NSM Polyester-Reinforced *Albizia chinensis* Beams: Flexural Performance Evaluation

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Abstract: This study investigates the flexural performance of *Albizia chinensis* wood beams strengthened using Near Surface Mounted (NSM) polyester resin under four-point bending tests. The primary objective of this study is to evaluate the enhancement in flexural behavior due to the addition of NSM polyester reinforcement. Three beam configurations were tested: unreinforced (TO), single-groove reinforced (TPSE), and double-groove reinforced (TPR). The strengthening process involved embedding polyester resin into pre-cut grooves on the beam surface, where the resin served as both adhesive and filler for bonding the reinforcement with the wood substrate. The experimental results demonstrate that beams reinforced with NSM polyester exhibit higher load capacity and improved stiffness. Specifically, the TPR specimen achieved an increase in the ultimate load of more than 30% compared with the TO specimen. Furthermore, the use of polyester resin as an infill material in the grooves effectively bonded the reinforcement to the surrounding wood matrix. This not only contributed to improved mechanical performance but also showed promise due to its ease of application and cost-effectiveness. The strain distribution in the reinforced specimens suggested a more favorable deformation profile, especially in TPR. Additionally, cyclic testing on the reinforced beams revealed enhanced resilience against repeated loading, making the reinforcement system suitable for dynamic conditions. The results were validated using a theoretical flexural strength estimation based on section modulus and characteristic strength of *Albizia chinensis* wood. The findings further confirm the feasibility of using polyester as an effective shear reinforcement in structural timber applications, especially in low-cost rural construction. The study concludes that NSM polyester reinforcement is effective in improving the flexural performance of *Albizia chinensis* wood beams and offers a practical alternative for timber strengthening in engineering practice.

Keywords: Albizia chinensis; near surface mounted; shear-end; stirrup rebars.; timber polymer beam

1. Introduction

Reinforcement and retrofit techniques play a critical role in enhancing the structural integrity and lifespan of aging or damaged infrastructure. Near-surface-mounted (NSM) technology, which involves embedding reinforcement bars or fibers, such as carbon fiber-reinforced polymers (CFRP), into shallow grooves on the surface of concrete members, is a promising method in structural reinforcement. This approach provides an efficient, minimally invasive solution for improve the load-bearing capacity and seismic resistance of existing structures. Unlike traditional external bonding methods, NSM reinforcement is embedded, offering better protection from environmental degradation and improved load transfer. This method has gained popularity due to its effectiveness in reinforcing beams, columns, and slabs, especially in concrete structures that require increased strength without significant alterations to their appearance or functionality.

Developing carbon-neutral or green concrete is essential for achieving sustainability in concrete construction[1]. In addition, the preference for polymer concrete over traditional concrete stems from the desire to reduce the environmental impact of global cement manufacturing. According to Shobeiri et al.,[2] said that Cement manufacturing is a significant source of atmospheric carbon dioxide, responsible for roughly 5% to 7% of global CO_2 emissions. Also, in Almutairi et al.,[3] said that despite recent efforts by the cement and concrete industries to reduce carbon dioxide emissions, such as implementing

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carbon dioxide detection systems, these measures may not be sufficient to address the current environmental challenges. Several studies to reduce cement usage have been conducted, including by Zhakypova et al.,[4] who used ash of kazakhstan (namely: the influence of dispersion of hydro-removal ash and liquid glass additives on the properties of fine-grained concrete) in a concrete mixture to reduce cement. The results of which showed that it can be used in several construction applications such as brick mortar, wall blocks, paving slabs, and curbs.

