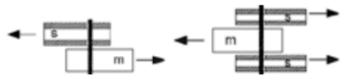
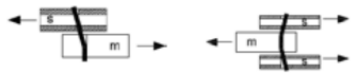
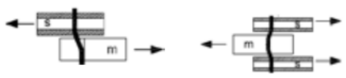
3.5 Connection Design

Dowelled-connections are principally designed using, Yield Model developed by J.W. Johansan in 1949, which is popular by the name ‘European Yield Model’. References from American Wood Council’s TR-12 and BS EN 1995-1-1:2004+Al:2008 is taken.

Yield Mode	Single Shear	Double Shear		Description
I_m	$P = q_m L_m$	$P = q_m L_m$		
I_s	$P = q_s L_s$	$P = 2 q_s L_s$		
II-IV	$P = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$	$P = \frac{-B + \sqrt{B^2 - 4AC}}{A}$		General equation for member bearing and dowel yielding
	Inputs A, B, & C for Yield Modes II-IV			
II[1]	$A = \frac{1}{4q_s} + \frac{1}{4q_m}$	$B = \frac{L_s}{2} + g + \frac{L_m}{2}$	$C = -\frac{q_s L_s^2}{4} - \frac{q_m L_m^2}{4}$	
III_m[1]	$A = \frac{1}{2q_s} + \frac{1}{4q_m}$	$B = g + \frac{L_m}{2}$	$C = -M_s - \frac{q_m L_m^2}{4}$	
III_s	$A = \frac{1}{4q_s} + \frac{1}{2q_m}$	$B = \frac{L_s}{2} + g$	$C = -\frac{q_s L_s^2}{4} - M_m$	
IV	$A = \frac{1}{2q_s} + \frac{1}{2q_m}$	$B = g$	$C = -M_s - M_m$	

[1]Yield Modes II and III_m do not apply for double shear connections.
[2]See Section 1.6 for notation.

Figure 3.6 yield equations for dowels in solid members (AWC-TR12)

Yield Mode	Single Shear	Double Shear		Description
I_m	$P = q_m L_m$	$P = q_m L_m$		
I_s	$P = 2 q_s t_{ws}$	$P = 4 q_s t_{ws}$		
II-IV	$P = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$	$P = \frac{-B + \sqrt{B^2 - 4AC}}{A}$		General equation for member bearing and dowel yielding
	Inputs A, B, & C for Yield Modes II-IV			
II[1]	$A = \frac{1}{4q_s} + \frac{1}{4q_m}$	$B = t_{ws} + v_s + g + \frac{L_m}{2}$	$C = -q_s t_{ws}(t_{ws} + v_s) - \frac{q_m L_m^2}{4}$	
III_m[1]	$A = \frac{1}{2q_s} + \frac{1}{4q_m}$	$B = g + \frac{L_m}{2}$	$C = -M_s - \frac{q_m L_m^2}{4}$	
III_s	$A = \frac{1}{4q_s} + \frac{1}{2q_m}$	$B = t_{ws} + v_s + g$	$C = -q_s t_{ws}(t_{ws} + v_s) - M_m$	
IV	$A = \frac{1}{2q_s} + \frac{1}{2q_m}$	$B = g$	$C = -M_s - M_m$	

[1]Yield Modes II and III_m do not apply for double shear connections.

Figure 3.7 yield equations for dowels in hollow members (AWC-TR12)

Expressions as per BS EN 1995-1-1:2004+Al:2008 to evaluate the row-shear or plug shear capacity of dowelled connection are as follows:

$$F_{bs,Rk} = \max \begin{cases} 1{,}5\, A_{net,t}\, f_{t,0,k} \\ 0{,}7\, A_{net,v}\, f_{v,k} \end{cases}$$

with

Anet, t = Lnet, t tl
A1

Anet, v = $\begin{cases} L_{net,v} t_1 \\ \frac{L_{net,v}}{2} (L_{net,v} + 2t_{ef}) \end{cases}$

And

Lnet, v = $\sum_i l_{v,i}$

Lnet, t = $\sum_i l_{t,i}$

failure modes (c,f, j/l, k, m) (BS EN 1995-1-1:2004+Al:2008)
all other failure modes

- for thin steel plates (for failure modes given in brackets)

tef = $\begin{cases} 0,4\ t_1 \\ 1,4 \sqrt{\frac{M_{y,Rk}}{f_{h,k}\ d}} \end{cases}$

- for thick steel plates (for failure modes given in brackets)

tef = $\begin{cases} 2 \sqrt{\frac{M_{y,Rk}}{f_{h,k}\ d}} \\ t_1 \left[\sqrt{\frac{M_{y,Rk}}{f_{h,k}\ d}} - 1 \right] \end{cases}$

where
Fbs, Rk - characteristic block shear or plug shear capacity;
Anet, t - net cross-sectional area perpendicular to the grain;
Anet, v- net shear area in the parallel to grain direction;
Lnet, t - net width of the cross-section perpendicular to the grain;
Lnet, v - total net length of the shear fracture area;
lv, i, lt, i - defined in Figure A.1;
tef - effective depth depending of the failure mode of the fastener, see Figure 8.3;
tl - timber member thickness or penetration depth of the fastener;
My, Rk - characteristic yield moment of the fastener;
d - fastener diameter;
ft,0,k - characteristic tensile strength of the timber member;
fv, k - characteristic shear strength of the timber member;
fn, k - characteristic embedding strength of the timber member.

Determination of Characteristic Values:

Following expressions are adopted to evaluate characteristic strength from each of the test, these equations are prescribed in ISO 12122-1:2014.

Xmean, 0.75 = Xmean (1- $\frac{k_{mean,0.75}\ V}{\sqrt{n}}$)

Where
Xmean, 0.75 is the characteristic value expressed as the mean value with 75% confidence
Xmean is the average of the individual test values (Xi)
kmean, 0.75 is a multiplier to give a mean value with 75% confidence and shall be the value obtained

V is the coefficient of variation of the test data found by dividing the standard deviation of the test data by the average of the test data

$$X_{0.05,\,0.75} = X_{0.05}\,(1 - \frac{k_{0.05,0.75}\,V}{\sqrt{n}})$$

Where

n is the number of test values

$X_{0.05,\,0.75}$ - 5 percent lower tolerance limit with 75% confidence

$X_{0.05}$ -5th percentile from the test data

$k_{0.05,\,0.75}$ - multiplier to give the 5 percent lower tolerance limit with 75% confidence

V -coefficient of variation of the test data found by dividing the standard deviation of the test data by the average of the test data

Table 3.1 value for multipliers for evaluation by fitting data to log-normal distribution (ISO 12122-1:2014)

Number of specimens *n*	$k_{0.05,0.75}$
5*	1.34
10*	1.28
30	1.18
50	1.13
100	1.07
>100	1

Figures and Pictures Description:

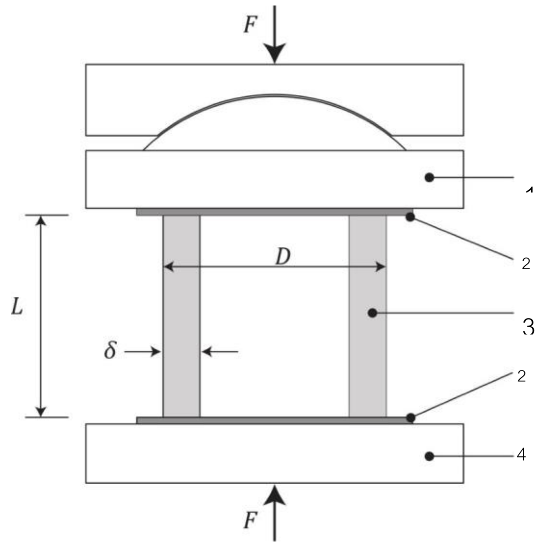


Figure 3.8 Experimental setup for compressive testing of bamboo specimens. The figure shows the bamboo specimen placed in the UTM for compression testing. The load cell and displacement sensor are also shown in the figure

Key:

D outer diameter
δ wall thickness
F load
L length of specimen (L is the lesser of D or 10δ. If D < 20 mm, L = 2D)
1 upper loading platen with spherical bearing
2 intermediate layer
3 bamboo specimen
4 intermediate layer
5 lower loading platen

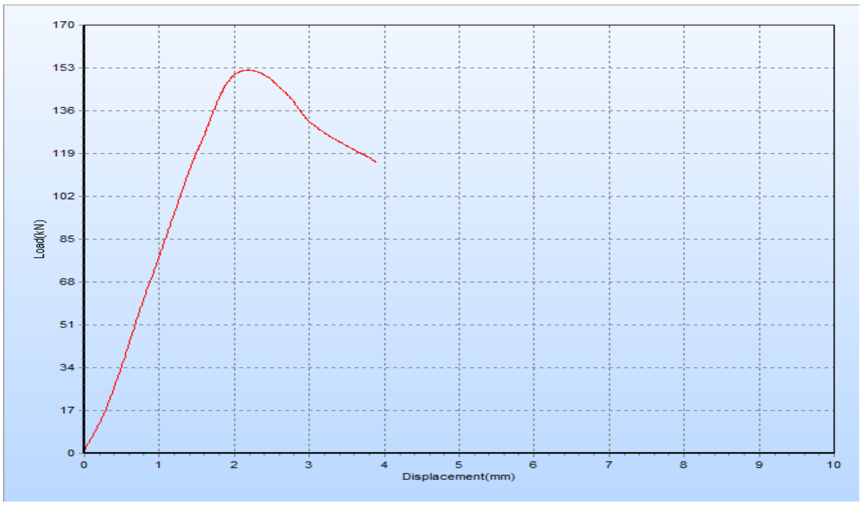


Figure 3.9 Stress-strain curve for a bamboo specimen tested according to ISO 22157:2019. The figure shows the stress-strain curve for a bamboo specimen tested under compression

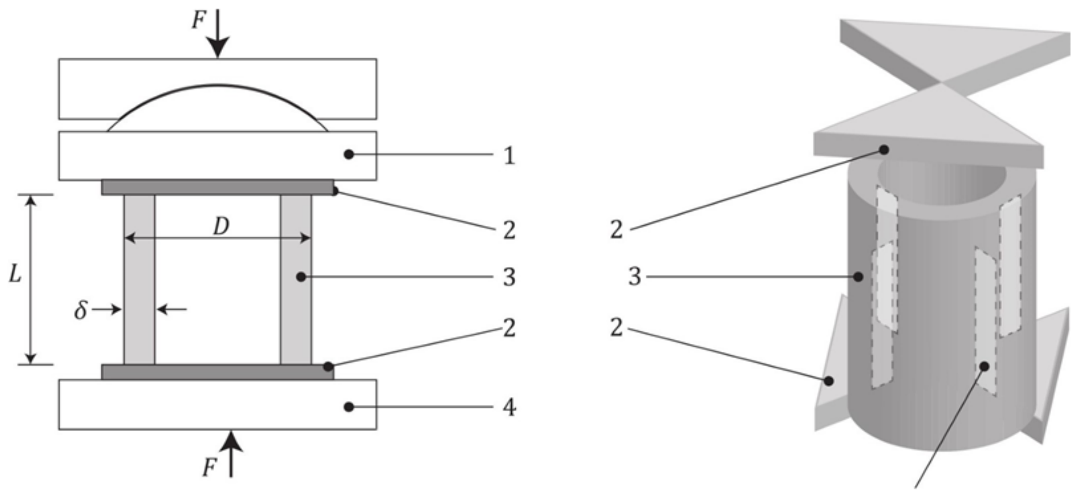
Figure 3.10 Setup for measuring geometric data of bamboo culms

Figure 3.11 A bamboo specimen being prepared for testing. The picture shows a bamboo culm being cut into a smaller section of uniform length and diameter using a saw

Figure 3.13 Gusset-plate connection bring tested in the UTM

Figure 3.12 A Shear Test Setup using shear apparatus

Figure 3.14 Shaft-bolt connection bring tested in the UTM



Key
δ wall thickness
D outer diameter
F load
L length of specimen (L is the lesser of D or 10δ. If D < 20 mm, L = 21))
1 upper loading platen with spherical bearing
2 shear plate
3 bamboo specimen
4 lower loading platen
5 shear area, normally calculated from δ x L

Figure 3.15 Shear Parallel to Fiber Test (schematic drawing)

Figure 3.16 Connection Specimen Fabrication using Milling Machine

s

4
RESULTS AND DISCUSSION

4.1 Analysis of Data

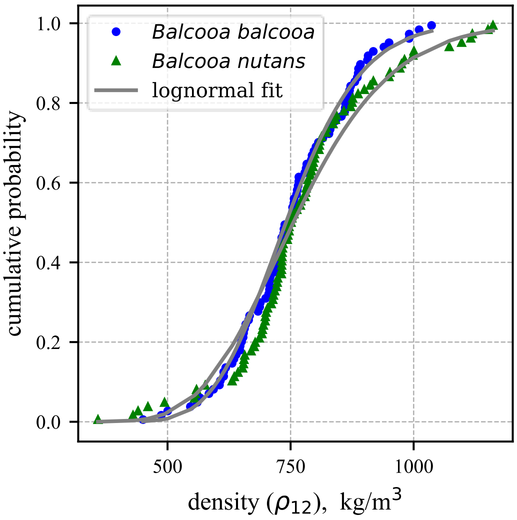
Data in this research/ thesis originated from measurement of geometric properties in grading process, measurement of specimen dimensions, conducting the tests and weighing for moisture content. These different types of data are related to same material hence, combining these data is also a very crucial process for their analysis consecuently it's interpretation.

Experimental setup of UTM provided us with the digital force-displacement data. These data were analysed using MS Excel and Python. On the analysis, different types of strengths were calculated using the experiment data and geometric data. The computed strengths/ parameters were again fitted to log-normal distribution so as to evaluate characteristic values. Log-normal fitting of results were compared for two of the species for different parameters.

Force-displacement curves were also plotted in single sheet for each test of each species. And analyses were carried out according to the mentioned methodology. In this chapter data and results are visualized in different forms and figures.

