

**NUMERICAL INVESTIGATION OF STEEL REINFORCED BAMBOO
SCRIMBER BEAMS**

By

Mweetwa Mulongo

A dissertation submitted to the University of Zambia in partial fulfilment of the requirements of the degree of Master of Engineering in Structural Engineering.

THE UNIVERSITY OF ZAMBIA

LUSAKA

2023

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Signature: _____ Date: _____

Supervisor's name: **Dr. CG Chizyuka**

Signature: Date: _____

Co-Supervisor's name: **Dr. Charles Kahanji**

Signature: Date: _____

CERTIFICATE OF APPROVAL

This dissertation of Mweetwa Mulongo is approved as fulfilling the requirements for the award of the Masters of Engineering in Structural Engineering at the University of Zambia.

Examiner 1: _____

Signature: _____

Examiner 2: _____

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ABSTRACT

In recent years, the world is gradually shifting away from the use of structural concrete in the construction sector. This is due to its retrogressive limitations such as costs, environmental degradation, low strength-to-weight ratio, its susceptibility to cracking. The world is moving towards "Green" technology, which incorporates a sustainability component due to the materials being natural and renewable. The main concentration is now on natural materials like bamboo scrimber which is a composite material and by-product of the bamboo grass. Before it is certified safe for structural use, there is a need to determine its strength characteristics i.e., by experimental and numerical methods.

Costly numerous laboratory experiments on the flexural capacity of Steel Reinforced Bamboo Scrimber (SRBS) Beams have been conducted, but very little has been done on cost-effective numerical models. As such due to this deficiency, this study focuses on the use of rapid numerical methods for analysing the flexural capacity of SRBS beams.

In this study a simplified mechanical model of a four-point bending test involving a Steel Reinforced Bamboo Scrimber Beam with epoxy resin as an adhesive material between the steel and Bamboo Scrimber is presented based on previous experiments. The results show that the reinforced beams fail due to rupturing of the bottom tensile Bamboo fibres; no significant yielding failure occurs in the top compression zone. The flexural capacity of the reinforced beams increases linearly with an increasing reinforcement ratio and can be enhanced compared with that of control beams.

The reinforced bamboo beams were modelled and analysed using a three-dimensional finite element model based on ABAQUS software to simulate the bending test. The flexural rigidity, load-deflection curves, and load-strain curves were compared between the analytical and experimental results. After model verification, additionally, the mechanical properties of the epoxy resin, diameter of the steel bars, mechanical properties of the steel bars etc. were parameterized, and the influence rules for each parameter were determined.

The flexural rigidity of reinforced bamboo beams is calculated using the cross-sectional strain and stress distributions, and the suggested models are found to offer appropriate predictions for the reinforced bamboo beams. Steel-reinforced bamboo scrimber beams can thus be used for long-span, heavy-load bamboo structural engineering. This exploratory investigation will aid in the design, fabrication, and use of bamboo-based structural composite materials in practical engineering.

This dissertation honours my late father, Wilfred Mulongo.

ACKNOWLEDGEMENTS

This dissertation would not have been feasible without the assistance of the following individuals:

- To begin, I want to express my gratitude to the Almighty God, Jehovah for providing me with the breath of life and light necessary to grasp structural engineering concepts. **36:9 Psalms.**
- Additionally, I would like to express my gratitude to my parents and siblings for being such a blessing to me. Their unwavering support throughout my academic career cannot be overstated.
- I owe a debt of gratitude to my supervisor, Dr. CG Chizyuka, who served as not just a mentor and coach, but also as a parent through times when I lost hope and direction. I continue to be impressed by this scholar, particularly his excellent work in Mechanics of Materials Engineering and Environmental Effects on Fracture Damage of Natural Fibre Reinforced Polymer Composites. I would be too proud to overlook his efforts in facilitating my academic career realization.
- Thank you very much to Dr. Charles Kahanji, who served as my co-supervisor and who taught me the fundamentals of finite element analysis from the beginning, which enabled me to complete this task.

March, 2023

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ACRONYMS AND ABBREVIATIONS

ACRONYMS

3D
CFRP
CI
DOE
FEA
FEM
FE
FRP
GFRP
JMP PRO

LVDT
LD
MC
mm
RMSE
SRBS

UMAT
ZrO₂

ABBREVIATIONS

Three Dimensional
Carbon fibre reinforced polymer
Confidence Interval
Design of Experiments
Finite Element Analysis
Finite Element Method
Finite Element
Fibre Reinforced Polymer
Glass Fibre Reinforced Polymer
John's Macintosh Project Professional
Statistical Software

Linear Variable Differential Transducer
Laser displacement meter
Moisture Content
Millimetres
Root Mean Square Error
Steel Reinforced Bamboo Scrimber
Beams

User Material
Zirconia

CHAPTER 1 : INTRODUCTION

1.1 Background

Bamboos are evergreen perennial flowering plants belonging to the Bambusoideae subfamily of the Poaceae grass family. The origin of the term "bamboo" is obscure, although it most likely derives from the Dutch or Portuguese language, which comes from the Malay word “Mambu” (Chung and Yu, 2002).

In bamboo, like in other grasses, the inter-nodal parts of the stem are often hollow, and the vascular bundles in the cross-section are dispersed throughout the stem as opposed to being arranged in a cylindrical pattern (Goh *et al.*, 2020).

Bamboo is a rapidly renewable material with numerous construction applications. Engineered bamboo products are made by converting raw bamboo culm into a laminated composite, much like glue laminated timber. These materials may be cut into standardized portions and have less inherent variability than natural materials.

As a building material, bamboo has numerous benefits: it is a fast renewable, sustainable resource with similar mechanical qualities to wood. Global interest in the development of bamboo products as a sustainable, cost-effective, and environmentally responsible alternative building material is increasing (Nurazka *et al.*, 2021).

Bamboo forests have up to four times the carbon density per hectare of spruce forests over the long term, due in part to the higher growth rate and harvest cycle. Bamboo is found in regions of the world where timber resources are frequently few and where development is rapid (Yiping *et al.*, 2010).

Although bamboo's potential is intriguing, its broad growth and use are impeded by a lack of engineering data on its mechanical qualities and acceptable building codes (Harries, Sharma and Richard, 2012). The mechanical characteristics of bamboo vary in the longitudinal, radial, and transverse axes, making it an anisotropic material. The raw material is a large grass consisting of a hollow culm with longitudinal fibres oriented within a lignin matrix, separated along the culm length by nodes (solid diaphragms). From the base to the top of the culm, the thickness of the culm wall decreases. As a functionally

graded material, bamboo fibres vary in density from the outer to the interior of the culm wall (Sharma *et al.*, 2015).

Due to the standardization of shape and the relative consistency of material qualities, bamboo composites are of great interest. Bamboo scrimber and laminated bamboo are two examples of engineered bamboo. Bamboo Scrimber, also known as Strand-weaved or parallel-strand bamboo, consists of resin-saturated, crushed fibre bundles squeezed into a solid block (Van der Lugt, 2008).

The focus of this research is on steel-reinforced bamboo Scrimber (SRBS) beams. Bamboo Scrimber, in particular, is a novel type of bamboo composite material produced by decomposing, dipping, recombining, and pressing bamboo; this process reorganizes bamboo fibres and decreases the degradation of the original material.

Therefore, Bamboo Scrimber offers a new renewable building material. Bamboo Scrimber, one of the most prevalent bamboo composite materials, is frequently used for flooring, furniture, and carriages. Bamboo Scrimber resembles wood in appearance and possesses superior and stable mechanical qualities (Wei, Yan, *et al.*, 2020a).

It is ideally suited for the crucial load-bearing components of beams and columns. As a flexural member, bamboo Scrimber has some drawbacks, including low cross-sectional stiffness, significant deflection under flexural pressure, and limited spanning capacity (Lv and Liu, 2019). In addition, according to the results of beam bending tests, bamboo Scrimber beams fail predominantly owing to the rupture of bamboo fibres in the bottom tensile zone. To improve the stress condition in this zone and increase the spanning capacity, technologies comparable to those used for wood have been proposed for strengthening bamboo flexural members, such as the use of natural fibre, fibre-reinforced polymers (FRPs), and steel (Zhang *et al.*, 2018).

Numerous experiments have been conducted, but numerical models have received comparatively less attention. It has been determined that numerical simulations are indispensable for the comprehension of engineering phenomena, particularly: (i) where the economy of analysis is a concern; and (ii) when it is difficult to control specific experimental variables. In the field of Structural Engineering, however, relatively few

researches have utilized the numerical simulation approach for the comprehension of SRBC Beams and their parametric changes. This work provides a numerical simulation method based on finite element analysis.

1.2 Statement of the problem

In the construction industry, the global trend in recent years has been to move away from structural concrete. This is due to its regressive limitations, which include high costs, environmental degradation, a low strength-to-weight ratio, susceptibility to cracking and many more. The world is moving toward "Green" technology, which incorporates a sustainability component because the materials are natural and renewable.

In this study, the focus is on the use of Bamboo Scrimber. One of the main advantages of building with bamboo is that it is a wonderful, natural and renewable resource, capable of rapid growth that can avoid future deforestation of precious tropical rain forests. With bamboo scrimber being very strong in compression and weak in tension, it does not make a good structural material when used on its own, as such steel reinforcement is added to improve its strength. The most common type of steel used as reinforcement in the construction industry is deformed steel. The reinforcement within the bamboo scrimber creates a composite material, with the bamboo scrimber providing strength against compressive stress, while the reinforcement provides strength against tensile stresses. Steel-reinforced bamboo scrimber beams were used in this study.

Numerous expensive laboratory experiments on the flexural capacity of Steel Reinforced Bamboo Scrimber Beams have been conducted, but very little work on cost-effective numerical models has been done. Due to this deficiency, the focus of this study is on the application of rapid numerical methods for analysing the flexural capacity of SRBS beams.

As previously noted, relatively few numerical studies on the flexural performance of SRBS beams and their parametric variants have been performed in the area of Structural Engineering. The study will address another gap in this area of Engineering with this dissertation by studying the numerical solution of beams, which entails developing a three-dimensional finite element model. Numerical techniques are utilized to solve differential equations since they are time-consuming and complicated to solve.

On the other hand, experimental solutions are very expensive to conduct as they need a lot of equipment to be procured and assembled. In this dissertation, the flexural capacity of SRBS beams will be investigated by numerical simulation by the use of a finite element analysis computer package called ABAQUS as opposed to experimental methods. The numerical model will be standard and only parameters will be input.

1.3 Objectives of the dissertation

1.3.1 Main objective

The main objective of this study is to develop a finite element model for the numerical investigation of Steel Reinforced Bamboo Scrimber beams under flexure.

1.3.2 Specific objectives

- To identify material properties of SRBS beams to be used as input parameters into a beam modelled in ABAQUS.
- To verify and validate the numerical model against experimental data.
- To use the validated finite element model to investigate the flexural capacity of SRBS Beams.

1.4 Significance of study

The finite element models created in this work are very useful for the application of performance-based design to bamboo Scrimber beams reinforced with steel. The numerical models laid the groundwork for future research that will concentrate on refining them to account for phenomena not simulated by the models presented here. Additionally, it is intended that the suggested finite element models would be used in parametric research to generate simple prescriptive design guidelines for use in ordinary practice. This work will aid in the comprehension and subsequent design of constructions using SRBC beams. Mechanical engineers, civil-structural engineers, construction project managers, and building owners are the intended audience for this research.

1.5 Conceptual framework

The general principles of this research, their interrelationships, and their role as the foundation of this study are examined. The link between the many principles underlying

this study is depicted in Figure 1.1. This study focuses on the structural performance of bamboo Scrimber beams strengthened with steel. In structural engineering, the performance of structural components (in this example, beams) is often characterized by their flexural rigidity.

This study is anchored on the following four concepts: literature review, development of the finite element model, model validation and the parametric study.

The performance-based flexural rigidity test evaluation of beams may be conducted using either experimental or numerical methods. The experimental technique is time-consuming, costly, and often too difficult to undertake, particularly in situations where it is impossible to parameterize crucial parameters of specific important beam areas. Due to the adaptability of contemporary finite element software packages, the tremendous capabilities of the finite element approach may be used to solve complicated engineering issues, and the flexural rigidity or bearing capacity of a beam can be estimated numerically.

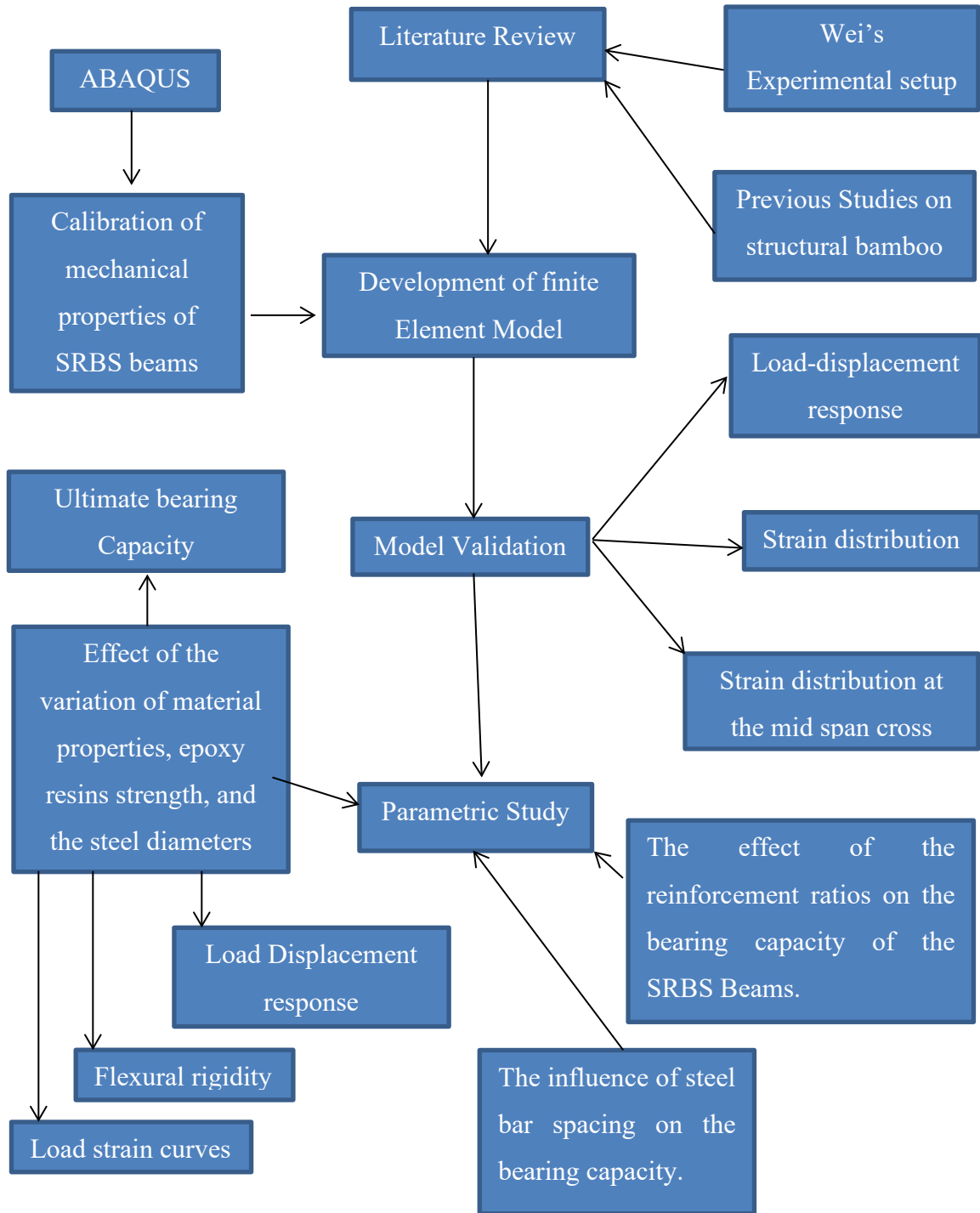


Figure 1.1: Conceptual framework

1.6 Dissertation outline

The dissertation consists of eight chapters including the current introduction chapter.

Chapter 2: Literature review- This chapter starts by outlining the definitions, important features, components, material and mechanical properties, and applications of SRBS Beams. The chapter then digs into the content of the literature review, concluding with a summary of the studied literature and noting the existing research gap that motivated the study described in this dissertation.

Chapter 3: Methodology- This chapter begins by emphasizing that this dissertation takes a numerical and computational approach, indicating a positivist epistemological viewpoint. The chapter next goes through the experimental results gained on SRBS beams as published by Wei, Yan, et al., 2020, with an emphasis on the experimental setup. Following that, the process used to create the finite element models is discussed in detail.

Chapter 4 and Chapter 5: Results and Discussion- Chapter 4 opens by presenting and discussing results collected during the four-point bending test simulation program. The chapters next go into presenting and analysing data obtained during the structural analysis phase of the simulation program. lastly, an overview of the chapter is offered.

Chapter 6: Parametric Analysis-This chapter introduces parametric research and describes how the DOE technique was used to identify the least number of experimental runs. Following that, several combinations of materials were studied in ABAQUS to assess the effect of different factors on the model and then the findings were compared.

Chapter 7: Conclusions and Recommendations- The main conclusions drawn from this study are presented. Then the main research contribution achieved by this dissertation is highlighted. The challenges that were faced during the study are presented and then the chapter ends by giving recommendations, in terms of what can be improved and future research directions.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction to bamboo Scrimber material

With the development of the world's economy and the strengthening of national awareness of environmental protection, natural and ecological building materials such as bamboo and wood are becoming more and more popular.

Bamboo is becoming increasingly popular as a green building material due to rising demand. Because of its environmental friendliness, sustainability, and ease of recovery and utilization, it is becoming an intriguing and promising construction material (Lakkad and Patel, 1981).

Bamboo not only grows quickly, reaching maturity in 3–5 years, but it also has a high strength-to-weight ratio when compared to other commonly used building materials such as wood, wood-based composites, concrete, and steel (Nadanwar, 2013).

Natural bamboo's usage as a construction material, on the other hand, is restricted due to the tiny diameter of bamboo culms and the significant diversity of its mechanical qualities. Bamboo-based composites have been produced and researched as a way to circumvent these limits (Xiao *et al.*, 2013).

Due to its high manufacturing efficiency, utilization, and mechanical properties, the bamboo Scrimber, which is manufactured without the use of chemicals and by moving the inner and outer layers of the bamboo, has a great deal of potential for use as a construction material (Yu *et al.*, 2014).

Bamboo has a number of benefits, including rapid growth, being green and renewable, fostering a low-carbon economy, having a low water expansion rate, and having great strength in the fibre direction. Bamboo composite materials, such as bamboo laminated timber (Lin *et al.*, 2020), bamboo Scrimber (Wei *et al.*, 2020), and bamboo bundle veneers (Zhou *et al.*, 2019), have been investigated using modern composite and recombination technology to manufacture structural components in order to improve the utilization rate and mechanical properties of bamboo.

Bamboo composite materials are eco-friendly, thermally insulating, energy-efficient, and earthquake-resistant, and their performance is comparable to that of wood used in structural engineering. Bamboo Scrimber is a novel form of bamboo composite material created by decomposing, dipping, recombining, and pressing bamboo fibres; this process reorganizes bamboo strands while minimizing erosion of the original material. Consequently, bamboo Scrimber is a new type of renewable building material.

Bamboo Scrimber is a common bamboo composite used for flooring, furniture, and carriages. Bamboo Scrimber has a beautiful, wood-like appearance and great, stable mechanical qualities. It is particularly advantageous for bearing components of beams and columns. In contrast, Bamboo Scrimber has disadvantages as a flexural member, including low cross-sectional stiffness, considerable deflection under flexural stress, and restricted spanning capacity (Zhang *et al.*, 2018).

2.2 Development of bamboo scrimber

2.2.1 Introduction

Bamboo is hollow on the inside, forming tube-like structures between the nodes where longitudinal fibres are aligned within a lignin matrix (Figure 2.1). The thickness of the culm wall diminishes as the culm grows taller. Bamboo fibres, which are distinguished by their slender shape-long, tapered at both ends, and occasionally forked-also vary in density within the culm wall, decreasing from the outer to the inner wall. Even though there are over 1200 bamboo species worldwide, these variations in geometric and mechanical properties limit the use of full culm bamboo construction. Furthermore, it is also difficult to fit spherical portions together since there is no easy way to construct

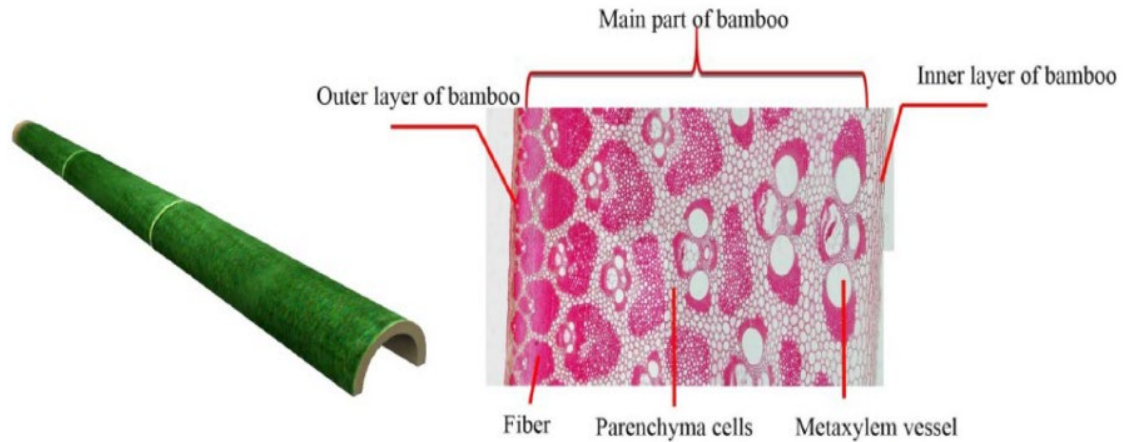


Figure 2. 1: Details of bamboo culm. Extracted from Huang *et al.* (2010)

connections and connectors. Due to this, tubes cannot be utilized in an application (Mahdavi *et al.*,2011).

In order to keep pace with the growth of the industry and to meet the increasing demand for sustainable construction materials, bamboo is utilized to make engineered bamboo composites to standardize the form and eliminate the variation in material qualities (Xiao, Yang and Shan, 2013). In developing a new sort of engineered bamboo composite, researchers discovered that the perfect combination of bamboo fibre and resin creates a material that has an equal distribution of both wood fibre and resin, which they call "bamboo Scrimber." This rectangular structural part has exceptional properties, including a high bamboo usage rate (over 80%), an attractive grain pattern, and comparable hardness and colour to hardwood, making it a viable alternative to regularly used construction and furniture materials (Wang *et al.*, 2015).

2.2.2 Evolution of bamboo scrimber

Bamboo Scrimber, also known as recombinant lumber or rebuilt lumber, emerged in the early 1980s as a structural material comprised of bamboo culms with tiny diameters. The first bamboo scrimber was created in a laboratory in China. In 1987, the laboratory of Nanjing Forestry University successfully created strong bamboo Scrimber from bitter bamboo (Li Q, Hua X, 2001).

Not until the late 1990s was industrial manufacturing of bamboo Scrimber accomplished, with the invention and manufacture of bamboo Scrimber via the use of cold-pressing

machinery. However, in comparison to wood-based panels, the bamboo Scrimber sector lacked advanced manufacturing techniques and automation. The outer and inner skins of bamboo were typically removed during the planning or splitting process, and the use rate of bamboo was around 50–60 percent. After more than a decade of research, the Chinese Academy of Forestry's Research Institute of Wood Industry produced a new generation of bamboo Scrimber (also known as bamboo-based fibre composites) utilizing small-diameter dispersed bamboo as raw material (Yu *et al.*, 2015).

The unique mechanical process extracts long bamboo fibre bundles straight from the bamboo culm without removing the bamboo outer and inner skins. This approach is not only applicable to large-diameter moso bamboo, but also to mixed bamboo with a small diameter. The use ratio of bamboo grew to more than 90%, significantly lowering the cost of producing bamboo scrimber.

2.2.3 Manufacturing process of bamboo scrimber

Initially, the major manufacturing methods of bamboo Scrimber at the laboratory test stage comprised truncation and splitting, softening, removing the bamboo outer peel, defibreing, drying, sizing, assembling, and hot-pressing as shown in Figure 2.2.

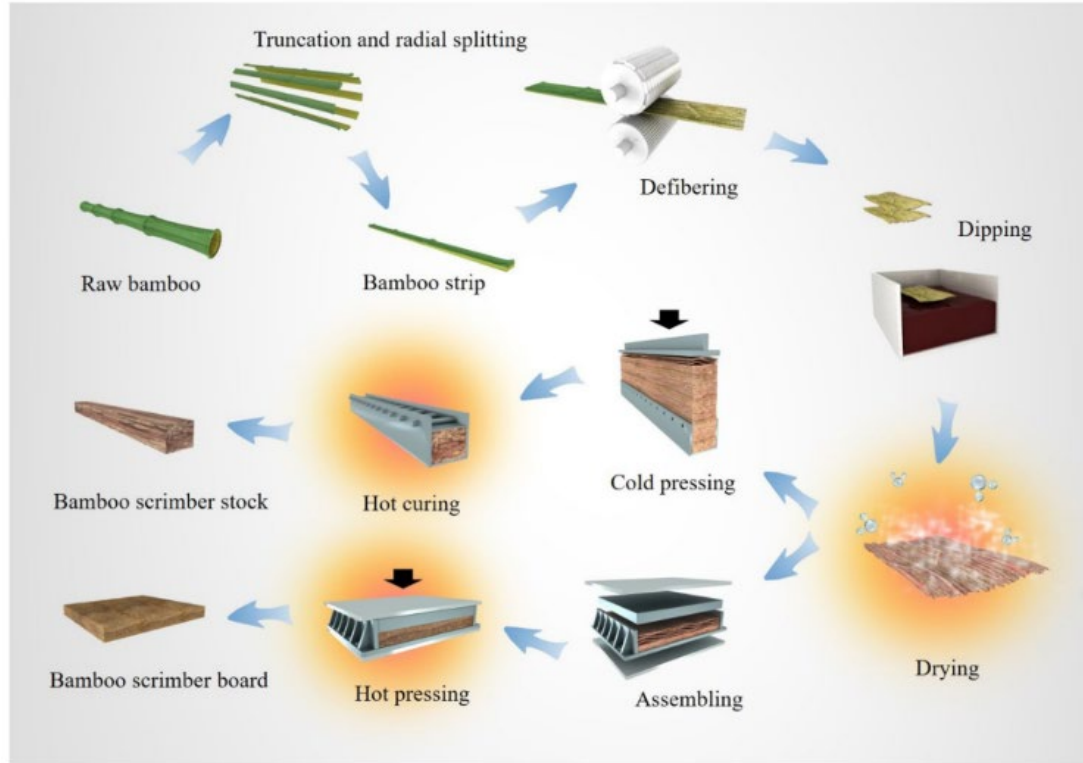


Figure 2.2: Process flow diagram of bamboo Scrimber. Extracted from (Huang *et al.* (2019).

2.2.3.1 Truncation and splitting

In the first step, bamboo is cut to meet the press's size. The number of dividing pieces is determined by the diameter of the bamboo. The greater the diameter of the bamboo, the greater the number of separating pieces, since the breadth of bamboo strips split from bamboo of different diameters is almost comparable (Huang *et al.*,2019).

2.2.3.2 Softening

Bamboo's intercellular layer could be separated using lye, which facilitated the defibreing process. Excessive alkalinity, on the other hand, has a significant effect on the physical and chemical properties of bamboo, as well as the mechanical properties of bamboo Scrimber. A more effective softening effect could be obtained by boiling bamboo in a 3% wt. NaOH or Na₂CO₃ solution. Due to the increased cost and pollution associated with the use of chemical reagents, the softening process was abandoned in actual production (Huang *et al.*,2019).

2.2.3.3 Taking off the bamboo's outer skin

Due to the high oil content in both the outer and inner skin of bamboo, the bonding strength between bamboo bundles is weak. Additionally, the outer and inner skins of bamboo have a significant impact on the mechanical properties and dimensional stability of bamboo Scrimber (Ye L, 1991). Thus, removing the outer and inner skins of the bamboo is a necessary process for manufacturing bamboo Scrimber. It does, however, add a manufacturing procedure and raise the cost of production. Most recent manufacturing processes eliminate the need for a separate process for removing the bamboo outer and inner skins; the majority of them are removed during the defibreing process.

2.2.3.4 Defibreing

The defibreing process also involves the manufacture of a bamboo bundle unit, which is a critical step in the creation of bamboo Scrimber and the primary distinction between it and other bamboo-based panels. Defibreing used to be mostly done by hand, which was inefficient and time-consuming (Wang J, 1989). As a result, this method was quickly phased out. Bamboo bundles were then prepared using manual hammering and roll-in. The former would harm bamboo mechanically, but the latter could be managed in terms of processing conditions. Direct use of the roll-in method makes obtaining optimal bamboo bundles more challenging. Before rolling the bamboo, it's normally required to soften it. It is no longer necessary to soften the bamboo when preparing the bamboo Scrimber, because of ongoing technological advancements in equipment. A bamboo bundle treatment approach was presented by Wang *et al.* (2003). Bamboo was rolled into unbroken and loosely interlaced bamboo bundles in the direction of the bamboo fibre after the outer skin was removed and the bamboo was divided. The Wood Industry Institute of China, the Chinese Academy of Forestry, and affiliated enterprises created a revolutionary fluffer machine (see Figure 2.3) (Yu *et al.*, 2006) as a result of the expanding close cooperation between scientific research institutes and businesses. The new machine's rollers were made up of multiple special-shaped gears with space between the teeth to



Figure 2.3: Diagrammatic Representation of the innovative fluffer machine invented by the Chinese Academy of Forestry. Extracted from Huang et al. (2019).

create linear-shaped cracks, and the driving rollers arranged uniform convex pocks on the bamboo to produce dotted cracks. The majority of the exterior and inner skin were removed during this mechanical therapy.

2.2.3.5 Drying

After defibreing, the moisture content (MC) of bamboo is higher than the fibre saturation threshold. The moisture content (MC) of bamboo bundles must be less than 10% in the drying room with an ambient temperature of 50–60°C. This is in order to reduce the effect of excessive delamination or long-term environmental impacts through the degradation of the final composite product. By measuring the moisture content of chosen bamboo culms for composite production, a preliminary estimation of the required time to achieve a certain MC percentage suitable for processing the raw bamboo and fabrication of composite becomes possible (Huang et al., 2019).

2.2.3.6 Dipping

Dipping is also an important step in the production of bamboo Scrimber, as it determines its bonding performance. The phenolic resin is currently in use, and the amount of resin impregnated is determined by the resin's solid content, impregnation method (in vacuum or at normal pressure), soaking time, and MC of bamboo units. The impregnation is designed in actual production to meet the performance and usage requirements of the

bamboo Scrimber. If the bamboo Scrimber is used for outdoor purposes, the impregnation may be higher (> 20%). This is due to high waterproof performance requirements (Huang, Ji and Yu, 2019).

2.2.3.7 Cold-pressing and hot-curing

Cold pressing and hot curing are two processes that are used to produce a finished product. The resin-impregnated bamboo bundles are directly moulded and shaped at high pressures of 70–80 MPa after drying to 12–15 percent moisture content (MC) in a wire belt dryer at 60 C. The mould is then sealed and sent to the resin curing channel. The square-edged bamboo Scrimber with a thickness of 15–18 cm is primarily manufactured using the cold-pressing process. 193x10.5x15.0 cm or 200x14.5x15.0 cm is the most commonly used size (length, width, and thickness) for square stock (Yu W, 2012).

2.2.3.8 Hot-pressing

In the case of hot-pressing, the slab is fabricated at a specific temperature using the traditional heat transfer technology of contacting. The unit pressure is 4–6 MPa, which is much lower than the pressure used in cold pressing. The bamboo Scrimber board's most common size (length, width, and thickness) is 244,122,1.5–4.0 cm.

Each of the two technologies has a number of benefits and drawbacks. Cold-pressing and heat curing have a high efficiency of production and low energy consumption. Bamboo bundles, on the other hand, are easily crushed by machinery due to the need for high pressure, resulting in lower mechanical properties. Furthermore, using cold-pressing technology, the density of bamboo Scrimber could reach 1.2 g/cm³. Because of the high density, the resin may not remain on the surface of the bamboo bundles, resulting in starved joints and further lowering the bonding strength.

Although the hot-pressing method has partially compensated for the cold-pressing method's deficiencies, there are still two issues. On the one hand, the slab requires artificial paving, resulting in significant variation in board density. Maximum density deviations may exceed 20%. On the other hand, a "cold-in and cold-out" process is required for hot-pressing technology, which consumes a great deal of water and energy and has low efficiency. Otherwise, defects such as bubbling are easily caused.

2.3 Wei's development of steel Reinforced Bamboo Scrimber Beams

A steel-reinforced bamboo Scrimber beam is a beam in which steel bars or pre-stressed steel bars are placed in the bamboo composite material. These beams are created by blending Bamboo Scrimber, Steel bars, and an adhesive binding compound.

2.3.1 Material properties

2.3.1.1 Bamboo Scrimber

To begin with, the tensile strength, compressive strength, and corresponding longitudinal elastic modulus of the bamboo Scrimber were determined using uniaxial tension and compression tests according to the Chinese national standard GB 1938 and GB 1935. Bamboo Scrimber was made into twelve tensile specimens and twelve compressive specimens along the grain direction. The features of the tensile specimens are shown in Figure 2.4; the strain in the specimens' centre region was determined using an extensometer. All tensile specimens were fractured in the midsection. The compressive specimens were 30mm x 30mm x 90 mm in size. As shown in Figure 2.5, shear failure and splitting failure are the two types of failure for the bamboo Scrimber compression specimens (Wei, Tang, *et al.*, 2020).

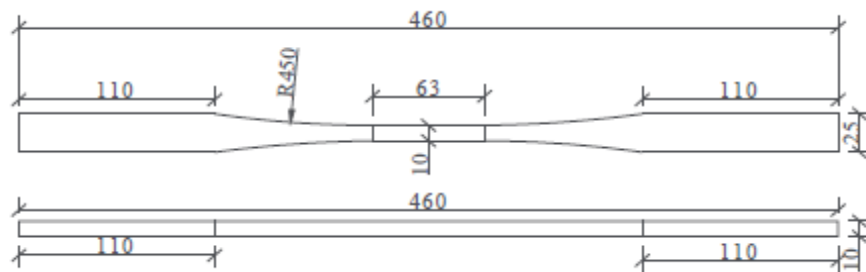


Figure 2.4: Details of the specimens in millimetres for the tensile tests for bamboo Scrimber. Extracted from Wei *et al.* (2020)



*Figure 2.5: Critical failure mechanisms in compressive bamboo Scrimber samples.
Extracted from Wei et al. (2020).*

The stress-strain curves of bamboo Scrimber in uniaxial tension and compression are illustrated in Figure 2.6. Tensile stress-strain curves are linear, but compressive stress-strain curves are nonlinear and have three stages: elastic, plastic yield, and plateau. Table 2.1 summarizes the mechanical parameters of bamboo Scrimber based on test results. The ultimate tensile strength, elastic modulus, and ultimate tensile strain of the bamboo Scrimber were determined to be 131.9 MPa, 15.6 GPa, and 0.0078, respectively, whereas the ultimate compressive strength, elastic modulus, and ultimate compressive strain were determined to be 105.2 MPa, 12.7 GPa, and 0.054, respectively.