However, in addition to reducing cement in non-structural construction, this is also required in structural construction parts, which require materials that are strong enough to reduce or even replace cement. Research conducted by Kumari et al.,[5] highlights the substantial contribution of cement production to carbon emissions. Their findings underscore the significant role of clinker production in this regard, with a carbon dioxide emission factor of 0.3838t/ton of limestone and 0.4373t/ton of cement, as determined by analyzing both direct manufacturing emissions and the complete life cycle of cement within the industry. Natural materials in the form of wood combined with unsaturated polyester (UP) will be used in this study strengthen wood, which is a more environmentally friendly material. The combination of natural materials with UP has recently become quite popular. As in the study conducted by Ganta et al.,[6] UP is combined with natural materials, namely bamboo. Reviewed how its mechanical and thermal performance is. Showed that the combination can produce alternative composite materials that are quite promising and have great opportunities for further research. New research investigates a novel cement-based adhesive for Near Surface Mounted (NSM) Fiber-Reinforced Polymer (FRP) systems in concrete structures, was investigated, addressing the limitations of epoxy in high-temperature and moisture conditions. Experimental pull-out testing demonstrated that the new adhesive achieved 65% of the epoxy's maximum bond stress while providing enhanced ductility and reducing environmental hazards. These findings underscore its potential as a sustainable and efficient alternative, contributing to safer, high-performance concrete strengthening applications[7]. This research presents a novel near-surface mounted (NSM) technique for shear-strengthening T-beams using closed-stirrup CFRP ropes. Experimental results from nine full-scale T-beams revealed load-bearing capacity increases of 1.8 to 2.2 times and deflection or displacement enhancements of 5.2–7.8 times. The rope stirrups outperformed external bonded carbon fiber-reinforced polymers (EB-CFRP) sheets with anchors, ensuring ductile flexural failure while minimizing installation complexities. This approach is practical, efficient, and reliable for overcoming the geometric restrictions in strengthening[8]. Another study utilized machine learning to predict the shear capacities of NSM FRP shear-strengthened RC beams, constructing a database of 130 beams with 15 parameters. A network called a genetic-algorithm-enhanced backpropagation neural network (GA-BPNN), trained with Bayesian regularization, achieved accurate predictions and robust generalization. Parametric analyses explored contributions of concrete, steel stirrups, and FRP, informing an optimized design-oriented strength model. Validated against existing models, it offers superior prediction accuracy, enhancing practical engineering applications[9].

Another research evaluated the flexural performance of concrete prisms strengthened with FRP using finite element models in ABAQUS, comparing grooved and externally bonded configurations. Grooved CFRP prisms demonstrated a 6% higher load-carrying capacity than externally bonded ones, highlighting potential bond improvements. However, the limited enhancement suggests low-strength concrete influenced failure modes, necessitating further studies on stronger substrates to optimize this grooving approach for higher-performance structural reinforcement[10]. Another study investigated the use of nanomaterial-modified epoxy adhesives (NMEAs) for Near-Surface Mounted (NSM) FRP flexural retrofitting of concrete. A total of 48 concrete prisms retrofitted with carbon FRP (CFRP), Glass FRP (GFRP), and basalt FRP (BFRP) were tested under three-point bending. Key findings include: (1) Silicon-based NMEAs (silica, clay) enhanced load capacities and ductility more than carbon-based NMEAs (carbon nano fiber, graphite), which prevented debonding but reduced ductility. (2) Increasing the groove size improved ductility, while larger grooves reduced the capacity at higher graphite wt.%. (3) Failure modes varied, with carbon-based NMEAs transitioning from shear to flexural failures. SEM and XRD analyses revealed that agglomeration and porosity in NMEAs significantly influenced mechanical performance[11]. Another study explores the use of a novel NSM U-shaped FRP (NUF) device for shear strengthening of reinforced concrete beams. Fabricated via a wet lay-up process, the NUF effectively enhances the bond efficiency between the FRP and concrete, addressing debonding failures common in NSM FRP applications. Experimental testing on seven full-scale beams demonstrated the device’s ability to postpone or prevent debonding, increasing the strengthening efficiency by up to 35%, showcasing its transformative potential[12].

Nowadays, NSM application in timber research has a nice beginning, such as Yeboah and Gkantou[13], who conducted research on enhancing the strength of timber beams by incorporating basalt and fiberglass fibers. Epoxy adhesive, commonly used in this method, plays a critical role in transferring loads between the timber and reinforcing fibers. The shear and tensile strength of the adhesive is crucial to the success of the technique, as it acts as the bonding agent between the two materials. NSM (near surface mounted) specimens are created by grooving the structural timber and embedding FRP bars into the grooves filled with adhesive. Another study by Mathuros et al.,[14] investigates the flexural performance of timber beams reinforced with glass fiber-reinforced polymer (GFRP) rods using the near-surface mounted technique. Sixteen beams, including controls and various GFRP ratios, were subjected to monotonic and cyclic loading. Results showed significant improvements: load capacity increased by 20%–61%, initial stiffness by 58%–71%, and energy absorption by 35%–96% under monotonic conditions, with similar enhancements under cyclic loading. Their results validate the effectiveness of GFRP reinforcement in enhancing timber beam performance.