4.2 Observation

4.2.1 Grading Results



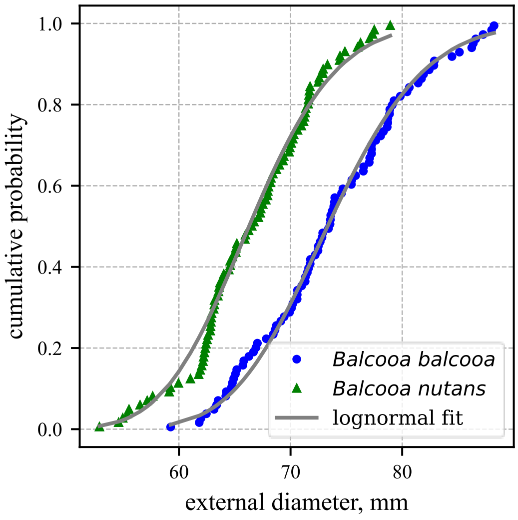


Figure 4.1 cdf of densities (12% moisture content) **Figure 4.2 1 cdf of external diameter measured**

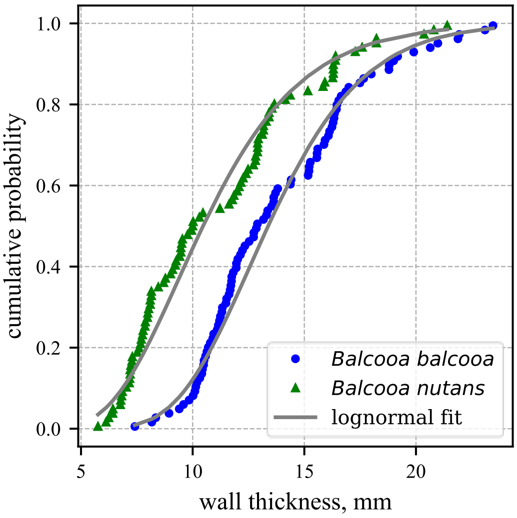
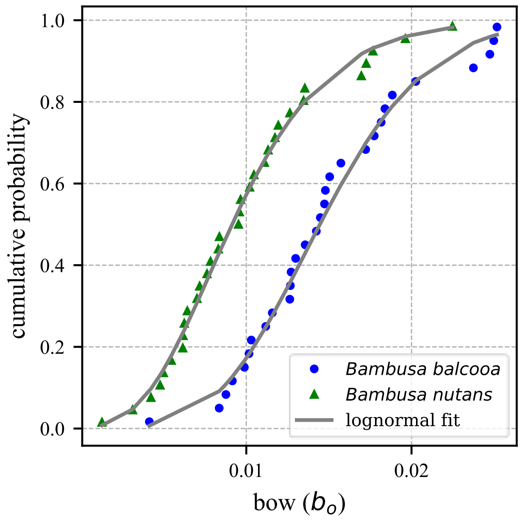


Figure 4.3 cdf of wall thickness measured

BOW:



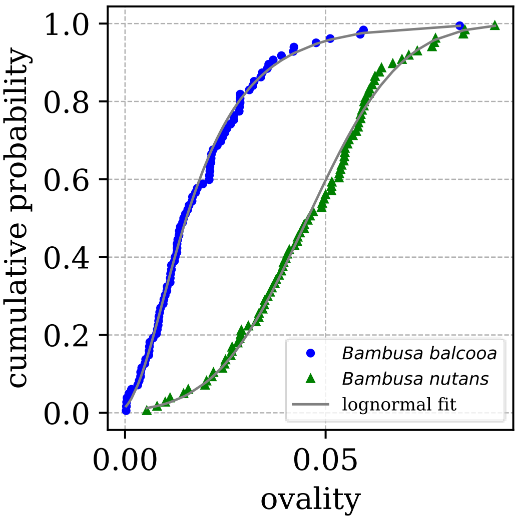


Figure 4.4 cdf of bow of sampled culms

Figure 4.5 cdf of ovality of sample culms

4.2.2 LOAD CALIBRATION FACTORS

Table 4.1 load calibration factors for the UTM at Thapathali campus

Load Gauge reading (kN)	Calibration Factor
0	1
100	0.987
200	0.973
300	0.978

4.2.3 COMPRESSION DATA

The data presented below are the graphs obtained from testing of *Bambusa balcooa* specimens in laboratory of IOE Pulchowk and Thapathali. The graphs show Force (kN) vs. Displacement (mm) and an equation of the linear elastic part of the curve. From the linear equation, peak load and the grading of specimens, compressive strength in MPa and modulus of elasticity in compression is found out for the samples.

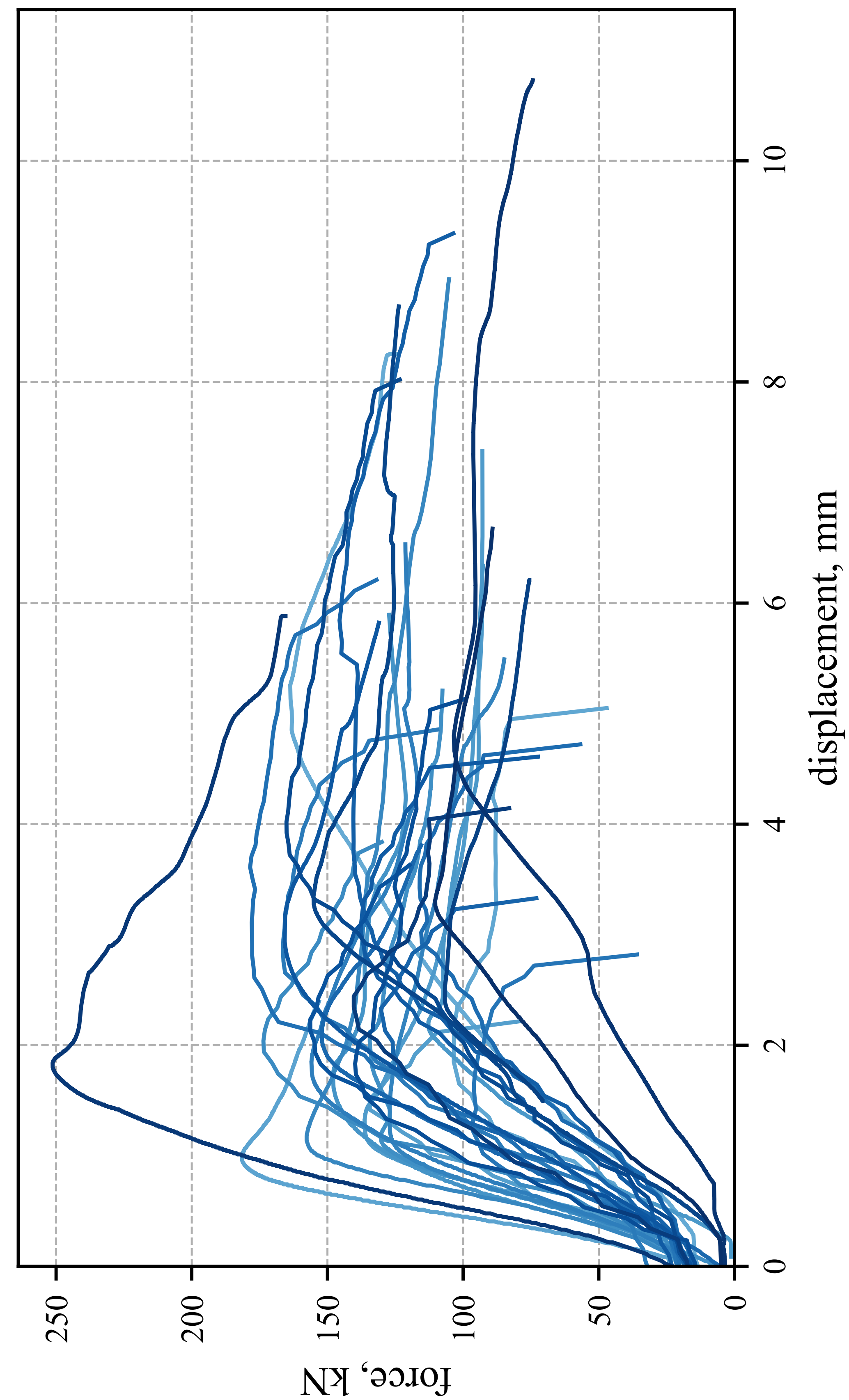


Figure 4.6 F-d curve for compressive tests of 31 *B. balcooa* samples

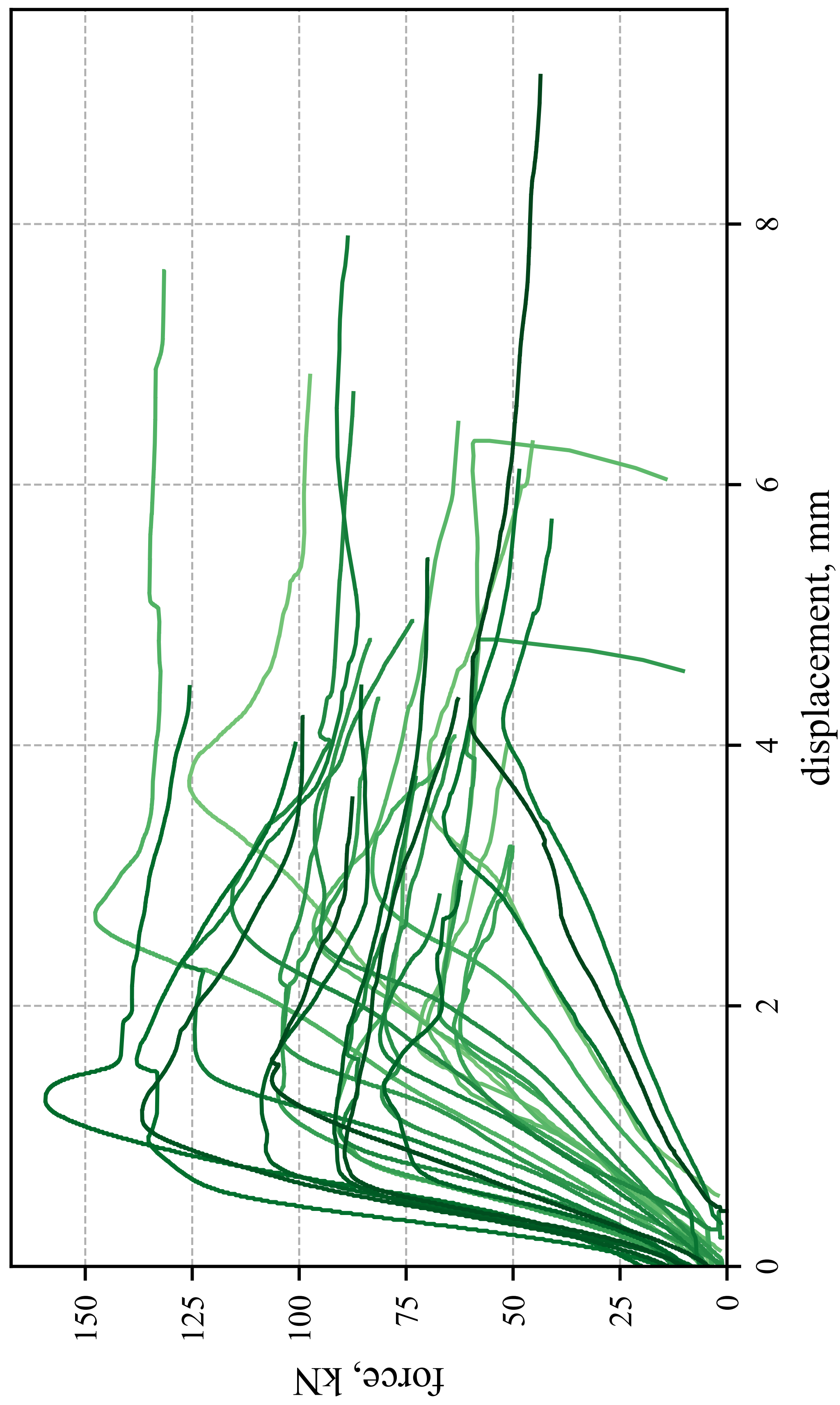


Figure 4.7 F-d curve for compressive tests of 30 *B. nutans* samples

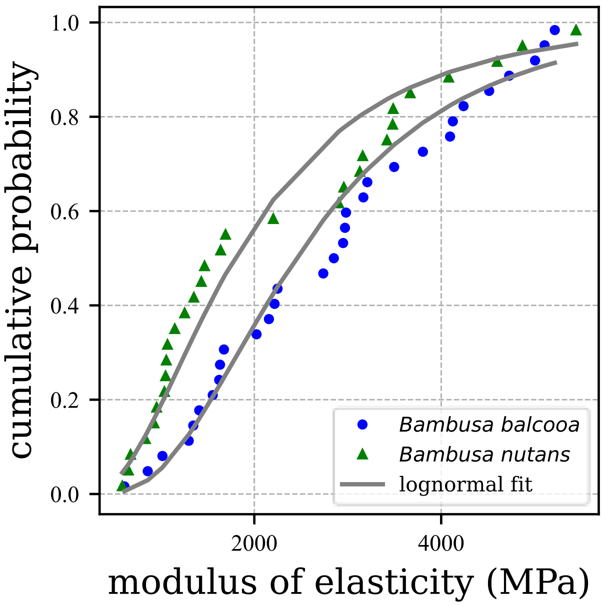


Figure 4.8 cdf of (compression) modulus of elasticity of two species

4.2.4 SHEAR DATA

The data presented below are the graphs obtained from testing of *Bambusa balcooa* specimens in laboratory of IOE Thapathali. The graphs show Force (kN) vs. Displacement (mm). From the linear equation fitted in elastic range of the curve, peak load and the grading of specimens, shear strength in N/mm^2 (MPa) and shear modulus is found out for the samples.