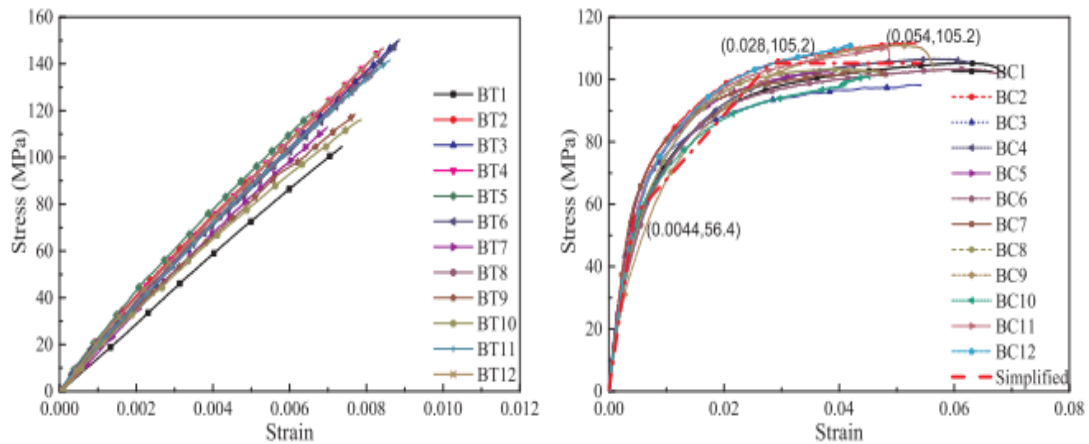


*Figure 2.6: Bamboo Scrimber's stress-strain curves in the natural direction of the grain.
Extracted from Wei et al. (2020).*

Table 2.1: Tested mechanical characteristics of the bamboo scrimber in grain direction.
Extracted from Wei et al. (2020)

Property	Average value	Standard deviation	Coefficient of variation
Tension test results			
Ultimate tensile stress	131.9(MPa)	14.9	0.114
Ultimate tensile strain	0.0078	0.00064	0.082
Modulus of elasticity	15.6(GPa)	0.71	0.046
Compression test results			
Ultimate compressive stress	105.2(MPa)	5.0	0.047
Ultimate compressive strain	0.0540	0.0090	0.169
Modulus of elasticity	12.7 (GPa)	0.6	0.05

2.3.1.2 Steel bars

This test utilized four steel bars with diameters of 6 mm, 8 mm, 12 mm, and 16 mm. The steel was in accordance with the GB1499.2-2007 executive standard for rebar. To determine the mechanical properties of the steel bars, three specimens of each diameter were prepared. A universal testing machine was used to evaluate the axial tensile parameters of the steel bars. Table 2.2 displays the test results. The yield strength and elastic modulus of the steel rebars were 408.4–436.0 MPa and 201.1–204.3 GPa, respectively. The yield strain was between 0.0020 and 0.0022. The stress-strain curves for the steel bars are shown in Figure 2.7. The mechanical characteristics of steel bars of varying diameters were the same.

Table 2.2: Measured mechanical characteristics of the tension steel bars. Extracted from Wei et al. (2020)

Steel bars	Diameter (mm)	Yield stress σ_{sy} (MPa)	Yield stress ϵ_{sy}	Ultimate stress σ_{su} (MPa)	Ultimate strain ϵ_{su} (MPa)	Elastic modulus Es1 (GPa)	Postyield modulus Es2 (MPa)
S06	6	408.4	0.0020	493.8	0.0989	201.1	1991.4
S08	8	414.0	0.0020	485.7	0.0627	204.3	1667.0
S12	12	436.0	0.0022	537.2	0.1397	202.2	2435.3
S16	16	432.5	0.0021	536.7	0.1547	202.4	2081.9

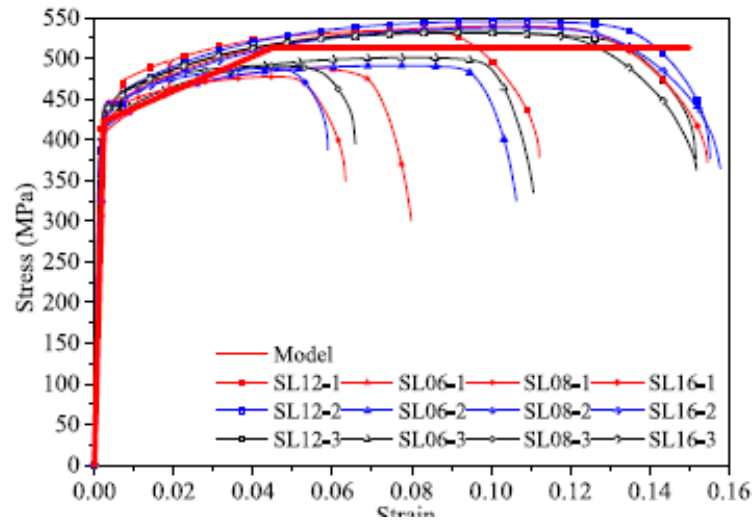


Figure 2.7: Model of tensile stress and strain of reinforced steel bars. Extracted from Zhao et al. (2021)

2.3.1.3 Adhesives

Because of their superior mechanical qualities, epoxy resin adhesives are ideal for filling and bonding. Epoxy resin shrinkage deformation is minimal after curing, and it can be fully cured in a general atmosphere. Epoxy resin can therefore be used to connect steel bars and bamboo Scrimber. The epoxy resin and curing agent that was used was L-500AS/L-500BS. A 2:1 mass ratio was used to combine the epoxy resin and the curing agent.

L-500AS/L-500BS is a liquid-type standard Epoxy Resin with excellent adhesion, chemical resistance, heat resistance, etc. Due to its special properties, it is generally used in many fields and is the most standard liquid resin for general use. L-500AS/L-500BS is cured together with the various hardeners (Polyamide resin, Aromatic Polyamine, Aliphatic Polyamine and Anhydride Compound). According to the manufacturer, the tensile strength, elastic modulus, and ultimate tensile strain were 67.7 MPa, 2.9 GPa, and 0.029 respectively.

2.4 Previous studies on bamboo Scrimber

2.4.1 Experimental studies

Numerous experiments have been conducted regarding the use of different types of reinforcements in order to improve the flexural capacity of wood products.

Bamboo Scrimber is one of the most frequently used bamboo composite materials for floors, furniture, and carriages. Bamboo Scrimber has a comparable look to wood and superior and stable mechanical characteristics. It is particularly well suited to the major bearing elements of beams and columns. However, bamboo Scrimber as a flexural member has a number of disadvantages, including low cross-sectional stiffness, significant deflection under flexural pressure, and a restricted span capacity (Wei *et al.*, 2017).

Bamboo Scrimber beams also fail due to rupturing of the local bamboo fibre at the bottom tensile zone, according to beam bending test data. Some solutions for strengthening bamboo flexural members that are similar to those used for wood, such as natural fibre, fibre-reinforced polymers (FRPs), and steel, have been proposed to improve the stress condition in this zone and increase the spanning capacity.

Borri *et al.* (2005) proposed using FRP materials such as FRP sheets and FRP bars to reinforce old wooden beams. Experiments revealed that external FRP materials could effectively improve the bending stiffness and bearing capacity of wooden beams, with flexural capacity increasing by up to 60.3 percent.

Donadon *et al.* (2020) recommended utilizing Vectran fibre FRPs and epoxy adhesive to reinforce glued-laminated wood beams. The ultimate load and elastic stiffness increased the most, by 40% and 34.95 percent, respectively, when compared to control beams.

Vahedian *et al.* (2019) investigated the performance of glulam beams reinforced with fibre glass-reinforced plastic (FRP) sheets that were externally bonded. The stiffness of the reinforced beams was significantly influenced by the thickness of the FRP bonding material used in their construction.

Glišović *et al.* (2015) placed fibre-reinforced plastic (FRP) plates on the bottom of a glulam beam to investigate the impact of FRPs on the bending performance of the beam. Mechanical testing showed that the FRP plates had a positive impact on the strength, stiffness, and ductility of the glulam beam during construction.

Rescalvo *et al.* (2018) bonded fibre glass reinforced plastic (FRP) strips to the tension side of wood beams with natural defects and showed that the bending carrying capacity of the beams could be restored via the use of an external strengthening technique.

D'Ambrisi *et al.* (2014) inserted fibre glass reinforced plastic (FRP) plates into grooves in the tensile zone of wood beams in order to improve flexural strength. The results of the experiments showed that the flexural strength and ductility of the beams were significantly improved.

De Luca and Marano (2012) used steel bars to strengthen hardwood flexural components. The bending stiffness of the beams reinforced with regular steel bars rose by 25.9%, while the bending stiffness of the beams reinforced with pre-stressed steel bars increased by 40.2 percent, as compared to the performance of control beams. The pre-stressing procedure was carried out by applying the same tensile load to the warp and fill bundles and keeping it constant until the matrix was cured. The pre-stressing technique has been shown to improve the mechanical characteristics of composite materials and structural components.

Yang *et al.* (2016) investigated the influence of pre-stressed FRP bars on the strength of hardwood beams. The test findings indicated that the reinforced, pre-stressed, and pre-stressed and reinforced (bottom pre-stressed and top reinforced) beams had a significant

increase in flexural capacity of 64.8 percent, 93.3 percent, and 131%, respectively. The aforementioned research established that glueing FRP materials, embedding FRP materials, embedding steel bars, and pre-stressing may significantly enhance the bearing capacity and bending stiffness of hardwood beams. (Wei *et al.*, 2017) suggested a novel form of reinforced bamboo beam with FRP sheets inserted into the tension zone for added strength. FRP sheets can improve the cross-sectional stiffness and load-carrying capability of bamboo beams, according to four-point bending tests.

Lv *et al.* (2019) conducted a static loading test on laminated bamboo beams reinforced with pre-stressed FRP sheets, and the experimental findings indicated that prestress had no discernible influence on the bamboo beams' ultimate strength.

Wei *et al.* (2017) proposed a new type of reinforced bamboo beam, and preliminary research results indicated that the bearing capacity and cross-sectional stiffness of the beams were significantly improved; the stiffness improvement was greater for steel bar reinforced bamboo beams than for FRP bar reinforced bamboo beams. To enhance the bending performance and span capacity of bamboo beams, a unique side-embedded steel bar technique was developed in which steel bars were implanted on both sides of the bamboo beam. Four-point bending tests were conducted on fourteen reinforced bamboo beams to determine their load-bearing capacity. The diameter of the steel bar and the amount of pre-stressing were factors. Theoretical techniques for estimating the flexural rigidity and bearing capacity of reinforced beams were provided based on the test findings by considering the cross-sectional strain and stress distribution of the reinforced beams.

2.5 Wei's experimental setup

As earlier indicated, the beams considered for this study's numerical analysis are taken from an experimental study conducted by (Wei *et al.*, 2020b).

2.5.1 Test specimens and preparation

Four steel-reinforced beams were prepared and labelled based on the diameter of the embedded bars. All of the bamboo beams were 70 mm wide, 140 mm high, and 2500 mm long, respectively. The cross-sectional features of the bamboo Scrimber beam reinforced with steel bars of various diameters are shown in Figure 2.8. The groove depths of the

bamboo Scrimber beams reinforced with steel bars of diameters of 6 mm, 8 mm, and 12 mm were 15 mm, while the groove depths of the bamboo Scrimber beams reinforced with steel bars of diameters of 16 mm were 20 mm. Grooves with widths of 20 mm and 15 mm were cut from the bottom. All of the reinforced steel bars were placed 25 mm from the bottom, at the centre of gravity. The grooves of the reinforced beams were covered with bamboo plates of various thicknesses after the steel bars were fastened and bonded (Wei *et al.*, 2020b).

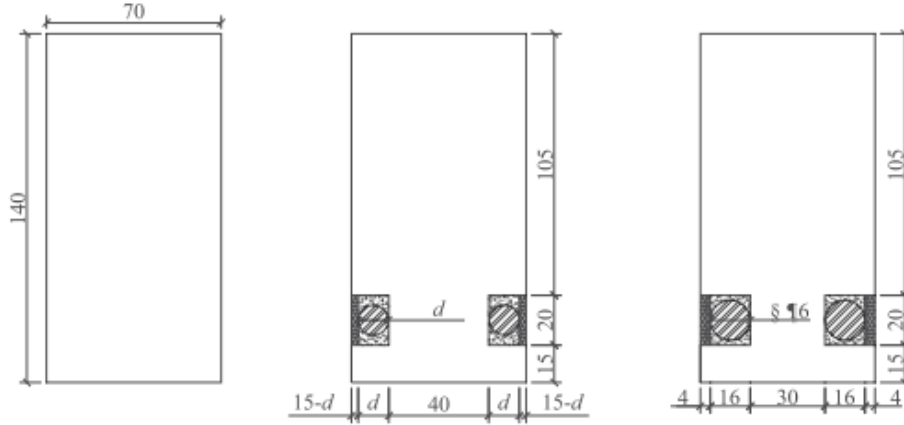


Figure 2.8: Sectional characteristics of bamboo Scrimber beams reinforced with steel bars of varying sizes (mm). Extracted from Wei *et al.* (2020).

2.5.2 Test setup and procedure

The specimens were subjected to a four-point bending static load test. Figures 2.9 and 2.10 illustrate the test setup and apparatus schematically. The loading device was a servo actuator with a force of 300 kN. During the test loading, displacement control was used and the loading speed was set to 2 mm/min. A 1200 mm long rigidly distributed beam was connected to the loading test machine. All beam specimens were supported simply with a clear span of 2340 mm, and the load was delivered to the test beams via the dispersed beam at the two loading sites. The loading points divided the beams into three equal lengths of 780 mm. A laser displacement meter (LD) was set on the ground directly beneath the test beams' mid-span to record the mid-span deflection; two linear variable displacement transducers (LVDTs) were installed at the test beam's support to measure the vertical displacement. To determine the beam's true mid-span deflection, the displacement generated by the supports was subtracted from the LD's recorded data. The strain gauges were equally distributed over the mid-span section in accordance with the

groove positions. Two strain gauges were affixed to the surface of each steel bar at the mid-span portion prior to implanting them. A TDS-530 collection equipment was used to obtain displacement and strain data (Wei *et al.*, 2020b).

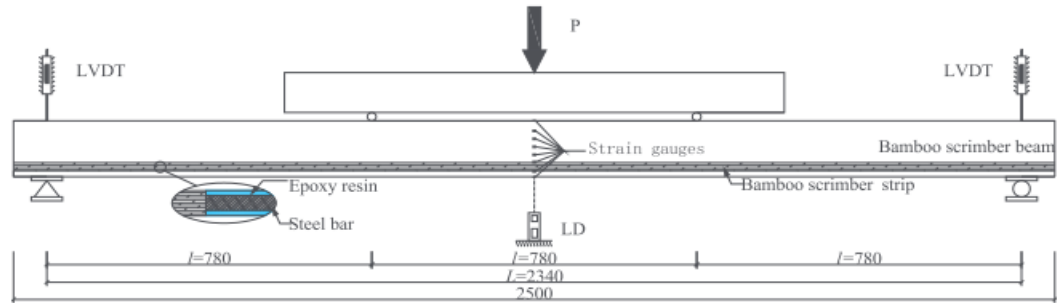


Figure 2. 9: Schematic of the test setup. Extracted from Wei *et al.*

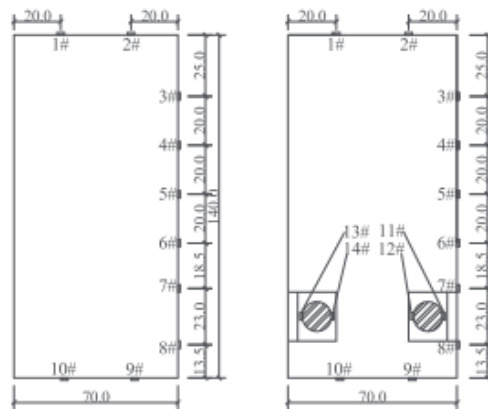


Figure 2.10: Strain gauges for the control beams (Left) and Strain gauges for the reinforced beams (Right). Extracted from Wei *et al.* (2020).

2.6 Previous numerical studies on recombinant bamboo

Recent researchers have found the Finite Element Analysis method to be an efficient tool for investigating the enhancing impact and influence of parameters for structural member strengthening methods.

Guan *et al.* (2005) used finite element models to predict the structural behaviour of glulam beams pre-stressed using pultruded glass fibre-reinforced plastic (GFRP) tendons. Due to the transmission of the pre-stressing force, the model was able to simulate the pre-stressing technique chosen for the glulam and suggested a precamber at the mid-span of the beam. GRP with a thickness of 4 mm and a prestress of 60 percent is the ideal choice for ensuring that the glulam beam is subjected to its full stress.

Anshari *et al.* (2012,2017) created a preliminary finite element model of the upward deflection of glulam beams reinforced by compressed wood, which was then modified to simulate the initial stress and precamber of pre-stressed glulam beams. In addition, it was determined that the effect of prestress on long glulam beams was more substantial than that on short ones.

Through the use of FEMs and cohesive failure models, Campilho *et al.* (2009) investigated the failure mechanism, elastic stiffness, and maximum load for the repair of wood beams reinforced with composite materials.

Kim and Harries, (2010) developed a modelling technique for predicting the behaviour of carbon fibre-reinforced polymer (CFRP) composite beams. The beams' strength improvement was restricted to a 1.9 percent CFRP reinforcement ratio.

Valipour and Crews, (2011) assessed the effectiveness of FE modelling for estimating the load-carrying capacity of wood beams flexurally reinforced with externally bonded FRP strips and near-surface mounted FRP bars. The generated model displayed excellent agreement with the mid-span deflection test findings.

Uzel *et al.* (2018) investigated the strengthening impact of several bonding surface materials on hardwood beams and used finite element analysis to determine the final flexural capacity.

Ngudiyono *et al.* (2017) developed a finite element model of creep glued-laminated bamboo to examine the creep behaviour of glue-laminated bamboo. Because it has qualities that are common to both perfect solids and liquids, glued-laminated bamboo was classed as a viscoelastic material. Three methods for describing the creep behaviours of viscoelastic materials have been identified. The four solid elements, sometimes known as the Burger model, is a widely used mechanical model for predicting creep in glued-laminated bamboo. The constitutive equation Burger model is translated into relaxation shear modulus of Prony series in ABAQUS finite element software in this manuscript.

Zhao *et al.* (2018) research group used the numerical simulation of bamboo glueing performance. They studied the bamboo slabs lap peeling and shear failure process of the bamboo slab under the loading condition. In this study, it was noted that the property of the bamboo reorganization material depends on the performance of the bamboo units and the performance of the bamboo glueing. So, the glueing property of the whole bamboo and bamboo bundles is a key factor. The model provided in this study is consistent with the experimental findings. The bonding length and glueing effectiveness of various bamboo species are analysed. The model is beneficial for the application of bamboo-integrated timber.

Fu *et al.* (2017) studied the properties of recombinant bamboo by comparing the stress and deformation of bamboo Scrimber, Rosewood, and Elm under stress states by using ANSYS finite element analysis software. Meanwhile, the impact of the current mainstream three legs on the mechanical properties of the back chair was analysed in order to determine which leg shape is best for the back chair of recombinant bamboo. Furthermore, the parametric design method can determine the ideal leg and seat sizes, which are two of the most important design elements of a back chair. This provides a method for furniture design that is both evidence-based and effective.

Tian *et al.* (2020) used the finite element program ABAQUS to simulate and assess the compressive performance of glue-laminated cornstalk Scrimber specimens with various slenderness ratios under axial compression. The height of glue laminated cornstalk Scrimber is inversely connected with buckling load and nonlinear load under axial compression but positively correlated with transverse and axial displacements generated

by axial compression, according to the findings. The findings of this study can be used to improve the design and application of glue-laminated cornstalk Scrimber.

Zhao *et al.* (2018) research focuses on the Numerical Simulation of Bamboo Bundle Glulam's Properties. A three-dimensional finite element model of bamboo bundles Glulam was created in this study. The model analysed the failure and evolution of damage in bamboo bundles using the Hashin criterion and continuous damage mechanics, while the cohesive zone model analysed the failure in the adhesive layer between bundles. The stress changes were investigated in different layers of bamboo bundles over time when subjected to displacement load.

2.7 Development of generalized FE model

2.7.1 Software programs used in the study

2.7.1.1 ABAQUS

ABAQUS is a commercial software suite for finite element analysis. The ABAQUS product line is comprised of three basic products: ABAQUS/Standard, ABAQUS/Explicit, and ABAQUS/CAE. ABAQUS is used in a number of different industries, including automotive, aerospace, and industrial products. The product's ability to represent a wide range of materials and its ability to be customized are highly regarded by academic and research institutions (Dassault Systèmes Simulia, 2008).

2.7.1.2 MCalibration

MCalibration is a software that enables the extraction of material parameters that are relevant to the simulation experiment, from the data collected from physical experiments. MCalibration is one of the best tools for choosing and calibrating material models and making it easier to get the material parameters because calibrating a material model is not easy. The accuracy of the finite element model is very dependent on the correctness of the material model.

2.7.2 Finite Element program of analysis

2.7.2.1 Introduction

The choice of finite element software has a significant impact on the quality and extent of analysis that may be conducted. The finite element (FE) approach has long been used to analyse engineering operations. FE formulations are easier to use than analytical methods, which can be time-consuming and require a lot of work with boundary conditions. The package used is critical for both the type of analysis that may be conducted and the quality of the results. This is due to the fact that different packages have varying capabilities, and it is vital to choose the package with a suitable feature set. Furthermore, the assumptions and solver approaches utilized in the package have far-reaching implications for the simulation results. ABAQUS was employed in this investigation because of its greater efficiency in model development and adaptability (Klocke *et al.*, 2002).

2.7.2.2 Overview of ABAQUS

ABAQUS is a general-purpose finite element method (FEM) tool that can be used to solve a wide range of engineering problems. It is part of the SIMULIA family of codes, which helps engineers' model and simulate experiments. There are also other subprograms, like Insight and Tosca for optimization, or Fe-safe for more advanced fatigue analysis, which are some of them. It is used for problems that can be solved by implicit schemes, and it is used for problems that can be solved quickly. ABAQUS, which is one of the most popular commercial FE programs, is able to work with a lot of other programs that do the same thing.

2.7.2.3 Advantages of ABAQUS

One of the main features of ABAQUS is that it comes with two solvers: Standard and Explicit. They can be used to run a wide range of simulations. Using keywords, ABAQUS can be used to set up simulations. These keywords show how the simulation will work. The user can choose how to model the machining process, which gives them a lot of control over the simulation. Despite the fact that ABAQUS doesn't support any materials, users can use a variety of models to make the materials how they want them. The user can

also make very small changes to the meshing and the types of elements in the model. The most significant benefit of ABAQUS is the ability to model at a high level of detail.

The user can create a fairly complex model that describes numerous types of behaviour and one that is simple and gives general information. The software can also be used on the command line and can be used with scripts.

The user must explicitly describe the tool and work piece, process parameters, and simulation controls in order to conduct in ABAQUS.

2.7.2.4 Disadvantages of ABAQUS

The software has a steep learning curve because of its level of flexibility. Simulations take a long time to configure with the program since the user has to specify many of the parameters manually. Mesh optimization is a good example of this.

2.7.2.5 Summary

ABAQUS is a good program if the user wants to do a very detailed analysis "from scratch" without using any pre-made controls or assumptions. This can be a long learning process, though. It has a lot of tools that give the user a lot of control over how the simulation works.

2.7.3 Analysis type

The capabilities of the ABAQUS finite element analysis software suite is illustrated in Figures 2.11 and 2.12. It lists the subprograms and the types of analysis that they are capable of performing. One of the materials used in this study is Epoxy resin, which is modelled as a cohesive substance in order to get the desired results. This means that the program can only perform a dynamic explicit analysis with such elements, which necessitates the inclusion of the material's damage parameters in the analysis.

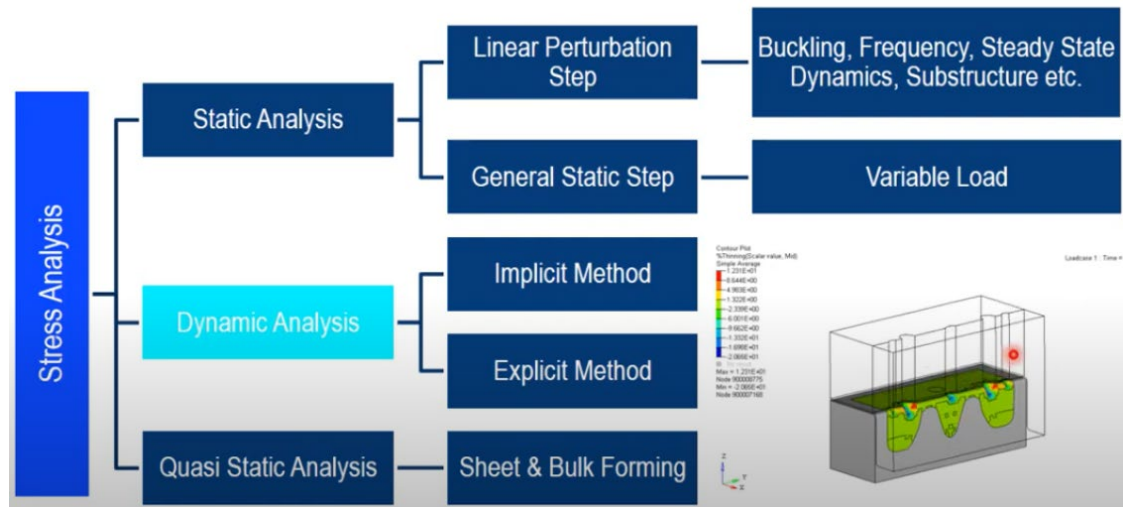


Figure 2.11: Types of stress analysis employed in ABAQUS. Extracted from (Gokhale, 2008).

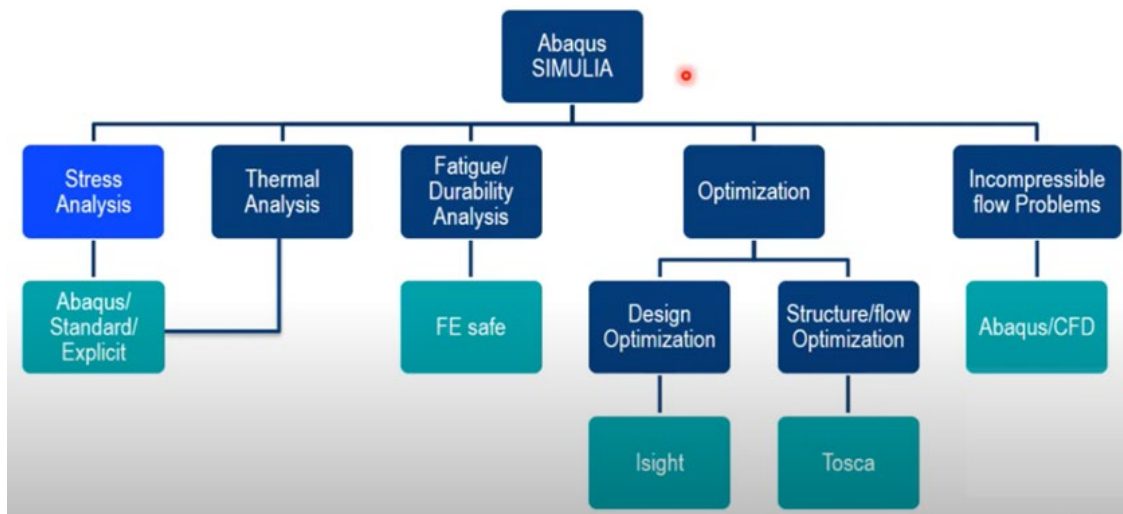


Figure 2.12: Types of analyses conducted in ABAQUS. Extracted from (Gokhale, 2008).

The type of analysis that was performed in this study is a stress analysis, which was carried out using ABAQUS Standard Dynamic Explicit software program.

When dealing with dynamic problems, the dynamic analysis method is employed. For the most part, while dealing with a dynamic problem, the effect of inertia should be taken into consideration, and the goal should be to investigate the temporal response of the system under specific conditions. When dealing with dynamic problems, the solution step is

frequently comprised of the direct integration of the system of equations that describe the motion of the system being considered. This problem can be investigated using both ABAQUS/Standard and ABAQUS/Explicit software packages. Because these products use various approaches to solving the nonlinear system of equations that describes the problem, there is a significant difference between them. This is accomplished by the use of implicit direct integration methods in ABAQUS/Standard, whereas explicit integration strategies are utilized in ABAQUS/Explicit (User, 2014).

When dealing with a large nonlinear system of equations that characterizes the dynamics of a system, explicit schemes are generally more cost-effective than implicit systems. The explicit approaches have a significant disadvantage in that their stability is highly sensitive to the choice of the time step used. Implicit schemes, on the other hand, allow for the selection of greater time steps; but they entail a higher computing cost for solving a nonlinear system with a large number of variables. In some cases, the choice between the explicit and implicit (Standard) products is limited by the type of analysis that is required, and in most cases, the choice is heavily influenced by the nature of the partial differential equation describing the physics of the problem, the type of boundary conditions describing the system, the total amount of analysis time required, and other factors such as these (Gokhale, 2008).

2.7.3.1 Units

The system of units to be employed was decided upon before beginning to define the model. ABAQUS itself does not count in units; it needs to be defined artificially, using consistent units. Table 2.3 provides examples of consistent systems of units. As points of reference, the unit length and area of this model are mm and mm²; the unit of force is N; the unit of weight is in tons, and the unit of stress and modulus of elasticity is MPa. The mass density and Young's Modulus of steel are provided in each system of units. "GRAVITY" is the gravitational acceleration.

Table 2.3: Example of consistent systems of units. Extracted from LS DYNA support

MASS	LENGTH	TIME	FORCE	STRESS	ENERGY	DENSITY	YOUNG's	35MPH 56.33KMPH	GRAVITY
kg	m	s	N	Pa	J	7.83e+03	2.07e+11	15.65	9.806
kg	cm	s	1.0e-02 N			7.83e-03	2.07e+09	1.56e+03	9.806e+02
kg	cm	ms	1.0e+04 N			7.83e-03	2.07e+03	1.56	9.806e-04
kg	cm	us	1.0e+10 N			7.83e-03	2.07e-03	1.56e-03	9.806e-10
kg	mm	ms	kN	GPa	kN-mm	7.83e-06	2.07e+02	15.65	9.806e-03
g	cm	s	dyne	dyne/cm ²	erg	7.83e+00	2.07e+12	1.56e+03	9.806e+02
g	cm	us	1.0e+07 N	Mbar	1.0e+07 Ncm	7.83e+00	2.07e+00	1.56e-03	9.806e-10
g	mm	s	1.0e-06 N	Pa		7.83e-03	2.07e+11	1.56e+04	9.806e+03
g	mm	ms	N	MPa	N-mm	7.83e-03	2.07e+05	15.65	9.806e-03
ton	mm	s	N	MPa	N-mm	7.83e-09	2.07e+05	1.56e+04	9.806e+03
lbf-s ² /in	in	s	lbf	psi	lbf-in	7.33e-04	3.00e+07	6.16e+02	386
slug	ft	s	lbf	psf	lbf-ft	1.52e+01	4.32e+09	51.33	32.17
kgf-s ² /mm	mm	s	kgf	kgf/mm ²	kgf-mm	7.98e-10	2.11e+04	1.56e+04	9.806e+03
kg	mm	s	mN	1.0e+03 Pa		7.83e-06	2.07e+08		9.806e+03
g	cm	ms	1.0e+1 N	1.0e+05 Pa		7.83e+00	2.07e+06		9.806e-04

2.7.4 Chapter overview

As can be shown in this chapter, several researchers have investigated the enhancement of the load-bearing capacity of bamboo Scrimber and plain wood using experimental and computational approaches. The flexural performance of wood components reinforced with steel bars, pre-stressed FRP, CFRP, etc., has been demonstrated to be advantageous. Due to the requirement to determine the material's flexural performance in order to utilize it as a load-bearing structural component, researchers continue to have several issues regarding the flexural capacity of SRBS beams. Wei *et al.* (2020) evaluated the full-scale flexural performance of SRBS beams despite the fact that the majority of previous research in this subject has focused on the flexural performance of wooden members.

In the literature review, it was pointed out that to make performance-based design possible and inexpensive; the need for numerical tools cannot be ignored. As a result of being a new technology, most numerical tools for performance-based flexural capacity design have been developed for various materials in structural engineering. Very few studies have applied a numerical approach to investigate the flexural capacity of SRBS beams. With the objective of investigating the flexural capacity of SRBS beams within the context of performance-based design, developing a numerical model for that purpose is indispensable. Such a model would be able to determine the flexural capacity of the beams and other parameters requested by the users such as strains, shear etc. The numerical model and investigations considered in this dissertation provide very useful information about the design of SRBS Beams in the context of performance-based design.

CHAPTER 3 : METHODOLOGY

3.1 Introduction

The flexural performance of a reinforced bamboo Scrimber beam with different reinforcement ratios and different levels of pre-stressing forces was investigated by a four-point bending test (Wei *et al.*,2020b). To increase the flexural capacity and stiffness of bamboo Scrimber beams, this experimental study offered a unique approach for strengthening the beams by inserting steel bars or pre-stressed steel bars into both side surfaces of the beams. Seven groups of bamboo Scrimber beams were produced and prepared, as well as groups of two parallel specimens. The diameter of the steel bars and the level of pre-stressing were factors. The control specimen was a group of bamboo Scrimber beams without reinforcement coded BSB_S0; two identical steel bars were symmetrically implanted on each side surface of the four groups of beams, with diameters of 6 mm, 8 mm, 12 mm, and 16 mm and where coded BSB_S6, BSB_S8, BSB_S12, and BSB_S16 respectively.

However, it is not possible to get a full insight into the beam's behaviour using an experimental approach. This is mainly due to impractical issues such as: it may not be possible from an economic perspective to cast an adequate number of beams to study all different kinds of behaviours, and it may not be practical to place thermocouples or Linear Variable Differential Transducers (LVDT) in some regions of the beams, and thus it may not be possible to conduct a parametric study. By building on the principle of the Finite Element Method (FEM), this study investigated the flexural performance of steel-reinforced Bamboo Scrimber beams using a four-point bending test.

This chapter discusses the approach used to investigate SRBS beams numerically using the finite element analysis software package ABAQUS. To begin, the chapter discusses the ABAQUS sequentially linked four-point bending test analysis approach used in this investigation, and then the investigation methodology is employed in achieving the dissertation's given objectives. Last but not least, an overview of the chapter is presented.

3.2 General description of the assembly

A four-point bending test was performed on the test specimens as shown in Figure 3.1. It is made up of a composite beam that is linked to two supports and two loading points. The beam is strengthened with steel bars of various diameters, which are kept in place by epoxy resin, which acts as an adhesive material. In the loading test, velocity loading control was used, and the loading speed was set at 2mm/min, or 0.03mm/second. Two stiff loading sections conveyed the load to the beams, which were simply supported with a clear span and length of 2340 mm and 2500 mm, respectively.

The loading points separated the beams into three sections of 780 mm each. This research was carried out over the course of several ABAQUS simulations.

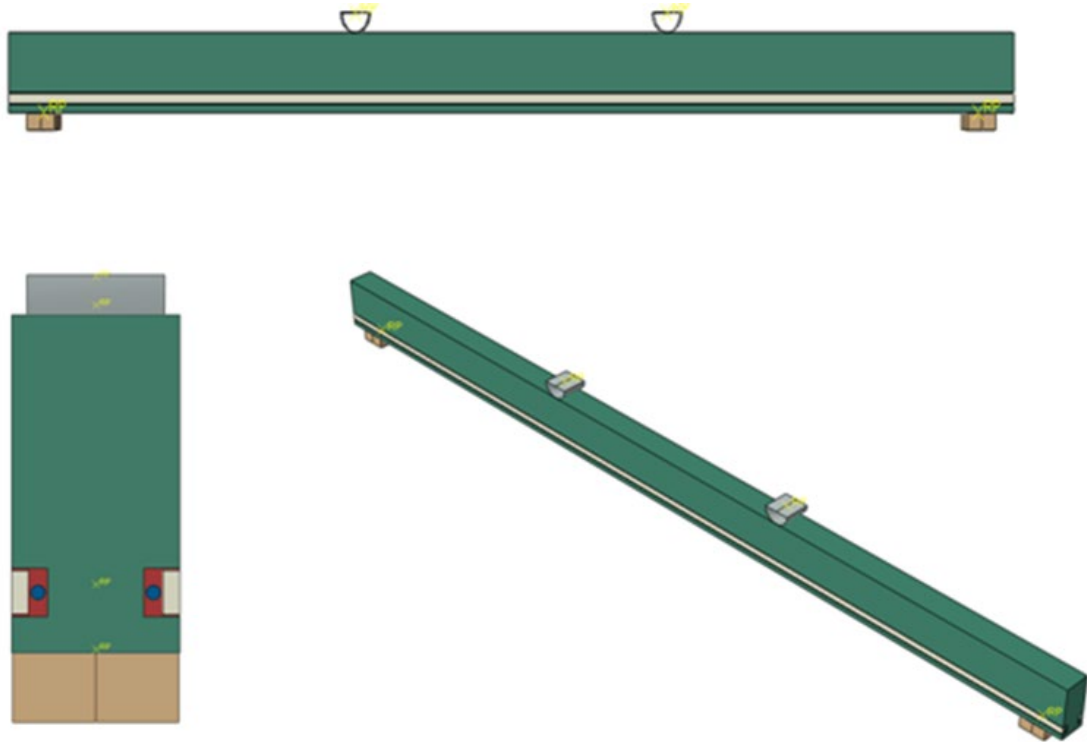


Figure 3. 1: Schematic of the assembled

3.2.1 Part module

The part module is used to set the geometry of the parts of the model. These are the building blocks of an ABAQUS model. As a geometric representation, a part can be made or imported from other programs. It can also be used to make or import a mesh. In this study, 5 parts were defined namely the semi-circular rigid loading plates (see Figure 3.2),

The diagram shows a rectangular floor plan on a grid. The overall dimensions are 140 units by 150 units. The plan is divided into several sections:

- A top rectangular section with dimensions 100 units by 40 units, shaded gray, with area 4000 .
- A large central rectangular section with dimensions 100 units by 100 units, shaded gray, with area 10000 .
- A bottom-left rectangular section with dimensions 15 units by 15 units, shaded gray, with area 225 .
- A bottom-right rectangular section with dimensions 15 units by 15 units, shaded gray, with area 225 .
- A central rectangular section with dimensions 70 units by 20 units, shaded gray, with area 1400 .
- A bottom-right rectangular section with dimensions 15 units by 20 units, shaded gray, with area 300 .