Another research by Melinda et al.,[15] examines the bending performance of laminated veneer lumber (LVL) beams strengthened with carbon fiber-reinforced polymer (CFRP) plates applied to the compression side using the near-surface mounted (NSM) technique. Fourteen beams underwent four-point bending tests, revealing enhancements: bending strength improved by 4.24%–28.85%, and stiffness increased by 16.48%–62.51%. The application of CFRP plates significantly reduced compressive strain by up to 91.81%, confirming the effectiveness of the NSM technique in enhancing timber durability and performance. The experimental study by Siha and Zhou[16] investigated the hysteretic behavior of circular timber columns strengthened with wrapped CFRP strips and near-surface mounted steel bars. The eight columns were subjected to lateral cyclic loading tests to evaluate the effectiveness of this composite reinforcement method. The results indicated significant improvements in the bearing capacity (32.3%–60.1%) and deformation performance (67.9%–89.4%). Their results confirm strong bonding between CFRP strips and timber, enhancing energy dissipation and reducing stiffness degradation, thus providing essential insights for seismic design applications. Previous studies on low-grade glulam timber beams reinforced with GFRP bars revealed that circular groove profiles provided greater stiffness and moment capacity improvements compared to square groove profiles. The variation in the reinforcement ratio also affected the performance, with strength increases ranging from 18% to 46% achieved by increasing the reinforcement ratio from 0.27% to 0.82%. However, stiffness improvements were significant only at relatively high reinforcement ratios. For optimal performance, it is recommended to place most of the reinforcement at the top and bottom of the beam to maximize strength, while distributing reinforcement evenly in both tension and compression zones to improve stiffness. To achieve maximum ductility, all reinforcement should be placed at the bottom of the beam. Another study explored the bond behavior between timber and near-surface-mounted steel bars through pull-out tests on 48 specimens. The investigation reveals four failure modes: pull-out, splitting, mixed, and shear failure. The results show an uneven strain distribution along the anchorage length, with a saddle-shaped bond stress distribution. Factors such as anchorage length, bar diameter, glue-line thickness, and groove depth significantly affect bond performance. A newly proposed pull-out load design model demonstrates strong predictive accuracy, while established bond stress-slip models align well with experimental results, ensuring reliable application in timber reinforcement[17]. Another study by Poletti et al.,[18] investigates the application of the near-surface mounted (NSM) strengthening technique on traditional timber frame walls, which are valued for their seismic resistance and cost-effectiveness. Through an extensive experimental program, static cyclic tests on various wall typologies demonstrate that NSM retrofitting enhances strength while accommodating timber deformation. The presence of infill affects the hysteretic response, and stiff infill can hinder the deformation of steel flat bars, reducing their effectiveness. Their findings contribute to better preservation and rehabilitation strategies for historic timber structures.

The study by Lu et al.,[19] examines the flexural behavior of glulam beams reinforced with near-surface mounted (NSM) CFRP laminates, utilizing Douglas fir and Poplar. Twenty-four beams were tested, revealing that NSM-CFRP significantly enhanced flexural strength by 34.2%–52.3% and stiffness by 8%–28.5%. The reinforced beams displayed pseudo-ductile behavior, which contracts contrasting with the brittle failure of unreinforced beams. Additionally, the reinforcement shifted the neutral axis location, improving compressive behavior. Theoretical predictions aligned closely with experimental findings, confirming the effectiveness of NSM-CFRP reinforcement in timber engineering.