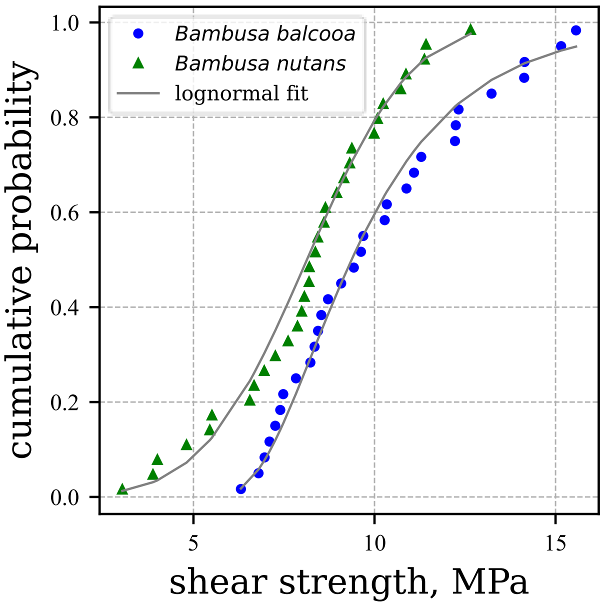


Figure 4.9 cdf of shear strengths of two species

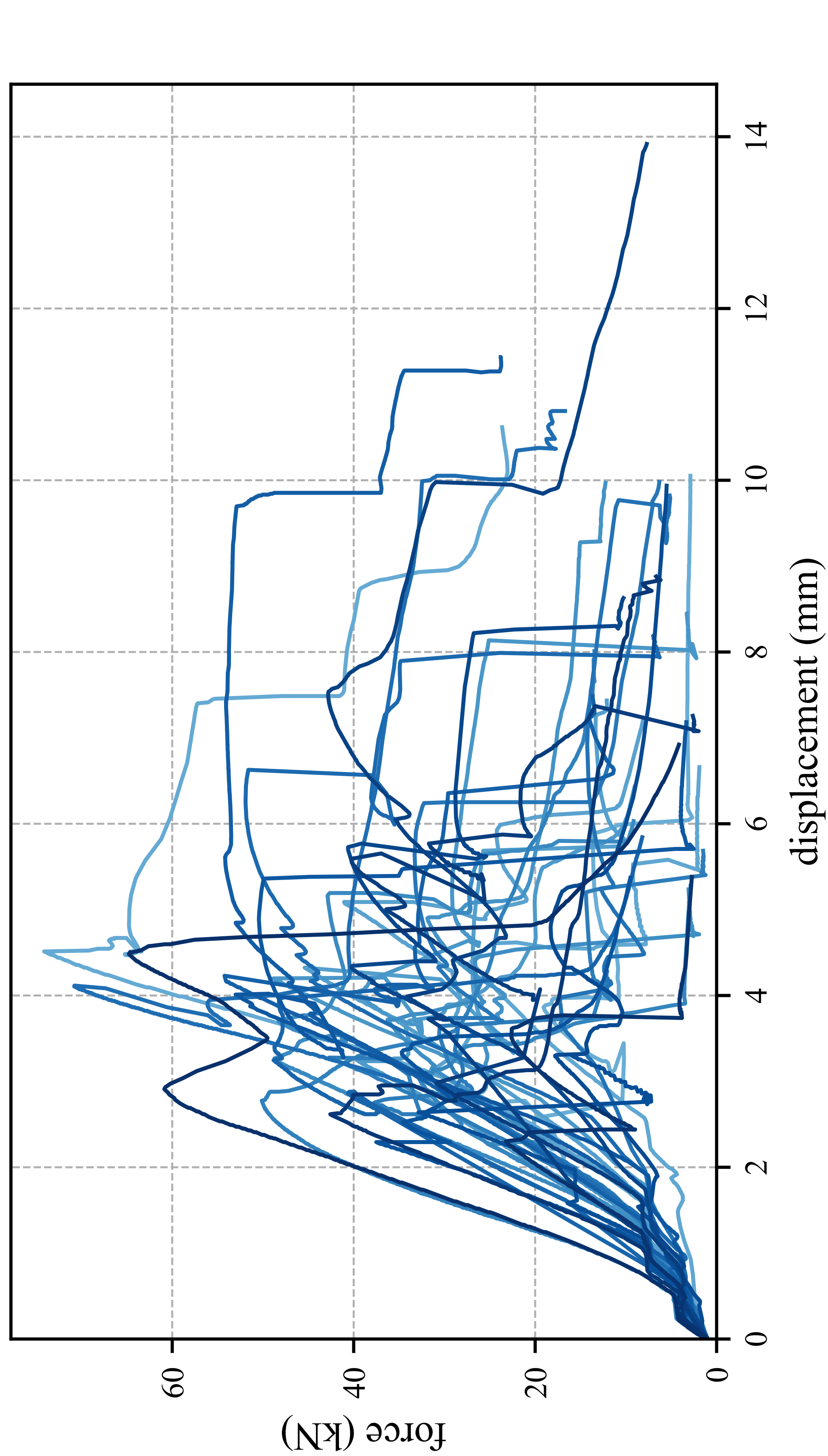


Figure 4.10 F-d curve for shear tests of 30 *B. balcooa* samples

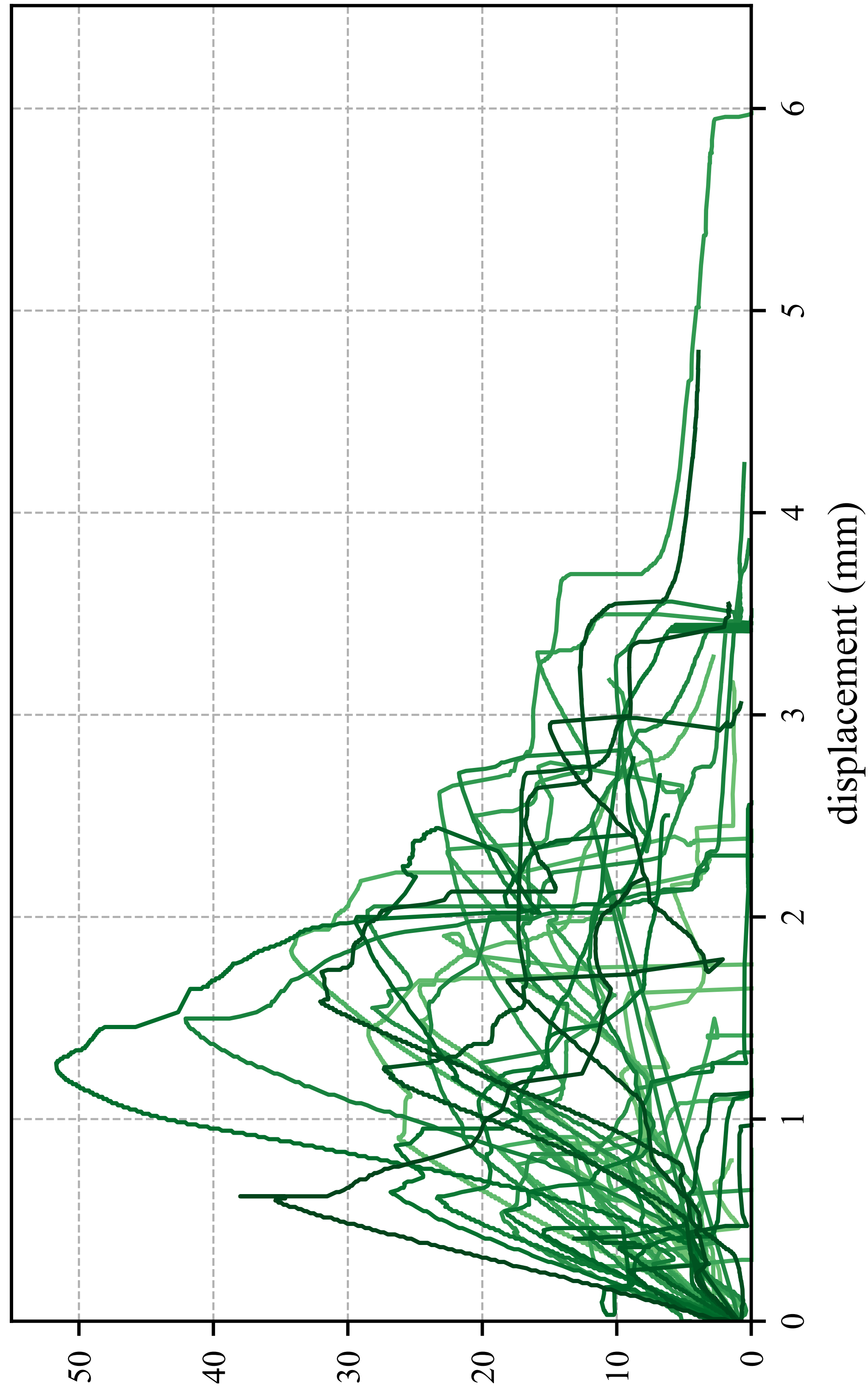


Figure 4.11 F-d curve for shear tests of 32 *B. nutans* samples

4.2.5 DOWEL EMBEDMENT DATA

The data presented below are the graphs obtained from testing of *Bambusa balcooa* specimens in laboratory of IOE Thapathali. The graphs show Force (kN) vs. Displacement (mm), an equation of the linear elastic part of the curve and it's offset slope. From the intersection of the offset equation and original graph, dowel embedment strength in N/mm^2 (MPa) is found out for the samples.