The total area is calculated as $4000 + 10000 + 225 + 1400 + 300 = 16125$.

A diagram of a semi-circle on a coordinate grid. The semi-circle is centered at the origin (0,0) with a radius of 4 units. The horizontal diameter is labeled 'RP' and the vertical radius is labeled 'H'.

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3.2.2 Material properties and calibration

ABAQUS has an extensive material library which can be used to model many engineering materials, including metals, rubbers, concrete, and fabrics. ABAQUS also provides the facilities to create and use a user-defined material model for the purpose of finite element simulation. In this study, the following materials were defined and calibrated.

3.2.2.1 Bamboo scrimber

The bamboo tensile specimens exhibit brittle failure without plastic yielding, according to the tensile test. A stress-strain model, as indicated in Equation (3.1), which designates the compression direction of material characteristics as "negative" and the compression direction as positive, can explain the stress-strain relationship.

$$\sigma = E_t \cdot \varepsilon - \varepsilon_{tu} \leq \varepsilon < 0 \quad \text{Equation 3.1}$$

where E_t is the modulus of tensile elasticity and ε_{tu} is the ultimate tensile strain. New additional parameters and improved formulae based on the Popovics model were added in accordance with the three failure stages of the bamboo compression test, and a stress-strain relationship model appropriate for elastoplastic materials was proposed (Wei et al., 2020a). Equations (3.2) and (3.3) provide the formula for elasto-plastic materials.

$$f(x) = \frac{\sigma}{\sigma_{cy}} = \frac{x \cdot a}{a - 1 + x^{a(x+\delta)^b+c}} \quad \text{Equation 3.2}$$

$$a = \frac{E_1}{E_1 - E_{sec}} \quad \text{Equation 3.3}$$

In the formula $x = \varepsilon_c / \varepsilon_{cy}$, ε_{cy} is the yield strain; σ_{cy} is the yield stress; a, b, and c are three specific parameters to control the shape of the curve or determined by boundary conditions; and δ is a very small constant (Wei et al., 2020a). E_1 is the compressive elastic modulus of bamboo, and E_{sec} is the yield point secant modulus.

The tensile stress-strain curve is linear, but the compressive curve is nonlinear and consists of three stages: an elastic stage, a plastic yield stage, and a plateau stage. Table 2.1 lists the mechanical characteristics of bamboo Scrimber based on the measured values. Based

on the measured data, the ultimate tensile strength, elastic modulus, and ultimate tensile strain of the Bamboo Scrimber were 131.9 MPa, 15.6 GPa, and 0.0078, while the ultimate compressive strength, elastic modulus, and ultimate compressive strain were 105.2 MPa, 12.7 GPa, and 0.054.

Figure 3.7 shows the parameters that were defined according to the calibration for bamboo Scrimber material and their subcategories. The materials were extracted from the stress-strain curves for the Bamboo Scrimber material. See Appendix A1.1 for the calibration of the Bamboo Scrimber.

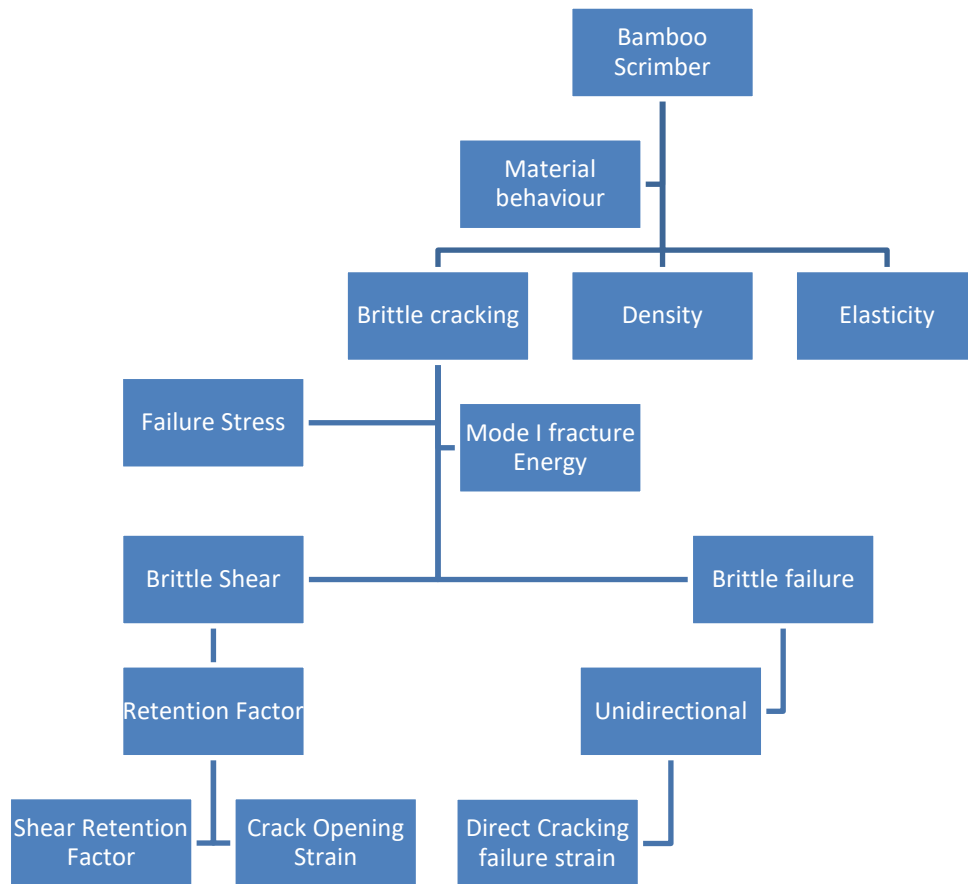


Figure 3.7: Defined Parameters for Bamboo Scrimber material in

3.2.2.2 Epoxy resin

Pure Epoxy resin adhesives with a curing agent are well suited for filling and bonding because of their excellent mechanical properties. A material Calibration was conducted based on the tensile strength, elastic modulus and ultimate tensile strain as provided by

the manufacturer were 67.7 MPa, 2.9 GPa and 0.029, respectively and were used in the simulation. The parameters defined for the Epoxy resin are illustrated in Figure 3.8.

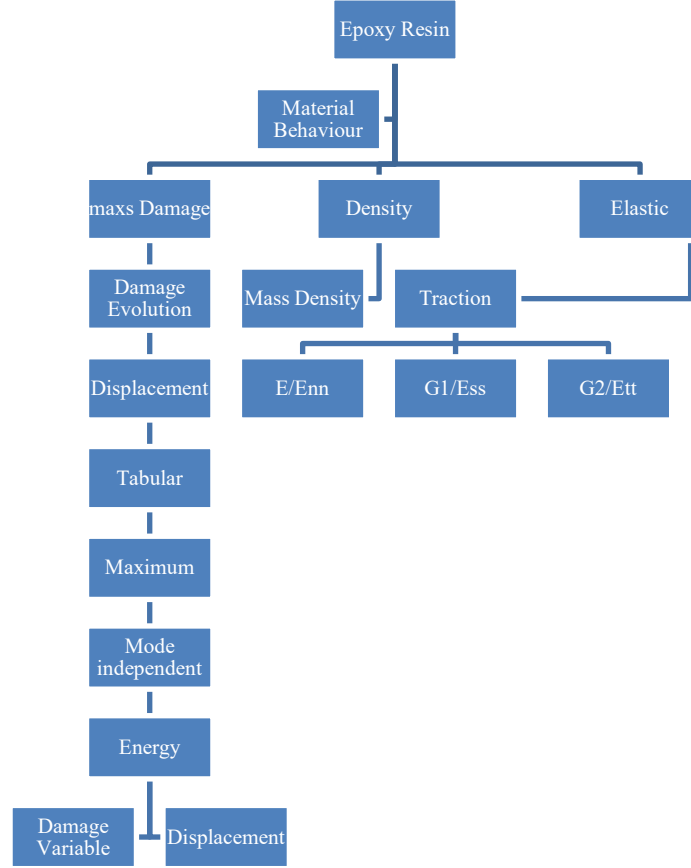


Figure 3.8: Defined Parameters for Epoxy resin material in

3.2.3 Steel

As demonstrated in Equation (3.4), the stress-strain curves of steel bars under unidirectional tension (see Figure 2.7) are characterized by a simple trilinear model (Akkaya et al.,2019).

$$\sigma = \begin{cases} E_1 \cdot \varepsilon & 0 < \varepsilon \leq \varepsilon_e \\ \sigma_e + E_2 \cdot (\varepsilon - \varepsilon_e) & \varepsilon_e < \varepsilon \leq \varepsilon_{ty} \\ \sigma_{tu} = \sigma_{ty} & \varepsilon_{ty} < \varepsilon \leq \varepsilon_{tu} \end{cases} \quad \text{Equation 3.4}$$

where E_1 is the elastic modulus of the steel bar during the elastic phase; E_2 is the elastic modulus of the steel bar after yield; σ_e is the ultimate tensile stress of elasticity; ε_e is the

corresponding ultimate elastic compressive strain; σ_{ty} is the tensile stress at the yield point; ϵ_{ty} is the corresponding tensile strain at the yield point; σ_{tu} is the ultimate tensile stress of the steel, and ϵ_{tu} is the corresponding ultimate tensile strain. The parameters defined for the steel are illustrated in Figure 3.9.

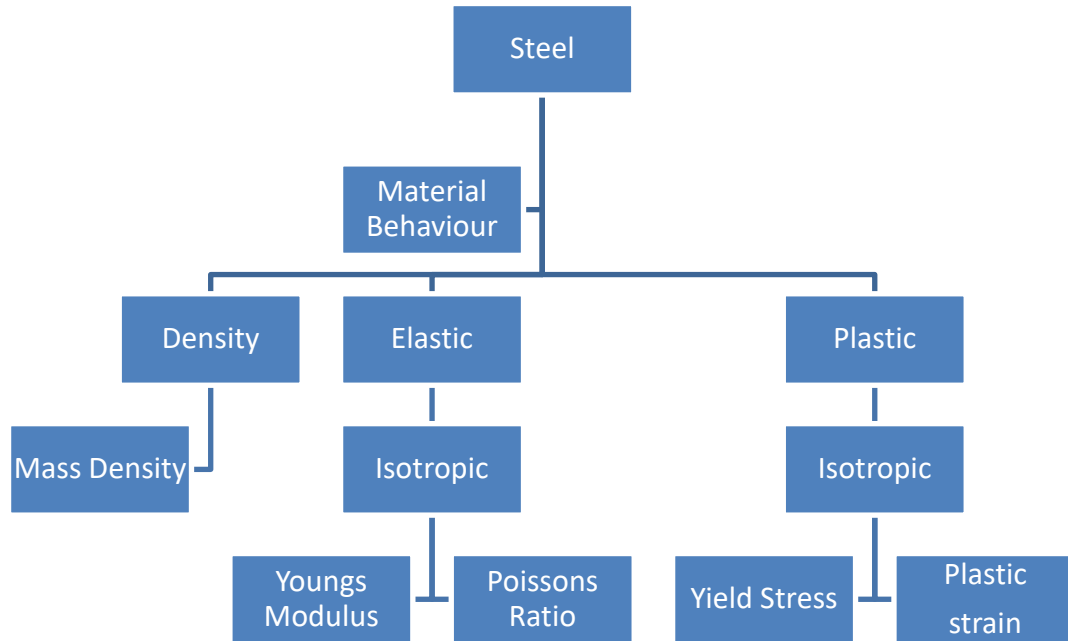


Figure 3.9: Defined Parameters for Steel material in ABAQUS

3.2.4 Section module and assignments

By first making a section, it can be assigned its properties to a part, a part region, or a group of elements. To do this, a section is created and then Assign Section is selected. Section properties that are set for a part are automatically set for all parts that use that part in the assembly. ABAQUS/CAE colours a region green in the Property module to show that the region has a section assignment, or colours the region yellow if there are two or more section assignments in the same region. All the parts were assigned to their relative sections and materials.

3.2.5 Assembly (instances, features, sets and surfaces)

A model in ABAQUS is merely a collection of part instances. It is typical for a physical model to consist of multiple components. The assembly interface of ABAQUS can be

used to generate a mesh of finite elements based on the physical assembly. A part instance in ABAQUS refers to the assembled components which consist of features, sets, and surfaces on these components.

3.2.6 Step

The step model in ABAQUS is used to create and define the analysis steps and associated output requests. The following are tasks that are performed:

3.2.6.1 Create analysis steps.

A step sequence is a handy approach to capture changes in the model's loading and boundary conditions, changes in the way sections of the model interact with each other, the removal or addition of parts, and any other changes that may occur in the model during the course of the analysis.

3.2.6.2 Specify output requests.

Output is described by generating output requests, which are then passed on to future analysis processes. An output request specifies which variables will be output during an analysis step, from which part of the model they will be output, and at what rate they will be output (for example, forces, displacements, stresses, and so on).

3.2.6.3 Interaction properties

Through the interaction module, a perfect bond was defined between the Bamboo Scrimber and the steel. Epoxy Resin and steel rebar, as well as the bamboo Scrimber material, were bonded using a surface-to-surface contact interaction type. In order to prevent any relative slip, we used ABAQUS' 'tie-constraint' interaction attribute.

3.2.6.4 Applying boundary conditions and loads to the model

Conditions, such as loads and boundary conditions, are step-dependent, requiring that the step or steps in which they become active be specified. Once the analysis has determined the step, the required conditions can be defined.

Boundary conditions were added to parts of this model where displacements and/or rotations were known. These regions may be limited to remaining stationary throughout

the simulation or may have specified nonzero displacements and/or rotations. One of the supports in this model is a pin, while the other is a roller. The upper regions of the loading plates were subjected to a 2mm/minute or 0.033mm/second velocity loading.

3.2.7 Mesh and element types

The mesh module is one of the most important processes in using the finite element method to solve an engineering problem, which entails discretizing a system into finite elements and choosing element types that closely match the real physical behaviour of the system. ABAQUS provides a variety of element types to use for analyses of different types.

The Mesh module offers tools that enable the production of meshes on ABAQUS/CAE-created parts and assemblies. In ABAQUS/CAE, the meshing technique, element shape, and element type were specified.

However, an ABAQUS analysis will not run or it would give unreasonable results if the wrong choice of element type(s) is made. In this section, the choice of element types for the SRBS matrix and the steel reinforcement bar considered in the 3D model for the four-point bending test is discussed.

3.2.7.1 Bamboo scrimber element types

The Bamboo Scrimber beam was modelled using solid 3D linear stress hex elements. In ABAQUS, these element types are labelled as C3D8R, which corresponds to an 8-node linear brick with reduced integration and hourglass control. They are the optimal choice for simulating the 3D Bamboo Scrimber matrix for the four-point bending test. A total of (404+404+3434) 4242 DC3D8 elements were generated when the Bamboo Scrimber Material was seeded with a mesh of size 25mm (See Figure 3.10).

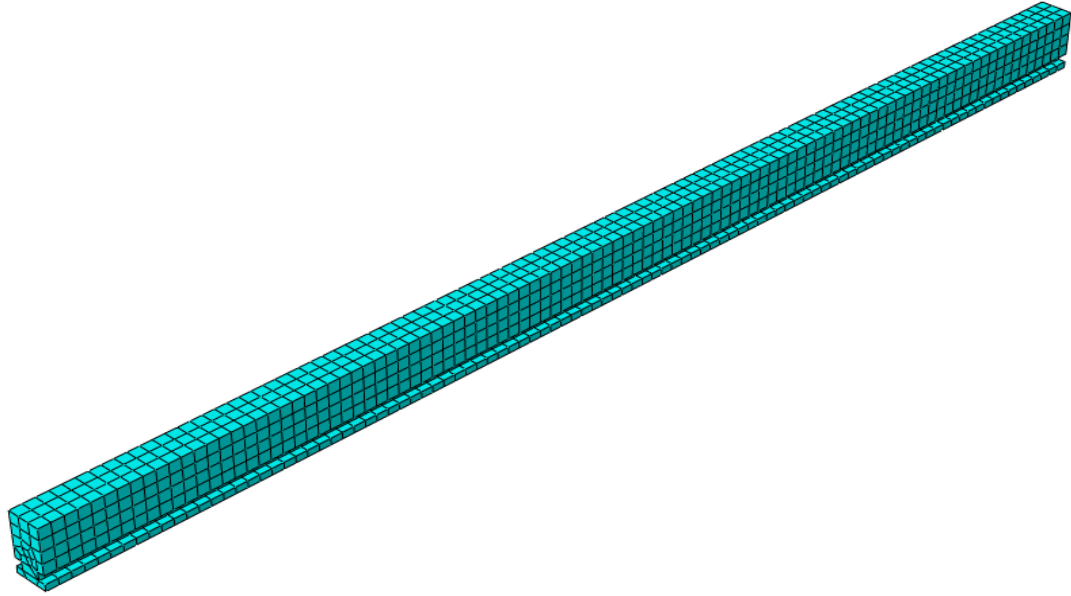


Figure 3.10: BSB matrix meshed with ABAQUS 4242 DC3D8

3.2.7.2 Epoxy resin element types

The epoxy resin was modelled with standard linear cohesive solid hex elements. These element types are designated in ABAQUS as COH3D8 which is an 8-node three-dimensional cohesive element. Through a number of simulations, they are found to be the most appropriate to model a cohesive element. The Epoxy Resin Material was seeded with a mesh of 5 size and a total of 16032 COH3D8 elements were created (see Figure 3.11).

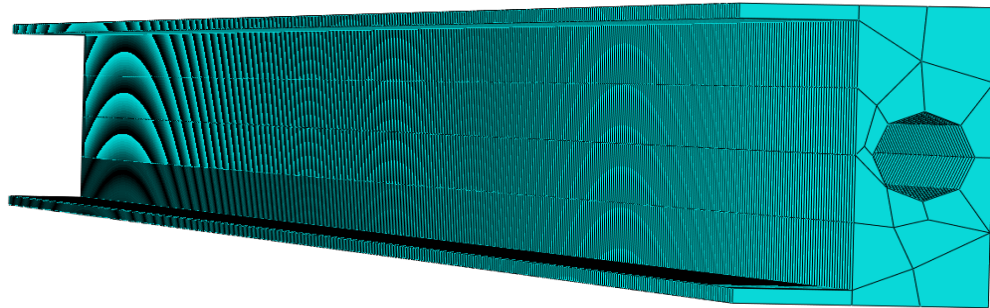


Figure 3.11: Epoxy resin matrix meshed with ABAQUS 16032 COH3D8

3.2.7.3 Steel element types

The steel reinforcement bars were modelled using 8-node linear brick, reduced integration, and hourglass control elements, which are linear 3D solid tetrahedral elements. In ABAQUS, these element kinds are identified as C3D8R. They are the optimal choice of modelling elements for the integrated 3D steel reinforcing bar in a four-point bending test. The steel reinforcing bars were seeded with a 15-size mesh and 398 DC3D8 elements were generated (see Figure 3.12).



Figure 3.12: Steel reinforcement bar meshed with ABAQUS 398 DC3D8

3.2.7.4 Rigid elements

A rigid body is made up of nodes, and components in ABAQUS whose movement is governed by a single node called the rigid body reference node. This beam contained a total of four stiff components (see Figure 3.13).

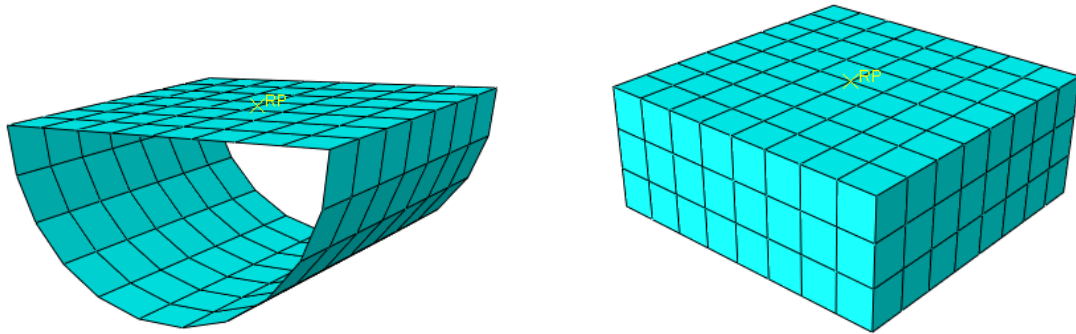


Figure 3.13: Matrix of the rigid plates (support and loading

3.2.8 Analysis Module “Job”

After performing all model definition-related tasks (such as defining the model's shape, assigning section attributes, and identifying contacts), the job was used to analyse the model. The job module allows users to create jobs, submit them for analysis, and monitor their progress. In this investigation, numerous jobs with distinct parameters were generated, executed, and monitored concurrently to achieve multiple outcomes.

3.2.9 Visualization

The Visualization module was used to read the output database generated by ABAQUS/CAE during the study to view and analyse the results.

3.3 Chapter overview

This chapter discussed the approach used to accomplish the study's objectives. The chapter described the general assembly of the model in order to lay the groundwork for the designation of the beams to be analysed utilizing this study's numerical technique. Then, as an appropriate method for this study's examination, the ABAQUS Standard Dynamic Explicit software program in ABAQUS was utilised. The methodology for developing three-dimensional finite element models for the analysis of steel-reinforced bamboo Scrimber beams utilizing a four-point bending test in ABAQUS was provided, as well as an investigation methodology for which the results are reported in the next chapter. Following the development of the FE models, the examination of flexural rigidity using a four-point bending test can be explored, and this information is provided in the following chapter.

CHAPTER 4 : RESULTS

4.1 Introduction

Finite element models of steel-reinforced bamboo Scrimber beams were created following the approach presented in the preceding chapter. Here, the models are evaluated and validated in comparison to experimental results. The models are then employed in the parametric analysis to determine flexural rigidity. The following is the structure of this chapter: Specifically, Section 4.2 has presented the predicted and experimental load-displacement response, Section 4.3 has the predicted and experimental strain distribution, Section 4.4 has presented the predicted and experimental strain distribution at mid-span, and Section 4.5 provides an overview of this chapter.

4.2 Load-displacement response

Figures 4.2 to 4.6 shows the load-displacement relationships of the beams tested. The simulated results showing the stress and deflection of the SRBS beams are shown in Figure 4.1 and Figure 4.7, respectively. Generally, the curves demonstrate overall linear features initially until a certain loading level, which was varied from curve to curve. However, there were slope reductions in the later stage, which were likely caused by local deformations in the Bamboo Scrimber material interface regions. The graphs clearly show the distinguished initial stiffness of beams with different reinforcing arrangements compared with the beam without any reinforcement.

On the load-displacement curves, the line of standard deflection of a wood member according to De Normalisation, (2004) is $L/300$ (L is span) is plotted and coincides with the curve. The point at which the $L/300$ line coincides with the curve is the increase in the load for that particular beam. This value is then recorded in Table 5.1 and together with the increase in the midspan deflection, the distance between the support and the nearest loading point, and the clear span is used to calculate the flexural rigidity of the beam corresponding to the serviceability limit state of the test beams in the elastic stage.

The load-displacement response yields an average absolute error of the ultimate bearing capacity and flexural rigidity of 3.25 Percent and 9.83 Percent respectively. Based on the maximum percentage difference between the FE and experimental responses, it can be

concluded that the general FE model is calibrated and properly validated. Further details are explained in section 5.2 of chapter 5 of this study.

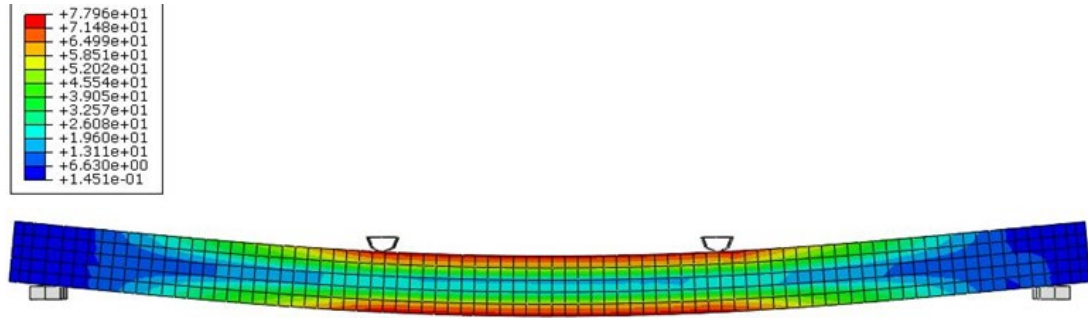


Figure 4.1: Stress distribution of FE model of the SRBS

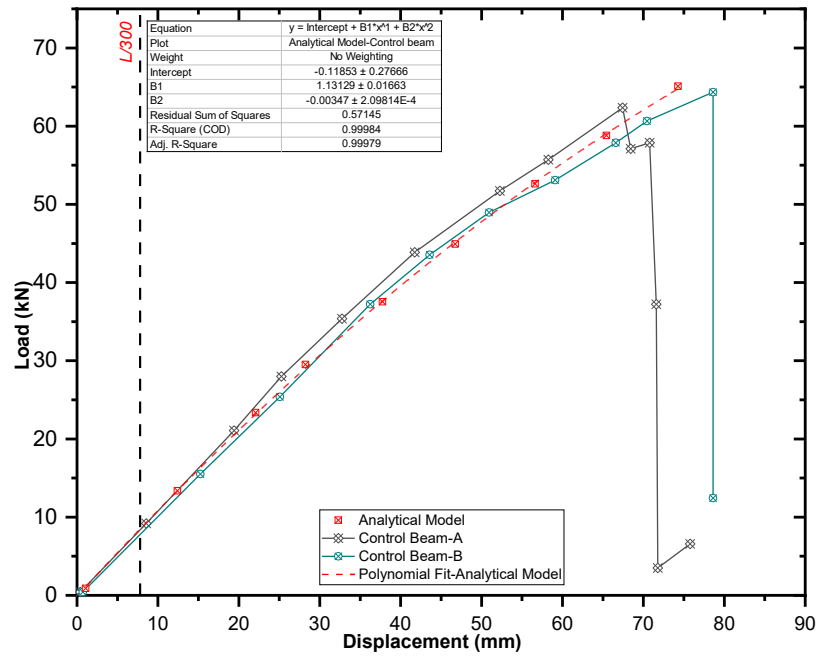


Figure 4.2: Contrast between the analytical and experimental load-displacement curves of BSB_S0.

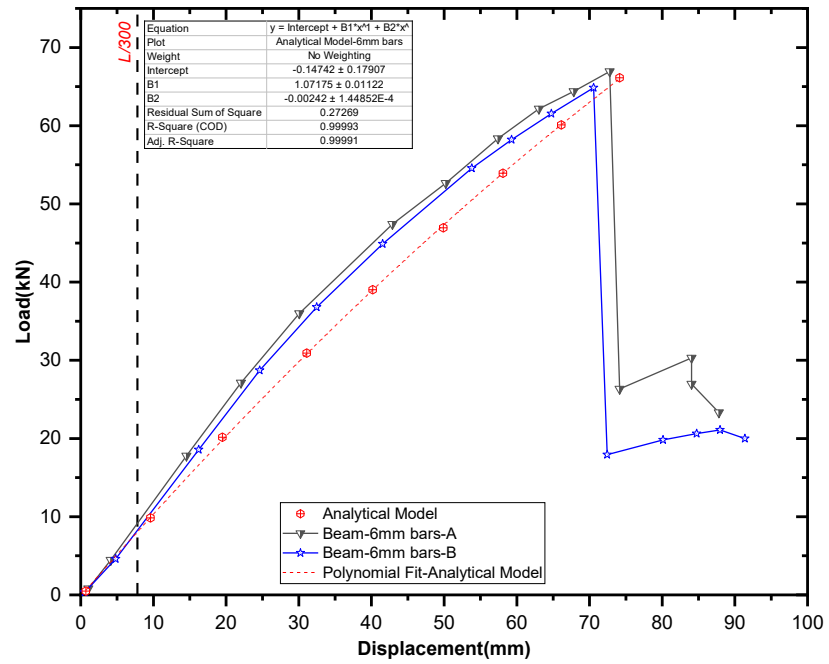


Figure 4.3: Contrast between the analytical and experimental load-displacement curves of BSB_S6

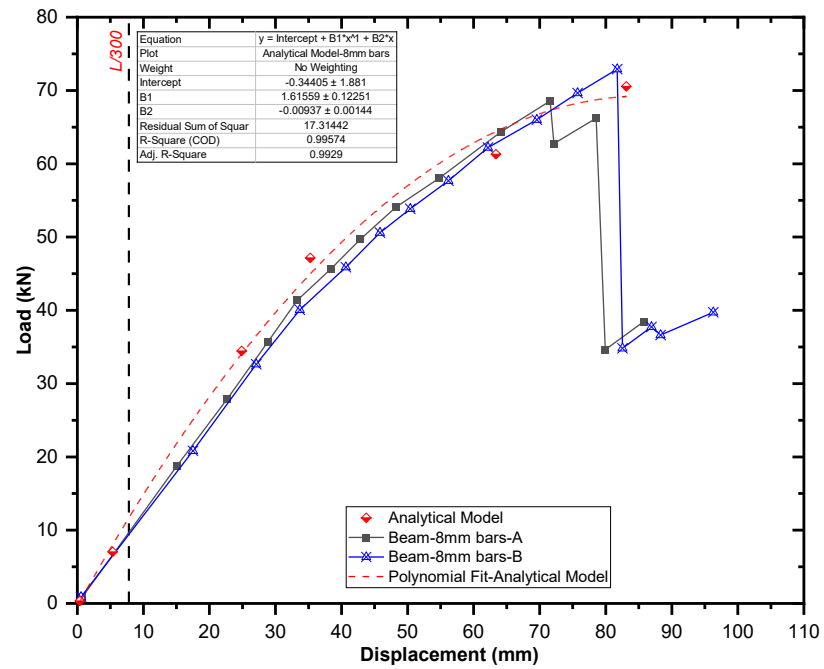


Figure 4.4: Contrast between the analytical and experimental load-displacement curves of BSB_S8.

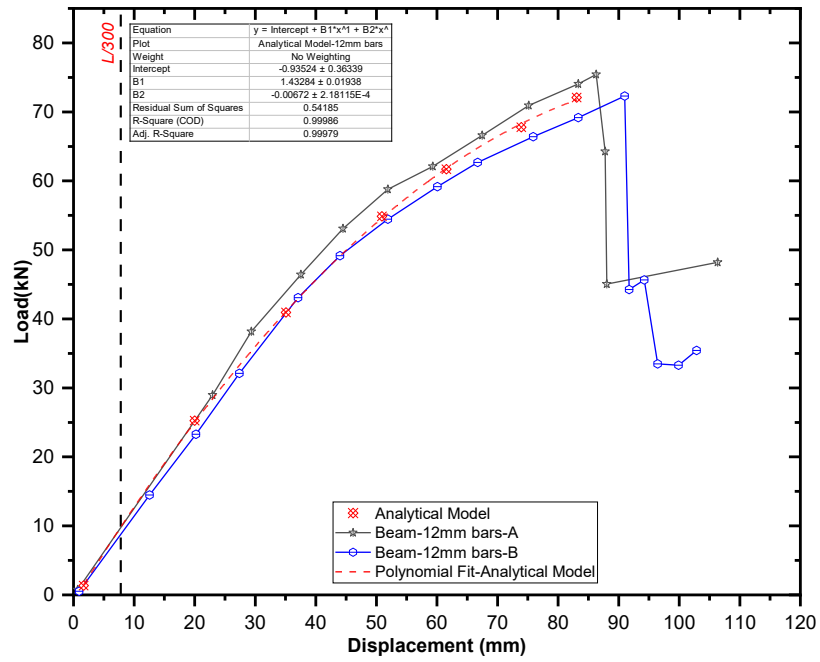


Figure 4.5: Contrast between the analytical and experimental load-displacement curves of BSB S12

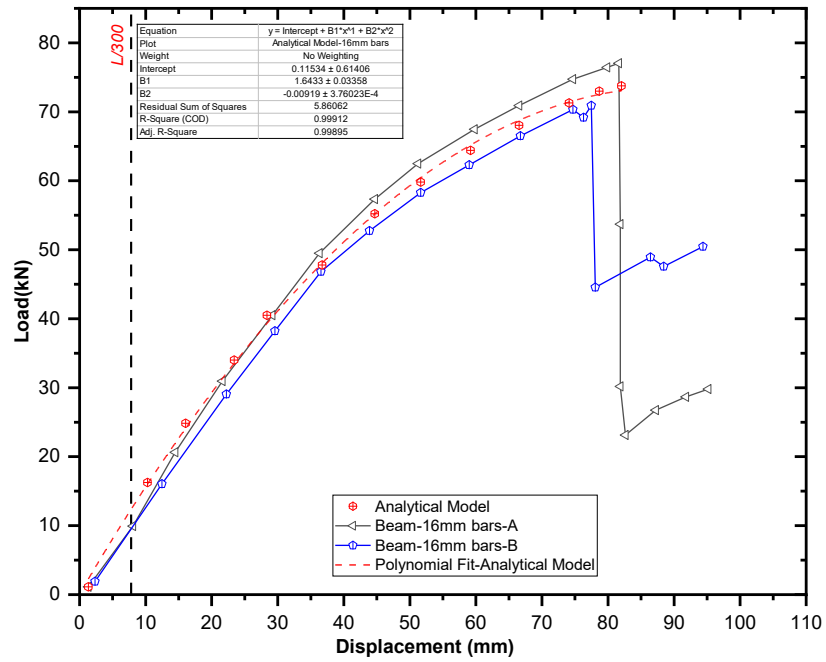


Figure 4.6: Contrast between the analytical and experimental load-displacement curves of BSB S16

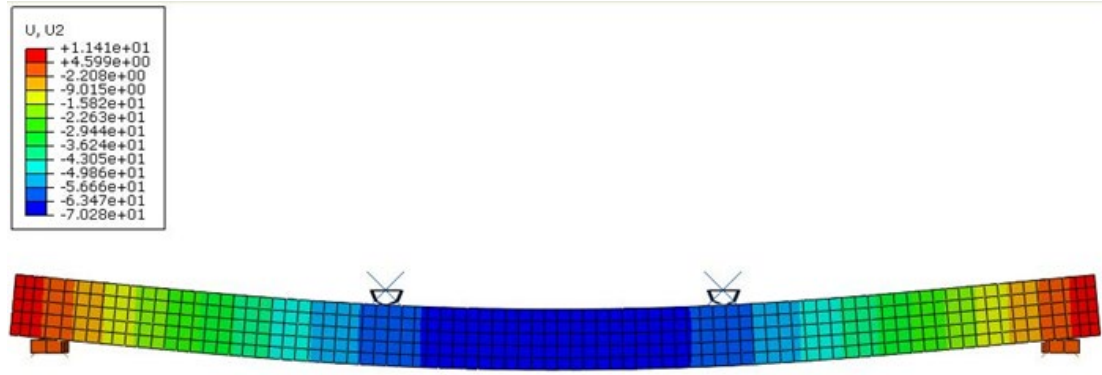


Figure 4.7: Deflection of a FE model of the SRBS

4.3 Strain distribution

Figures 4.8 to 4.12 show the comparison of the analytical and experimental load-strain curves for the tested beams with reference to Figure 2.10 for strain gauges for the control beams and strain gauges for the reinforced bamboo Scrimber beams.