Yeboah and Gkantou[13] observed that the addition of FRP reinforcement to the compression zone of NSM beams, in addition to the tensile zone, does not always correlate with an increase in the ultimate load capacity. They concluded that to significantly improve load-bearing capacity, optimization in both the tensile and compression zones is necessary. It is also important to consider geometric factors, such as the spacing between grooves and the edge distance of the beam, before increasing the reinforcement cross-sectional area. According to the Forest Products Laboratory[20], key parameters for evaluating the mechanical behavior of wood include compressive and bending strength. The compressive strength parallel to the grain represents the maximum load wood can sustain under axial compression, and is influenced by specimen geometry, especially the slenderness ratio. Generally, the recommended length-to-width ratio should not exceed 11 to avoid buckling effects. In contrast, compressive strength perpendicular to the grain is considerably lower and varies significantly across species, with limited consensus on

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standardized values due to wood's anisotropic nature. The investigation by Yeboah and Gkantou[13] focuses on the flexural behavior of structural timber beams reinforced with near-surface mounted (NSM) basalt and glass FRP bars. A total of 20 four-point bending tests were conducted on white spruce specimens, comparing beams reinforced in the tension zone only and those reinforced in both tension and compression zones. The results indicated that NSM FRP significantly enhanced the ultimate load capacity by 33%–69% and flexural stiffness by 22%–33%. The predominant failure mode was brittle tensile failure. A theoretical flexural strength model showed strong agreement with experimental data, advancing the understanding of NSM FRP applications in timber engineering.

The study by Song et al.,[21] explores the flexural performance of square and circular timber beams reinforced with hybrid fiber-reinforced polymer (HFRP) plates using near-surface-mounted (NSM) and externally bonded methods. Circular cross-sections strengthened with HFRP-I plates using carbon:aramid=2:1:1 showed the highest ultimate bearing capacity, improving by 39.1% to 104.5%. Theoretical and numerical models validated the findings, with deviations within 16.5% and 10%, respectively, supporting reliable engineering applications and enhanced cost-effectiveness.

Unsaturated polyester is a macromolecule formed through the reaction of a diacid or dianhydride with a hydroxyl compound (diol), typically ethylene glycol or propylene. In the production of unsaturated polyester, fumaric acid or maleic anhydride is used to introduce unsaturation, which is depicted in Figure 1[22]. Furthermore, Massy[23] explained that polyester has a low acid value, indicating good resistance to alkalis. Reinforcement with glass fibers in a polyester matrix results in a composite with high strength and stiffness, making it suitable for large-scale structural applications such as storage tanks and ship hulls. The use of unsaturated polyester (UP) on wood in the research conducted by Huang shows that there is a good opportunity to use UP with wood in terms of bonding and fire resistance[24]. The use of UP as polymer concrete has been quite common. Among them is further research on polyester polymer concrete that has increased material strength, including ultimate stress and strain[25]. Even Unsaturated polyester polymer concrete is commonly used in repair construction because of its relatively fast curing[26]. Methyl Ethyl Ketone Peroxide (MEKP) is a commonly used complex peroxide that serves as an initiator or catalyst for polymerization in industrial applications. When applied to polyester polymer resin, MEKP triggers the thickening process. Increasing the amount of MEKP in the polyester resin accelerates the curing process[27].

Fly ash is the finest particulate matter from coal combustion, called "fly ash" because it is carried out of the combustion chamber via exhaust gases. It is a fine powder

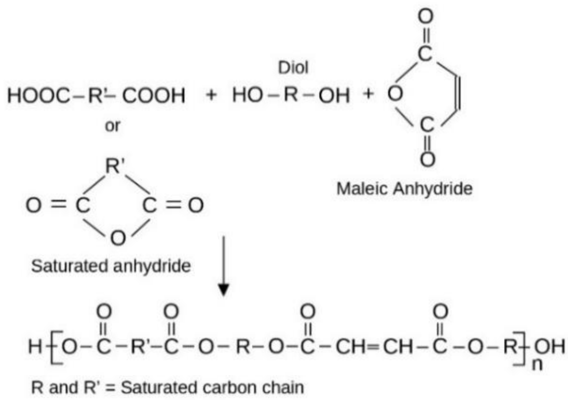


Fig. 1: UPE resin synthesis reaction scheme

formed from the mineral content in coal, consisting of non-combustible materials and trace amounts of carbon resulting from incomplete combustion. Fly ash is generally light brown in color[28]. Garbazc and Sokolowska's[29] study explored how calcium fly ash affects polymer concrete made with vinyl ester and unsaturated polyester. They found that this material (CFA-PC) achieved impressive average strengths: 75.4 MPa in compression, 9.37 MPa in tension, and 17.57 MPa in flexure. Their research also indicated that increasing the fly ash content generally boosts the composite's mechanical strength and chemical resistance, up to a certain limit. Rochman et al.,[30] In his research, he found that the use of fly ash together with polymer concrete in certain amounts can indeed increase the strength of its properties.