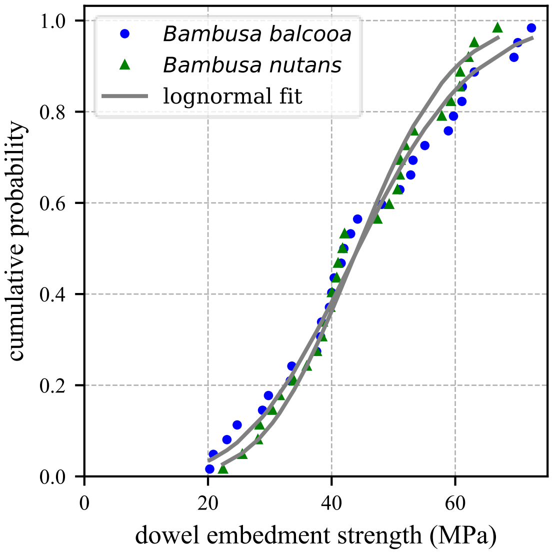


Figure 4.12 cdf of dowel embedment strengths

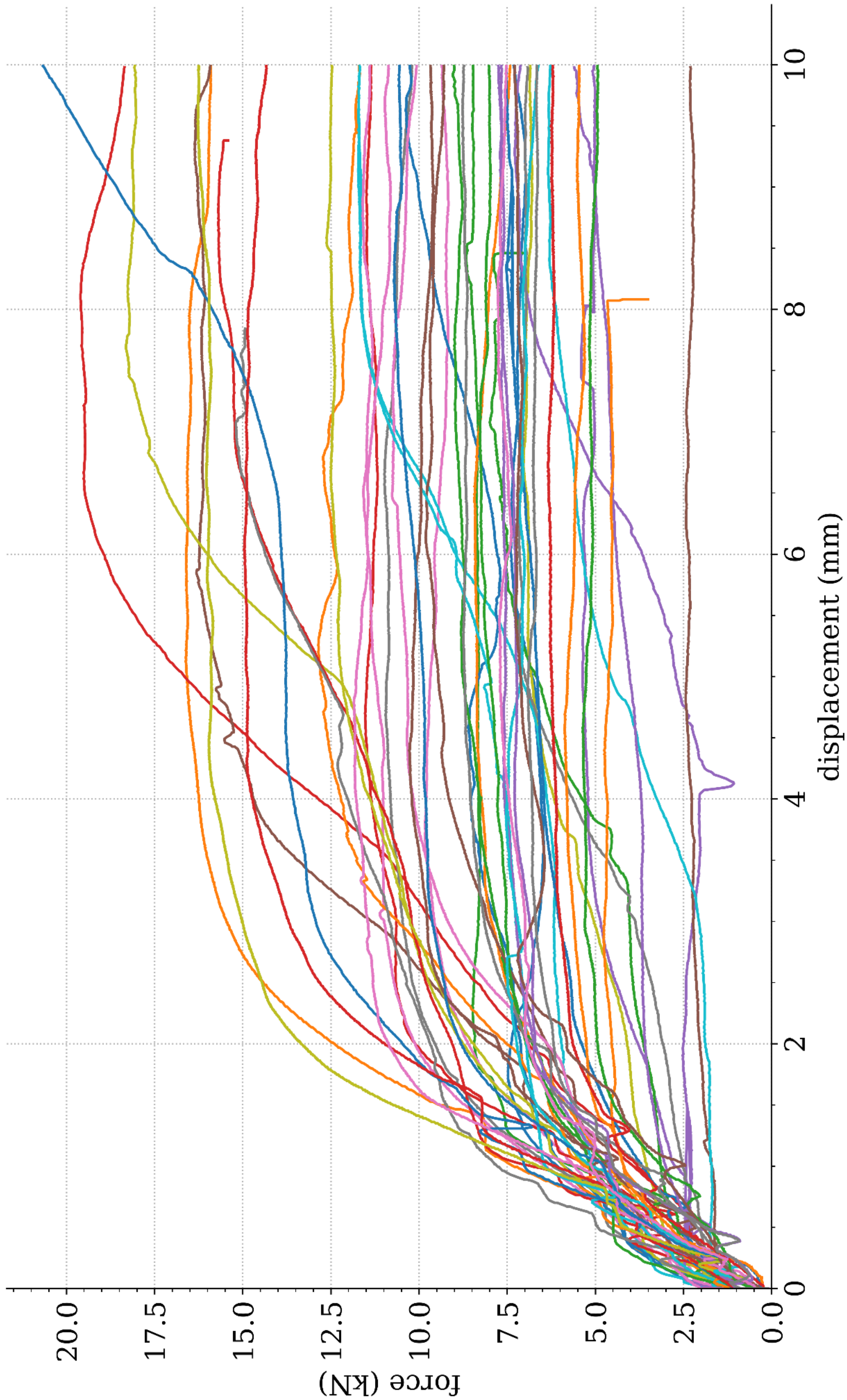


Figure 4.13 F-d curve for dowel embedment tests of *B. balcooa* samples

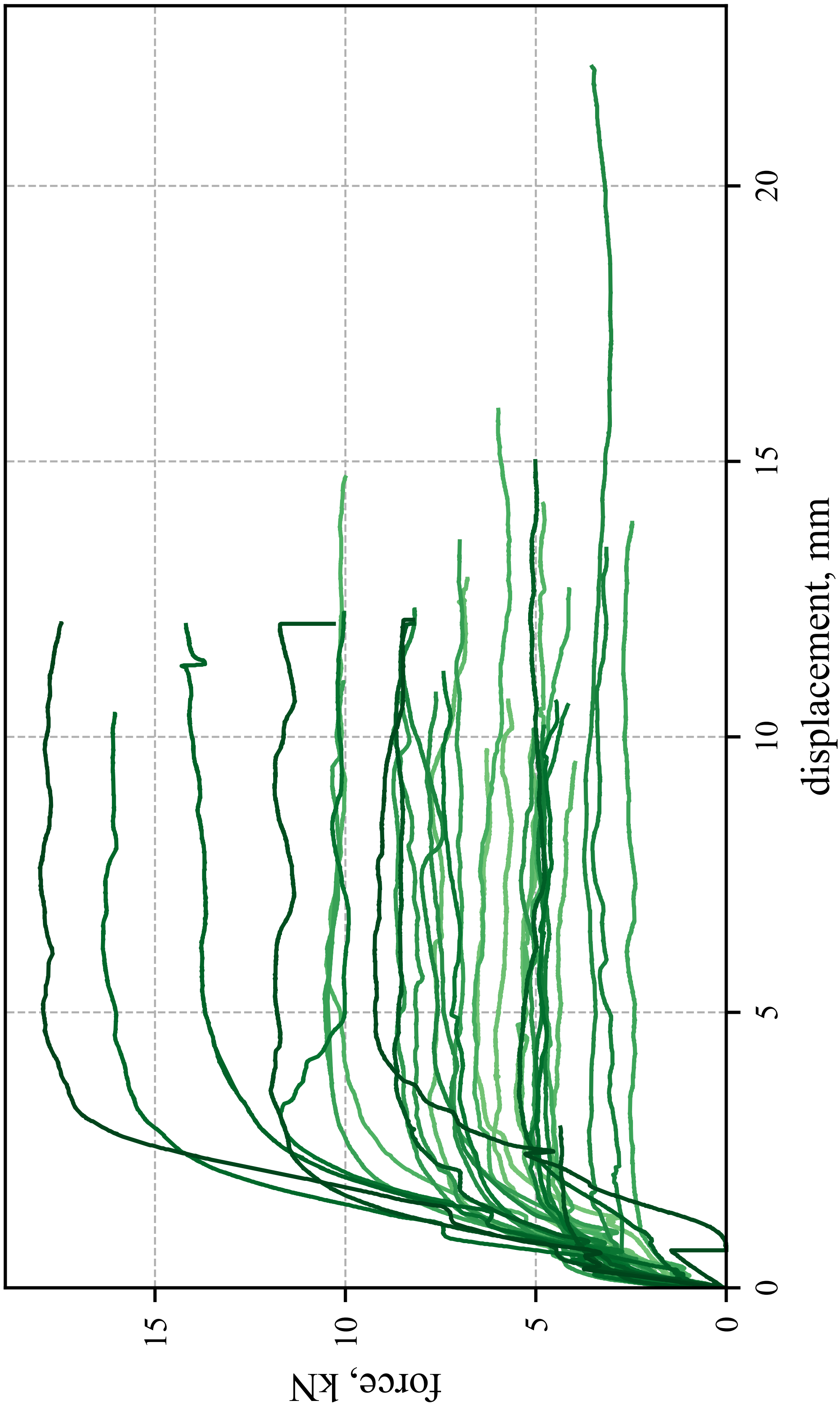


Figure 4.14 F-d curve for dowel embedment tests of 31 *B. nutans* samples

4 . 3 Connections Results

4.3.1 Force-displacement curves

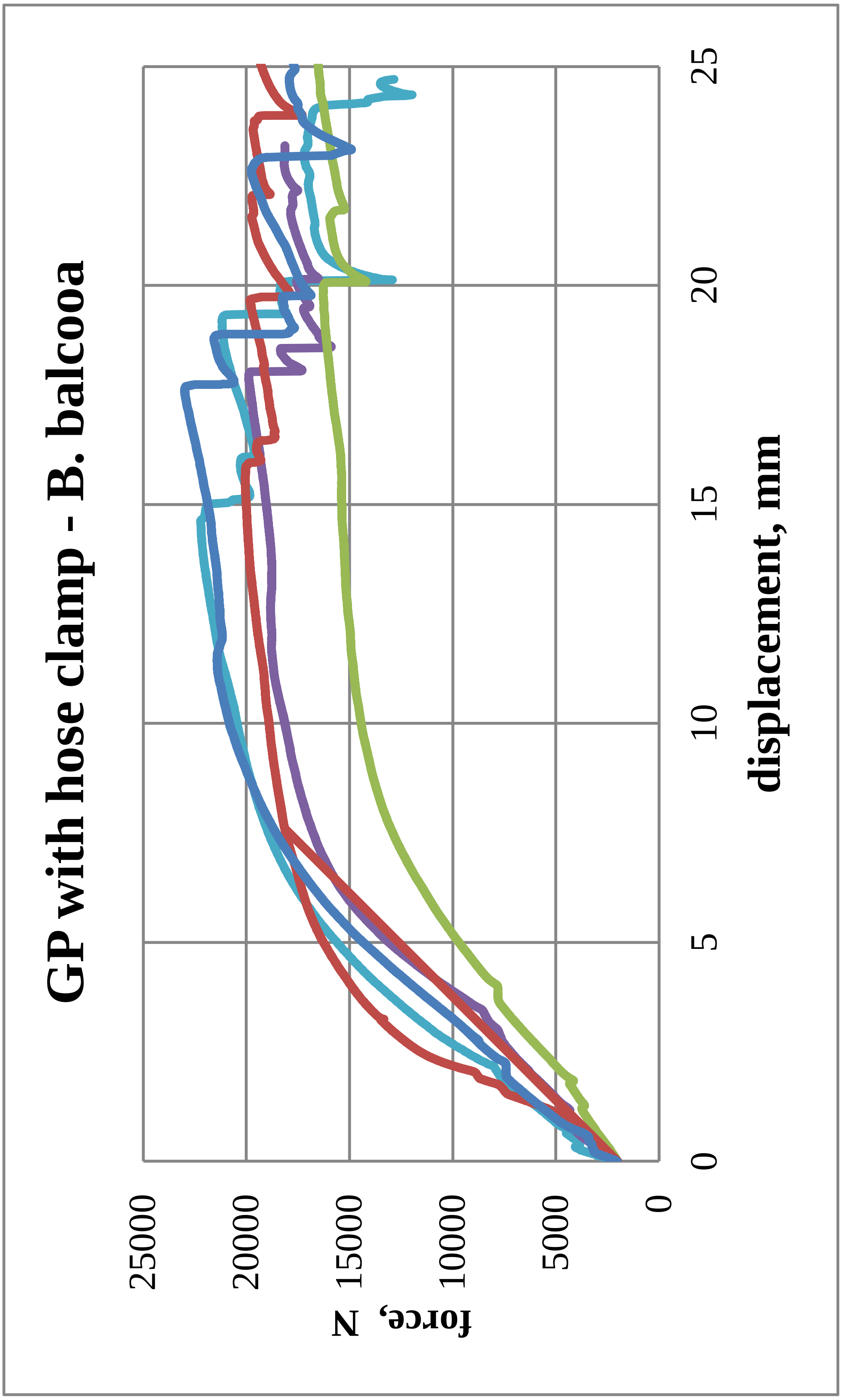


Figure 4.15 F-d curves of Bb GP connections with hose

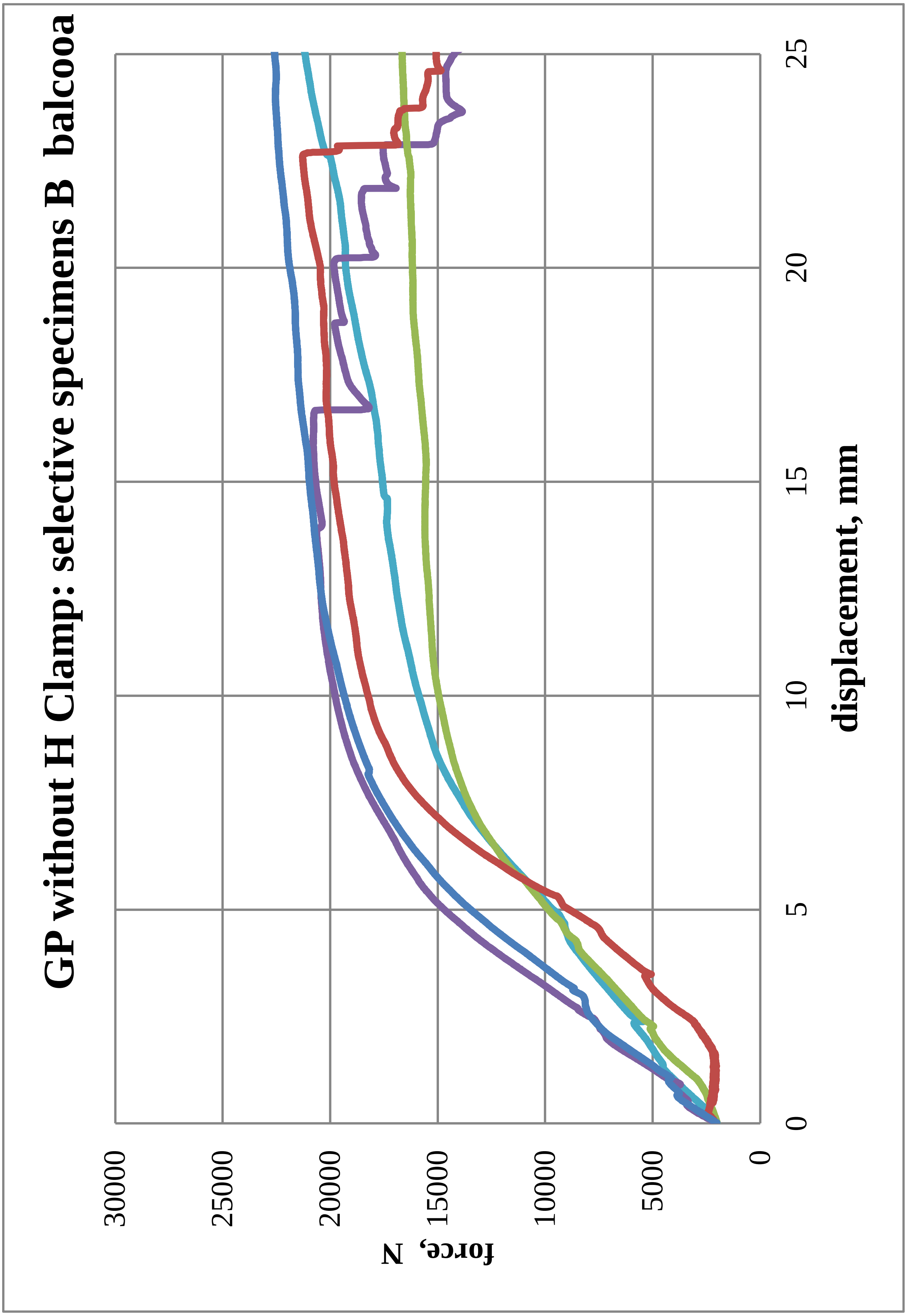


Figure 4.16   F-d curves of Bb GP connections without hose

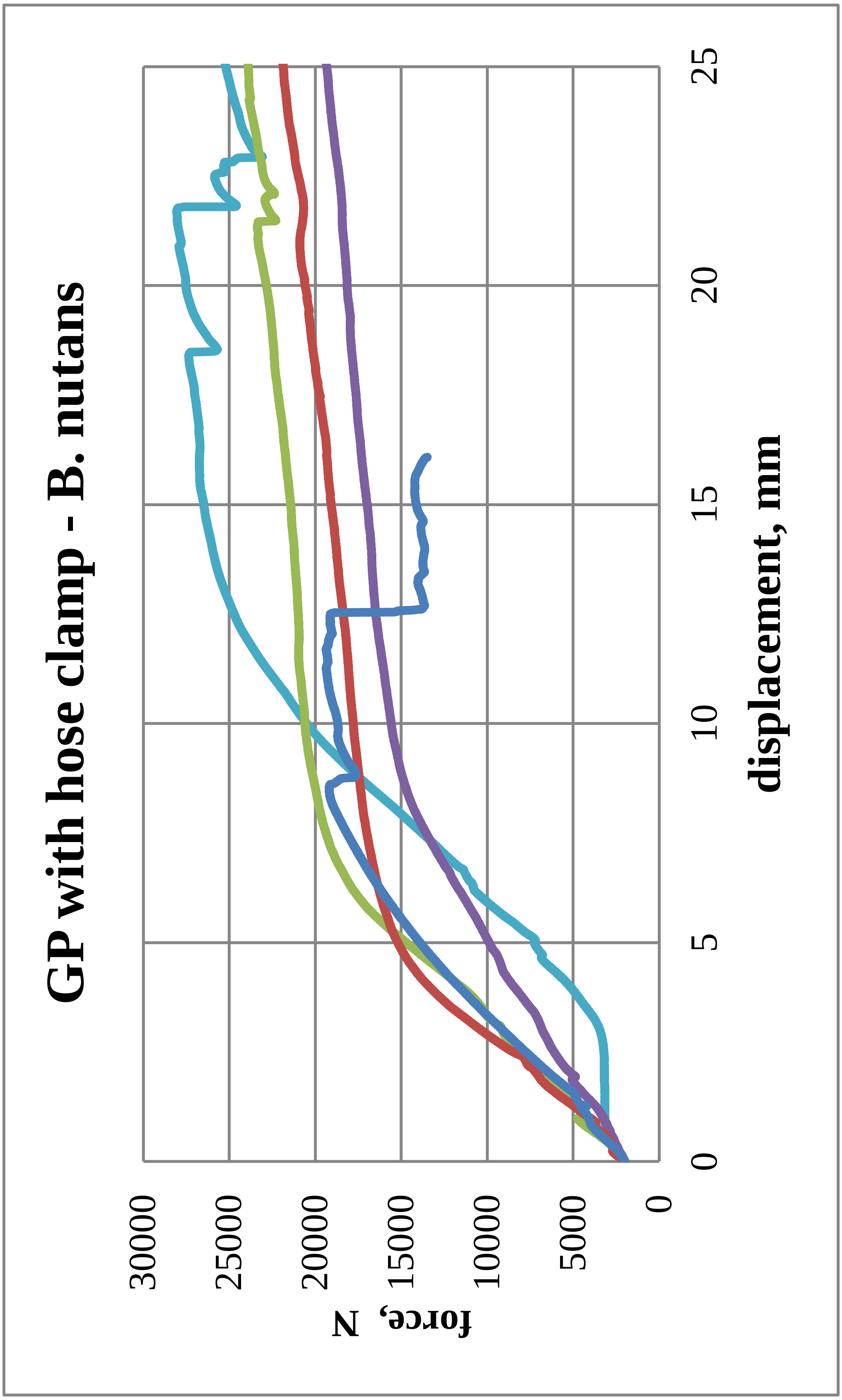


Figure 4.17 F-d curves of Bn GP connections with hose

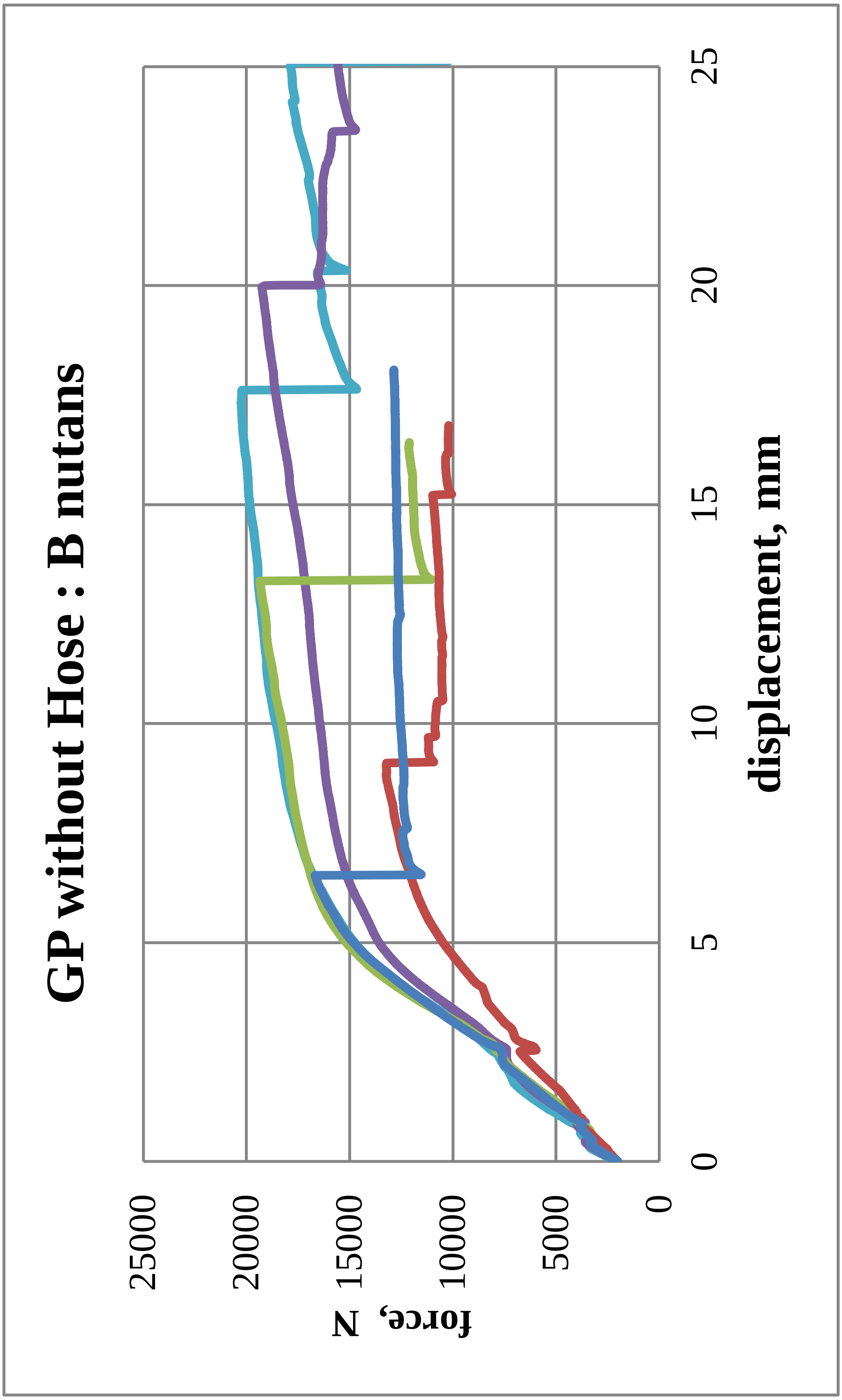


Figure 4.18 F-d curves of Bn GP connections without hose

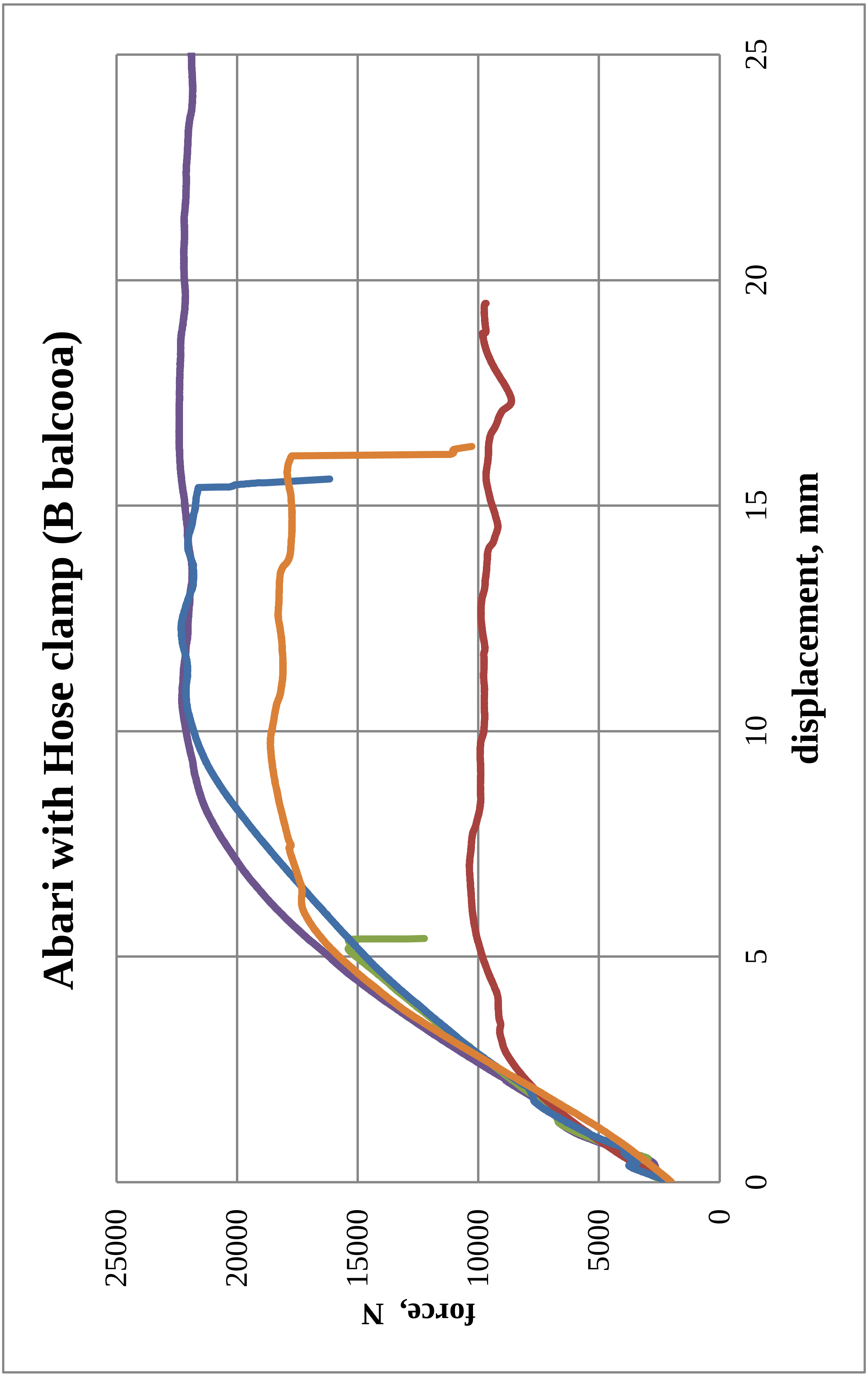


Figure 4.19 F-d curves of Bb S-b connections with hose

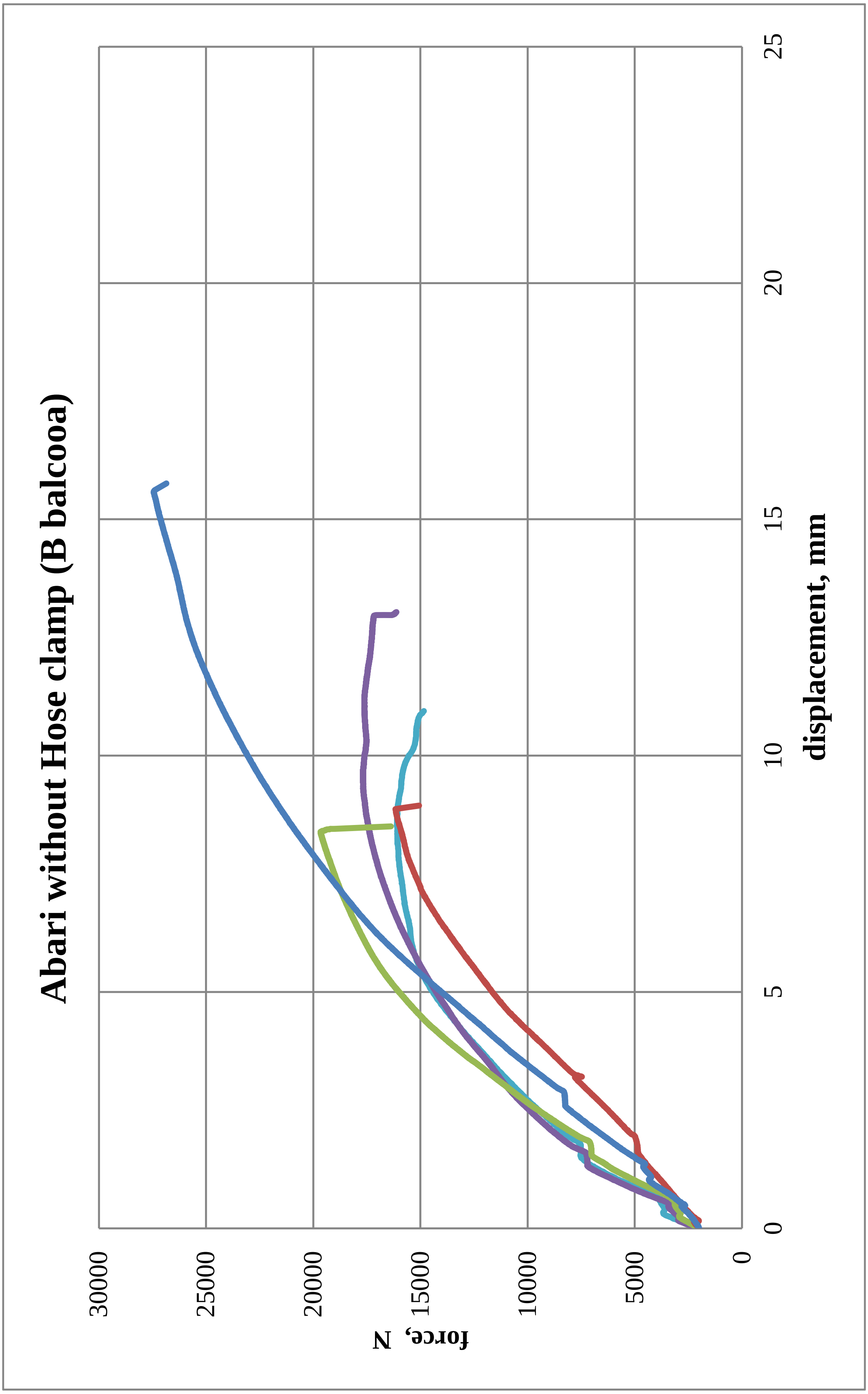


Figure 4.20 F-d curves of Bb S-b connections without hose

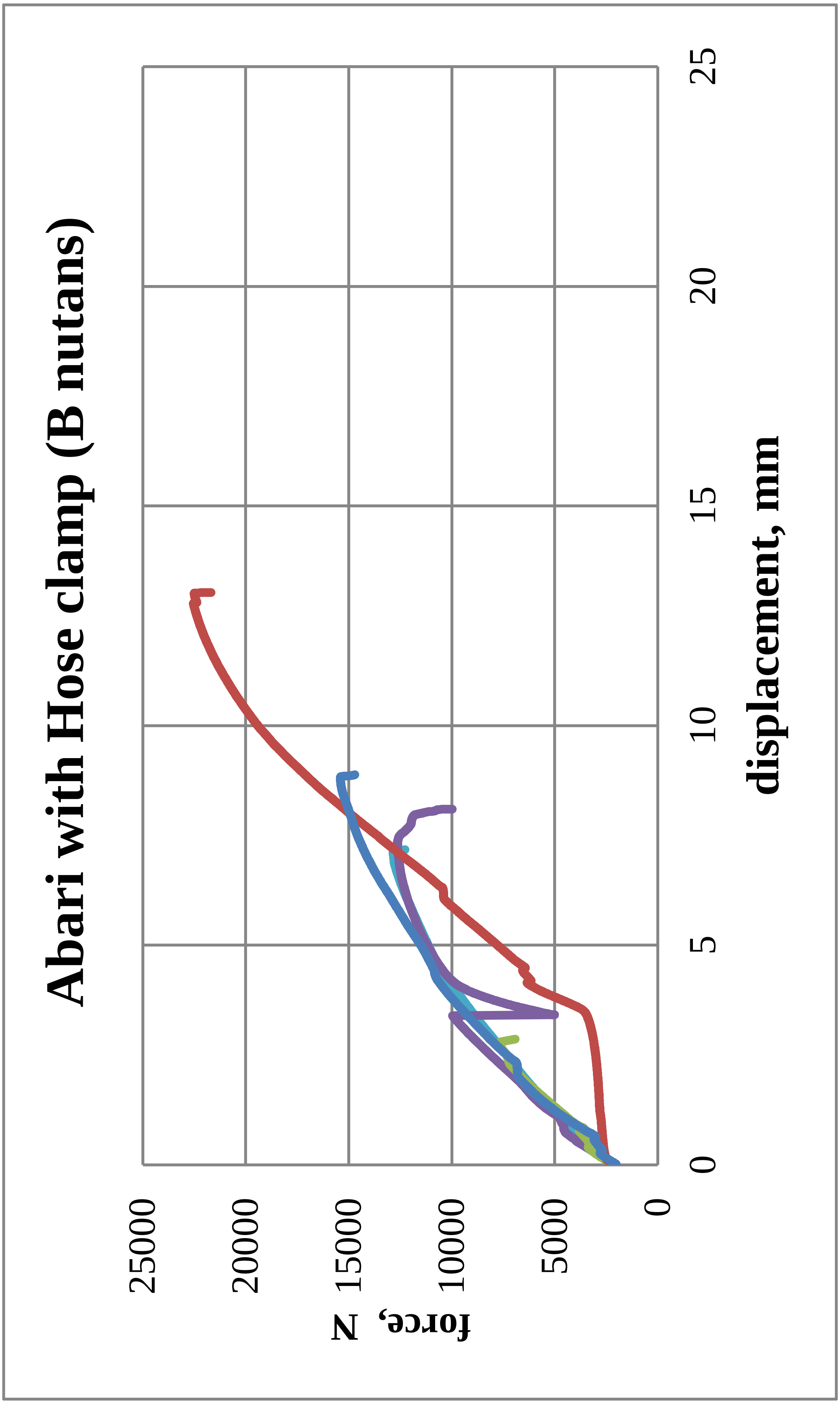


Figure 4.21 F-d curves of Bn S-b connections with hose

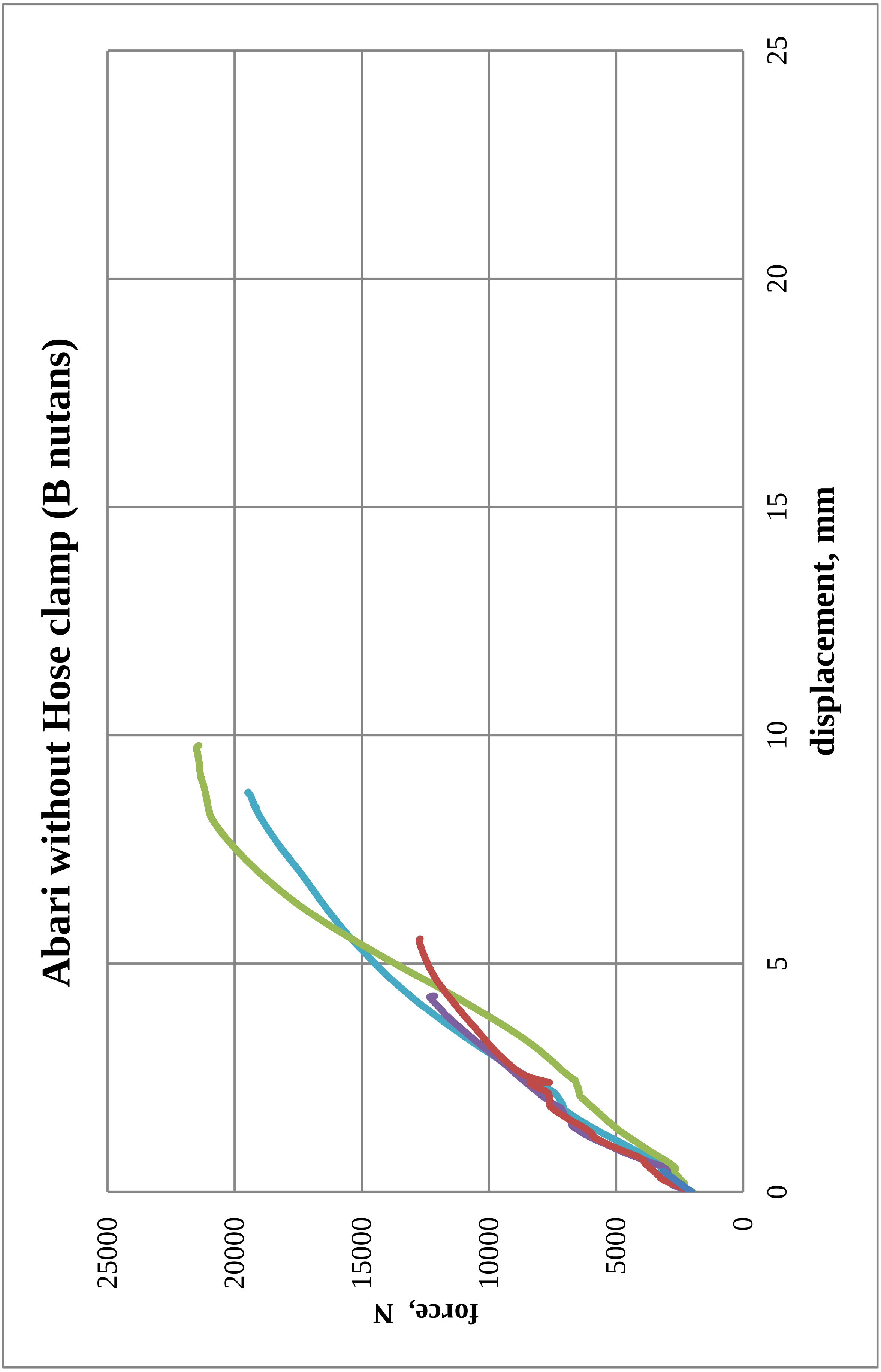


Figure 4.22 F-d curves of Bn S-b connections without hose

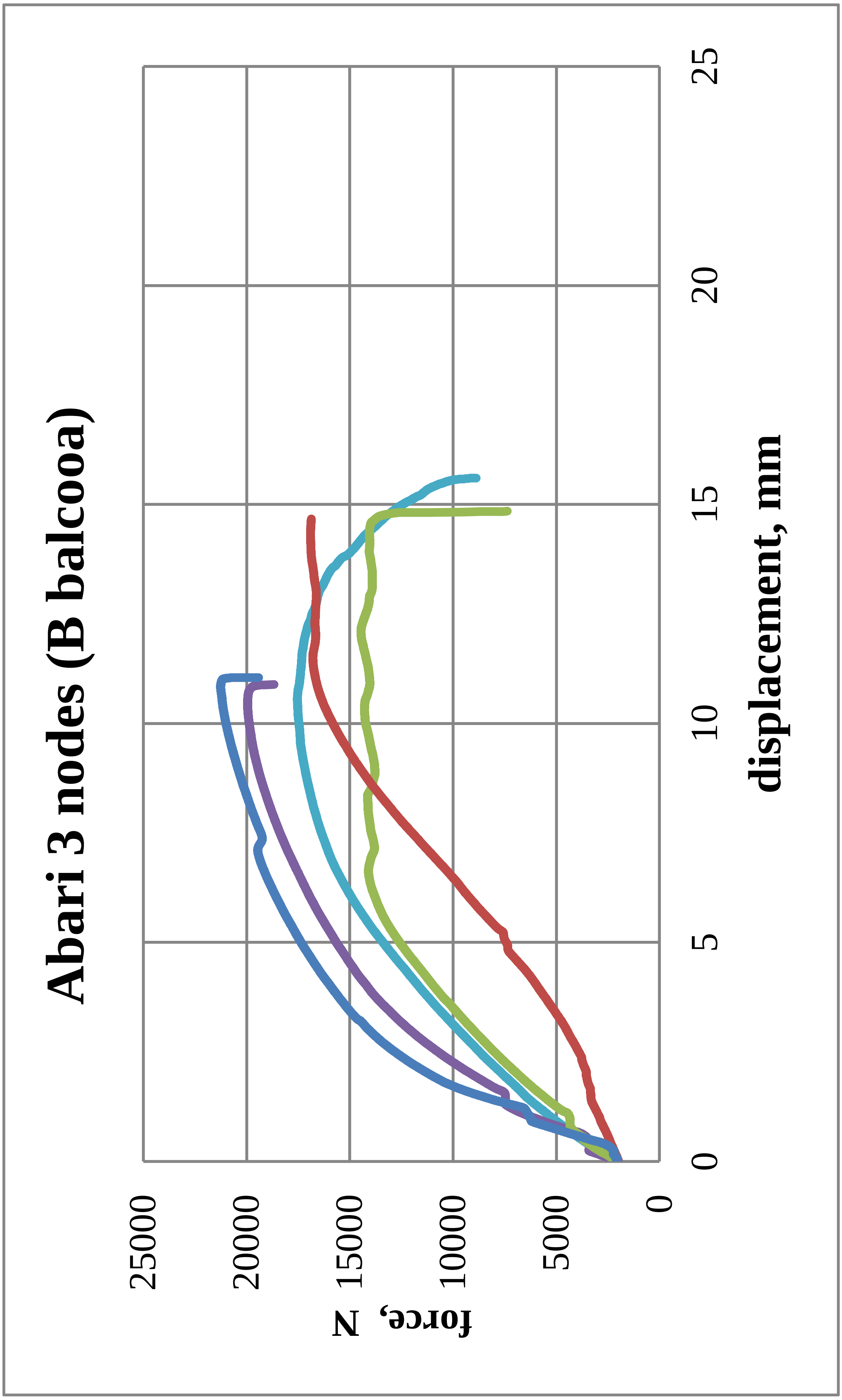


Figure 4.23 F-d curves of BB node ended Shaft-bolt connections

Failure Patterns

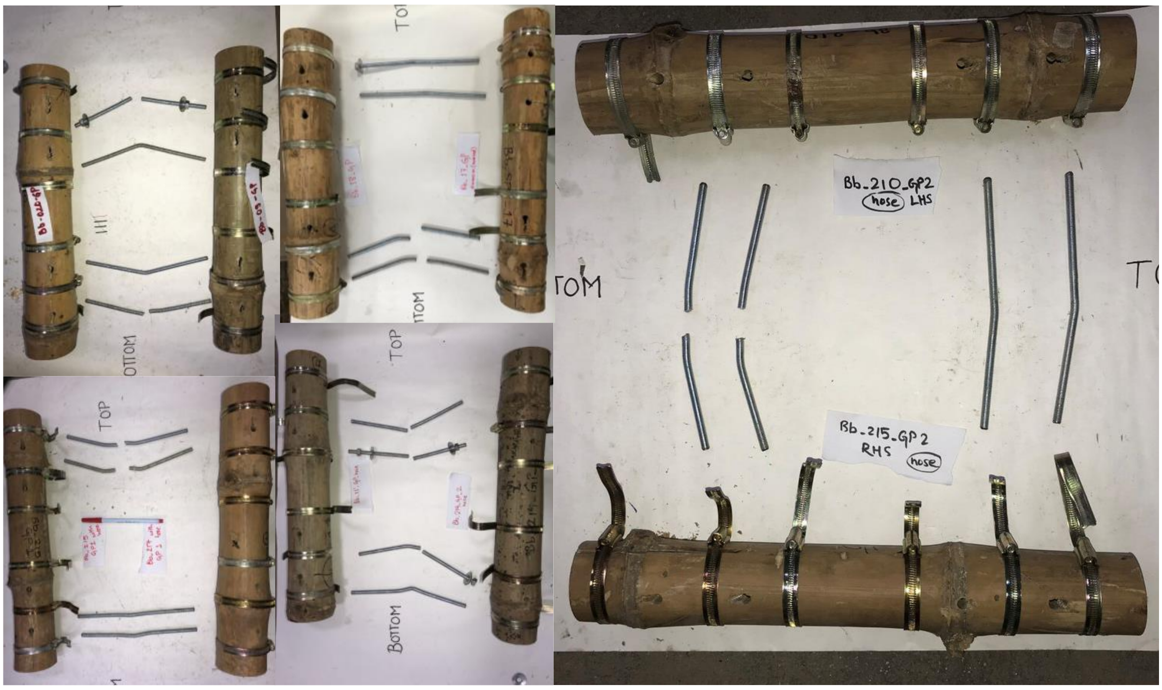


Figure 4.24 *B. balcooa* GP with hose clamp

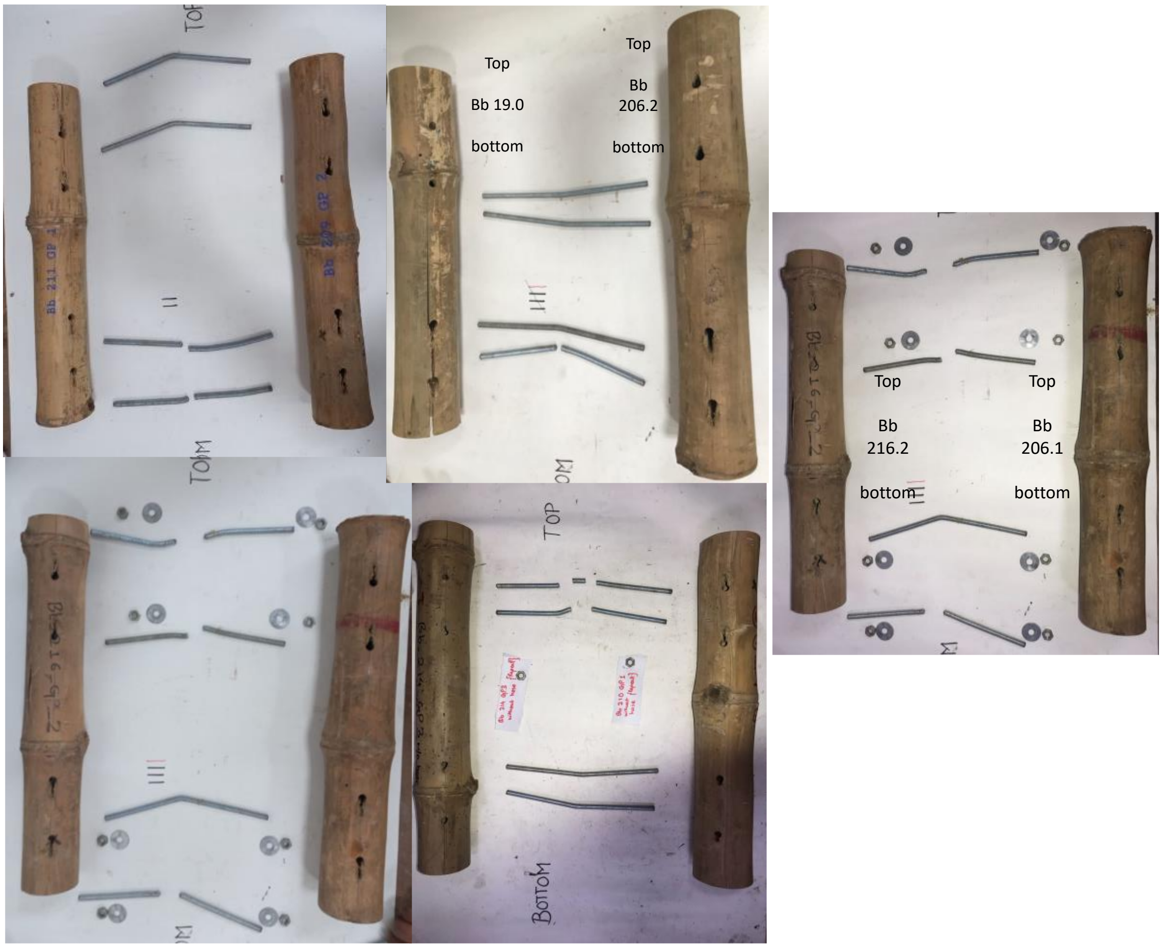


Figure 4.25 *B. balcooa* GP without hoseclamp

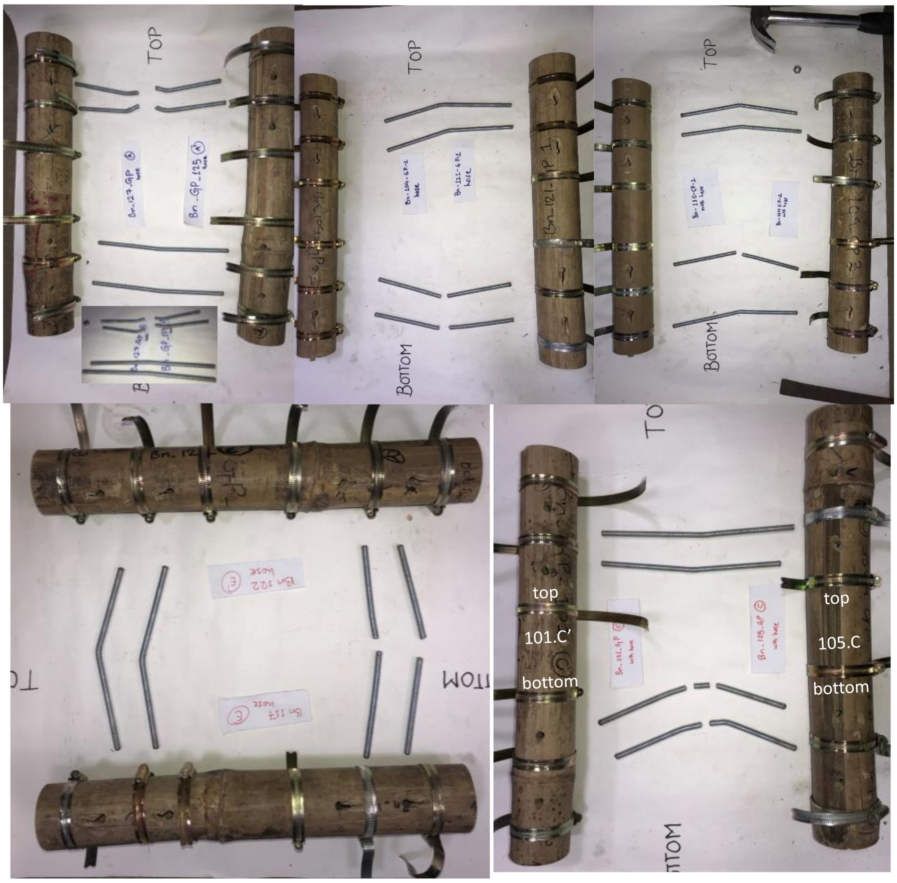


Figure 4.26 ***B. nutans*** **GP with hose clamp**

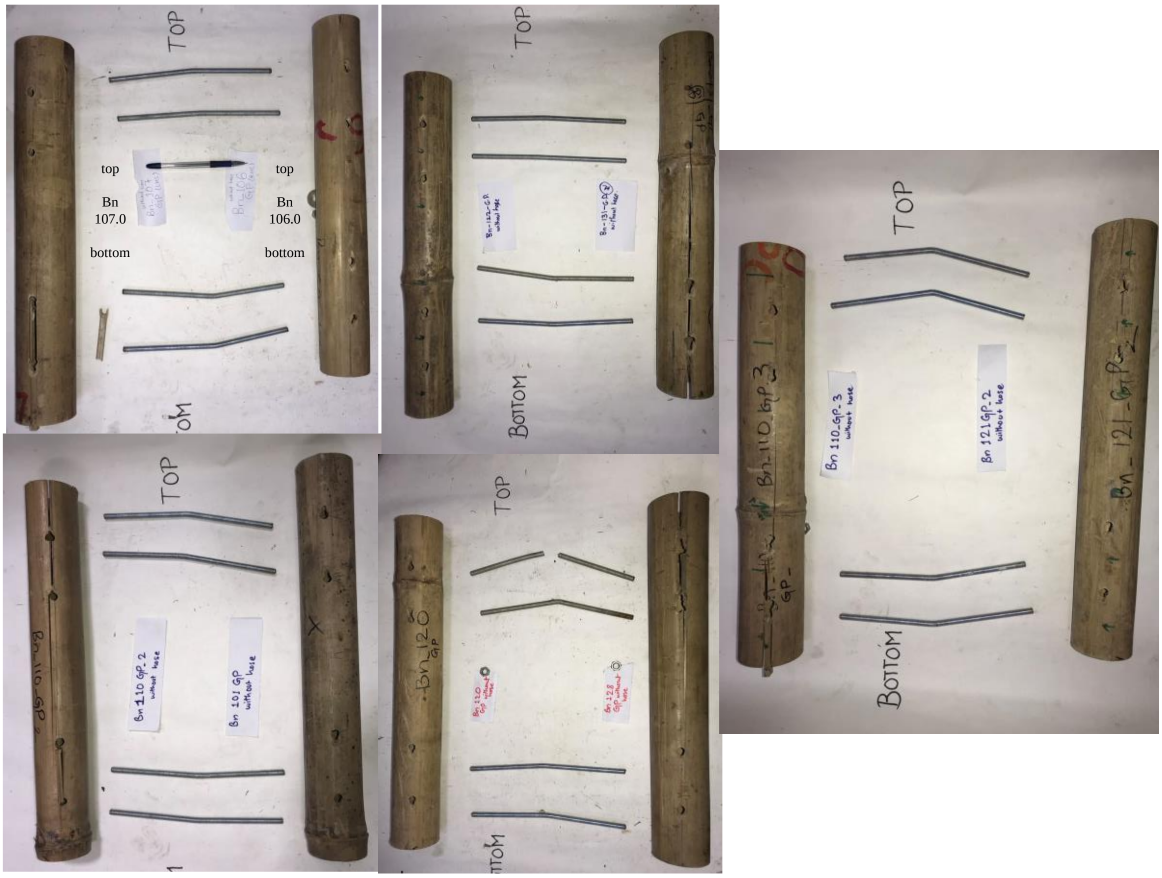


Figure 4.27 ***B. nutans*** **GP without hose clamp**

Figure 4.28 *B. balcooa* Shaft-bolt connection with hose clamp

Figure 4.29 *B. balcooa* shaft-bolt connection without hoseclamp

Figure 4.30 ***B. nutans*** **Shaft-bolt connection with hose clamp**

Figure 4.31 ***B. nutans*** **Shaft-bolt connection without hose clamp**

Figure 4.32 *B. balcooa* Shaft-bolt connections (Noded near bores)

5

CONCLUSION AND RECOMMEDATION

5.1 Conclusion

Different irregularities of *B. balcooa* and *B. nutans* culms can rationalize the grading procedure of bamboo culms. For Nepalese *Bambusa balcooa* geometrical properties/ irregularities of the culms and material properties are found to be as below from this work:

Table 5.1 characteristic values of *Bambusa balcooa* from the sampled population of treated bamboo from Nepalese market

property	n	$\bar{x}$	s	KS p-value	$k_{0.05,0.75}$	$x_{0.05,0.75}$	$x_{0.95,0.75}$	$\bar{x}_{0.75}$
diameter, mm	92	73.63	6.885	0.96	1.0796	62.249	86.343	73.146
thickness, mm	92	13.81	3.564	0.41	1.0796	8.622	20.749	13.557
density (ρ_{12})	92	750.16	119.330	0.77	1.0796	556.46	985.141	741.702
bow, b_0	30	0.0149	0.00527	0.96	1.18	0.007	0.026	0.009
external taper	30	0.00299	0.00124	0.48	1.18	0.001	0.005	0.003
ovality	91	0.0189	0.01475	0.93	1.0808	0.002	0.05	0.018
Compressive strength	31	59.158	12.852	0.70	1.1775	37.904	87.708	57.589
Embedment strength	31	45.015	14.833	0.95	1.1775	20.67	75.18	43.204
Shear strength	30	10.00	2.636	0.95	1.18	6.341	16.502	9.677
Young's modulus of Elasticity (compression)	31	2802.30	1357.83	0.633	1.1775	883.885	6701.380	2636.468

For Nepalese *Bambusa nutans* geometrical properties/ irregularities of the culms and material properties are found to be as below from this work:

Table 5.2 characteristic values of *Bambusa nutans* from the sampled population of treated bamboo from Nepalese market

property	n	$\bar{x}$	s	KS p-value	$k_{0.05,0.75}$	$x_{0.05,0.75}$	$x_{0.95,0.75}$	$\bar{x}_{0.75}$
diameter, mm	93	66.52	5.672	0.61	1.0784	56.997	77.059	66.119

thickness, mm	93	11.06	3.774	0.13	1.0784	5.853	18.684	10.792
density (ρ_{12})	93	771.07	152.26	0.14	1.0784	527.049	1082.813	760.33
bow, b_0	33	0.00982	0.00489	0.99	1.1725	0.003	0.021	0.009
external taper	32	0.00172	0.00045	0.50	1.1749	0.001	0.003	0.002
ovality	92	0.05	0.0182	0.74	1.0796	0.015	0.079	0.044
Compressive strength	30	46.298	11.02	0.60	1.18	28.578	70.616	44.929
Embedment strength	31	44.576	12.239	0.83	1.1775	24.3	69.2	43.082
Shear strength	32	8.133	2.316	0.79	1.1749	4.146	12.603	7.855
Young's modulus of Elasticity (compression)	30	2207.855	1423.21	0.325	1.18	521.03	6025.909	2031.163

*Note: KS p-value > 0.05 indicates the data follows lognormal distribution

This is quite good strength and even prove to be better as per existing price for a single bamboo culm and its strength. And also due to its higher strength to weight ratio it is promising in seismic performance of a bamboo structures.