From the results in all the tested beams it can be seen that the top portion of the cross-section with strain gauge node point numbers 1-5 falls on the negative side of the curves denoting compression while the points from 6 to 10 are on the positive denoting a tensile strain on the beam. This is in accordance with Euler-Bernoulli's beam theorem in which for the bending beam, the greatest tensile and compressive stresses occur on the outer covers of the beam. The neutral axis or the layer that runs along the middle of the beam experiences zero stresses while bending as can be seen in the curves between strain gauges 5 and 6 or halfway the height of the beam (70mm) which corresponds to a zero stress.

From the FEM's analytical results, it can be seen that the strain and load increase in a straight line at the beginning of the process. When the load gets to about 50% of the peak load, the bamboo starts to bend more in the compression zone. As the reinforcement ratio goes up, so do the bamboo beams' ultimate compressive strain and compressive stress.

The dashed lines indicate the FEM results and are denoted by "An" meaning analytical while the solid lines are denoted by "Ex" meaning experimental results. A good correspondence between the FEM results and the Experimental results is noticed and further explained in section 5.3 of chapter 5.

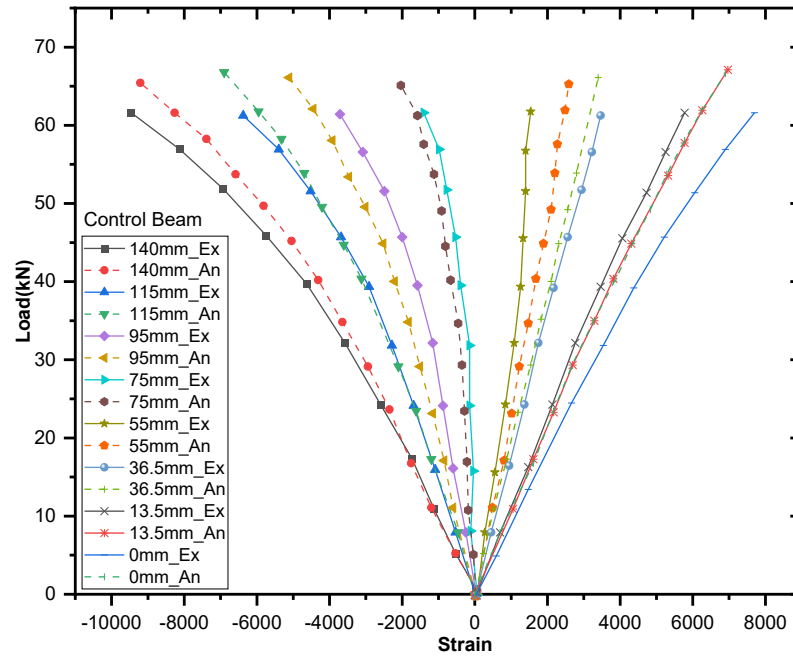


Figure 4.8: Contrast of the load-strain curves determined analytically and experimentally for BSB S0.

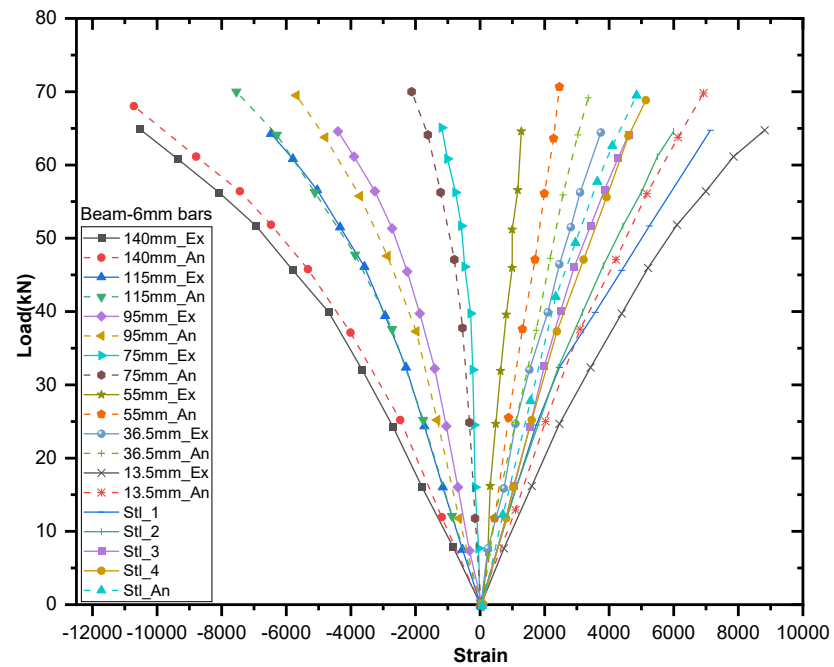


Figure 4.9: Contrast of the load-Strain curves determined analytically and experimentally for BSB S6.

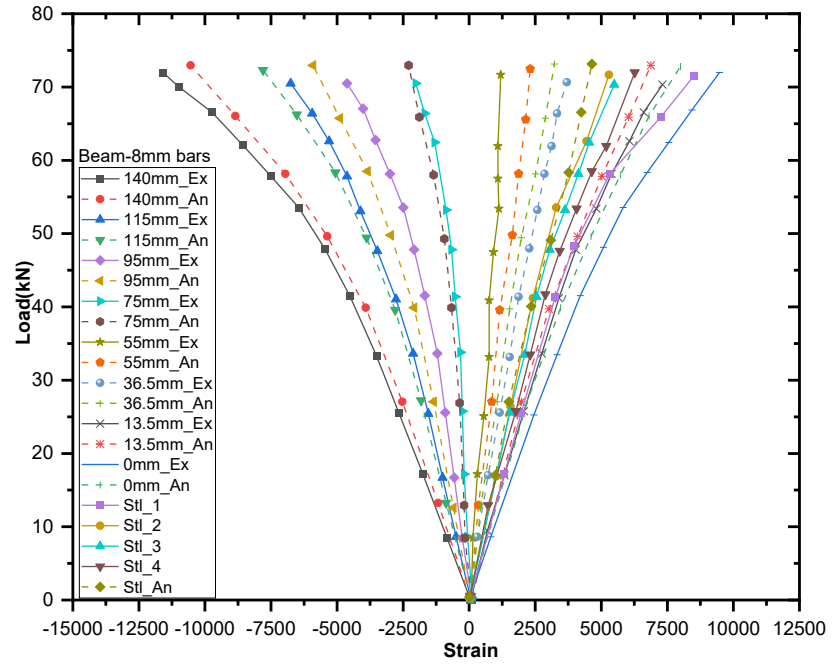


Figure 4.10: Contrast of the load-Strain curves determined analytically and experimentally for BSB S8.

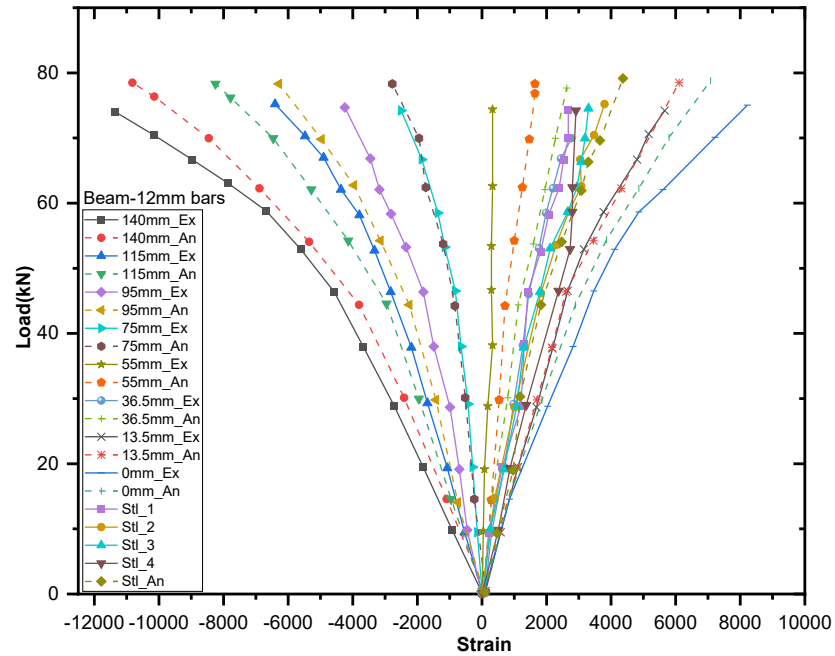


Figure 4.11: Contrast of the load-Strain curves determined analytically and experimentally for BSB S12

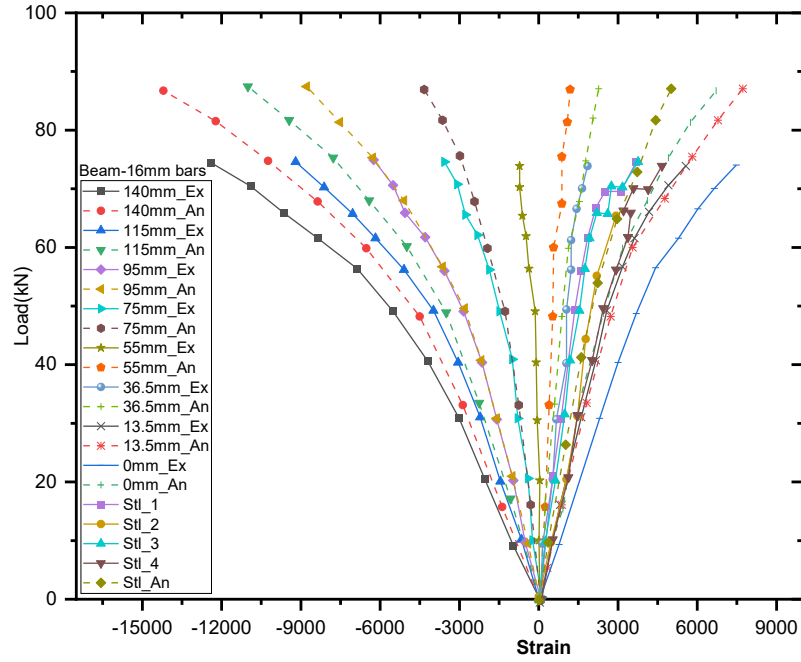


Figure 4.12: Contrast of the load-Strain curves determined analytically and experimentally for BSB_S16

4.4 Strain distribution at the mid-span cross-section of reinforced bamboo beams

The Comparisons of the analytical and experimental strain distribution at the mid-span cross-section of the beams are shown in Figures 4.13 to 4.17. According to the results of the finite element analysis, it can be seen that, in the initial stage of test loading, the strain is linearly distributed along the height of the cross-section, and the position of the neutral axis of the cross-section is invariably stable. With the increase of the load and moment, the bamboo in the compression zone of beams enters the plastic yield stage, the compression modulus decreases, and the neutral axis moves down correspondingly as further explained in section 5.4 of chapter 5.

Above the neutral axis of the beam, the section experiences compression stress while the area below the neutral axis experiences tension stress. Steel reinforcement is provided in the tensile stress region because the bamboo Scrimber fibre material is weak in tension,

The strain distribution shows that bamboo Scrimber reaches a maximum at the top of the beam (in compression) and a maximum strain in steel at the bottom portion of the beam (in tension). At a depth from the compression face, the stress is zero at the neutral axis as can be seen in Figures 4.13 to 4.17. At the time when failure occurs at ultimate limit state, steel and the bamboo Scrimber material reach their maximum stress and strain.

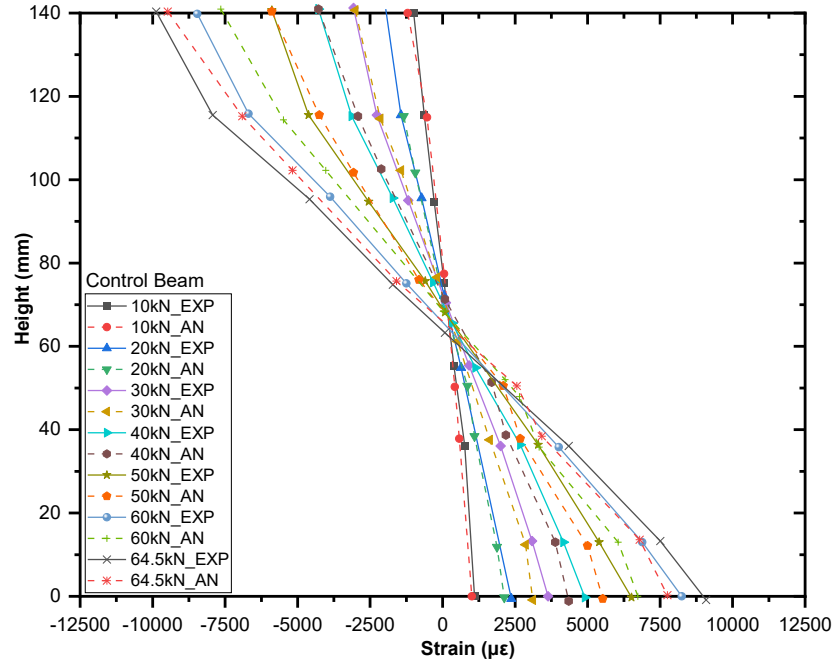


Figure 4.13: Contrast between the analytical and experimental distributions of strain at the control beams' mid-span cross section

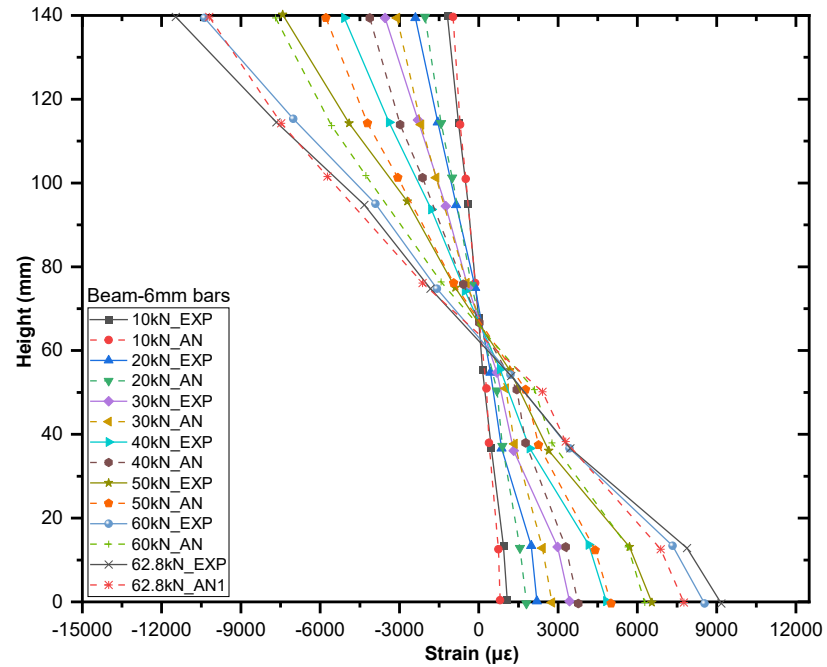


Figure 4.14: Contrast between the analytical and experimental distributions of strain at the mid-span cross section of BSB_S6

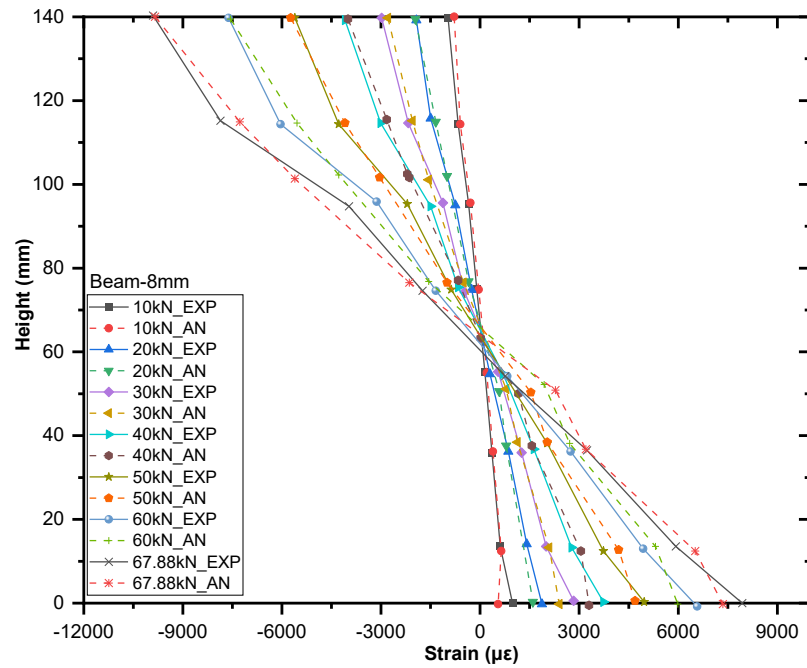


Figure 4.15: Contrast between the analytical and experimental distributions of strain at the mid-span cross section of BSB_S8

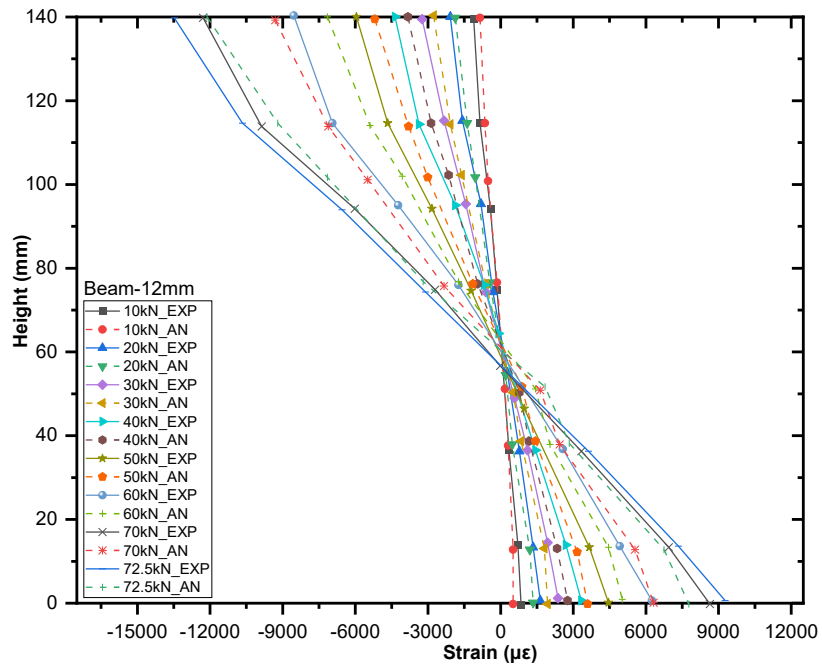


Figure 4.16: Contrast between the analytical and experimental distributions of strain at the mid-span cross section of BSB_S12

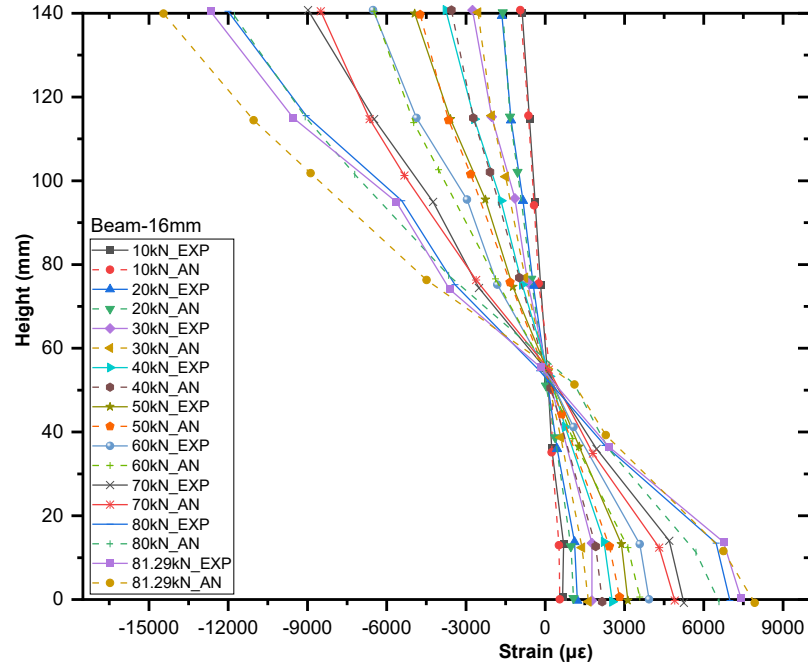


Figure 4.17: Contrast between the analytical and experimental distributions of strain at the mid-span cross section of BSB S16

4.5 Chapter overview

This chapter presented results that were observed during the study. The chapter began by first comparing the predicted and experimental Load Displacement response. The strain distribution throughout the length of the beam was given next, followed by the strain distribution at the mid-span cross-section. The results of the created FEM model were in close accord with experimental findings. Generally, a good matching between numerical and experimental results was obtained even if there was a minor variation in the approximation of the reality.

Although the created FEM models were in close accord with experimental data, they had their own limits. These limits may be the consequence of random and instrumental errors during the experiment; numerical approaches are influenced by the specified physical model and its parameters. In contrast, the used mesh is another source of variations in results. The combination of mesh, models, adaption and convergence process affect the simulation as well.

CHAPTER 5 : DISCUSSION

5.1 Introduction

This chapter discusses in detail the results that were obtained and presented in the preceding chapter. The following is the structure of this chapter: Specifically, Section 5.2 has discussed the predicted and experimental load-displacement response, Section 5.3 has discussed the analytical strain distribution, Section 5.4 has discussed the predicted and experimental strain distribution at mid-span, and Section 5.5 provides an overview of this chapter.

The chapter includes explanations and interpretations of the results in the context of the problem statement and literature review, and follows to discuss the implications, acknowledges their limitations, and gives recommendations. Conclusions in terms of the trends and material behaviours under different parametric conditions were drawn based on the understanding of the results deduced from this chapter.

5.2 Load displacement response

An illustration of the contrast between the analytical and experimental load-displacement curves is shown in Figures 4.2 to 4.7. This shows that the load-displacement curve generated by the finite element method (FEM) is compatible with the test results, particularly during the early elastic stage and the yield stage. It demonstrates that the FEM is capable of simulating the four-point bending test of bamboo beams with acceptable accuracy. On the subject of maximum load-carrying capacity, the modelling results are marginally greater than the test results. Specifically, the European Committee for Standardization (De Normalisation, 2004) specifies that when a wood member is employed as a bending beam, the prescribed deflection at the serviceability limit state is $L/300$ mm (L is the span). This test was carried out to determine the flexural capacity at a deflection of $L/300$ (7.8 mm), which was then transformed into the measured cross-sectional stiffness for the sake of comparison. As indicated in equation 5.1, the bending stiffness can be converted by increasing the load at the elastic stage and decreasing the deflection at the mid-span

$$EI = \frac{\Delta Pl}{48\Delta w} (3L^2 - 4l^2) \quad \text{Equation 5.1}$$

where E is the elastic modulus in N/mm^2 ; I is the moment of inertia of the reinforced beam's cross-section in mm^4 ; ΔP is the load increment at the elastic stage in N ; $\Delta \omega$ is the displacement increment corresponding to the load increment at the elastic stage in mm ; L is the net span in mm ; and l is the distance between the bearing and the nearest loading point in mm .

The flexural rigidity ($EL_{/300}$) at $L/300$ corresponding to the serviceability limit state of the test beams in the elastic stage can be calculated by substituting the data obtained from the four-point bending test, as shown in Table 5.1. The average flexural stiffness at $L/300$ is compared by groups in Figures 5.1 to 5.3. The flexural stiffnesses ($EL_{/300}$) of the reinforced beams are approximately -1.27%~47.11% higher than those of the control beams. The average flexural rigidities of BSB_S6, BSB_S8, BSB_S12 and BSB_S16 are enhanced by -1.27%, 41.11%, 18.32%, and 47.11%, respectively. The flexural rigidity increases almost linearly with an increasing reinforcement ratio, which indicates that the reinforcement and the bamboo Scrimber beam can work together with the epoxy resin and are in an ideal intact state. The load corresponding to $L/300$ also increases with an increasing reinforcement ratio, increasing from an average of 8.18 kN for the control beams to 12.01 kN for the beams reinforced with 16 mm bars, an enhancement of 46.82%.

Table 5.2 lists the ultimate bearing capacity, bending stiffness, and error analysis of reinforced bamboo beams. The ultimate bearing capacity and flexural rigidity computed using finite element simulation are slightly greater than those established by test analysis, with an average absolute error of 3.25 percent and 9.83 percent, respectively. This is because the finite element model had a thicker layer of epoxy resin than the experiment and because the model utilized a different approach to cover the side grooves of the beam body; however, this has no effect on the overall outcome of the finite element simulation.

Table 5. 1: Test results for the reinforced bamboo Scrimber beams.

Experimental Run	Ultimate Load (kN)	Increase Ratio of ultimate Load (%)	$P_{(L/300)}$	Increase Ratio of ultimate $P_{(L/300)}$	$EI_{(L/300)}$ (10^8 kN·mm ²)	Increase Ratio of $EI_{(L/300)}$ %	Ultimate Displacement(mm)	Ultimate tensile strain ($\mu\epsilon$)	Ultimate compressive strain ($\mu\epsilon$)
BSB_S0	65	N/A	8.18	N/A	2.38	N/A	73	6898.39	-9210.17
BSB_S6	66.17	1.80	8.06	-1.47	2.35	-1.27	74	7808.84	-10721.93
BSB_S8	69	6.15	11.52	40.83	3.36	41.11	78	7995.43	-10543.63
BSB_S12	71.9	10.62	9.66	18.09	2.82	18.32	79	8199.22	-9727.9
BSB_S16	73.01	12.32	12.01	46.82	3.50	47.11	83	6717.08	-14199.19

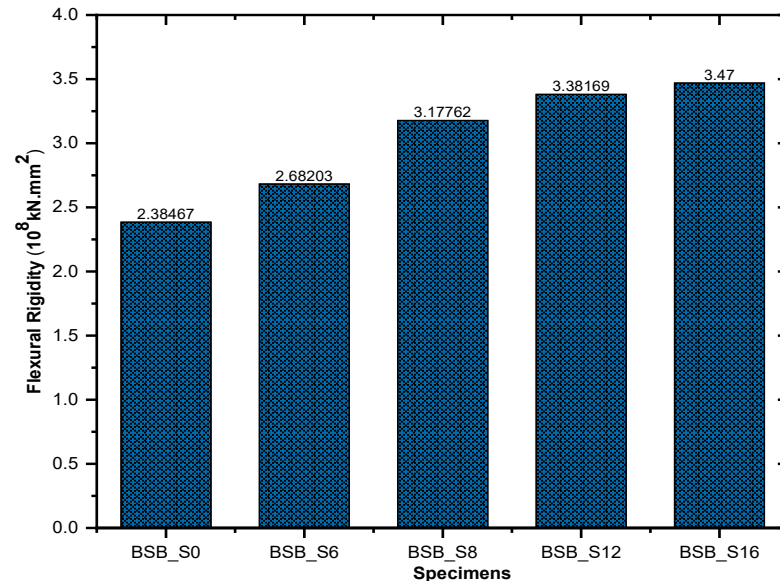


Figure 5.1: Comparisons of the ultimate flexural rigidity of the reinforced bamboo scrimber beams by FEM

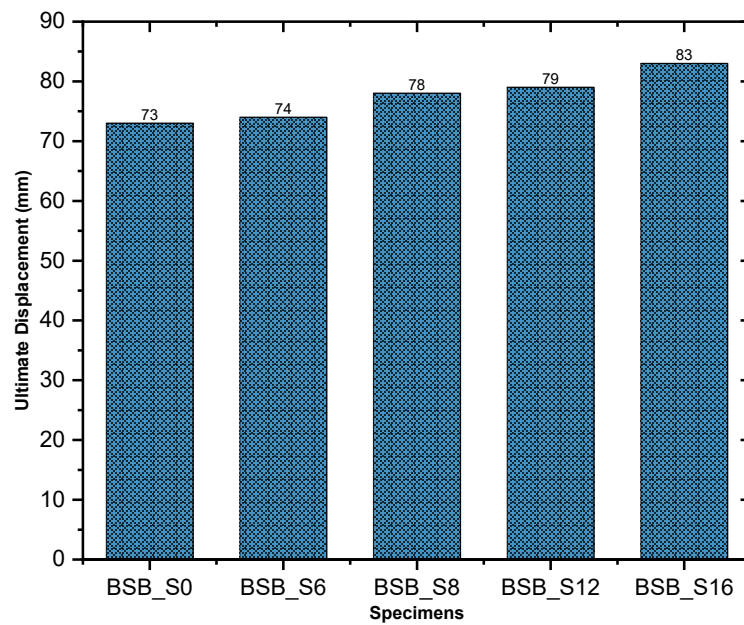


Figure 5.2: Comparisons of the ultimate displacement of the reinforced bamboo scrimber beams by FEM.

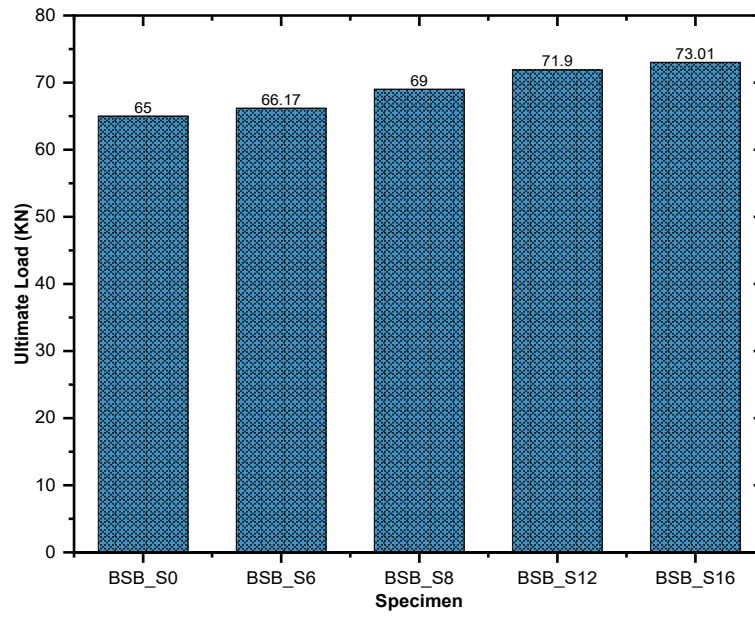


Figure 5.3: Comparisons of the ultimate flexural capacity of the reinforced bamboo scrimber beams by FEM.

	Ultimate Load				Cross-Sectional Stiffness $EI_{(L/300)}$			
Beam Type	Analytical I (kN)	Growth Rate	Experimental (kN)	Error	Analytical 10^8 kN.mm ²	Growth rate (%)	Experimental (10^8 kN.mm ²)	Error (%)
BSB_S0	65	N/A	63.28	2.72	2.38	N/A	2.4	0.83
BSB_S6	66.17	1.8	64.14	3.16	2.68	12.61	2.51	6.77
BSB_S8	69	6.15	69.88	1.26	3.18	33.61	2.67	19.10
BSB_S12	71.9	10.62	73.93	2.75	3.38	42.02	2.93	15.36
BSB_S16	73.01	12.32	77.96	6.35	3.47	45.80	3.24	7.10

Table 5.2: Experimental and numerical contrast of the bending behaviour of reinforced bamboo Scrimber beams

5.3 Strain distribution

As illustrated in Figures 4.8 to 4.12, the experimental load–strain curves of specimens are compared to the analytical curves with the tensile strain being positive and the compressive strain being negative. Because ABAQUS software can only extract stress and strain values at the element or node level, 8 elements are separated according to the grid partition, and the nodes closest to the actual strain gauge are picked in order. Nodes have heights of 0 mm, 13.5 mm, 36.5 mm, 55 mm, 75 mm, 95 mm, 115 mm, and 140 mm. As can be observed from the analytical results obtained using the FEM, strain and load increase linearly during the early stage. When the load is approximately 50% of the peak load, the bamboo plastic deformation in the compression zone becomes more apparent. The ultimate compressive strain and compressive stress of bamboo beams increase proportionately as the reinforcement ratio increases. The maximum value for bamboo BSB_S16 is 14199.19 (up to 54.16%), while the maximum value for pure bamboo beams is 9210.17 $\mu\epsilon$. Due to the fact that steel bars have a far smaller elastic strain than bamboo, they enter the plastic yield stage early, resulting in the entire tension area of the bamboo beam having elastic-plastic properties.

5.4 Strain distribution at the mid-span cross-section of reinforced bamboo beams

Figures 4.13 to 4.17 compares the mathematical and experimental strain distributions in reinforced bamboo beams' mid-span cross-sections. When the findings of the FEM strain distribution are compared to those of the testing, it is discovered that the two curves practically coincide. For example, the ultimate strain estimated by FEM is 7622.21 $\mu\epsilon$, while the ultimate strain determined by test results is 7428.14 $\mu\epsilon$, and the relative error is just 2.61 percent for the BSB_S16. This demonstrates that the strain and stress in reinforced bamboo beams can be precisely calculated using finite element modelling.

According to the findings of the finite element analysis, the strain is linearly distributed throughout the height of the cross-section during the initial stage of test loading, and the location of the cross-section's neutral axis is consistently stable. When the load is increased, the bamboo in the compression zone of beams enters the plastic yield stage, the compression modulus lowers, and the neutral axis moves downward. For instance, the

neutral axis BSB_S0 shifts from 71.3 mm in the elastic stage to 66.0 mm from the top in the final state. In comparison, the neutral axis of the experimental specimen of the control beam shifts from 72.2 mm to 65.4 mm.

The similarity of the results demonstrates the practicality of the finite element model. Under the same load level, the strengthened steel beams can help to alleviate bamboo's bottom tension strain. For example, with a load of 20 kN, the analytical bottom tension strain of BSB_S0 is 2016 $\mu\epsilon$, but the reinforced beam BSB_S12 has a value of 1366 $\mu\epsilon$, indicating that the steel bars can efficiently share the tensile stress generated by the bottom bamboo fibres.

5.5 Chapter overview

This chapter discussed the results that were presented in chapter 4. The chapter began by first discussing the load-displacement response followed by the discussion of the strain distribution and finally the strain distribution at mid-span. The discussion provided an explanation of the phenomena that were observed and studied.

The results are explained and interpreted in the chapter, after which the implications are discussed, their limits are acknowledged, and suggestions are made. Based on an understanding of the information from this chapter, conclusions were reached on the trends and material behaviours under various parametric settings.

CHAPTER 6 : PARAMETRIC STUDY

6.1 Introduction

A sensitivity study was carried out to determine the influence of various parameters on the flexural capacity of the Bamboo Scrimber Beam when exposed to a four-point bending test load. The primary parameters examined in this sensitivity study were: (1) the effect of the variation of material properties such as epoxy resins strength, the steel material characteristics, and the steel diameters (2) the influence of steel bar spacing on the flexural capacity and (3) the effect of the reinforcement ratios on the flexural capacity of the SRBS Beams.

6.2 Impact of material variation of epoxy resin and steel physical properties on the flexural rigidity

In this study, the impact of variations of the Epoxy Resin material characteristics and the steel diameters on the bearing capacity of the SRBS beam were examined. The material characteristics of the bamboo Scrimber and the material characteristics of the steel were held constant as they were the only types available from the experimental study and the type of reinforcing steel respectively.

As multiple inputs have an effect on the output in this study, it is critical to note that when conducting the sensitivity analysis, the Design of Experiments (DOE) criteria were used to determine the individual and interactive effects of various parameters that can affect the numerical study's output results. The DOE helped to study the relationship between the multiple input variables and key output variables, in order to have the maximum information from the minimum number of tests that will enable us to make a decision.

The DOE is a subsection of applied statistics that deals with the planning, execution, analysis, and interpretation of controlled tests with the goal of discovering the variables that affect the value of a parameter or combination of parameters. DOE is a highly adaptable data collection and processing technique that may be used in a broad variety of experimental conditions (Yuangyai and Nembhard, 2010).

It is a strategy for rapidly exploring the correlations between parameters and gaining a better understanding.

The DOE software that was used in this case is called JMP Statistical Discovery version Pro 16.0.0.

6.2.1 Parametric research methodology

The DOE strategy was utilized in this study to analyse the parameters of interest and their variations in order to achieve a cost-effective optimum number of tests to run in the ABAQUS simulation program. The materials input variables for this study used were as follows; Bamboo Scrimber material, Epoxy Resins strength, steel material characteristics, and steel diameters.

6.2.1.1 Design of experiments

Numerous industrial processes in engineering are either not optimized or appear to be subject to random variance. Due to the quantity of required testing, researchers have found it challenging to make critical modifications.

The experimental design provides a strategy for obtaining the most information from the fewest tests. In addition, vital information can be gathered regarding interactions between variables. Interactions are frequently quite essential but might be ignored when only one variable is altered at a time.