NSM reinforcement involves embedding high-strength fiber-reinforced polymer (FRP) bars or strips near the surface of concrete, providing additional strength and enhance the load-carrying capacity of structural elements. The use of NSM reinforcement not only offers an effective solution for addressing structural deficiencies but also promotes sustainable and cost-efficient construction practices. NSM reinforcement requires less material, reduces environmental impact, and minimizes construction waste by strategically placing reinforcement in areas where tensile stress is most critical[31]. Another study evaluated the bond behavior between glulam and NSM CFRP laminates through pull-out tests, focusing on bond length and test configuration. Two testing methods—beam pull-out tests (BPT) and direct pull-out tests (DPT)—were employed to assess bond performance. The results demonstrated that the maximum pull-out force and slips at both loaded and free ends increased with bond length, with BPT yielding higher maximum forces and bond shear stress. An analytical-numerical approach successfully established the local bond stress-slip relationship, showcasing the reliability of inverse analysis for determining the bond properties[32].

Furthermore, recent years have witnessed growing interest in the interaction between wood and polymer materials within the framework of Near Surface Mounted (NSM) strengthening, as reflected in several recent studies by Chen et al.[33], Al-Mashgari et al.[34], Melinda et al.[35], Pisani et al.[36], and Shhabat et al.[37]. Chen et al.[33] emphasized the superior bonding characteristics of NSM techniques compared to surface-bonded reinforcements, particularly in enhancing load transfer efficiency and minimizing premature debonding in timber beams. Al-Mashgari et al.[34] demonstrated that NSM-FRP systems can substantially improve the flexural performance and crack distribution in softwood elements, outperforming traditional methods. Similarly, Melinda et al.[35] stressed the importance of adhesive compatibility between polymer resin and timber substrates, which significantly affects the mechanical integrity of the composite. Pisani et al.[36] contributed further insights by showing that groove orientation, depth, and spacing are critical design factors influencing the stiffness, load capacity, and ductility of NSM-reinforced wooden members. In addition, Shhabat et al.[37] investigated the long-term behavior of polymer-based reinforcements under thermal cycling and repeated loading, revealing strong environmental resilience and structural stability. These collective findings indicate that NSM polymer reinforcement in timber elements offers not only technical advantages but also economic and practical feasibility in structural rehabilitation and new timber construction. For all these reasons, the present study is seen as both relevant and necessary in continuing this expanding area of research.

2. Methods

This research used several variations of test specimens, namely TO, TP, TPR, and TPSE, which will be explained in detail later. The specimens were subjected to bending tests using a four-point bending setup.

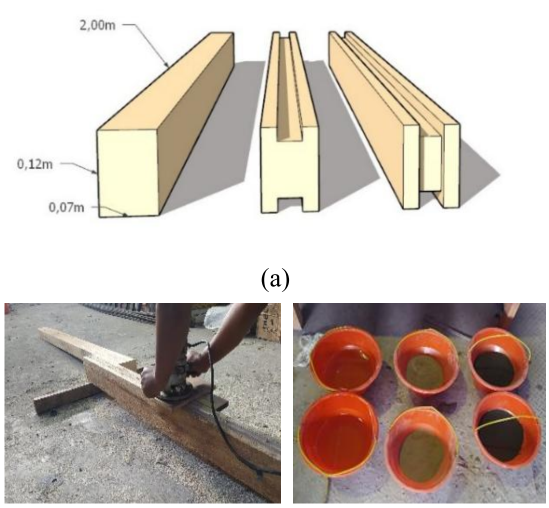
2.1. Specimen Preparation

The bending test specimens were wooden beams measuring 7 cm by 11 cm in cross-section and 2 meters in length, reinforced with D10 steel rebars using the NSM (Near Surface Mounted) method. The reinforcement used polyester, fly ash, and sand as the base materials. The mixture was prepared using an unsaturated polyester polymer with its catalyst, combined with fly ash and sand, with considerations of both mechanical strength and workability based on general recommendations from previous studies.