5.2 Conclusion on Connections

Material properties extracted from the dowel embedment test of *B. balcooa* specimen was considered while designing G.P. connections. The dowel embedment test is comprised of confinement of bamboo (below bore holes) by hose-clamps, by which splitting or row-shear failure was prevented in those samples. The characteristic dowel embedment strength used while G.P. connection design was specifically effective for population of *B. balcooa* species, which is empirically verified too. Experiments is concurrent to the motto of this connection design for avoiding the sudden failure of bamboo for balcooa species. However, nutans' G.P.-connections is not having the desired failure mode.

The reason behind sudden/ brittle failure in some of nutans' GP connection is because, although characteristic (x0.05,0.75) dowel embedment strength of nutans (24.3 MPa) is more than that of balcooa (20.67 MPa), thickness of nutans (5.853mm) is way less compared to that of balcooa 8.622mm similar for the case of shear strengths (6.341 MPa for balcooa and 4.146 MPa for nutans), which greatly influence the failure pattern as observed in the experiments.

GP-connections

B. balcooa with and without hose clamps:

As designed, hose-clamp confined connections failed majorly in mode III and rest in mode IV of EYM. Non confined (without hose clamp) connection experienced majorly mode III while bamboo are also damaged indicating mode-I failure.

B. nutans with and without hose clamps:

For confined bamboo members no brittle damage of bamboo have been seen except in GPWHO_110.1+104.2 which has row shear but only after having huge bearing deformation, which signifies avoidance of brittle failure of bamboo to large extent. Meanwhile unconfined nutans GP connections has experienced huge damages on bamboo, majorly by cracking/ splitting or even row shear.

Shaft-bolt connections

These connection samples were not designed for the experiment but tested which was being used in present days site of bamboo constructions. The performance was satisfactory as it was never designed and intuitional. But technically it is not wise to use these connection in same configuration, as it has been seen that there is very little non-linearity in the force-deformation curve before failure, signifying brittle-failure of the connection in both confined as well as unconfined samples.