During this study, JMP software required identifying the essential parameters and their influencing elements prior to executing them in the software package in order to acquire the smallest number of tests.

6.2.2 Details of materials used in the parametric study

6.2.2.1 Hardened epoxy resin

A compound of epoxy resin and a hardener called Zirconia (ZrO_2) was used. The combination of epoxy resin with the hardener is a mixture of highly dispersive ultrafine nanoparticles prepared using a modified sol-gel process and used as fillers in epoxy resins with higher tensile strength, tensile modulus, fracture toughness, critical strain energy release rate, and hardness than neat epoxy resin. As shown in the stress-strain curve of Figure 6.1, the yield strength of the composites was greatly enhanced as a result of the integration of nanoparticles and more cross-connection between nanoparticles and matrix.

The typical stress-strain curves of ZrO_2 reinforced epoxy resin nanocomposites from which effects of Nano-zirconia contents (0–5 wt.%) on the tensile strength and elasticity modulus are obtained (Ma *et al.*, 2018). Curves indicate that the higher the percentage of the hardener the greater the strength of the material.

The use of the modified type of epoxy resin was intended to have different strengths of the compound in order to be used for the parametric study. The following were the mixtures; Epoxy Resin with 1% hardener, Epoxy Resin with 2% hardener, Epoxy Resin with 3% hardener Epoxy Resin with 4% hardener and Epoxy Resin with 5% hardener.

Appendix A1.2 shows the material calibration values and curves of hardened epoxy resin as extracted from MCalibration v633 that was used in ABAQUS.

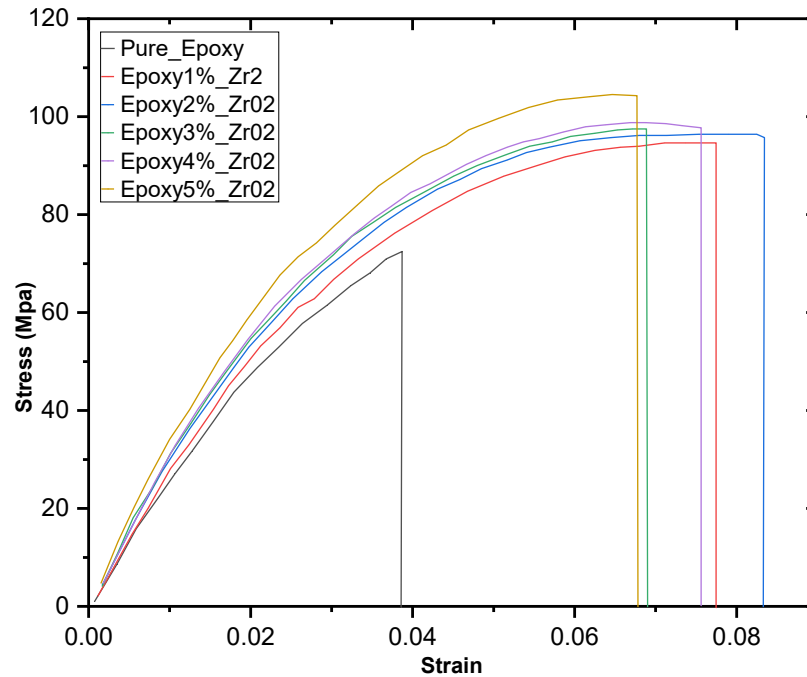


Figure 6.1: The stress-strain curves of ZrO_2 /epoxy resin nanocomposites.
Extracted from Ma *et al.* (2018)

6.2.2.2 Bamboo scrimber material

Only one type of Bamboo Scrimber material was used, and the mechanical parameters of bamboo Scrimber were determined using the collected experimental data from literature according to Wei *et al.*, (2020c). The ultimate tensile strength, elastic modulus, and ultimate tensile strain of the bamboo Scrimber were determined to be 131.9 MPa, 15.6

GPa, and 0.0078, respectively, while the ultimate compressive strength, elastic modulus, and ultimate compressive strain were determined to be 105.2 MPa, 12.7 GPa, and 0.054, respectively (ibid).

6.2.2.3 Steel

Four steel bars with diameters of 6 mm, 8 mm, 12 mm, and 16 mm were utilized in this test. The only type of reinforcing steel utilized in this experiment was S460. This choice was motivated by the frequency with which S460 is utilized as reinforcing steel in beams and columns. The tensile strength of the steel rebar was 460 MPa, and the elastic modulus varied from 201.1 to 204.3 GPa. The yield strain ranged from 0.0020 to 0.0022. The mechanical properties of steel bars of differing diameters were the same.

6.2.3 Design of experiments using the JMP software package

Generally speaking, there are two groups of DOE: classical and contemporary designs.

The following designs are examples of classical styles:

- Full factorial designs:
- Fractional factorial designs (Screening designs)
- Response surface designs
- Mixture designs.
- Taguchi array designs.
- Split plot designs.

In this investigation, full factorial designs were utilized, which yielded a substantial amount of data when combined. Following this, a screening technique was utilized to reduce the number of potential combinations while preserving the relevance level.

6.2.4 Full factorial design

A full factorial design enables the researcher to examine the influence of each factor on the response variable, as well as the effects of interactions between factors. In a full factorial experiment, experimental units are assigned randomly to any of the discrete possible values or "levels" associated with each of the study's components.

From Figure 6.2 and Table 6.1, twenty experimental runs were created from the selected parameters shown in the responses TAB. It depicts the responses, the variables, the number of experimental runs, and the run requirements.

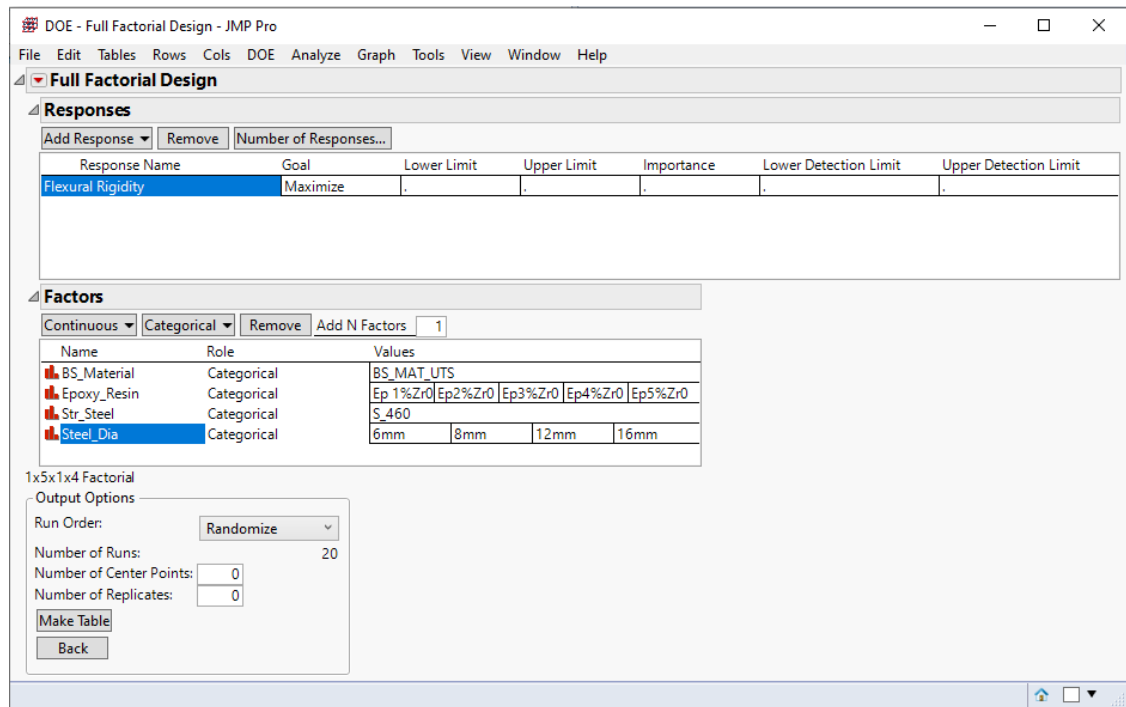


Figure 6.2: Image from JMP PRO depicting the responses, the variables and the number of experimental runs.

Table 6. 1: Full factorial design of the study

Sn	Pattern	BS Material	Epoxy Resin	Strength Steel	Steel Diameter
1	1313	BS_MAT_UTS	Ep3%Zr0	S_460	12mm
2	1111	BS_MAT_UTS	Ep_1%Zr0	S_460	6mm
3	1211	BS_MAT_UTS	Ep2%Zr0	S_460	6mm
4	1114	BS_MAT_UTS	Ep_1%Zr0	S_460	16mm
5	1411	BS_MAT_UTS	Ep4%Zr0	S_460	6mm
6	1212	BS_MAT_UTS	Ep2%Zr0	S_460	8mm
7	1412	BS_MAT_UTS	Ep4%Zr0	S_460	8mm
8	1513	BS_MAT_UTS	Ep5%Zr0	S_460	12mm
9	1311	BS_MAT_UTS	Ep3%Zr0	S_460	6mm
10	1113	BS_MAT_UTS	Ep_1%Zr0	S_460	12mm
11	1514	BS_MAT_UTS	Ep5%Zr0	S_460	16mm
12	1312	BS_MAT_UTS	Ep3%Zr0	S_460	8mm
13	1413	BS_MAT_UTS	Ep4%Zr0	S_460	12mm
14	1112	BS_MAT_UTS	Ep_1%Zr0	S_460	8mm
15	1512	BS_MAT_UTS	Ep5%Zr0	S_460	8mm
16	1314	BS_MAT_UTS	Ep3%Zr0	S_460	16mm
17	1214	BS_MAT_UTS	Ep2%Zr0	S_460	16mm
18	1511	BS_MAT_UTS	Ep5%Zr0	S_460	6mm
19	1213	BS_MAT_UTS	Ep2%Zr0	S_460	12mm
20	1414	BS_MAT_UTS	Ep4%Zr0	S_460	16mm

6.2.5 Fractional factorial design

6.2.5.1 Screening designs

Screening designs are among the most common industrial experimenting designs. Typically employed in the earliest phases of an experiment, they analyse a large number of variables to discover those that have the biggest impact on the outcome. The discovered parameters are further investigated using more sensitive designs. Owing to the fact that screening designs often require fewer trial runs than other designs, they are a very affordable and effective method for initiating process improvement. If a standard screening design exists for the experimental circumstance, many standard screening designs may be selected. The list includes blocked designs when applicable. The variables may be two-level continuous variables, three-level categorical variables, or continuous variables with only discrete values (discrete numeric factors) (SAS, 2009).

There are instances, however, where traditional screening designs are unavailable. In such situations, the Screening Design platform creates a screening design for the primary effects. The main effects of screening design are orthogonal or nearly orthogonal. It focuses on estimating the main effects in the presence of negligible interactions.

There are two kinds of design layouts:

- Classical designs: In instances where conventional screening designs exist, fractional factorial designs, Plackett-Burman, Cotter, and mixed-level designs can be selected from a list.
- Main effects screening designs: JMP can create a main effects screening design, regardless of whether a standard design is available. These designs are orthogonal or nearly orthogonal and are focused on estimating the main effects in the presence of minimal interactions.

6.2.6 Conclusions of the analysis

As described in detail in Appendix II, the number of experimental runs to be undertaken has been decided, and they will be conducted in order to ascertain the flexural rigidity and final bearing capacity. Using the JMP statistical software, a total of eight experiments were identified and the experimental runs were coded ER1, ER2, ER3, ER4, ER5, ER6, ER7 and ER8 respectively. Table 6.2 displays the reduced number of input variables for ABAQUS experimental runs to be conducted.

Table 6.2: Fractional factorial design, details using bamboo scrimber and 460 MPa steel.

Experimental Run	Epoxy Resin	Diameter of Steel (mm)
ER1	Epoxy Resin @2% Zirconia	12
ER2	Epoxy Resin @5% Zirconia	8
ER3	Epoxy Resin @3% Zirconia	8
ER4	Epoxy Resin @1% Zirconia	12
ER5	Epoxy Resin @4% Zirconia	16
ER6	Epoxy Resin @2% Zirconia	6
ER7	Epoxy Resin @3% Zirconia	6
ER8	Epoxy Resin @1% Zirconia	16

6.2.7 Results

From the effect of the variation of material properties such as cured epoxy resin strength, the steel material characteristics, and the steel diameters, the results of the parametric study and the explanation are similar to those conducted during the model verification presented in sections 4.1 to 4.4 of chapter 4.

The following graphs in Figures 6.3 to 6.30 indicate the results from the eight experiments that were conducted namely:

- 1) Load Displacement response;
- 2) Ultimate bearing capacity;
- 3) Flexural rigidity;
- 4) Load strain curves;
- 5) Strain distribution curves.

The results are discussed in detail in section 6.2.8.

6.2.7.1 Load displacement response

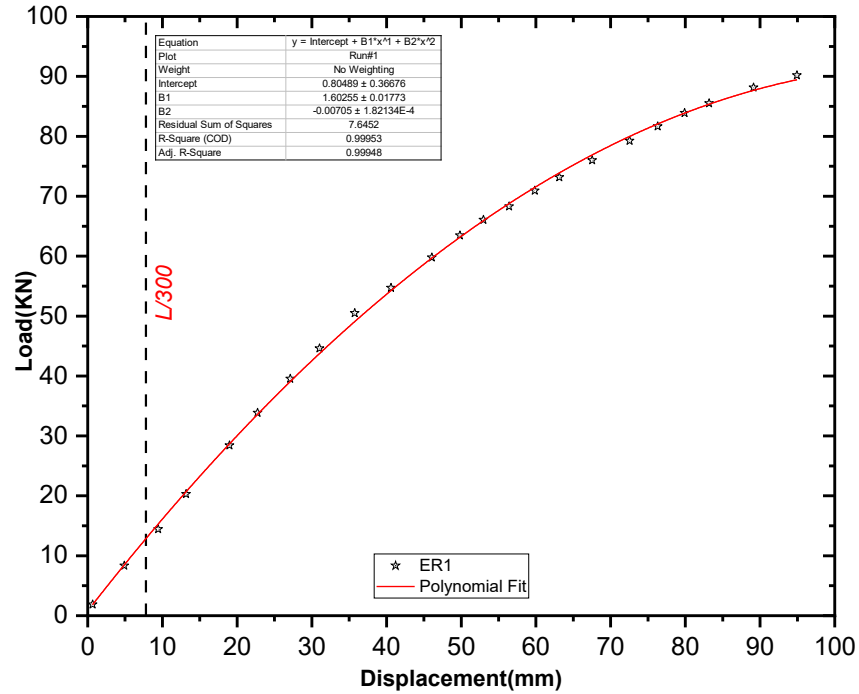


Figure 6.3: ERI-Load displacement effect due to the variation of material properties.

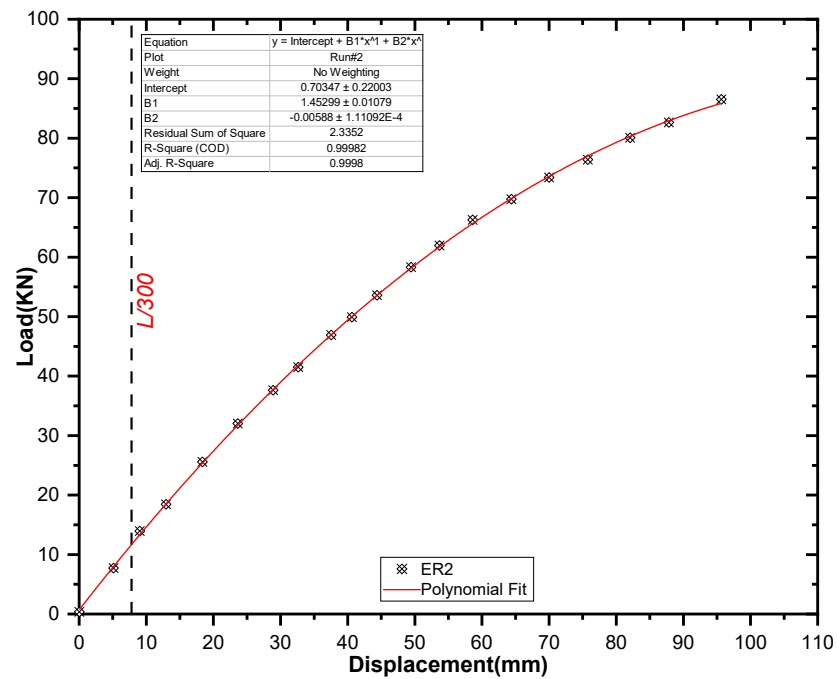


Figure 6.4: ER2-Load displacement effect due to the variation of material properties.

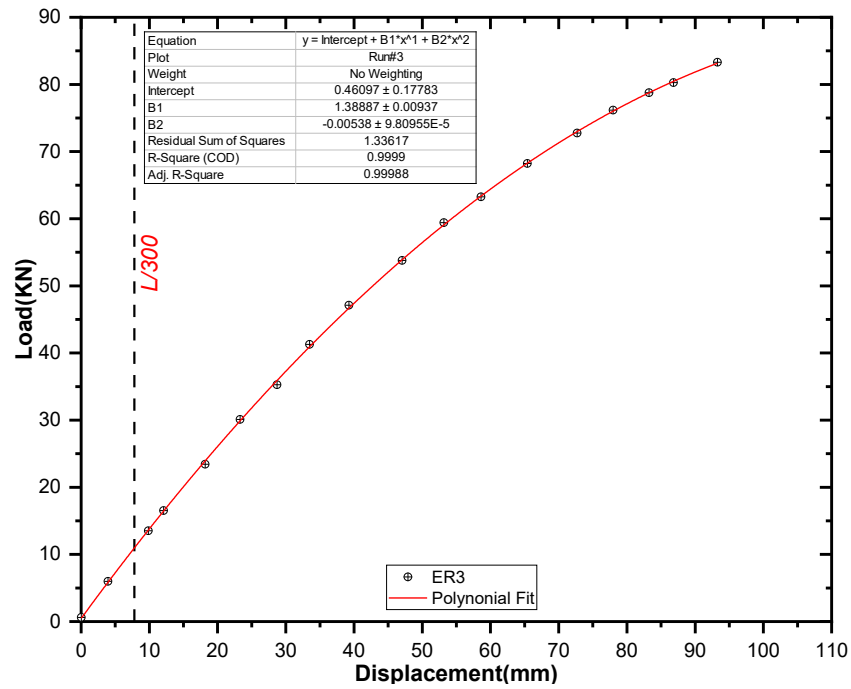


Figure 6. 5: ER3-Load displacement effect due to the variation of material properties.

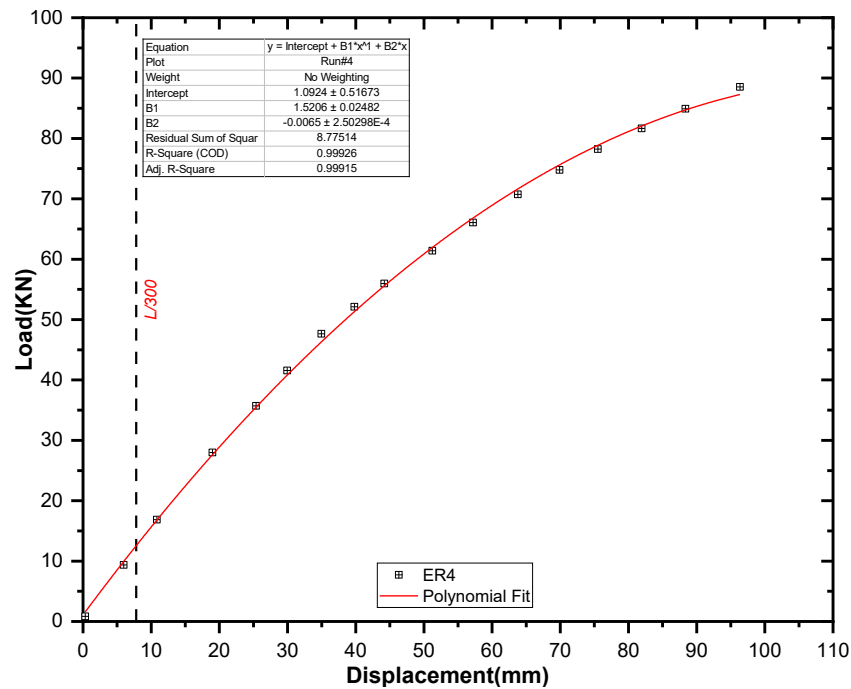


Figure 6.6: ER4-Load displacement effect due to the variation of material

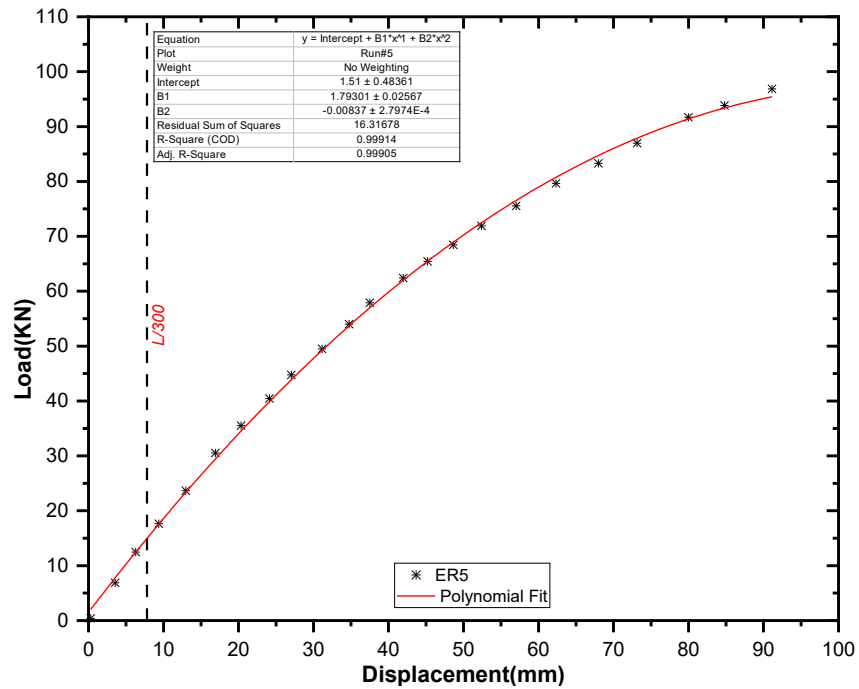


Figure 6.7: ER5-Load displacement effect due to the variation of material

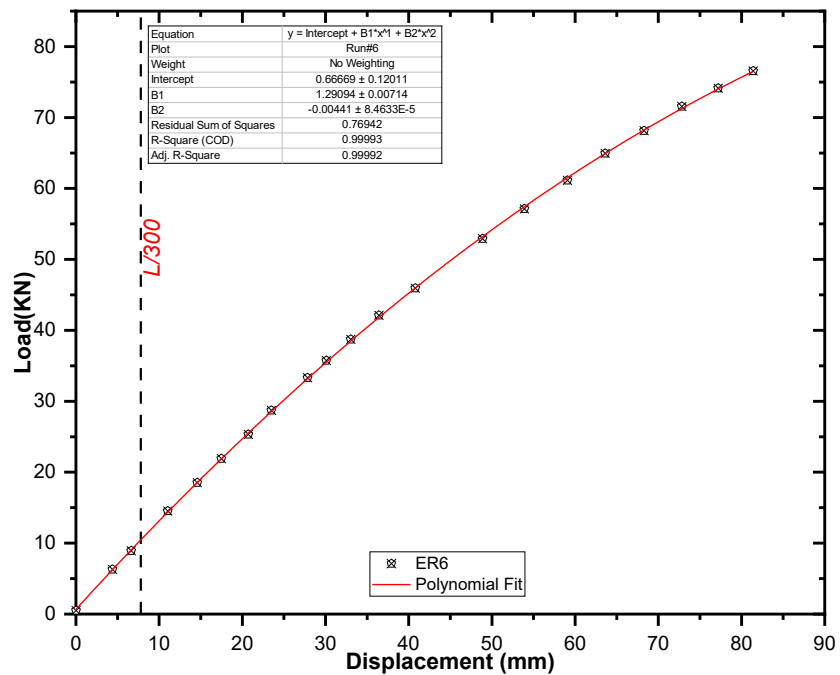


Figure 6.8: ER6-Load displacement effect due to the variation of material

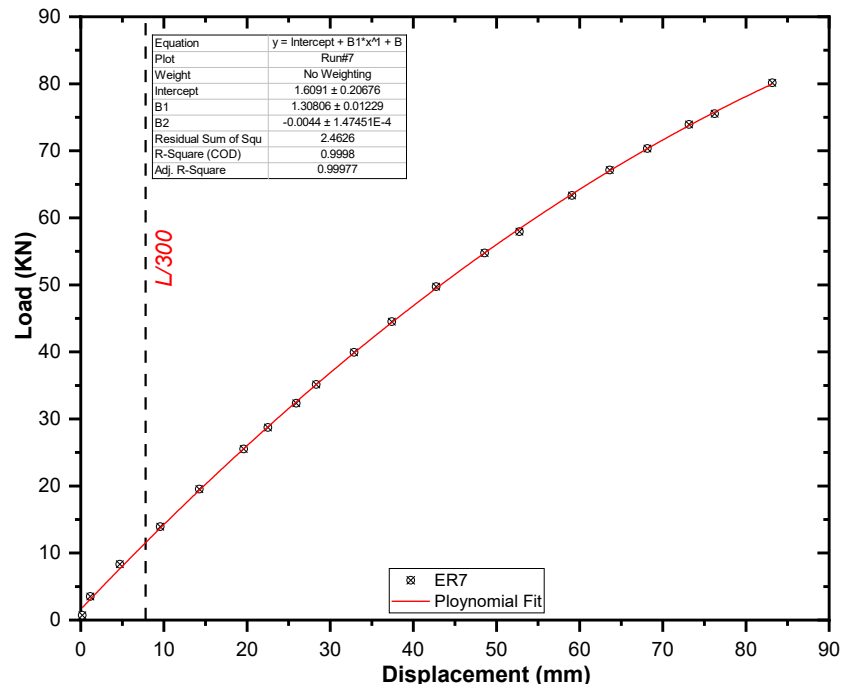


Figure 6.9: ER7-Load displacement effect due to the variation of material

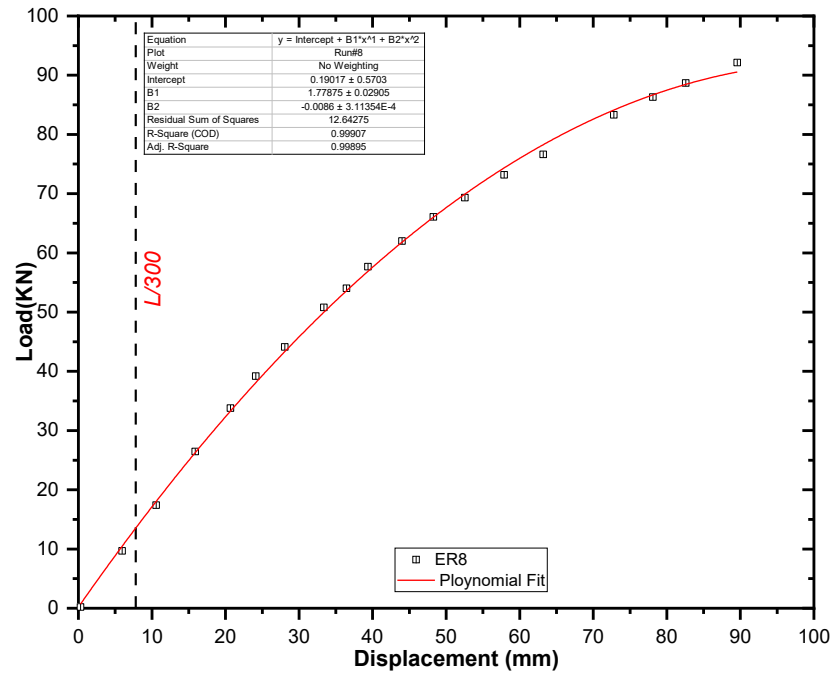


Figure 6.10: ER8-Load displacement effect due to the variation of material

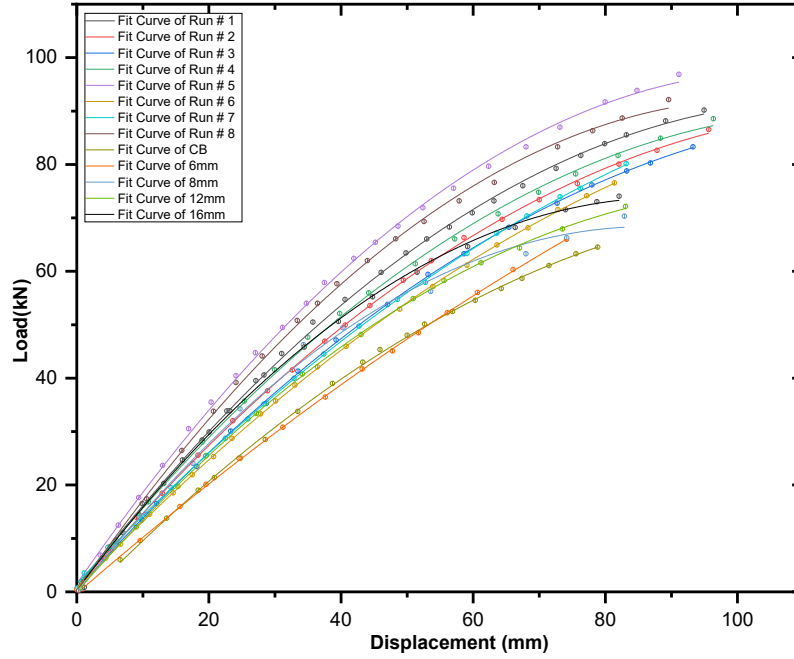


Figure 6.11: Family of curves depicting the load displacement effect due to the variation of material properties.

6.2.7.2 Ultimate flexural capacity

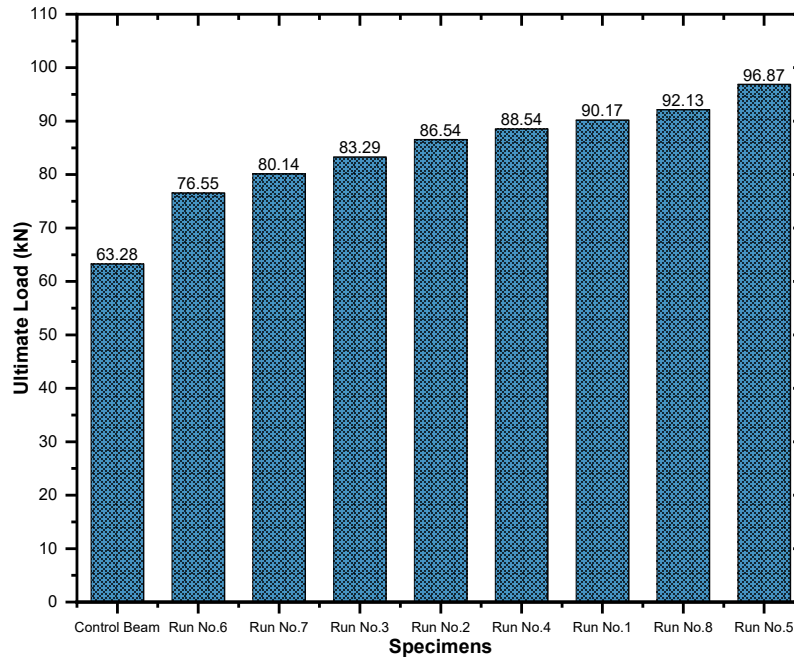


Figure 6.12: Comparisons of the ultimate flexural capacity from the variation of material parameters of the different experimental runs by FEM.

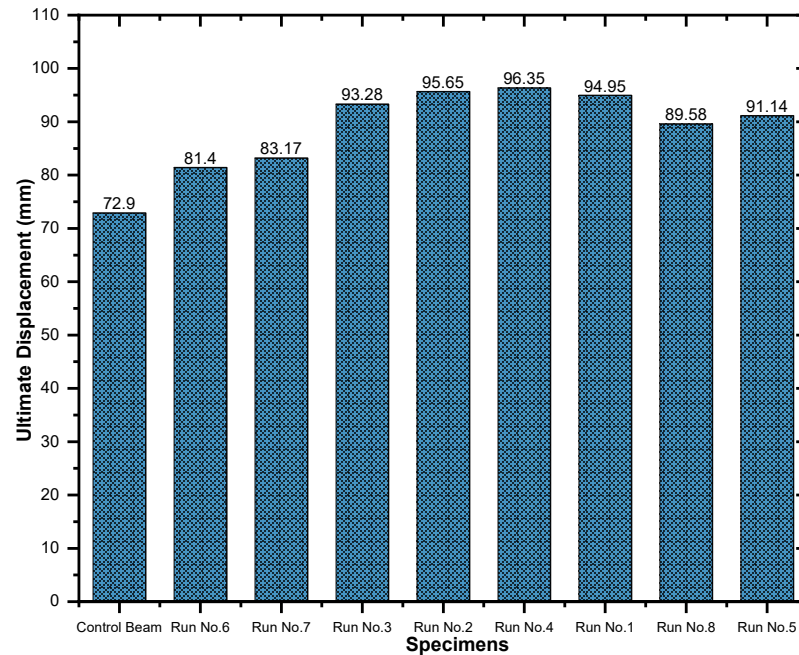


Figure 6.13: Comparisons of the ultimate displacement capacity from the variation of material parameters of the different experimental runs by FEM

6.2.7.3 Flexural rigidity

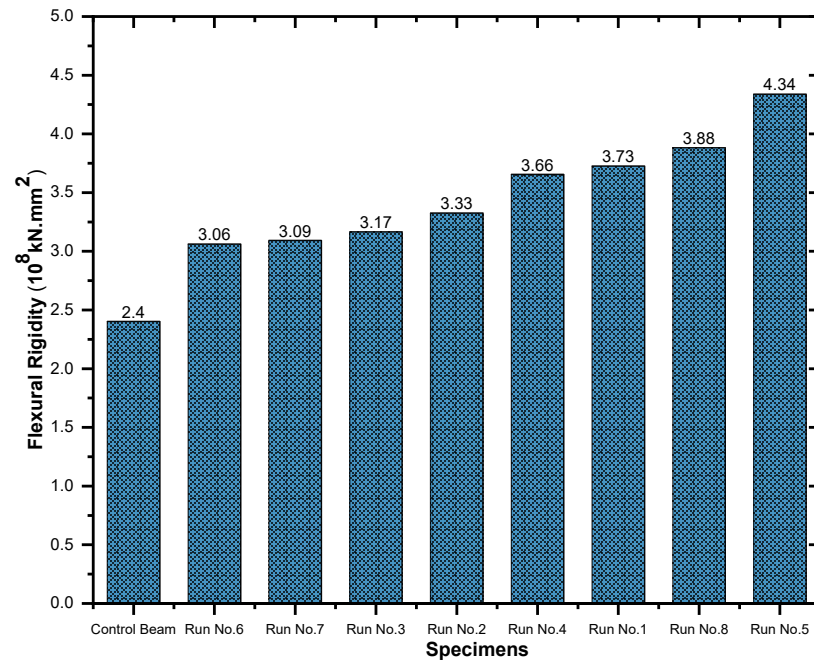


Figure 6.14: Comparisons of the flexural rigidity from the variation of material parameters of the different experimental runs by FEM.

Table 6. 3: Test results for the parametric study of the reinforced bamboo Scrimber beams.