The specimens were divided into four distinct types that can be seen in Figure 3. The first type was a pure timber beam or timber only (TO) without the addition of polymer or reinforcement, and therefore did not require any grooves. The second type, timber polymer (TP), and the third type, timber polymer rebar (TPR), both had longitudinal grooves on the top and bottom surfaces of the beam. The difference between these two is that the second type involved only timber and polymer, whereas the third included timber, polymer, and rebar.

Table 1: Materials and tools

Component	Description
Wood Beam	Sengon wood
Polymer Concrete	Polymer resin (50%), Catalyst (1,5%), FA (25%), Sand (23,5%)
UP Resin	Unsaturated polyester resin
Catalyst	Methyl ethyl ketone peroxide (initiator)
Fly Ash	Class F fly ash (pozzolanic material)
Sand	Fine sand (passing 4.75 mm sieve)
Steel Bar	D10
Grooving Tool	Wood Router
Measuring Tools	Caliper, ruler, tape measure
Loading Frame	Four-point bending test setup
Dial Gauge	0.01 mm precision



(a)

(b) (c)

Fig. 2: (a) Illustration types of grooves in wood (left to right: OT, TP, and TPR, TPSE), (b) documentation of making a groove on the specimen, and (c) preparation of UP, FA, and sand

The fourth type, timber polymer rebars with shear end stirrup rebars (TPSE), was similar to the third variant but with the addition of vertical reinforcement at both ends of the beam, necessitating extra grooves. This configuration is illustrated in Figure 2 (a).

As previously outlined, the structural integrity of the third and fourth structural beam configurations is augmented through the incorporation of reinforcements. Specifically, two D10 reinforcement bars are strategically positioned above and below each beam. This enhancement is anticipated to significantly improve the mechanical strength of the wooden beam specimens. The reinforcement bars will be securely bonded using a viscous polymer, resulting in a unified composite with the timber. Figure 2 (b) and (c) illustrate two main stages in the specimen preparation process. Figure 2 (b) shows the groove cutting procedure performed on a Sengon wood block, which is a crucial step in the Near Surface Mounted (NSM) reinforcement method. Precise groove dimensions

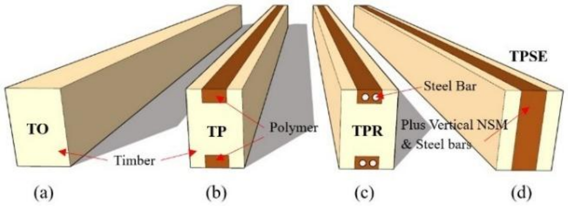


Fig. 3: Illustration of specimens (a) timber only, (b) timber-polymer, (c) timber-polymer-rebars, and (d) timber-polymer-rebars and shear-end stirrup rebars

and alignment are crucial for ensuring an effective bond between the reinforcement and the wood substrate. Meanwhile, Figure 2 (c) displays the preparation of polymer concrete ingredients, including sand, fly ash, and unsaturated polyester resin. Proper proportioning and mixing of the materials are crucial to achieve optimal mechanical performance and workability during the casting process.

The resin used is an unsaturated polyester variety. The formulation process for the polymer concrete entails an initial thorough mixing of sand and fly ash to achieve homogeneity. Following this, polyester resin and the MEKP catalyst are introduced, and the mixture is agitated once more to ensure consistency. Subsequently, the composite is transferred into a mixing container and blended thoroughly. Once all ingredients are uniformly combined, the mixture is carefully poured into the grooves of the timber housing the D10 rebar, and excess material is smoothed with a spatula. The assembly was then allowed to cure until the polymer concrete beams reached full stiffness and flexural strength. Any polymer overflow that occurs during the pouring can be effectively removed using a grinder or similar apparatus. This refined approach highlights the near-surface mounted (NSM) application of timber and wood materials in structural engineering, emphasizing the integration of innovative materials to enhance both performance and durability.