Noded Shaft-bolt arrangements

Failure mode in these noded connections are sudden, and no remarkable difference has been seen in the failure pattern. But there is some increase in load bearing capacities in these connection type then bare (without hoseclamp) Shaft-bolt connection.

5.3 Recommendation

Compressive, Shear and Dowel Embedment strength were found to be good for using full culm bamboo as structural element. This research is first of its kind (according to the typology and scale of the work) in Nepal, and this has dealt with only two species of Nepalese bamboo. Among 12 genera and more than 53 species of bamboo distributed in Nepal (Das, 2002, Ghimire, 2008), many of the species have varying characteristics in the domain: engineering properties, edibility, growth rate, dimensions, etc. We can select new species on the basis of their material and engineering properties and start characterizing their strength so that we may find bamboo with better properties among Nepalese bamboo to be used in construction. Research in standardization of culm irregularities via ISO standards, grading may result in efficient sorting mechanism, eventually making a viable solution to increase efficiency of utilization of every part of any culms as per intended requirements. Bamboo structures like other structures are critical in the joints.

This work has investigated the behavior of two types of joints for bamboo member connection. Many other existing joints have not been rationally analyzed, while the author strongly recommend to find out newer connection mechanism in the bamboo (keeping in mind that bamboo is never a regular shaped, and is not necessarily has standardized dimension).

Works can be done in finding out newer treatment procedure or mechanisms to sustain durability of bamboo while using in structures. Increase in design loads in bamboo structures may require extensive use of multi-culm elements in near future, thus research on using grading results in assembly of individual culm, connections between them and tackling individual buckling ideas maybe a promising sector.