Experiment al Run	Ultimate Load (KN)	Load (Ultimate) /Load (Control)	$P_{(L/300)}$	Increase Ratio of ultimate $P_{(L/300)}$	$EI_{(L/300)}$ (10^8 $kN \cdot m$ m^2)	Increase Ratio of $EI_{(L/300)}$ %	Ultimate Displacement(mm)	Ultimate tensile strain ($\mu\epsilon$)	Ultimate compressive strain ($\mu\epsilon$)
Control Beam	63.28	NA	8.24	NA	2.40	NA	72.9	8261	-9668
ER6	76.55	1.21	10.5	27.43	3.06	27.54	81.4	9395.68	-12280.07
ER7	80.14	1.27	10.61	28.76	3.09	28.88	83.17	9691.391	-12689.98
ER3	83.29	1.32	10.86	31.80	3.17	31.92	93.28	10376.06	-10301.31
ER2	86.54	1.37	11.41	38.47	3.33	38.60	95.65	11335.341	-11117.35
ER4	88.54	1.4	12.54	52.18	3.66	52.32	96.35	9437.528	-13754.735
ER1	90.17	1.43	12.78	55.10	3.73	55.24	94.95	9951.77	-14402.99
ER8	92.13	1.46	13.32	61.65	3.88	61.80	89.58	7983.61	-12754.58
ER5	96.87	1.53	14.88	80.58	4.34	80.75	91.14	9016.72	-14467.78

6.2.7.4 Load-Strain curves

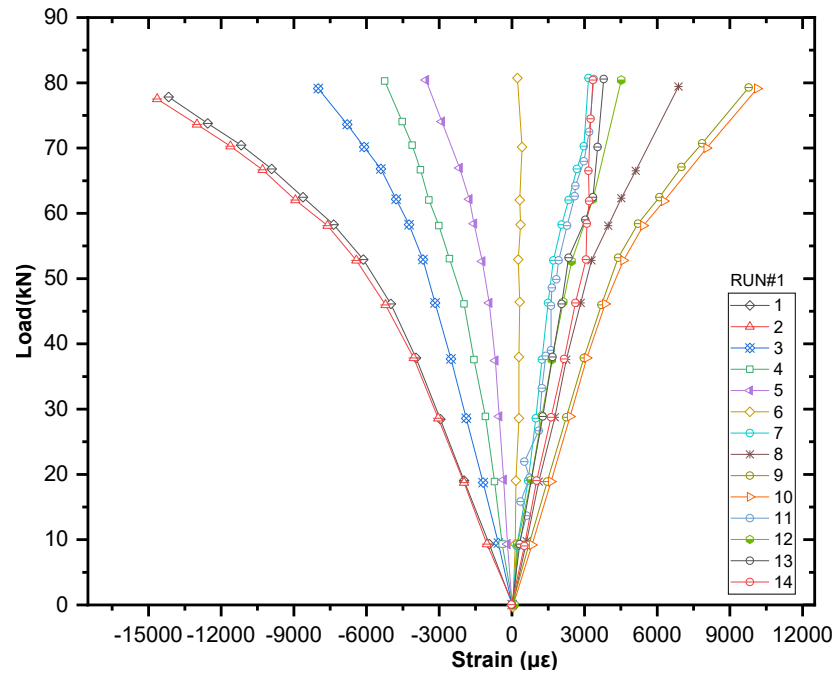


Figure 6.15: ER1-Load-strain effect due to the variation of material properties.

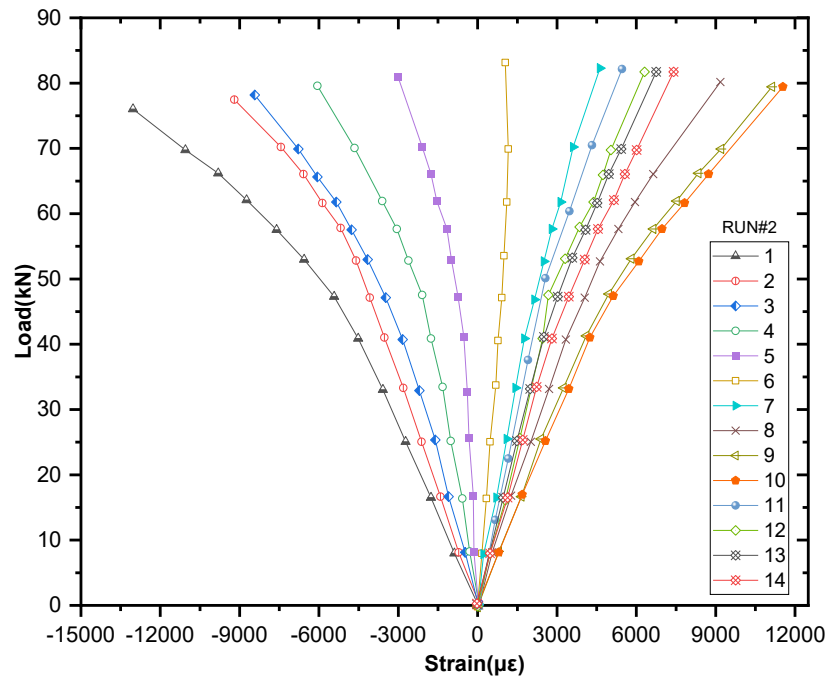


Figure 6.16: ER2-Load-strain effect due to the variation of material properties.

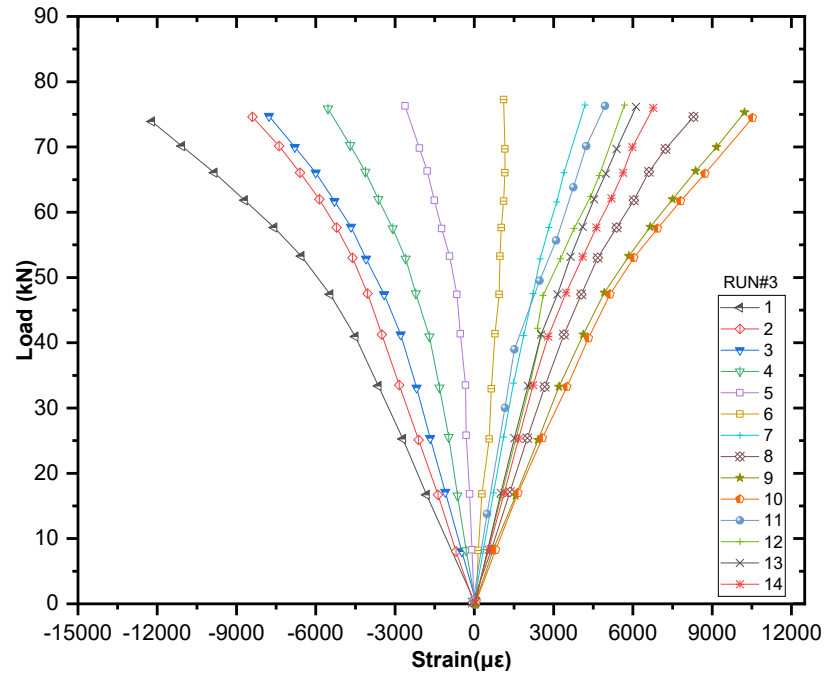


Figure 6.17: ER3-Load-strain effect due to the variation of material properties.

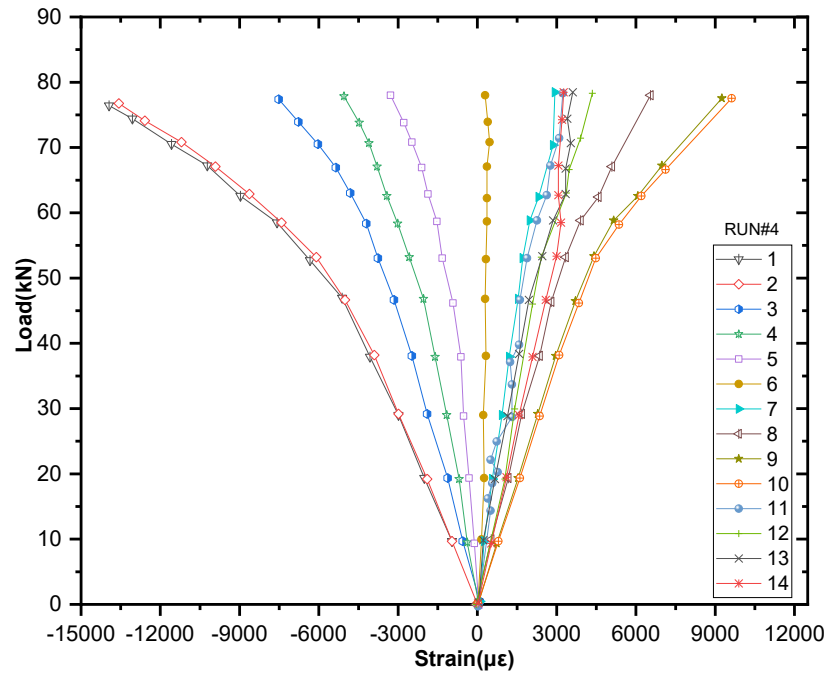


Figure 6.18: ER4-Load-strain effect due to the variation of material properties

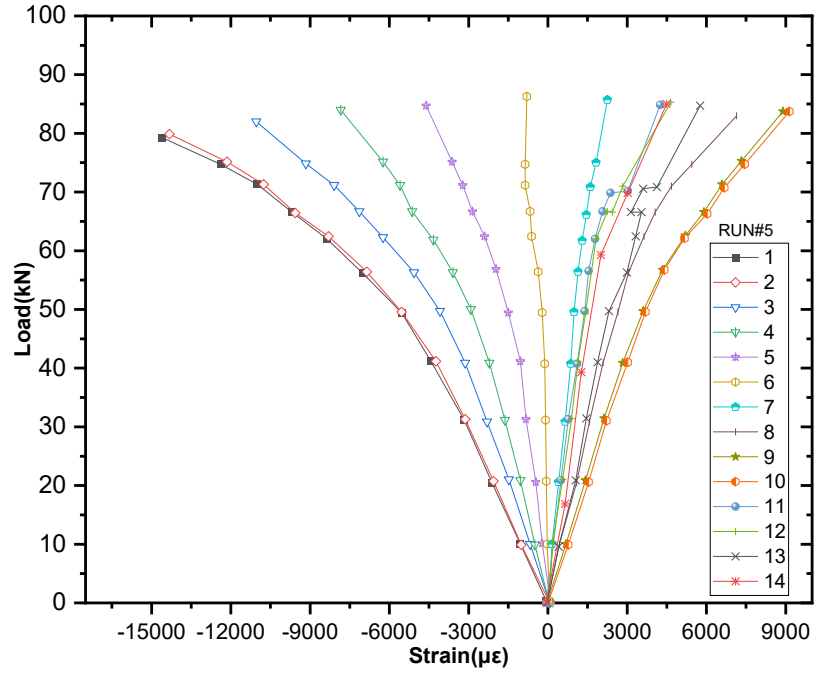


Figure 6.19: ER5-Load-strain effect due to the variation of material properties.

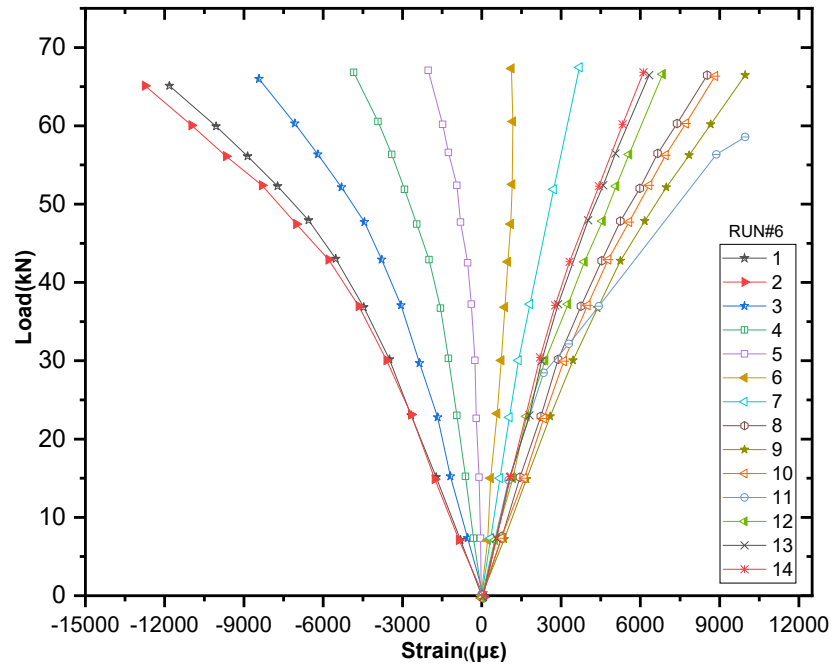


Figure 6.20: ER6-Load-strain effect due to the variation of material properties.

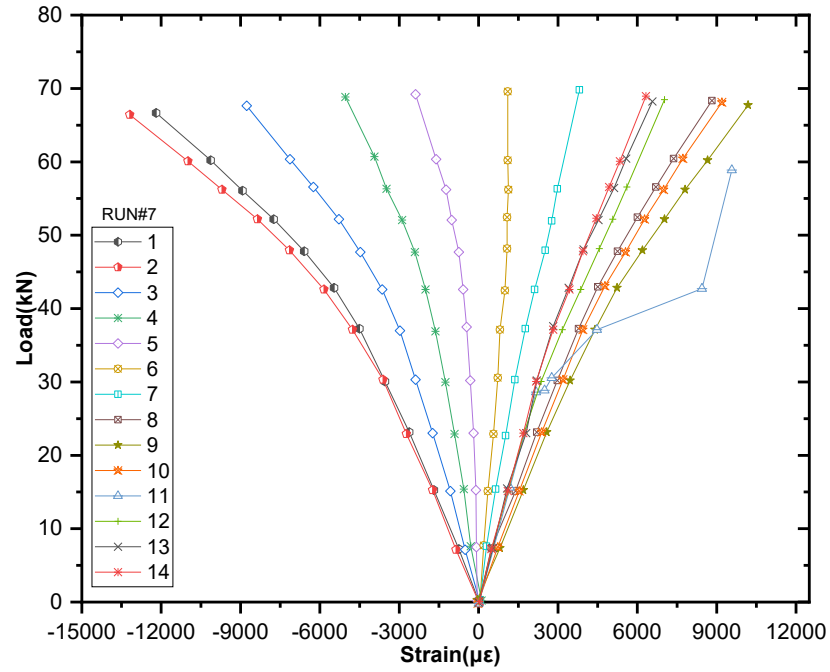


Figure 6.21: ER7-Load-strain effect due to the variation of material properties.

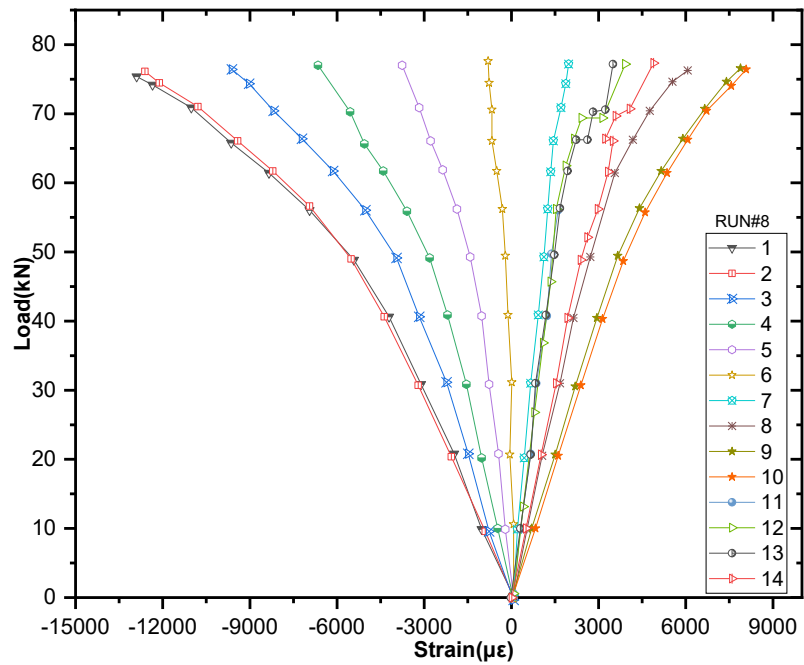


Figure 6.22: ER8-Load-strain effect due to the variation of material properties.

6.2.7.5 Strain distribution Curves

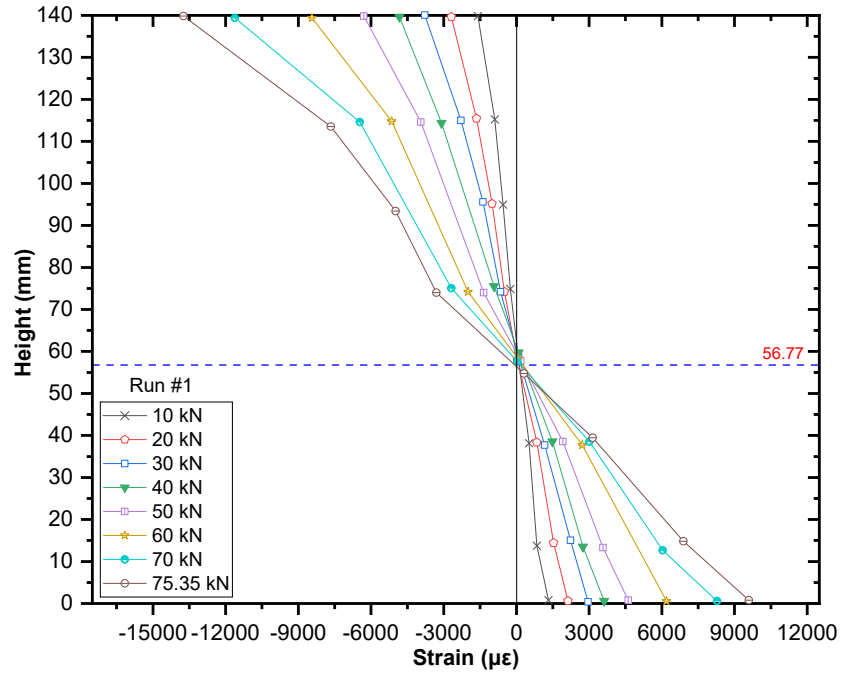


Figure 6.23: ERI-Distribution of strain at the mid-span cross-section due to the variation of material properties.

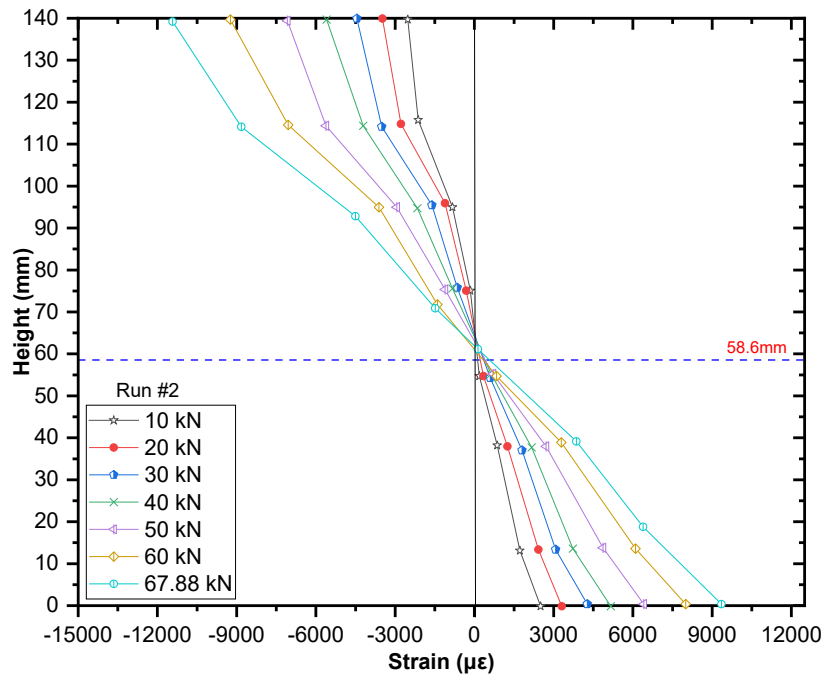


Figure 6.24: ER2-Distribution of strain at the mid-span cross-section due to the variation of material properties.

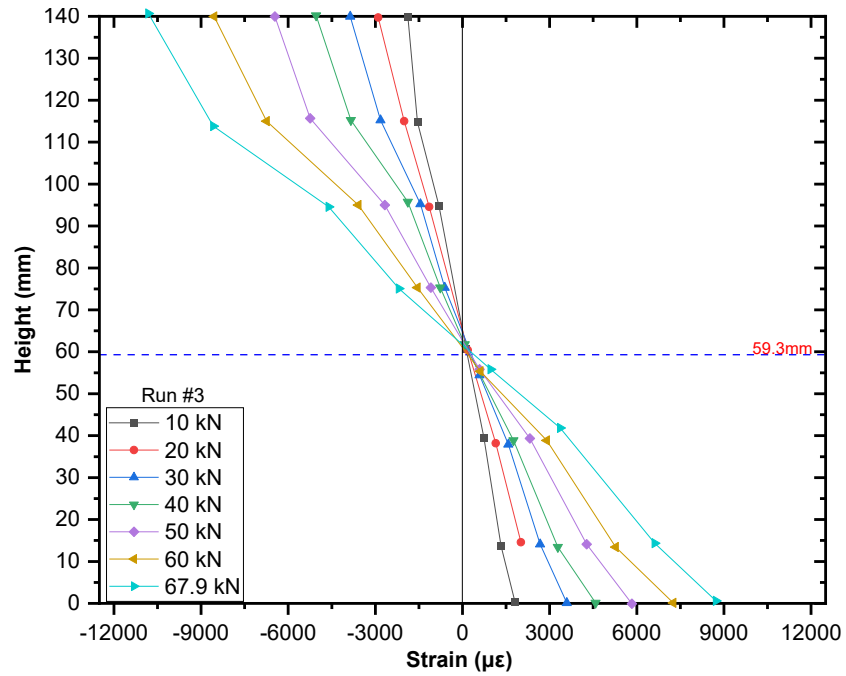


Figure 6.25: ER3-Distribution of strain at the mid-span cross-section due to the variation of material properties.

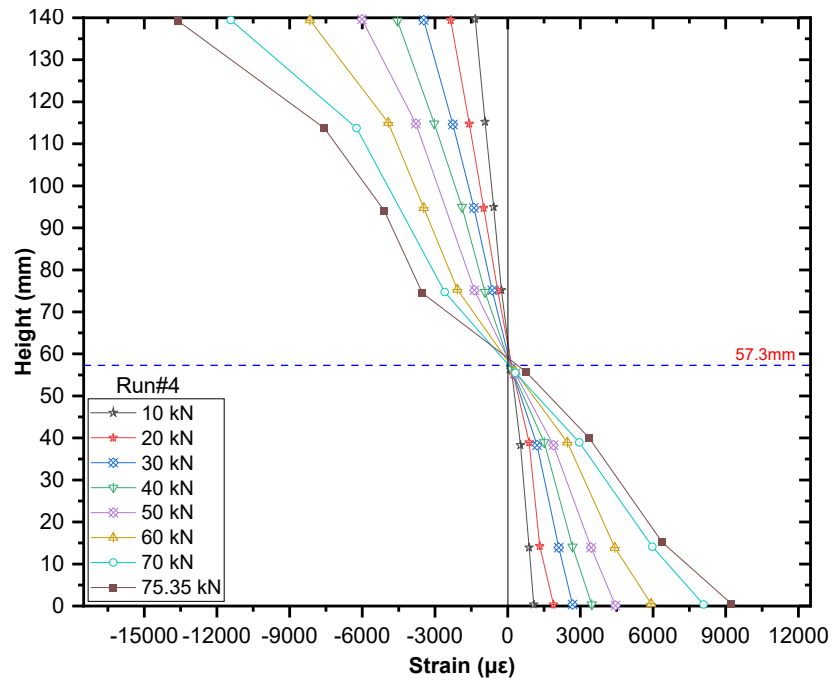


Figure 6.26: ER4-Distribution of strain at the mid-span cross-section due to the variation of material properties.

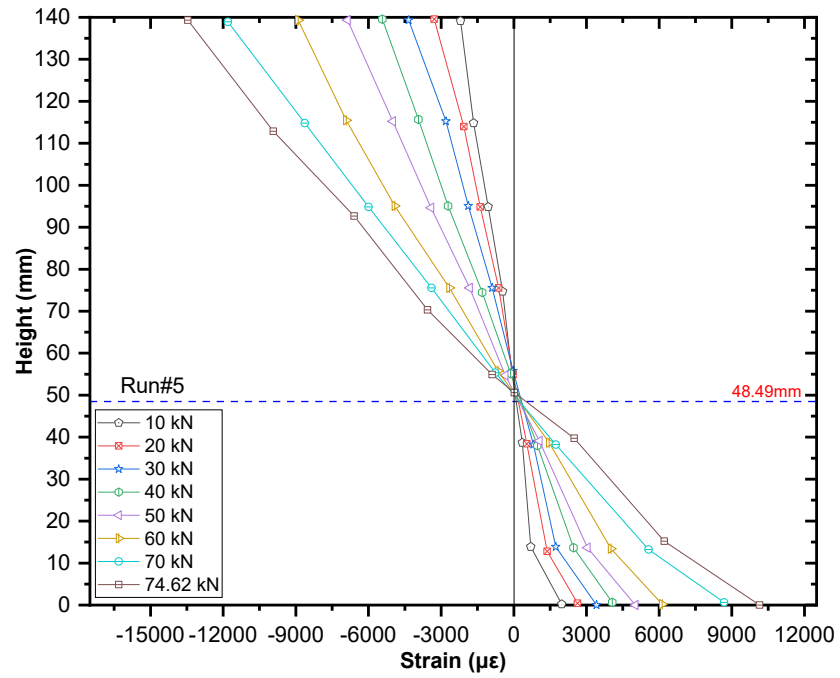


Figure 6.27: ER5-Distribution of strain at the mid-span cross-section due to the variation of material properties.

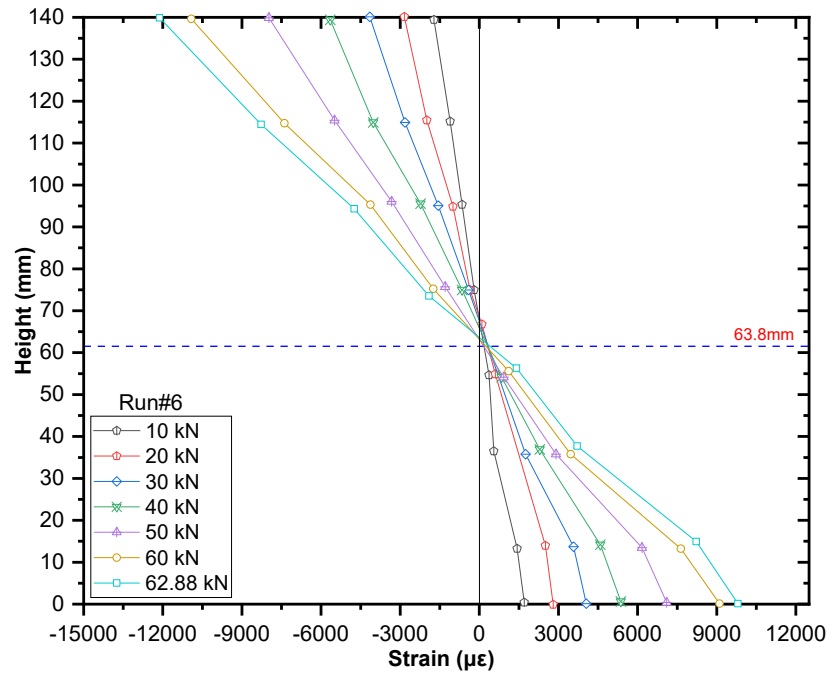


Figure 6.28: ER6-Distribution of strain at the mid-span cross-section due to the variation of material properties.

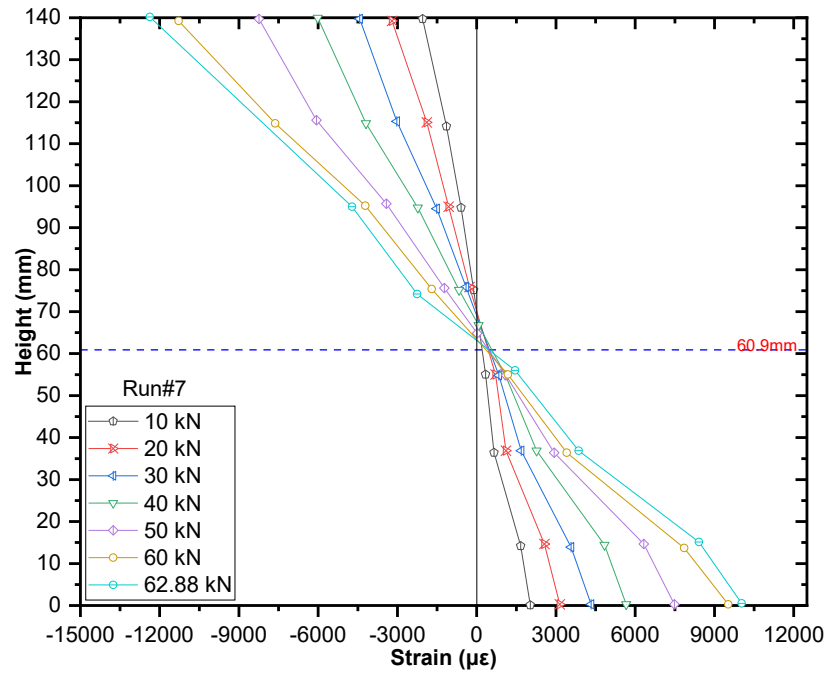


Figure 6.29: ER7-Distribution of strain at the mid-span cross-section due to the variation of material properties.

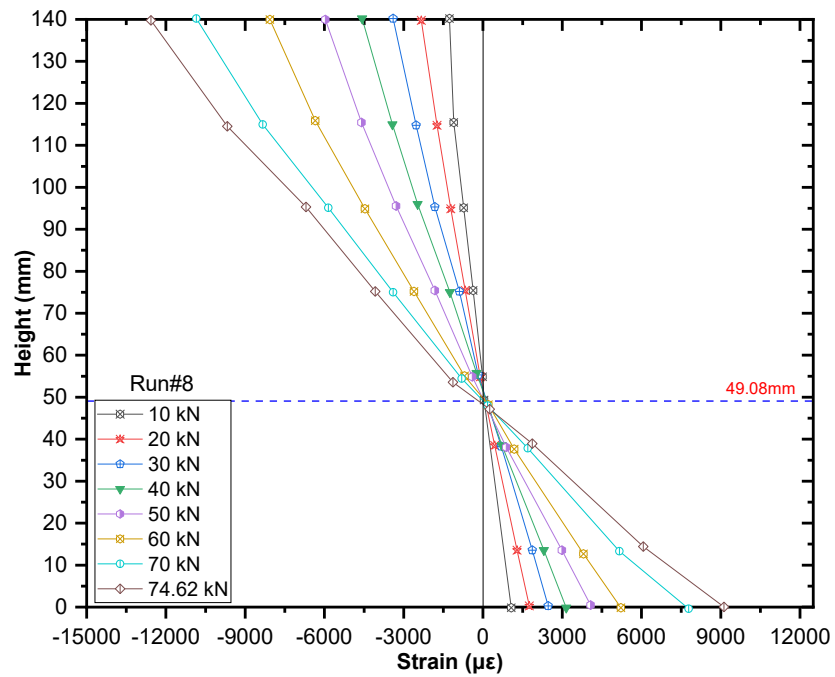


Figure 6.30: ER8-Distribution of strain at the mid-span cross-section due to the variation of material properties.

6.2.8 Discussion of the results

6.2.8.1 Load displacement response

Figures 6.3 to 6.11 illustrate the load-displacement curves derived from the parametric analysis for the reinforced bamboo Scrimber beams. In Figures 6.3 to 6.11, the displacement refers to the mid-span deflection of the beams. The effect of the variation of material properties for the epoxy resin strength, the steel material characteristics, and the steel diameters are compared. At the first stage of loading, the displacement at the mid-span of all beams is linearly proportional to the load.

The flexural rigidity of the beams reduces gradually as the load increases, while the load-displacement curves become nonlinear. This is because the bamboo scrimber material in the upper compression zone gradually enters the plastic stage, the compression stiffness decreases, and the deformation of the beams increases at a faster rate.

Once the beams have been loaded up to their maximum capacity, the bearing capacity of the beams starts to rapidly diminish, which ultimately leads to their initial failure. As can be seen in Figures 6.3 to 6.11, the load-carrying capacity of the steel beams experience a slight reduction.

This is consistent with the experimental findings that the effective section height drops after the initial failure and that the steel bars linked to the upper portion of the bamboo beams continue to bear the load jointly.

According to the findings, the beam with the highest percentage of hardener and the largest steel diameter also has the highest flexural capacity. For instance, experimental run number 5 has a maximum flexural capacity of 96.97 kN and a maximum steel diameter of 16 mm with a 4 percent hardener. The diameter of experimental run number 6 is 6 mm, and it contains a 2 percent hardener content, which results in the lowest bearing capacity of 76.55 kN.

In conclusion, there were two runs for each steel diameter, each with a different hardener percentage number. According to Table 6.4, the group of steel diameters with the highest hardener percentage had the highest flexural capacity. In comparison to the findings of the physical experiment, the results from the parametric investigation had greater carrying capabilities. This may be ascribed to the parametric study's use of epoxy resin that was

hardened using varying amounts of Zirconia as well as a higher strength of steel, S460, which is already available on the Zambian market.

Table 6. 4: Load displacement response of the parametric runs

Experimental Run	Constitutive Material	Diameter of Steel	Strength of Steel (MPa)	Epoxy Resin (%)	Displacement (mm)	Maximum load(kN)
ER6	Bamboo Scrimber	6	460	2	81.39367	76.55061
ER7	Bamboo Scrimber	6	460	3	83.17355	80.14163
ER3	Bamboo Scrimber	8	460	3	93.27681	83.28953
ER2	Bamboo Scrimber	8	460	5	95.65371	86.53599
ER4	Bamboo Scrimber	12	460	1	96.35158	88.55054
ER1	Bamboo Scrimber	12	460	2	94.94588	90.17396
ER8	Bamboo Scrimber	16	460	1	89.58067	92.13377
ER5	Bamboo Scrimber	16	460	4	91.13849	96.8731

6.2.8.2 Ultimate bearing capacity

The test results for the parameterized bamboo Scrimber beams are illustrated in Table 6.3. Comparisons of the flexural performance of the reinforced bamboo beams are shown in Figure 6.12 to 6.14. The average ultimate bearing capacity of the control beams is 63.28 kN, and the average ultimate bearing capacities of the eight parameterized bamboo Scrimber beams, Beams , ER6, ER7,ER3, ER2, ER4,ER1,ER8, ER5 are 76.55 kN, 80.14 kN, 83.29 kN and 86.54 kN, 88.54 kN, 90.17 kN ,92.13kN and 96.87 kN respectively, which are 20.97%, 26.64%, 31.62% , 36.76%, 39.92% , 42.49%, 45.59% and 53.08%

higher than those of the control beams respectively. The ultimate flexural capacities of the parametric steel-reinforced bamboo Scrimber beams increase with an increasing reinforcement ratio and or epoxy resin percentage, but the increase is not linear. For example, when the reinforcement ratio of ER4 and ER1 are both 12mm, the hardener percentage/ Epoxy resin percentage is 1% and 2% respectively, and the bearing capacities of ER4 is 88.55 kN while that of ER1 is 90.17 kN, with an ultimate displacement of 96.35mm and 94.95mm respectively. Alternatively, when the Hardener percentage of ER7 and ER3 are both 3%, the reinforcement ratio is 6mm and 8mm respectively, and the flexural capacities of ER7 is 80.14 kN while that of ER3 is 83.23 kN with an ultimate displacement of 83.17mm and 93.28mm respectively. The high reinforcement ratio may lead to the end shear failure of the bamboo Scrimber beams, which is a kind of over-reinforcement failure. Therefore, required steps such as the usage of end anchor plates should be adopted to avoid shear failure for an excessive reinforcement ratio.

6.2.8.3 Flexural rigidity

Euro code 5 (Wang et al., 2020) specifies that when wood is used as a bending element, the mid-span deflection at the serviceability limit state is $L/300$ (Wang et al., 2020), where L is the span of the beam, which results in 7.8 mm for the beams in this test. The average ultimate displacement of the control beams is 72.9 mm, while the average ultimate displacement of the parametric steel-reinforced beams ranges between 72.9 mm and 91.14 mm. Most parameterized beams reinforced with steel bars and epoxy adhesive have a larger final displacement than control beams. By reinforcing bamboo Scrimber beams, their deformation capacity and ductility are enhanced. The ultimate displacement of the beams is around 1/25 to 1/32 of the span length, which is significantly greater than the specification's serviceability limit state as indicated in Figure 6.13. Under identical loads, the reinforced beam's deflection is considerably less than that of the control beams. The use of steel bars has a significant favourable impact on the enhancement of the bending rigidity of bamboo Scrimber beams. As demonstrated in Equation 5.1, the flexural stiffness in the elastic stage may be derived from the increase in load and the increase in the mid-span deflection.

The flexural rigidity ($EI_{L/300}$) at L/300 corresponding to the serviceability limit state of the test beams in the elastic stage can be calculated by substituting the data obtained from the four-point bending test, as shown in Table 6.3.