Recommendation on Connections:

GP connection for balcooa have performed as designed, so it is recommended that on designing the connection, detailing of 8mm threaded rod as dowel in GP connection will be good to work with. Hose clamping near the bores of connection (not more than 30mm distance) are recommended so as to make failure more ductile or even protect the bamboo in overall. *B. nutans*' connection as compared to balcooa's is more susceptible to unwanted failure, which can be avoided by designing the connection using the characteristic material properties of the same species, rather than using detailing from the design from other species (which is the very reason that it failed in this manner, here).

Shaft-bolt connections as used in field, now known to have not suitable to be used in the exact form as it fails in brittle way. Thus Shaft-bolt connections should be redesigned to have ductile failure with the help of characteristic strengths of particular species of bamboo to be used in field.

For good performance of the joint the failure pattern is of much more importance than load carrying capacity, thus 3-Noded Shaft-bolt connection did not perform comparatively well than samples in which nodes are not considered. As it is not convenient to find the perfect bamboo member with nodes at the ends with required dimension, thus it is not recommended to watch out for member with required dimensions and ending at nodes, which is inconvenient to find, results in waste, with very little advantage.

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Annex I

Determination of Geometrical and Mechanical Characteristic Values

Bow

B nutans

Statistics: BOW
Number of Data Points: 33
Mean: 0.009828625897496591
Standard Deviation: 0.004899130633836432
Coefficient of Variation: 0.4984552962875786%
5th Percentile: 0.0032036336626515742
95th Percentile: 0.018803245189407486
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.29611243393044656, loc=-0.006257306211600123, scale=0.015397933952986264)
Mean of Logarithm: -4.759907818354609
Standard Deviation of Logarithm: 0.576229038109628
KS test statistic: 0.06883500435129375
KS test p-value: 0.99455808578755594

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.1724999999999999
The fifth percentile characteristic value with 75% confidence: 0.003
The ninety fifth percentile characteristic value with 75% confidence: 0.021
The characteristic mean value with 75% confidence: 0.009

B. balcooa

Statistics: BOW
Number of Data Points: 30
Mean: 0.014878331714950041
Standard Deviation: 0.005275740090785242
Coefficient of Variation: 0.35459218088839517%
5th Percentile: 0.007117494881569573
95th Percentile: 0.02408359011161572
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.16521248074343756, loc=-0.016380451087429485, scale=0.030835399361488998)
Mean of Logarithm: -4.274443180992757
Standard Deviation of Logarithm: 0.388051284412123
KS test statistic: 0.08756413999653911
KS test p-value: 0.9600458340044254

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.1724999999999999

The fifth percentile characteristic value with 75% confidence: 0.007
The ninety fifth percentile characteristic value with 75% confidence: 0.026
The characteristic mean value with 75% confidence: 0.009

Compressive Strength

B. balcooa

Statistics: compressive strength
Number of Data Points: 31
Mean: 2802.302660461417
Standard Deviation: 1357.8344564570639
Coefficient of Variation: 0.48454239993958675%
5th Percentile: 984.8006099919894
95th Percentile: 6078.494833538174
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.5532629651475526, loc=0, scale=2446.6518795900556)
Mean of Logarithm: 7.8024757891579055
Standard Deviation of Logarithm: 0.5624084271156126
KS test statistic: 0.1290410973151403
KS test p-value: 0.6338006359635144

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.1775
The fifth percentile characteristic value with 75% confidence: 883.885
The ninety fifth percentile characteristic value with 75% confidence: 6701.38
The characteristic mean value with 75% confidence: 2636.468

B. nutans

Statistics: compressive strength
Number of Data Points: 30
Mean: 2207.8559214228712
Standard Deviation: 1423.2139811339189
Coefficient of Variation: 0.6446136123849588%
5th Percentile: 605.0566207008575
95th Percentile: 5291.110986667212
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.65916548502164, loc=0, scale=1789.251724421705)
Mean of Logarithm: 7.489552780386137
Standard Deviation of Logarithm: 0.6704340873595259
KS test statistic: 0.16843448415674067
KS test p-value: 0.325031209175372

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.18
The fifth percentile characteristic value with 75% confidence: 521.03
The ninety fifth percentile characteristic value with 75% confidence: 6025.909
The characteristic mean value with 75% confidence: 2031.163

Shear Strength

________________B Nutans_____________________
Statistics: shear strength
Number of Data Points: 32
Mean: 8.133757598498265
Standard Deviation: 2.316385750692576
Coefficient of Variation: 0.2847866711838388%
5th Percentile: 4.383658762846608
95th Percentile: 11.883890252211131
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 8.696991490556101e-06, loc=-262140.96572341648, scale=262149.0994711008)
Mean of Logarithm: 2.0480540899185997
Standard Deviation of Logarithm: 0.3341440766095686
KS test statistic: 0.11073621620375929
KS test p-value: 0.7872779764486896

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.1749999999999998
The fifth percentile characteristic value with 75% confidence: 4.124
The ninety *fifth percentile*characteristic value with 75% confidence: 12.587
The characteristic mean value with 75% confidence: 7.855

B. balcooa

Statistics: shear strength
Number of Data Points: 30
Mean: 10.00451857539179
Standard Deviation: 2.6380678912616773
Coefficient of Variation: 0.2636876398781005%
5th Percentile: 6.722485309743386
95th Percentile: 15.614710459056429
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.5224508403259126, loc=4.779819278957249, scale=4.5878726053415)
Mean of Logarithm: 2.2705894728322717
Standard Deviation of Logarithm: 0.2573887011870408
KS test statistic: 0.08950402950715175
KS test p-value: 0.9523004811047795

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.1749999999999998
The fifth percentilecharacteristic value with 75% confidence: 6.342
The ninety fifth percentilecharacteristic value with 75% confidence: 16.498
The characteristic mean value with 75% confidence: 9.677

Dowel Embedment

________________B Nutans_____________________

Statistics: embedment strength
Number of Data Points: 31
Mean: 44.57677419354838
Standard Deviation: 12.239487567458799
Coefficient of Variation: 0.27457095738502824%
5th Percentile: 25.441908671689077
95th Percentile: 65.0788860862958
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.06657099064364731, loc=-136.45392919366748, scale=180.6303517881582)
Mean of Logarithm: 3.7582815277301367
Standard Deviation of Logarithm: 0.28952319822238437
KS test statistic: 0.11765895851184976
KS test p-value: 0.7404664581168279

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
Statistics: embedment strength
Number of Data Points: 31
Mean: 44.57677419354838
Standard Deviation: 12.239487567458799
Coefficient of Variation: 0.27457095738502824%
5th Percentile: 25.441908671689077
95th Percentile: 65.0788860862958
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.06657099064364731, loc=-136.45392919366748, scale=180.6303517881582)
Mean of Logarithm: 3.7582815277301367
Standard Deviation of Logarithm: 0.28952319822238437
KS test statistic: 0.11765895851184976
KS test p-value: 0.7404664581168279
Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.1775
The fifth percentilecharacteristic value with 75% confidence: 23.96
The ninety-fifth percentilecharacteristic value with 75% confidence: 68.86
The characteristic mean value with 75% confidence: 43.082

B. balcooa

Statistics: embedment strength
Number of Data Points: 31
Mean: 45.0152974029813

Standard Deviation: 14.833315199655974
Coefficient of Variation: 0.32951720982462257%
5th Percentile: 22.220299808073463
95th Percentile: 70.27832737305566
Log-Normal Fit:
Equation: CDF(x) = lognorm.cdf(x, 0.09918927098508142, loc=-102.33523903989483, scale=146.62870038650215)
Mean of Logarithm: 3.749388565387365
Standard Deviation of Logarithm: 0.355612379054263
KS test statistic: 0.08861968432674772
KS test p-value: 0.9501077093556847

Kolmogorov-Smirnov test: Data follows Log-Normal distribution (Failed to reject the null hypothesis)
kvalue: 1.1775
The fifth percentilecharacteristic value with 75% confidence: 20.67
The ninety-fifth percentile characteristic value with 75% confidence: 75.18
The characteristic mean value with 75% confidence: 43.204

Annex II

Sample Calculation of Joint Capacity for mode IIIs and IV, using yield equation from 'ASTM D 5764 – 97a (2002)'.

Characteristic values for *Bambusa balcooa* is condisdered and mid plate M.S. of 10mm, other details are as follows:

BAMBOO PROPERTIES

parameters	ch. 5th percentile	values in fps	units	notations
diameter (mm-inch)	62.249	2.450749355	inch	
thickness (mm-inch)	8.622	0.339449002	inch	
internal diameter (mm-inch)	45.005	1.771851351	inch	
shear strength (MPa-psi)	6.341	919.685958	psi	
dowel bearing strength (MPa-psi)	20.67	2997.93546	psi	qs*db

BAR PLATE PROPERTIES

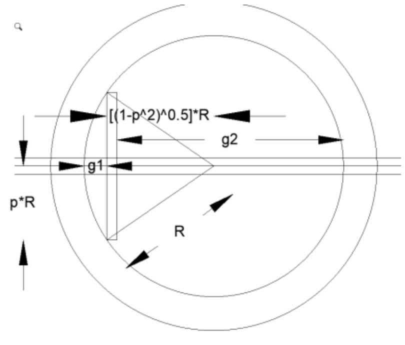
grade					
yield strength	240	MPa	34809.12	psi	qm*db
ultimate strength	400	MPa	58015.2	psi	
thickness	10	mm	0.393701	inch	Lm
width	18	mm	0.7086618	inch	
height	80	mm	3.149608	inch	
bore hole center to plate edge distance	30	mm	1.181103	inch	
bore diameter	12	mm	0.4724412	inch	

DOWEL/ BOLT PROPERTIES

grade					
yield strength	240	MPa	34809.12	psi	
ultimate strength	400	MPa	58015.2	psi	
diameter	10	mm	0.393701	inch	
root diameter	8.376	mm	0.329763958	inch	Dr
bolt diameter taken (1.1*root dia)	9.2136				db

POSSIBLE GEOMETRIC ARRANGEMENT OF CONNECTION IN PLAN VIEW

percent of ch. Diameter (p% of Internal dia of bamboo)	30
width of bar = p% of internal diameter of bamboo	13.502
distance betn leftest face of bar and center of bamboo	21.466
gap to left = g1	1.037
gap to right = g2	33.968



MODE IIIs

parameter	mks	fps
qs	2.243422766	325.3815512
qm	26.04845012	3778.015108
Ls	8.622	0.339449002
g1	1.037	0.040826794
Mm	__NA__	208.0421597
Lm	10	0.393701
Ms	__NA__	208.0421597

Side Member: $q_s = F_{es}D_r$ $M_s = \frac{F_{yb}D_r^3}{6}$

Main Member: $q_m = F_{em}D_r$ $M_m = \frac{F_{yb}D_r^3}{6}$

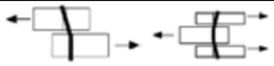
parameter	mks	fps
qs	2.243423	325.3816
qm	240	34809.12
Ls	8.622	0.339449
g2	33.968	1.337324
Mm	__NA__	208.0422
Lm	10	0.393701
Ms	__NA__	208.0422

Mode- IIIs

1 shear IIIs -- LEFT

1 shear IIIs -- RIGHT

III_s $A = \frac{1}{4q_s} + \frac{1}{2q_m}$ $B = \frac{L_s}{2} + g$ $C = -\frac{q_s L_s^2}{4} - M_m$



	coefficients
A	0.000900673
B	0.210551295
C	-217.4152328

	coefficients
A	0.000783
B	1.507048
C	-217.415

II-IV $P = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$ $P = \frac{-B + \sqrt{B^2 - 4AC}}{A}$

P 388.1433129lbs
1726.546847Newton
1.727kN

P 134.8249lbs
599.7309Newton
0.6kN

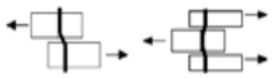
total P = 2.327kN

MODE IV

1 shear IV -- LEFT

1 shear IV -- RIGHT

IV $A = \frac{1}{2q_s} + \frac{1}{2q_m}$ $B = g$ $C = -M_s - M_m$



	coefficients
A	0.001669002
B	0.040826794
C	-416.0843193

	coefficients
A	0.001551022
B	1.337323557
C	-416.0843193

II-IV $P = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$ $P = \frac{-B + \sqrt{B^2 - 4AC}}{A}$

P 487.2196459 lbs
2167.260173 Newton
2.167 kN

P 242.7744485 lbs
1079.914157 Newton
1.08 kN

total P = 3.247 kN

Annex III

Calculation of Row Shear Capacity as per ‘BS EN 1995-1-1:2004+Al:2008’.

Row shear/ Block Shear Strength

Fbs,Rk	ch. Block shear/ plug shear capacity		
Anet,t	net X-section area, perpendicular to grain		
Anet,v	net shear area, parallel to grain		
Lnet,v	summation of lv,i	80	
Lnet,t	summation of lt,i	0	
lv,i	as shown in figure below	80	
lt,i	as shown in figure below	0	
tef	effective depth depended to failure mode of fastener	7.043126	
t1	timber thickness / penetration depth of fastener	8.622	for balcooa
My,Rk	ch. Yield moment of fastener, for 4.6 grade	18419.55	
d	fastener diameter =root dia *1.1	9.2136	
ft,0,k	ch. Tensile strength_timber		
fv,k	ch. Shear strength_timber	6.341	for balcooa
fh,k	ch. Embedment strength_timber	20.67	
	Min spacing from loaded end(max of 7d or 80 mm)	80	
	Lnet,t * t1	0	
	mode(c,f,j/l, k,m) = Lnet,t * t1	689.76	mm2
Anet,v	other modes = (Lnet,v / 2)* (lnet,t+2*tef)	563.4501	mm2
Lnet,v	SUM of lv,i	80	
Lnet,t	SUM of lt,i	0	

Thin Steel Plates

	for a mode = 0.4*t1	3.4488	
tef	for mode b = 1.4*(squareroot(My,Rk/(fh,k*d)))	13.76837	

Thick Steel Plates

	for e/h mode = 2*(squareroot(My,Rk/(fh,k*d)))	19.6691	tef=
tef	for mode d/g = t1*(squareroot(2+(My,Rk/(fh,k*(t1)^2)))-1)	7.043126	7.043126131

	1.5* Anet,t * ft,0,k	-	
	0.7 * Anet,v * fv,k	2500.986	N
Fbs,Rk	maximum of above two	2500.986	N

EXPERIMENTAL TESTING AND CHARACTERIZATION OF BAMBUSA BALCOOA AND BAMBUSA NUTANS FOR ANALYSIS AND DESIGN OF BAMBOO STRUCTURES

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