The average flexural stiffness at L/300 is compared by groups in Figure 6.14. The flexural stiffnesses $EI_{L/300}$ of the reinforced beams are 27.54%~80.75% higher than those of the control beams. The average flexural rigidities of Experimental runs; ER6, ER7, ER3, ER2, ER4, ER1, ER8, ER5 are 27.54 %, 28.88%, 31.92%, 38.60%, 52.32%, 55.32%, 61.80% and 80.75%, respectively.

The flexural rigidity increases linearly with increasing reinforcement ratio and hardener percentage, indicating that the reinforcement and bamboo Scrimber beam can operate in conjunction with the epoxy resin and are in perfect condition of integrity. The load corresponding to L/300 similarly increases as the reinforcement ratio increases, ranging from an average of 8.24 kN for the control beams and 10.6 for the least reinforced beams to 14.88 kN for the beams in ER5 with 16 mm bars, an increase of 80.58 percent.

6.2.8.4 Load-strain curves

Figures 6.15 to 6.22 depicts the load-strain curves of parametric bamboo Scrimber beams. At the beams' mid-span cross-section, tensile strain is positive and compressive strain is negative. Figure 6.6 displays the total number of strain gauges. In the first stage of loading, the compression strain of the control beams increases with a linear correlation and increases at a quicker rate in the later stage, when the compression zone reaches the plastic stage. The tensile strain increases linearly till failure in the tensile zone. The average ultimate tensile strain of the control beams is $8261\mu\epsilon$, which corresponds closely to the ultimate tensile strain determined by the tensile test in the experiment. This shows that the complete tensile capability of the bamboo Scrimber may be exploited in the tension zone of the bamboo beams. The average ultimate compressive strain of the control beams from the initial experiment is $9668\mu\epsilon$, which is significantly lower than the value observed during the compressive test, and the control beams' compressive performance is not completely developed.

The average ultimate compressive strain of the reinforced parameterized bamboo Scrimber beams ranges from $-12280.98\mu\epsilon$ to $-14467.78\mu\epsilon$, which is larger than that of the control beams. Due to the extra reinforcing, the performance of bamboo in the compressive zone improves for bamboo Scrimber beams. Similar to the control beams, the tensile strain in the tensile zone of the reinforced beams develops linearly during the first stage of loading but increases nonlinearly during the latter stage of loading due to the reinforcing bars entering the post-yield strengthening stage. The average ultimate tensile strain range for reinforced bamboo Scrimber beams is $9395.68\mu\epsilon$ – $9016.72\mu\epsilon$, which is larger than that of the control beams. This demonstrates that the failure of the reinforced bamboo beam is still governed by a tensile fracture at the bottom.

Observing the strains of the steel bars reveals that the steel strain (numbers 11–14) of all the reinforced increases constantly between the nearby higher strain gauge (no. 7) and lower neighbouring strain gauge (no.8) This demonstrates that the implanted steel bars are capable of deforming in concert with the bamboo Scrimber.

6.2.8.5 Strain distribution over depth of beam

The strain distributions in the height direction of the mid-span portion of the tested beams are depicted in Figures 6.23 to 6.30. At the first stage of loading, the strain along the height of the cross-section is practically linear and symmetrical, and the location of the neutral axis is nearly constant. This conforms to the section plane assumption for flexural members. In the later stages of loading, the compression zone of the bamboo Scrimber beam begins to reach the plastic yield stage. Since the compression modulus drops progressively as the load rises, the neutral axis similarly descends.

Using specimen ER6 as an illustration, the neutral axis location gradually decreases from 69.8 mm in the initial elastic stage to 63.8 mm before the beam is destroyed. The locations of the neutral axes of the specimens in the elastic phases of the reinforced bamboo Scrimber beams for Experimental runs are as follows; ER6, ER7, ER3, ER2, ER4, ER1, ER8, ER5 are 63.8mm, 60.9mm, 59.3mm, 58.6mm, 57.3mm, 49.08mm and 48.49mm respectively as shown in Table 6.5. Due to the increase in cross-sectional moment of inertia induced by the steel bars in the tension zone of the reinforced beams, the location

of the specimen's neutral axis drops as the reinforcement ratio increases. After the compression zones of the reinforced bamboo beams enter the plastic yield stage, the neutral axis locations shift downward until the load hits the ultimate load.

Table 6. 5: Location of the neutral axis of the parametric runs

Experimental Run	Position of Neutral axis (mm)
ER6	63.8
ER7	60.9
ER3	59.3
ER2	58.6
ER4	57.3
ER1	56.77
ER8	49.08
ER5	48.49

6.3 Effect of reinforcement placement

The centre of gravity of steel bars is maintained at a distance of 25 mm from the bottom of the beam during experimental testing and finite element analysis. To examine the impact of the spatial position of steel bars on the load-bearing capability of reinforced bamboo beams, the centre of gravity of steel bars was shifted 30 mm, 20 mm and 10 mm from the bottom of the beam. Based on the height of the centre of gravity of the steel bars (10mm,20mm,25mm, and 30mm), a bamboo Scrimber beam with 12mm diameter bars was utilized. Except for the location of the reinforcement, it should be noted that the parameters are identical to the study without parameterizations.

Figure 6.31 depicts the load-displacement responses of reinforced bamboo beams with varied reinforcing positions. With a shorter distance between the steel bars and the bottom of the beam, a higher ultimate flexural capacity and bending stiffness can be attained, but the effect was not substantial. The differences in ultimate bearing capabilities between the various reinforcing positions from the bottom of the beam are illustrated in Table 6.6. It is clear that the bearing capacity of a beam increases as the distance from its base decreases. The control beam has the smallest area under its curvature since it lacks reinforcing. The

magnitude of the beam's bearing capacity is inversely related to the reinforcement's distance from the beam's base. In addition, the eventual deflection is essentially unaffected by the change in reinforcement position.

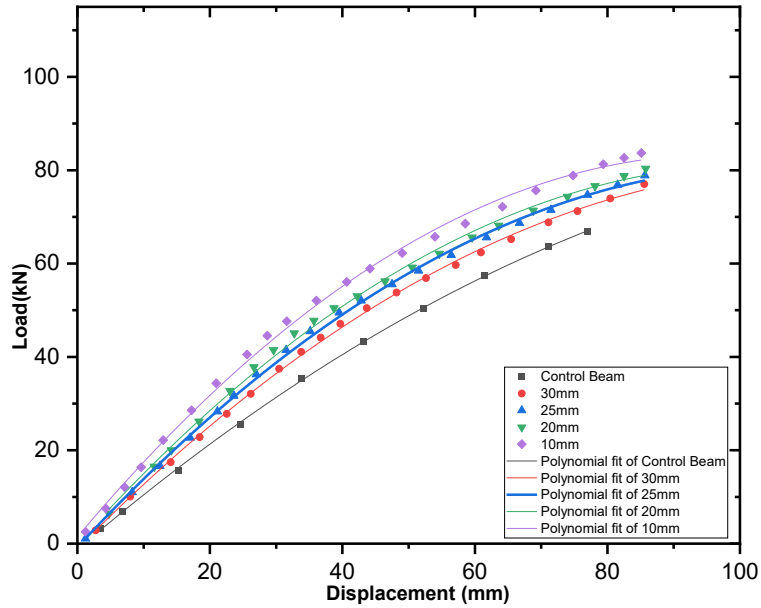


Figure 6.31: The load-displacement performance of bamboo beams with various reinforcement placement locations.

Table 6.6: The effect of the reinforcement locations

Sn	Distance from Bottom (mm)	Area under the Curve (mm ²)	Ultimate Bearing Capacity (kN)	Increment Ratio of Ultimate flexural Capacity
1	Control Beam (no reinforcement)	2828.9	66.8	N/A
2	10	4460.6	83.7	1.25
3	20	4168.4	80.4	1.20
4	25	4038.7	78	1.17
5	30	3842.7	77	1.15

6.4 Effect of reinforcement ratios

Based on prior study and analysis, it can be concluded that the reinforcement ratio of reinforced beams has a significant impact on the enhancement of bearing capacity. On the basis of the analysis of the aforementioned test beams, three groups of reinforced bamboo beams with varying diameters of steel bars are inserted; the diameters of the steel bars implanted were 18 mm, 20 mm, and 22 mm.

Figure 6.32 illustrates the load-displacement curves for reinforced bamboo beams with various reinforcing ratios. The maximum bearing capacity of the beam with 20mm bars (reinforcement ratio of 6.4%) simulated by FEM reached 86.7 kN, which is about 33.4% greater than that of the comparison beam. As demonstrated in Table 6.7, as the reinforcement ratio of the reinforced beam increases, the ultimate displacement/deflection of the beam increased from 73 mm to 92 mm. With an increase in reinforcement ratio, the ductility of bamboo beams increases dramatically. With an increase in reinforcement ratio, the deflection under the same load reduces, and the bending stiffness of bamboo beams is effectively increased.

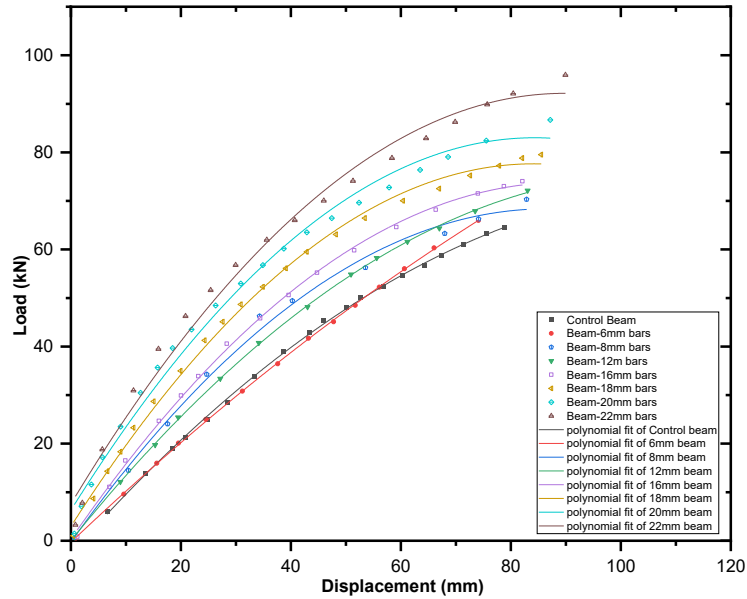


Figure 6.32: The load-displacement reaction of bamboo beams with various reinforcing ratios.

Table 6.7: The effect of the reinforcement ratios

SN	Bar Size(mm)	Displacement(mm)	Increase ratio of Displacement	Ultimate flexural Capacity(kN)	Increase ratio of Ultimate flexural Capacity
01	0	73	N/A	65	N/A
02	6	74	1.36	66.17	1.02
03	8	78	6.85	69	1.06
04	12	79	8.22	71.9	1.11
05	16	82	12.33	73.01	1.12
06	18	85	16.44	79.5	1.22
07	20	87	19.18	86.7	1.33
08	22	92	23.29	96	1.48

6.4.1 Failure criteria of beams

The effect of reinforcement ratios also affects the failure criteria of the SRBS beams. According to the physical experiment, the failure pattern of the control bamboo beams is primarily caused by the fibre breaking and cracking at the bottom of the mid-span, and as the load increases, the vertical crack gradually transforms into an oblique crack that extends from the bottom of the mid-span to the area around the loading point until the specimen fails. There are two categories of failure patterns for bamboo beams reinforced with steel.

The first failure mode, which affects the majority of specimens, is the fracture of the bamboo fibre at the lower end of the steel bar in the tension zone in the middle of the beam span. The second failure mode, which affects mostly beams with high reinforcement diameters of 16mm-22mm, is the shear failure at both ends of the beam.

The ultimate bearing capacity and load-displacement response of reinforced bamboo beams are not significantly affected by the bonded shear slip, according to the failure modes of earlier experimental study findings and this numerical phenomenon.

This study's computation of the finite element nonlinear response makes the assumption that it is possible to ignore slide between the surfaces made of bamboo, epoxy resin, and steel bars which is the complete bonding assumption. According to experimental findings, bamboo beam failure is caused by bamboo fibres breaking at the bottom.

As a result, the final failure for ABAQUS simulation is defined as the state of bamboo beams when the bottom tensile strain of bamboo approaches the ultimate tensile strain. The material properties of bamboo and reinforcing steel bars were computed in the programme using the ABAQUS elastic-plastic model in accordance with the test results. Equations 3.1-3.3 can be used to determine the material's constitutive relationship.

6.5 Chapter overview

This chapter offered a parametric analysis to investigate the effect of various factors on the flexural capacity of a Bamboo Scrimber Beam when subjected to a four-point bending test load. After validating the finite element model, several features of reinforced bamboo beams are simulated and analysed using FEA. Beams have the same cross-sectional dimension, with breadth measuring 70 mm and height measuring 140 mm. In addition, the boundary conditions and loading method remained unchanged.

The key variables studied in this sensitivity analysis were: (1) the effect of the variation of material properties for the, cured epoxy resins strength, the steel material characteristics, and the steel diameters (2) the influence of steel bar spacing on the bearing capacity and (3) the impact of reinforcing ratios on the bearing capacity of SRBS Beams.

Considering the first set of parameters that were varied, the flexural rigidity, ultimate bearing capacity, and strain distribution of bamboo beams were investigated and were all found to have a direct proportion with an increase of material properties for the, epoxy resins strength, the steel material characteristics, and the steel diameters.

Regarding the effect of steel bar spacing on flexural capacity, it can be seen that a greater ultimate flexural capacity and bending stiffness can be obtained for reinforced beams with a shorter distance between the steel bars and the bottom of the beam; however, this effect was not statistically significant. From the study of the effect of the reinforcement ratios of SRBS beams, it is evident that there is an increase in the ultimate load of the beams, the flexural capacity and the flexural rigidity as the reinforcement ratios increase.

CHAPTER 7 : CONCLUSION AND RECOMMENDATION

7.1 Conclusions

From the literature study, there is very little research on the development of finite element models that determine the stiffness of SRBS beams. This might be due to the novelty of using bamboo as a structural component. This research presents a finite element model that predicts the flexural performance of an SRBS beam exposed to a four-point bending test with reasonable accuracy.

The three-dimensional finite element model of reinforced bamboo beams was developed using ABAQUS software to simulate the bending test, including the loading phase. Analytical and experimental findings were compared in terms of the ultimate bearing capacity, load-deflection curves, and load-strain curves. The following significant findings can be drawn regarding the created FEM model:

- From the literature review, all the material input parameters involving the bamboo scrimber material, the steel, and the epoxy resin that were necessary to simulate a SRBS beam under flexure were successfully identified, calibrated and used as input parameters as shown in the literature review. It is well known that the accuracy of the finite element model is very dependent on the correctness of the material model.
- The finite element model developed in this study accurately captures the flexural behaviour of SRBS beams. Here, based on the Load Displacement Response, Strain distribution, and strain distribution at the mid-span cross-section, the models are assessed and validated in comparison to the experimental data. The developed FEM model's output closely matched experimental data. Even when the approximation of reality varied somewhat from the experimental data, a good match between the numerical and experimental results was generally attained.

Although the created FEM models were in close accord with experimental data, they had their own limits. These limits may be the consequence of random and instrumental errors during the experiment; numerical approaches are influenced by the specified physical model and its parameters. In contrast, the used mesh is another source of variations in results. The combination of mesh, models, adaption and convergence process affects the simulation as well.

From the study, it is clearly indicated that the load-displacement curve generated by the finite element method (FEM) is compatible with the test results, particularly during the early elastic stage and the yield stage. It demonstrates that the FEM is capable of simulating the four-point bending test of bamboo beams with acceptable accuracy.

With an average absolute error of 3.25 percent and 9.83 percent, respectively, the ultimate flexural capacity and flexural rigidity calculated using finite element simulation are slightly higher than those determined by test analysis. This is because the model used a different method to cover the side grooves of the beam body than the experiment did, and the model had a thicker covering of epoxy resin than the experiment did. However, this has no bearing on the overall result of the finite element simulation.

From the comparison of mathematical and experimental strain distributions in reinforced bamboo beams' mid-span cross-sections, it is discovered that the two curves practically coincide.

The developed FEM models were then used for subsequent parametric study. The objectives of the parametric study were to:

- Investigate the effect of the variation of material properties for the, cured epoxy resin strength, the steel material characteristics, and the steel diameters.
- Investigate the influence of steel bar spacing on the bearing capacity and
- Investigate the impact of reinforcing ratios on the bearing capacity of SRBS beams.

With respect to the conducted parametric study, the following conclusions can be drawn:

- Variations in the flexural rigidity, ultimate bearing capacity, and strain distribution of bamboo beams were investigated and shown to have a clear correlation with an increase in the material properties of the cured epoxy resins, steel material features, and steel diameters. The difference in the epoxy matrix strength appears to have no appreciable impact on the desired outcomes.

- Regarding the influence of steel bar spacing on bearing capacity, it can be seen that reinforced beams with a shorter distance between the steel bars and the bottom of the beam had a better ultimate bearing capacity and bending stiffness; nevertheless, this effect was not statistically significant.
- On the part of the effect of the reinforcement ratios on the bearing capacity of the SRBS beams, it is evident that the ultimate load of bamboo beams increases with the increase of reinforcement ratios, and the ultimate bearing capacity as the reinforcement ratio of the reinforced beam increases, the ultimate deflection of the beam as well is increased.

7.2 Research contribution

The use of bamboo as a structural material has gained substantial attention in recent years. The current bamboo structural design promotes performance-based design as the most reliable and logical method for assessing the flexural performance of structural elements. Nevertheless, the experimental approach to performance-based design is quite costly. With the development of numerical and computational simulations, flexible finite element software packages such as ABAQUS might be utilized to create numerical tools for conducting affordable flexural performance design. In as much as such tools are readily available for conventional concrete, they are extremely limited for SRBS beams. The primary contribution of this dissertation is the development of reasonably accurate FEM models of SRBS beams subjected to a four-point bending test and the utilization of these models in a parametric study to simulate the bending test, including the loading phase with variable parameters. The results of the computational study would also contribute to the establishment of simple prescriptive principles for the design of SRBS beams.

7.3 Challenges

Despite the tremendous effort made in developing the FEM models, the author faced a number of challenges, which included the following among others:

- First and foremost, this study was purely a numerical simulation study and numerical simulations in finite element software packages have a limitation with meshing refinement because the finer the mesh the more operation time is required and may not be able to get desirable results if a coarser mesh is used.

- Difficulty in modelling the failure modes of the SRBS Beams due to a lack of a Damage plasticity model for Bamboo Scrimber material.

7.4 Recommendations

In view of the challenges identified in the preceding section, the author recommends the following suggestions for future research:

- Research work should be directed towards the development of both analytical and numerical models that account for the influence of moisture and temperature influence on the flexural capacity of SRBS beams.
- Research work into the numerical modelling of the SRBS beams with steel bars embedded in them at a macroscopic level would help in developing models with realistic predictions.
- There is a need to develop a damaged plasticity model for wood fibre elements like Bamboo Scrimber material. Alternatively, a secondarily developed user material (UMAT) subroutine on a universal commercial FE platform is necessary.

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APPENDICES

A1 APPENDIX I: MATERIAL CALIBRATIONS

A1.1 Calibration of Bamboo Scrimber

```
*Material, name=MCal_Mat
** Calibrated with MCalibration
** Units: [length]=millimeter, [force]=Newton, [time]=seconds,
** Calibration file name: CALIBRATION FOR BS MATERIAL.mcal
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1e-09
*Elastic, type=traction
** Enn, Ess, Ett
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**
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
35.8853944673, 35.8853944673, 35.8853944673
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
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0.239065136603, 0.0263157894737
0.38531250088, 0.0526315789474
0.462271287008, 0.0789473684211
0.488168183483, 0.105263157895
0.493329216419, 0.131578947368
0.493456129507, 0.157894736842
0.496225069819, 0.184210526316
0.499295015874, 0.210526315789
0.522281881681, 0.236842105263
0.561207496116, 0.263157894737
0.607208279057, 0.289473684211
0.654815886813, 0.315789473684
0.703429283486, 0.342105263158
0.756194296362, 0.368421052632
0.816353135057, 0.394736842105
0.885321308476, 0.421052631579
0.951013865575, 0.447368421053
0.9952949092, 0.473684210526
1, 0.5
```

```

*Surface Interaction, name=coh
*Surface Behavior, pressure-overclosure=hard
*Cohesive Behavior, cohere=original contacts, type=uncoupled
** Knn, Kss, Ktt [unit: stress/length]
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*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
35.8853944673, 35.8853944673, 35.8853944673
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.239065136603, 0.0263157894737
0.38531250088, 0.0526315789474
0.462271287008, 0.0789473684211
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0.493456129507, 0.157894736842
0.496225069819, 0.184210526316
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0.522281881681, 0.236842105263
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0.607208279057, 0.289473684211
0.654815886813, 0.315789473684
0.703429283486, 0.342105263158
0.756194296362, 0.368421052632
0.816353135057, 0.394736842105
0.885321308476, 0.421052631579
0.951013865575, 0.447368421053
0.9952949092, 0.473684210526
1, 0.5
**
*Contact, op=NEW
*Contact Inclusions, ALL EXTERIOR
*Contact Property Assignment
botBlock.top, topBlock.bot, coh

```

A1.2 Calibration of Epoxy Resin/Zirconia compound

A1.2.1 Epoxy Resin @0% Zirconia

```
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** Calibrated with MCalibration
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** Calibration file name: Untitled
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*Elastic, type=traction
** Enn, Ess, Ett
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**
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** Snn, Sss, Stt
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**
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** damage variable, total displacement
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0.65829208731, 0.131578947368
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0.834747030041, 0.263157894737
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0.928192017005, 0.368421052632
0.938330017797, 0.394736842105
0.95042313984, 0.421052631579
0.965159009197, 0.447368421053
0.98189944186, 0.473684210526
1, 0.5
```

```

*Surface Interaction, name=coh
*Surface Behavior, pressure-overclosure=hard
*Cohesive Behavior, cohere=original contacts, type=uncoupled
** Knn, Kss, Ktt [unit: stress/length]
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*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
144.951280755, 144.951280755, 144.951280755
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.248110807, 0.0263157894737
0.420519316794, 0.0526315789474
0.534941507983, 0.0789473684211
0.60908225379, 0.105263157895
0.65829208731, 0.131578947368
0.692668697857, 0.157894736842
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0.754308758394, 0.210526315789
0.793754099808, 0.236842105263
0.834747030041, 0.263157894737
0.871555230855, 0.289473684211
0.898798400875, 0.315789473684
0.916363454027, 0.342105263158
0.928192017005, 0.368421052632
0.938330017797, 0.394736842105
0.95042313984, 0.421052631579
0.965159009197, 0.447368421053
0.98189944186, 0.473684210526
1, 0.5
**
*Contact, op=NEW
*Contact Inclusions, ALL EXTERIOR
*Contact Property Assignment
botBlock.top, topBlock.bot, coh

```

A1.2.2 Epoxy Resin @1% Zirconia

```
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** Calibrated with MCalibration
** Units: [length]=millimeter, [force]=Newton, [time]=seconds,
** Calibration file name: Untitled
*Density
1e-09
*Elastic, type=traction
** Enn, Ess, Ett
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**
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
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**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
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0.995745034851, 0.447368421053
0.999705956946, 0.473684210526
1, 0.5
```

```

*Surface Interaction, name=coh
*Surface Behavior, pressure-overclosure=hard
*Cohesive Behavior, cohere=original contacts, type=uncoupled
** Knn, Kss, Ktt [unit: stress/length]
2696.63390398, 2696.63390398, 2696.63390398
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
46.6340251303, 46.6340251303, 46.6340251303
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.268790526013, 0.0263157894737
0.466935097437, 0.0526315789474
0.608269195083, 0.0789473684211
0.706619677633, 0.105263157895
0.77398551246, 0.131578947368
0.818287400005, 0.157894736842
0.846894224467, 0.184210526316
0.867126867526, 0.210526315789
0.884440112953, 0.236842105263
0.901864617336, 0.263157894737
0.922269028761, 0.289473684211
0.948100427231, 0.315789473684
0.956190640551, 0.342105263158
0.959118477901, 0.368421052632
0.975497985084, 0.394736842105
0.982401922497, 0.421052631579
0.995745034851, 0.447368421053
0.999705956946, 0.473684210526
1, 0.5
**
*Contact, op=NEW
*Contact Inclusions, ALL EXTERIOR
*Contact Property Assignment
botBlock.top, topBlock.bot, coh

```

A1.2.3 Epoxy Resin @2% Zirconia

```
*Material, name=MCal_Mat
** Calibrated with MCalibration
** Units: [length]=millimeter, [force]=Newton, [time]=seconds
** Calibration file name: Untitled
*Density
1e-09
*Elastic, type=traction
** Enn, Ess, Ett
2869.63274256, 2869.63274256, 2869.63274256
**
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
47.7190696265, 47.7190696265, 47.7190696265
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.275069993288, 0.0263157894737
0.484257734944, 0.0526315789474
0.638383372613, 0.0789473684211
0.748260701589, 0.105263157895
0.823356818168, 0.131578947368
0.870134155325, 0.157894736842
0.894648595392, 0.184210526316
0.900952211293, 0.210526315789
0.902259389536, 0.236842105263
0.902982774661, 0.263157894737
0.907625305818, 0.289473684211
0.929973070351, 0.315789473684
0.936240464959, 0.342105263158
0.93999617908, 0.368421052632
0.962677082453, 0.394736842105
0.973124217191, 0.421052631579
0.99040162532, 0.447368421053
0.997553302553, 0.473684210526
1, 0.5
```

A1.2.4 Epoxy Resin @3% Zirconia

```
*Material, name=MCal_Mat
** Calibrated with MCalibration
** Units: [length]=millimeter, [force]=Newton, [time]=seconds,
** Calibration file name: Untitled
*Density
1e-09
*Elastic, type=traction
** Enn, Ess, Ett
2920.70358268, 2920.70358268, 2920.70358268
**
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
49.0890355795, 49.0890355795, 49.0890355795
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.283070746563, 0.0263157894737
0.49676049042, 0.0526315789474
0.652885562646, 0.0789473684211
0.763255424656, 0.105263157895
0.838223170244, 0.131578947368
0.884892544689, 0.157894736842
0.909927635119, 0.184210526316
0.919994744088, 0.210526315789
0.921846298803, 0.236842105263
0.922346605444, 0.263157894737
0.928367447248, 0.289473684211
0.939712614095, 0.315789473684
0.941025008184, 0.342105263158
0.946080572427, 0.368421052632
0.970280554335, 0.394736842105
0.971183131006, 0.421052631579
0.991308906581, 0.447368421053
0.993884264964, 0.473684210526
1, 0.5
```

```

*Surface Interaction, name=coh
*Surface Behavior, pressure-overclosure=hard
*Cohesive Behavior, cohere=original contacts, type=uncoupled
** Knn, Kss, Ktt [unit: stress/length]
2869.63274256, 2869.63274256, 2869.63274256
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
47.7190696265, 47.7190696265, 47.7190696265
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.275069993288, 0.0263157894737
0.484257734944, 0.0526315789474
0.638383372613, 0.0789473684211
0.748260701589, 0.105263157895
0.823356818168, 0.131578947368
0.870134155325, 0.157894736842
0.894648595392, 0.184210526316
0.900952211293, 0.210526315789
0.902259389536, 0.236842105263
0.902982774661, 0.263157894737
0.907625305818, 0.289473684211
0.929973070351, 0.315789473684
0.936240464959, 0.342105263158
0.93999617908, 0.368421052632
0.962677082453, 0.394736842105
0.973124217191, 0.421052631579
0.99040162532, 0.447368421053
0.997553302553, 0.473684210526
1, 0.5
**
*Contact, op=NEW
*Contact Inclusions, ALL EXTERIOR
*Contact Property Assignment
botBlock.top, topBlock.bot, coh

```

A1.2.5 Epoxy Resin @4% Zirconia

```
*Surface Interaction, name=coh
*Surface Behavior, pressure-overclosure=hard
*Cohesive Behavior, cohere=original contacts, type=uncoupled
** Knn, Kss, Ktt [unit: stress/length]
2920.70358268, 2920.70358268, 2920.70358268
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
49.0890355795, 49.0890355795, 49.0890355795
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.283070746563, 0.0263157894737
0.49676049042, 0.0526315789474
0.652885562646, 0.0789473684211
0.763255424656, 0.105263157895
0.838223170244, 0.131578947368
0.884892544689, 0.157894736842
0.909927635119, 0.184210526316
0.919994744088, 0.210526315789
0.921846298803, 0.236842105263
0.922346605444, 0.263157894737
0.928367447248, 0.289473684211
0.939712614095, 0.315789473684
0.941025008184, 0.342105263158
0.946080572427, 0.368421052632
0.970280554335, 0.394736842105
0.971183131006, 0.421052631579
0.991308906581, 0.447368421053
0.993884264964, 0.473684210526
1, 0.5
**
*Contact, op=NEW
*Contact Inclusions, ALL EXTERIOR
*Contact Property Assignment
botBlock.top, topBlock.bot, coh
```

A1.2.6 Epoxy Resin @5% Zirconia

```
*Material, name=MCal_Mat
** Calibrated with MCalibration
** Units: [length]=millimeter, [force]=Newton, [time]=seconds,
** Calibration file name: Untitled
*Density
1e-09
*Elastic, type=traction
** Enn, Ess, Ett
3511.35999728, 3511.35999728, 3511.35999728
**
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
21.3928250715, 21.3928250715, 21.3928250715
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.288906821484, 0.0263157894737
0.506102209315, 0.0526315789474
0.664203400845, 0.0789473684211
0.775820303988, 0.105263157895
0.85200898614, 0.131578947368
0.900358691269, 0.157894736842
0.927989579412, 0.184210526316
0.941997929269, 0.210526315789
0.94335597107, 0.236842105263
0.943780554455, 0.263157894737
0.948551632442, 0.289473684211
0.952612572866, 0.315789473684
0.959062034953, 0.342105263158
0.97116461908, 0.368421052632
0.972270620969, 0.394736842105
0.988967615154, 0.421052631579
0.996063444773, 0.447368421053
0.99938732348, 0.473684210526
1, 0.5
..
```

```

*Surface Interaction, name=coh
*Surface Behavior, pressure-overclosure=hard
*Cohesive Behavior, cohere=original contacts, type=uncoupled
** Knn, Kss, Ktt [unit: stress/length]
3093.40891171, 3093.40891171, 3093.40891171
*Damage Initiation, criterion=maxs, rate dependent
** Snn, Sss, Stt
37.2816599946, 37.2816599946, 37.2816599946
**
*Damage Evolution, type=displacement, softening=tabular
** damage variable, total displacement
0, 0
0.266027197229, 0.0263157894737
0.473231392655, 0.0526315789474
0.630200884771, 0.0789473684211
0.745519080325, 0.105263157895
0.826732336463, 0.131578947368
0.879073215699, 0.157894736842
0.907461208968, 0.184210526316
0.910016528731, 0.210526315789
0.913746962906, 0.236842105263
0.914421324848, 0.263157894737
0.916870963437, 0.289473684211
0.927980620288, 0.315789473684
0.932621231125, 0.342105263158
0.934722326489, 0.368421052632
0.967378309929, 0.394736842105
0.970749217053, 0.421052631579
0.994854522738, 0.447368421053
0.999271422619, 0.473684210526
1, 0.5
**
*Contact, op=NEW
*Contact Inclusions, ALL EXTERIOR
*Contact Property Assignment
botBlock.top, topBlock.bot, coh

```

A1.2.7 Epoxy Resin @0% Zirconia

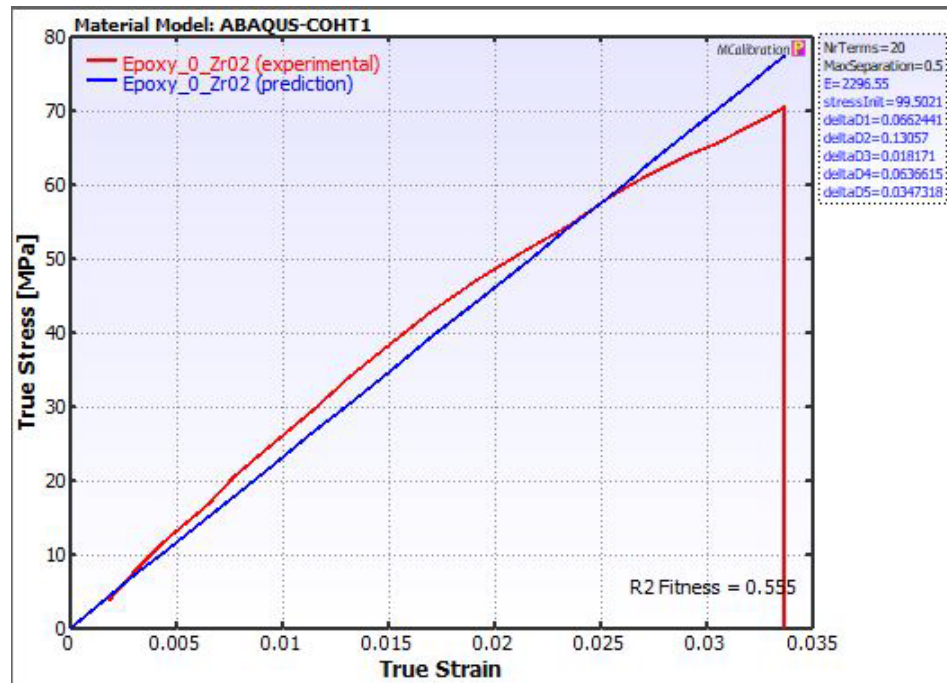


Figure A 1: Screenshot of material calibration of Epoxy resin with ZrO₂ at 0% nanocomposites. Extracted from MCalibration v633.

A1.2.8 Epoxy Resin @1% Zirconia

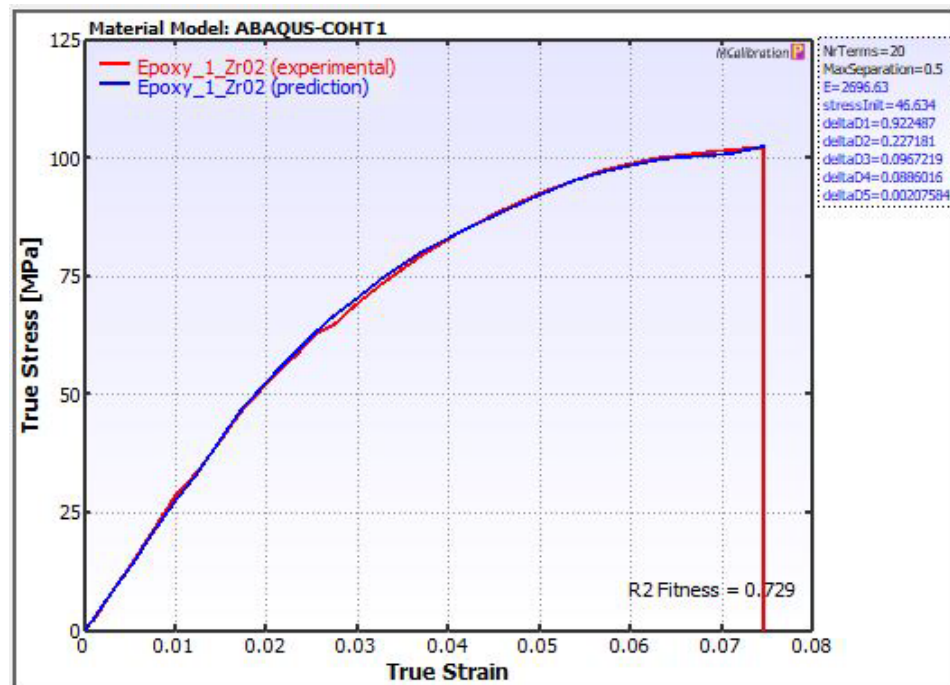


Figure A 2: Screenshot of material calibration of Epoxy resin with ZrO₂ at 1% nanocomposites. Extracted from MCalibration v633.

A1.2.9 Epoxy Resin @2% Zirconia

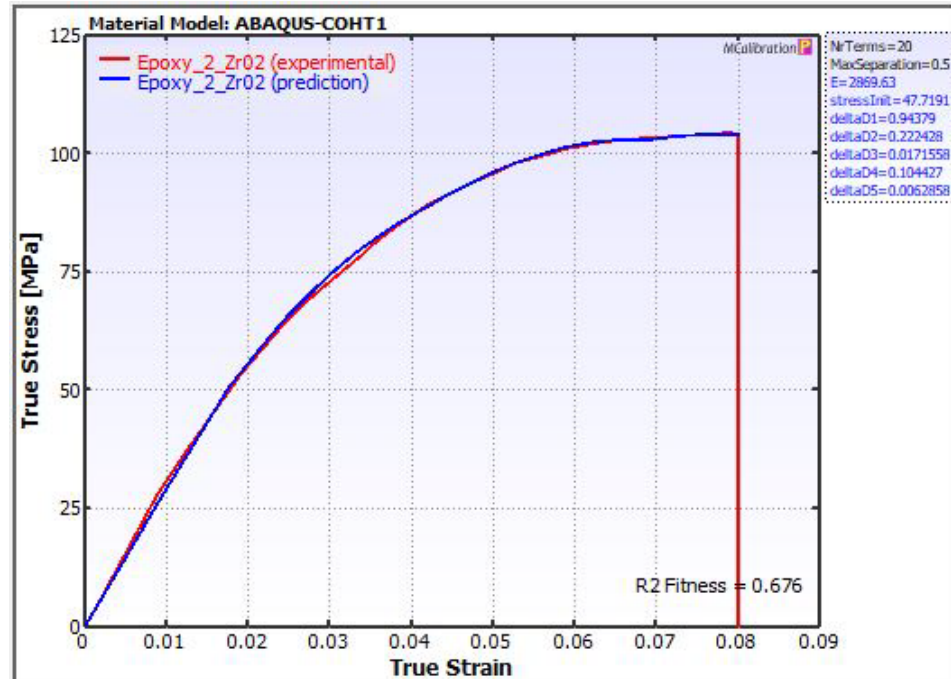


Figure A 3: Screenshot of material calibration of Epoxy resin with ZrO2 at 2% nanocomposites. Extracted from MCalibration v633.

A1.2.10 Epoxy Resin @3% Zirconia

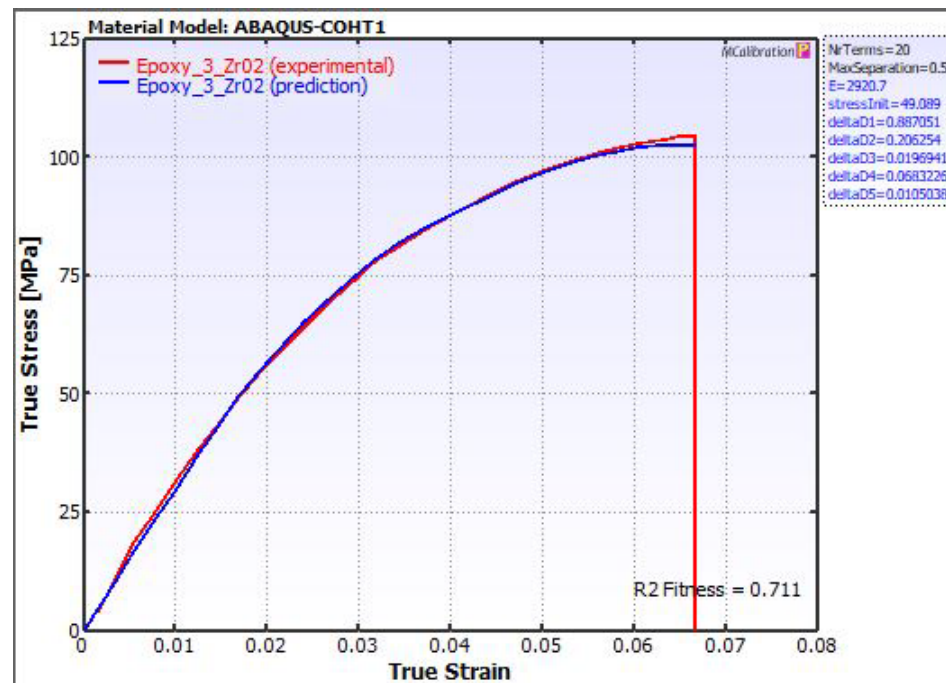


Figure A 4: Screenshot of material calibration of Epoxy resin with ZrO2 at 3% nanocomposites. Extracted from MCalibration v633.

A1.2.11 Epoxy resin @4% Zirconia

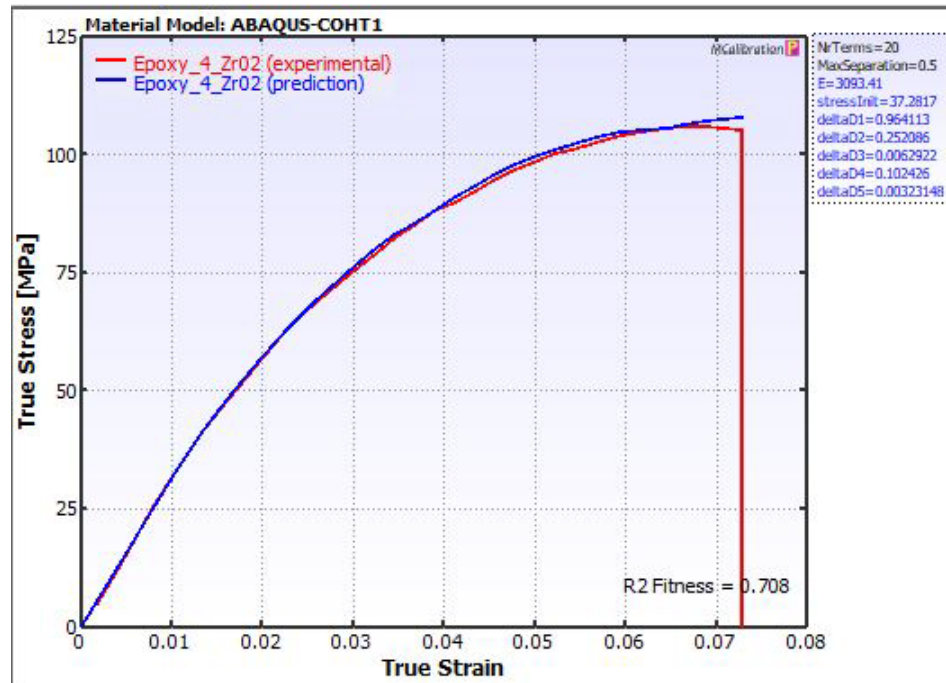


Figure A 5: Screenshot of material calibration of Epoxy resin with ZrO₂ at 4% nanocomposites. Extracted from MCalibration v633.

A1.2.12 Epoxy resin @5% Zirconia

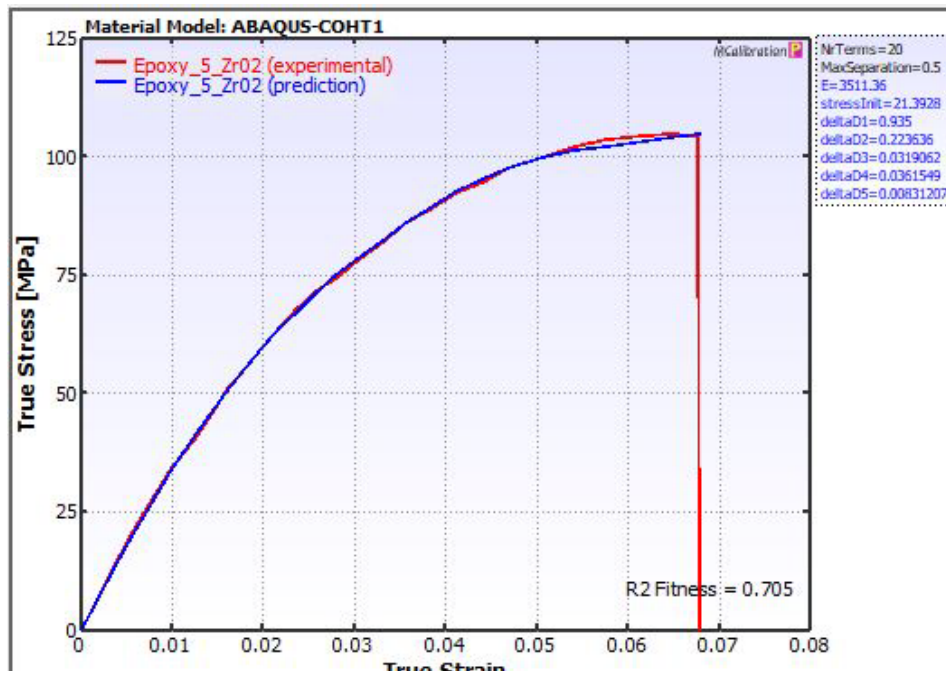


Figure A 6: Screenshot of material calibration of Epoxy resin with ZrO₂ at 5% nanocomposites. Extracted from MCalibration v633.

A2 APPENDIX II: JMP DESIGN PROCEDURE

A2.1 JMP DESIGN PROCEDURE OF A MAIN SCREENING DESIGN

A2.1.1 Main Effects Screening Design where No Standard Design Exists (Methodology)

This is where designs for evaluating the primary impacts are orthogonal or nearly orthogonal. They can be utilised in circumstances when standard designs are unavailable or do not exist. When interactions are insignificant, main effects screening methods are optimal for estimating main effects.

In this experimental situation, no standard design exists. There is need of a design to study 4 factors: All the 4 are categorical, one with 1 level, the second with 5 levels, the third with 1 and the last one with 4 levels.

- 1) Choose DOE > Classical > Two Level Screening > Screening Design. From the drop-down menu there is a single default response labelled Y within the Responses tab. This was recorded as the number of runs.
- 2) Select 1 Level by clicking Categorical in the Factors section. This adds the level variable X1 to the variable L1.
- 3) Choose 5 Level by clicking Categorical. This adds the variable X2, with levels L1 through L5, to the expression.
- 4) Choose 1 Level by clicking Categorical. This includes the variable X3, which has the level L1.
- 5) Select 4 Level by clicking Categorical. This includes the X4 variable, with levels L1 through L4.
- 6) Continue by clicking Continue. The panel for Design Generation appears. There is no opportunity to choose a design from the Design List since there are no standard designs available. Maintain the default number of runs, which is 20, with a minimum of 8 runs.
- 7) Click Create Design to generate a design and a Design Evaluation outline.
- 8) Access the random design by opening the Design outline. The method that creates the design begins with a random design. To recreate this design, choose Save Script to Script Window from the red triangle option next to the report title and

enter the random seed. Examine the Colour Map for Correlations to determine that this particular design is orthogonal.

- 9) Open the blueprint for Design Evaluation > Colour Map on Correlations. On the main diagonal, black entries (using JMP's default colours) represent one-to-one correlations. This is because each diagonal cell refers to the one-to-one connection between a phrase and itself. All off-diagonal correlations are white, signifying that there are no correlations between unique concepts. While hovering over a cell, the relevant words and their absolute correlation are displayed.
- 10) Click Create Table to build the design table. The table comprises the experimental runs in a random order. Perform the experiment in this random sequence and record the findings in column Y. To examine your results, execute the Model script in the data table.

A2.2 JMP SCREENING DESIGN PROCEDURE

The following are the steps involved in the screening design process (See Figure A7).

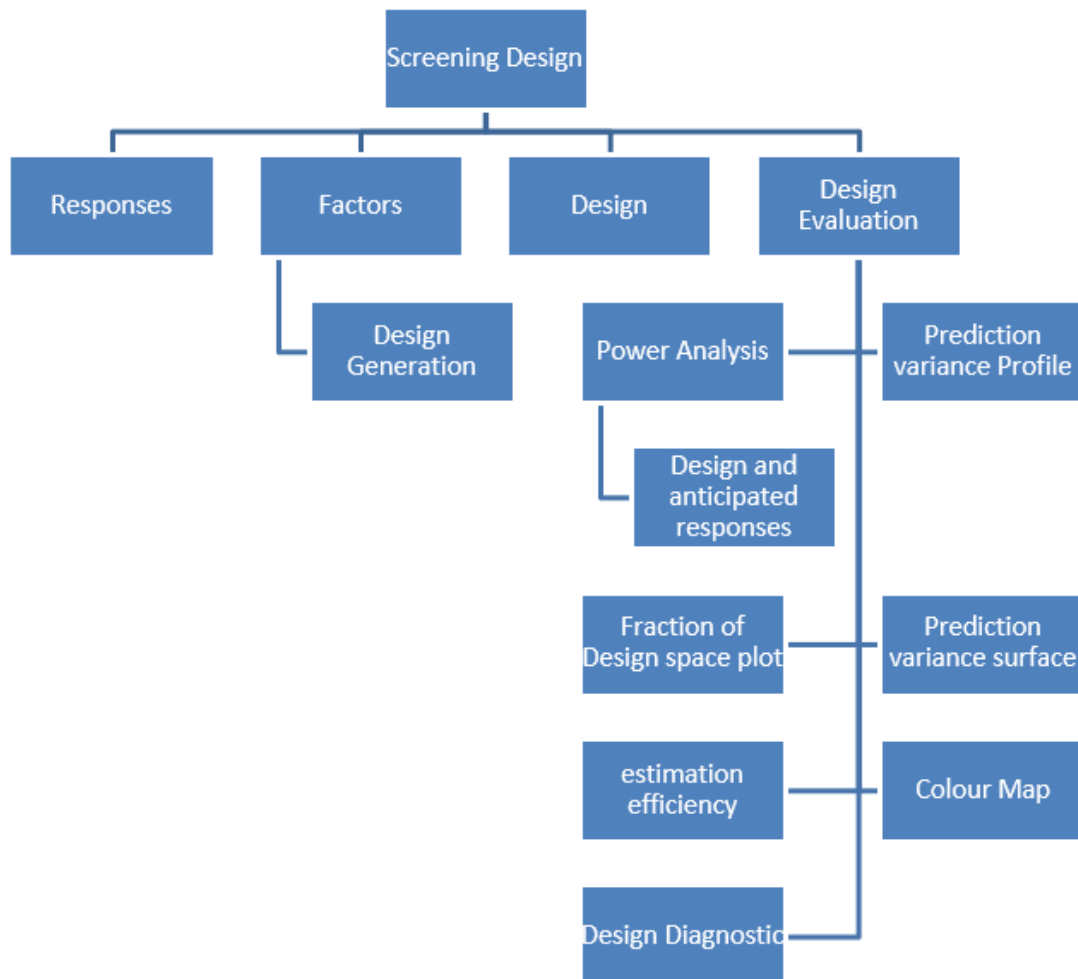
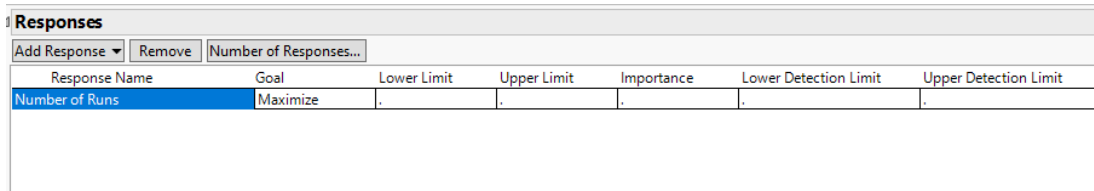


Figure A 7: JMP design procedure of a main screening design

A2.2.1 Responses

As depicted in Figure A8, the needed output was set in the responses panel of the JMP software. In this study, the JMP software was utilized largely to determine the least number of experimental runs required for parametric analysis.



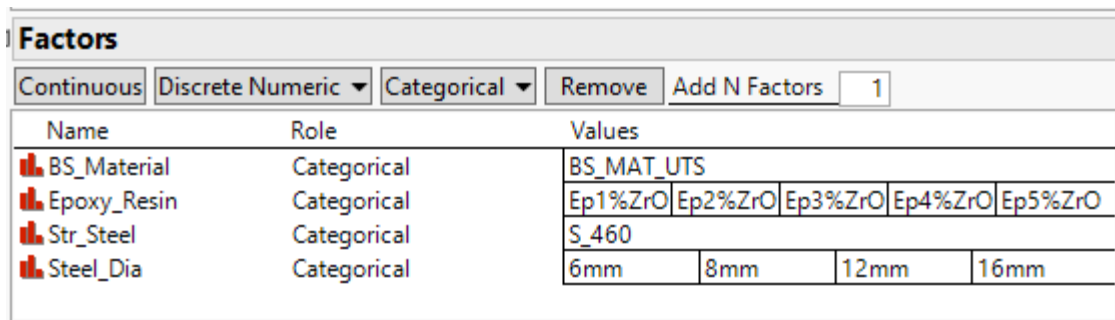
The screenshot shows the 'Responses' panel in JMP. At the top, there are buttons for 'Add Response', 'Remove', and 'Number of Responses...'. Below these is a table with columns: 'Response Name', 'Goal', 'Lower Limit', 'Upper Limit', 'Importance', 'Lower Detection Limit', and 'Upper Detection Limit'. The first row, 'Number of Runs', is highlighted in blue and has 'Maximize' in the 'Goal' column and '.' in the other columns.

Response Name	Goal	Lower Limit	Upper Limit	Importance	Lower Detection Limit	Upper Detection Limit
Number of Runs	Maximize	.	.	.	.	.

Figure A 8: Screenshot from JMP indicating the ultimate goal of the

A3.2.2 Factors

The parameters and their various levels that were analysed in the JMP package in order to calculate the minimum number of runs were inputted as depicted in Figure A9.



The screenshot shows the 'Factors' panel in JMP. At the top, there are buttons for 'Continuous', 'Discrete Numeric', 'Categorical', 'Remove', 'Add N Factors', and a text box with '1'. Below these is a table with columns: 'Name', 'Role', and 'Values'. The 'Name' column lists four factors: 'BS_Material', 'Epoxy_Resin', 'Str_Steel', and 'Steel_Dia'. The 'Role' column lists 'Categorical' for all four. The 'Values' column lists the levels for each factor: 'BS_MAT_UTS' for BS_Material, 'Ep1%ZrO', 'Ep2%ZrO', 'Ep3%ZrO', 'Ep4%ZrO', and 'Ep5%ZrO' for Epoxy_Resin, 'S_460' for Str_Steel, and '6mm', '8mm', '12mm', and '16mm' for Steel_Dia.

Name	Role	Values
BS_Material	Categorical	BS_MAT_UTS
Epoxy_Resin	Categorical	Ep1%ZrO Ep2%ZrO Ep3%ZrO Ep4%ZrO Ep5%ZrO
Str_Steel	Categorical	S_460
Steel_Dia	Categorical	6mm 8mm 12mm 16mm

Figure A 9: Screenshot from JMP showing the factors and different

From the design generation tab, a full factorial of the possibilities resulted in twenty experimental runs, but a fractional factorial resulted in only eight runs, as illustrated in Figure A10.

Design Generation

Number of Runs:

☒ Minimum 8

☐ Default 20

☐ User Specified

Figure A 10: Screenshot from JMP indicating the minimum and maximum combinations of experimental runs

A2.2.2 Design

Figure A11 shows the combination of the 8 experimental runs that shall be considered in the flexural capacity determination.

Design				
Run	BS_Material	Epoxy_Resin	Str_Steel	Steel_Dia
1	BS_MAT_UTS	Ep2%ZrO	S_460	12mm
2	BS_MAT_UTS	Ep5%ZrO	S_460	8mm
3	BS_MAT_UTS	Ep3%ZrO	S_460	8mm
4	BS_MAT_UTS	Ep1%ZrO	S_460	12mm
5	BS_MAT_UTS	Ep4%ZrO	S_460	16mm
6	BS_MAT_UTS	Ep2%ZrO	S_460	6mm
7	BS_MAT_UTS	Ep3%ZrO	S_460	6mm
8	BS_MAT_UTS	Ep1%ZrO	S_460	16mm

Figure A 11: Screenshot from JMP indicating the minimum eight detailed combinations.

A2.2.3 Design evaluation

The design evaluation consists of; power analysis, Prediction variance profile, Fraction of design space plot, Estimation efficiency, Colour map and correlation and Design diagnostics.

A power analysis was performed to ascertain whether the reason an effect was not significant was due to a lack of power. It is a measure of the likelihood of finding a substantial effect (if there is). It demonstrates the design's ability to identify significant effects and determines the power of tests for parameters in the a priori model. The significance level is stated, as are the RMSE estimations.

All power estimations have been made in accordance with these criteria. Then, within the outline for Power Analysis, power calculations were approached in two ways:

- For each model term, Anticipated Coefficient values that reflect the differences to be found are specified. The power calculations were performed through Applying Changes to Anticipated Coefficients (See Figure A12).

Power Analysis		
Significance Level	0.05	
Anticipated RMSE	1	
Term	Anticipated Coefficient	Power
Intercept	6.327	0.8
Epoxy_Resin 1	15.061	0.719
Epoxy_Resin 2	-15.061	0.814
Epoxy_Resin 3	15.061	0.719
Epoxy_Resin 4	-15.061	0.554
Steel_Dia 1	16.3	0.86
Steel_Dia 2	-16.3	0.666
Steel_Dia 3	16.3	0.86
Apply Changes to Anticipated Coefficients		
Effect	Power	
Epoxy_Resin	0.8	
Steel_Dia	0.8	

Figure A 12: Screenshot from JMP indicating the results of the power analysis

- For all design parameters, Anticipated Response values that reflect the variations that must be noticed were defined. Applying Changes to Predicted Responses computed the anticipated coefficients and provided the associated power calculations (See Figure A13).

In either case, computing the power of the impacts at the provided values was computed by applying the changes.

Design and Anticipated Responses				
Anticipated Response	BS_Material	Epoxy_Resin	Str_Steel	Steel_Dia
7.566	BS_MAT_UTS	Ep2%ZrO	S_460	12mm
-9.973	BS_MAT_UTS	Ep5%ZrO	S_460	8mm
5.088	BS_MAT_UTS	Ep3%ZrO	S_460	8mm
37.688	BS_MAT_UTS	Ep1%ZrO	S_460	12mm
7.566	BS_MAT_UTS	Ep4%ZrO	S_460	16mm
37.688	BS_MAT_UTS	Ep2%ZrO	S_460	6mm
-25.034	BS_MAT_UTS	Ep3%ZrO	S_460	6mm
5.088	BS_MAT_UTS	Ep1%ZrO	S_460	16mm

Figure A 13: Screenshot from JMP showing the design and anticipated responses.

The Prediction Variance Profile plot: illustrates the prediction's precision across all factor levels. For any factor setting, the prediction variance is the product of the error variance and a quantity that varies according to the design and factor configuration. The ratio of prediction variance to error variance, referred to as the relative prediction variance, is determined entirely by the design, not by the experimental results. In an ideal world, the design would have a low relative prediction variance across the region covered by the components.

The Prediction Variance Profile plot was used to investigate the values of the relative prediction variance by varying the factor settings, to compare designs by comparing their Prediction Variance Profile plots side by side, and to determine the design's maximum prediction variance and the factor settings where it occurs using the Maximize Desirability option (see Figure A14).

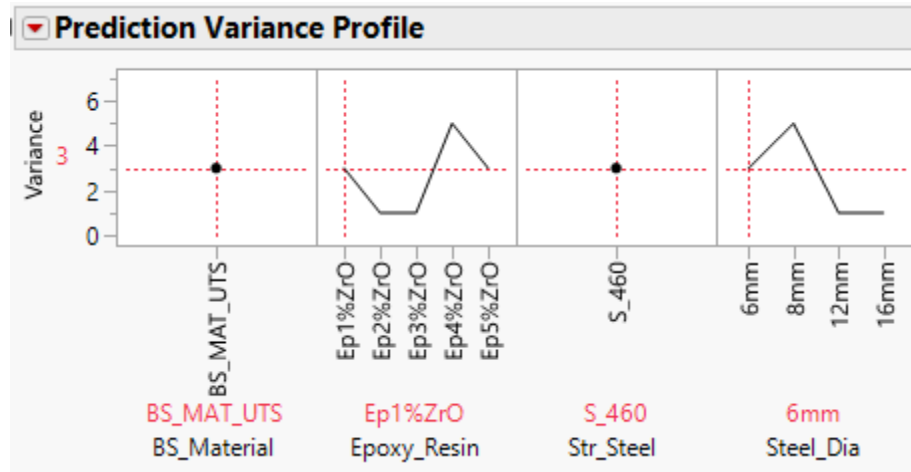


Figure A 14: Screenshot from JMP indicating the prediction variance profile

Fraction of design space plot; Due to the interest in prediction, it is also beneficial to evaluate the Fraction of Design Space plot. This graphic depicts the percentage of the design space where the relative prediction variance is smaller than a specified value. The relative prediction variance should ideally be small across the majority of the design area. On the basis of their Fraction of Design Space plots, designs can be compared (see Figure A15).

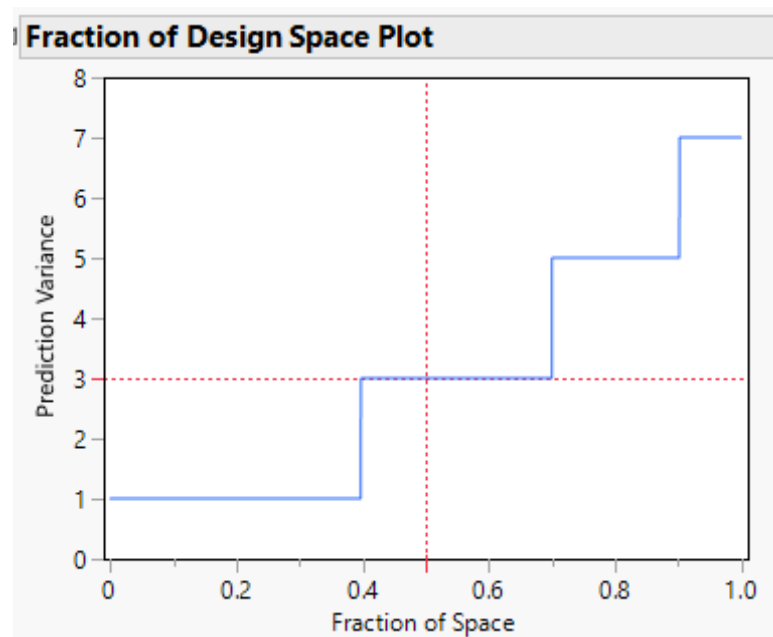


Figure A 15: Screenshot from JMP indicating the fraction of design space plot.

Prediction variance surface; was used to investigate the precision of the predictions at any two factor settings. The plot depicts a surface illustrating the relative prediction variance as a function of design variables. The plot can be dragged to rotate and adjust the perspective (see Figure A16).

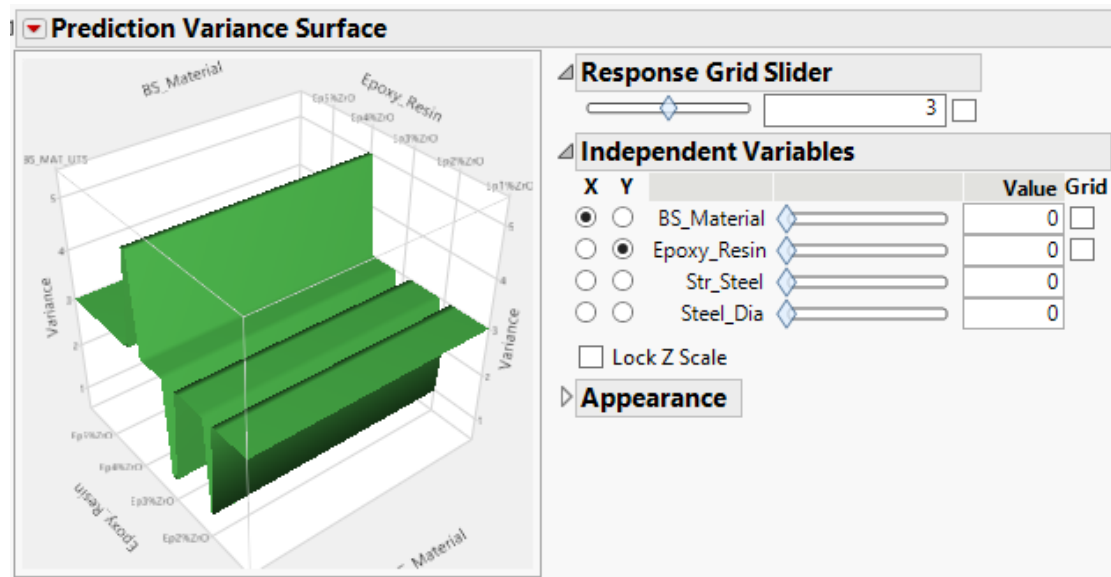


Figure A 16: Screenshot from JMP indicating the prediction variance surface.

Estimation efficiency; The Estimation Efficiency report gives a measure of precision called the fractional increase in confidence interval (CI) length. It also gives the relative standard error for each parameter estimate in the model. It is important in the estimation of parameters with the greatest possible precision.

The Fractional Increase in CI Length parameter compares the length of a parameter's confidence interval as specified by the present design to the length specified by an ideal design.

If such a thing exists, the best design would be orthogonal.

When choosing a design, it is important to keep the fractional increase in confidence interval length as modest as possible.

To be more precise, the Fractional Increase in CI Length is calculated as follows: The length of the parameter's ideal confidence interval is deducted from the length of the

parameter's actual confidence interval. This difference is then multiplied by the desired confidence interval's length.

Certain parameters in this study have fractional increases in confidence interval length around 1, implying that their confidence intervals are twice as lengthy as the ideal design's confidence intervals. In response surface designs, larger increases in the lengths of confidence intervals are frequent. This is because quadratic effects range between 0 and 1, whereas the "ideal" design assumes that each column in the model matrix contains an equal number of +1 and -1 values. As a result, when it comes to reaction surface designs, this statistic is better used for design comparison rather than being taken literally. (See Figure A17).

Estimation Efficiency		
Term	Fractional Increase in CI Length	Relative Std Error of Estimate
Intercept	0.095	0.387
Epoxy_Resin 1	1.191	0.775
Epoxy_Resin 2	0.265	0.447
Epoxy_Resin 3	0.265	0.447
Epoxy_Resin 4	1.191	0.775
Steel_Dia 1	1	0.707
Steel_Dia 2	1	0.707
Steel_Dia 3	0.414	0.5

Figure A 17: Screenshot from JMP indicating the estimation efficiency

Colour map and correlation: The Colour Map on Correlations was explored in the interest of Inference. Correlations between effects increase standard errors, making it more difficult to identify active effects. Correlations' Colour Map displays the absolute value of the correlation between any two effects in the Model or Alias Terms outline. Each effect has its own cell in the Model outline, and each effect has its own cell in the Alias Terms outline (see Figure A18).

By default, the correlations' absolute magnitudes are visualized using a blue-to-grey-to-red intensity colour theme. In general, a good design's colour map contains a lot of blue off the diagonal, indicating orthogonality or a low degree of correlation between dissimilar concepts.

The deep red colouration shows one-to-one absolute relationships. As expected, there are red cells on the diagonal, indicating that model terms are correlated with one another. The remaining cells are either deep blue or pale blue. Correlations between quadratic terms are represented by the light blue squares. Correlationally, this is an excellent design.

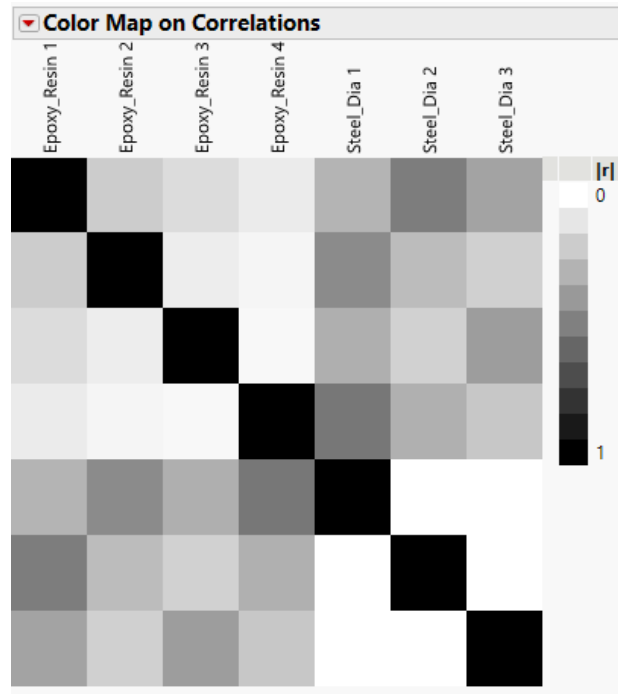


Figure A 18: Screenshot from JMP showing the colour map on correlations

Design diagnostics; The Design Diagnostics was used to compare designs' efficiency to three widely used efficiency measures (D, G, and A efficiency). The various efficiency values are set to 100% in an ideal design. However, when a model contains quadratic effects, inequality constraints, or disallowed combinations, these efficiency measures are best used to compare design alternatives rather than to be taken literally. Additionally, the report includes the average prediction variance across the entire design region (see Figure A19).

Design Diagnostics	
Alias Optimal	
D Efficiency	68.35909
G Efficiency	14.28571
A Efficiency	33.33333
Average Variance of Prediction	3
Design Creation Time (seconds)	16

Figure A 19: Screenshot from JMP indicating the design diagnostics



THE UNIVERSITY OF ZAMBIA

DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka10101 | Tel: +260-211-290 258/291 777
 Fax: (+260)-211-290 258/253 952 | E-mail: director.drgs@unza.zm | Website: www.unza.zm

APPROVAL OF STUDY

11th February, 2022

REF NO. NASREC-2021-SEP-015

Mweetwa Mulongo
 The University of Zambia
 School of Engineering
 P.O. Box 32379
LUSAKA

Dear Mr. Mulongo,

RE: “NUMERICAL INVESTIGATIONS OF STEEL REINFORCED BAMBOO SCRIBER BEAMS.”

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

Review Type	Ordinary Review	Approval No. NASREC-2021-SEP-015
Approval and Expiry Date	Approval Date: 11 th February, 2022	Expiry Date: 10 th February, 2023
Protocol Version and Date	Version - Nil.	10 th February, 2023
Information Sheet, Consent Forms and Dates	<ul style="list-style-type: none"> English. 	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

Conditions of Approval

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.
- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.
- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.
- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.
- Principal investigators are responsible for initiating Continuing Review proceedings. NASREC will only approve a study for a period of 12 months.
- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.
- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled “late submissions” and will incur a penaltyfee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.
- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.
- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO),both NASREC
- and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.
- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.
- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.
- A reprint of this letter shall be done at a fee.
- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address

or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented. Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,



Dr. E. M. Mwanaumo

**CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCH
ETHICS COMMITTEE - IRB**

CC: Director, Directorate of Research and Graduate Studies
 Assistant Director (Research), Directorate of Research and Graduate Studies
 Assistant Registrar (Research), Directorate of Research and Graduate Studies

A4 APPENDIX IV: PROOF OF ARTICLE SUBMISSION

The University of Zambia
Department of Civil and Environmental Engineering
Lusaka,
Zambia,
10101.

Email: mweetwamulongo@gmail.com

25th, March, 2023

**Prof. Leroy Gardner ,
Editor-in-Chief
Journal of Structures**

Dear Professor Gardner,

REF: REQUEST TO SUBMIT A MANUSCRIPT

We would like to submit the enclosed manuscript to be considered for publication in Journal of Structures.

Title: *Numerical investigation of steel reinforced bamboo scrimber beams.*

Authors: *M. Mulongo, C.G. Chizyuka, C. Kahanji*

The manuscript presents a finite element (FE) three-dimensional model of a steel-reinforced bamboo scrimber beam (SRBS) exposed to a four-point bending test in order to determine its flexural strength through numerical simulation. After model validation, various physical and mechanical properties were parametrized, and the influence rules for each parameter were established.

The manuscript is original work and is not being considered for publication elsewhere.
Each of the credited authors played a role in the study.

Yours sincerely,



Mweetwa Mulongo

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Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status
Action Links		NUMERICAL INVESTIGATION OF STEEL REINFORCED BAMBOO SCRIMBER BEAMS.	Mar 25, 2023	Mar 25, 2023	Submitted to Journal

Page: 1 of 1 ([1 total submissions](#))

Results per page 10 ✓



mweetwa mulongo <mweetwamulongo@gmail.com>

Submission Confirmation

STRUCTURES <em@editorialmanager.com>
Reply-To: STRUCTURES <support@elsevier.com>
To: Mweetwa MULONGO <mweetwamulongo@gmail.com>

Sat, Mar 25, 2023 at 11:11 AM

Re: NUMERICAL INVESTIGATION OF STEEL REINFORCED BAMBOO SCRIMBER BEAMS.
by %ALL Authors%
Research Paper

Dear Mweetwa,

We have received your article "NUMERICAL INVESTIGATION OF STEEL REINFORCED BAMBOO SCRIMBER BEAMS." for consideration for publication in Structures.

Your manuscript will be given a reference number once an editor has been assigned.

To track the status of your paper, please do the following:

1. Go to this URL: <https://www.editorialmanager.com/structures/>
2. Enter your login details
3. Click [Author Login]
This takes you to the Author Main Menu.
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Thank you for submitting your work to this journal.

Kind regards,

Editorial Manager
Structures

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