2.2. Flexural Test

The flexural testing of beams is performed in accordance with ASTM D 7264[38] employing a four-point bending configuration. This method involves a systematic approach, commencing with initial measurements taken while applying a specified load to the test specimen repeatedly. The Final measurements are subsequently recorded until the specimen reaches its failure point. The testing procedure begins with the preparation of the wooden beam specimen, which has been reinforced using the Near Surface Mounted (NSM) technique with polyester. The specimen's dimensions are measured to establish baseline measurements. The specimen is then positioned on a support frame with supports located at both ends. Once the specimen is securely in place, the setup of the testing apparatus continues as depicted in the accompanying diagram. The Figure 4 (a) detailed approach ensures that

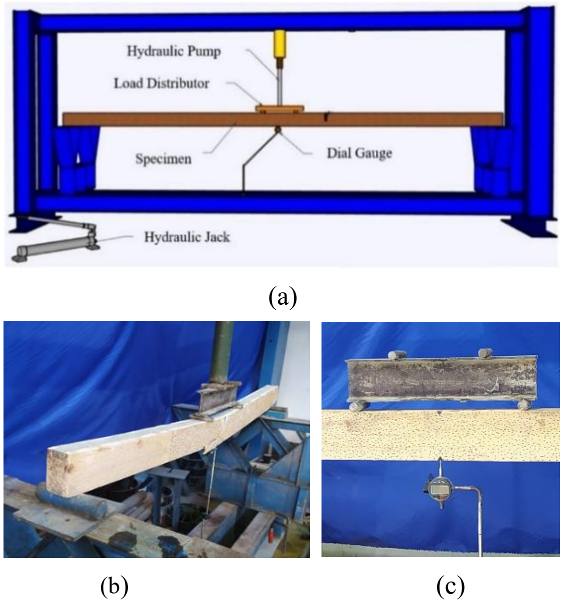


Fig. 4: (a) Scheme of timber beam flexural test, (b) Specimen after test, and (c) position of dial gauge (middle span)

the structural performance of the NSM-reinforced timber beams can be accurately evaluated, providing valuable insights into their mechanical behavior under flexural loads.

The hydraulic cylinder jack is installed at the upper section of the frame in an inverted orientation, equipped with a vertical platform that acts as a load intermediary for the four-point bending test. A dial gauge is strategically positioned beneath the speciment. Following the preparation of equipment and materials, the load is incrementally applied until failure occurs. Readings from the dial gauge are recorded at each load stage. The location of the dial gauge is at the bottom center of the beam span, which can be seen in Figure 4 (c). The testing process concludes when the wooden beam specimen attains its maximum load capacity or reaches the failure threshold. In Figure 4 (b), an example of one specimen that was cracked after the test is shown.

Flexural testing serves as a critical method for analyzing and determining the flexural properties of polymer matrix composite materials, encompassing aspects such as strength, stiffness, and deflection behavior. Flexural strength is defined as the maximum stress exerted on the outer surface of the test specimen until it reaches its peak limit and undergoes flexural failure. The ratio of stress to strain is known as the flexural modulus[39]. The flexural strength is a crucial method for evaluating and determining the flexural properties of polymer matrix composite materials, which encompesses aspects such as strength, stiffness, and deflection behavior. It is defined as the maximum stress exerted on the outer surface of the test specimen until it reaches its peak limit and subsequently fails under bending. The relationship between stress and

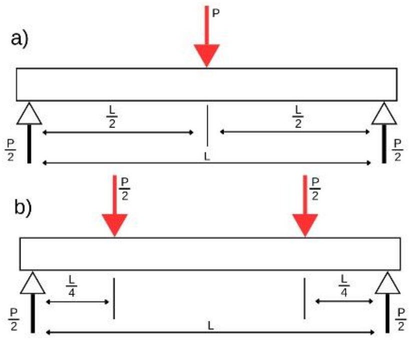


Fig. 5: Scheme of bending test (a) three-point bending, and (b) four-point bending

strain is referred to as the flexural modulus, which provides insight into the material's rigidity and performance under load[39]. This testing protocol adheres to ASTM D 7264[38], ensuring a standardized assessment of the material's performance.

$$\sigma = \frac{3PL}{2bh^2} \qquad (1)$$

Apart from flexural testing using the three-point bending method in Eq. (1) and Figure 5 (a), the four-point bending scheme offers an alternative approach. In this configuration, the applied load is split into two points and distributed across different points on the beam's cross-section, as depicted in Figure 5 (b).
The corresponding equations are performed using the formula in Eq. (2).

$$\sigma = \frac{3PL}{4bh^2} \qquad (2)$$

where: σ – flexural stress/ strength in the mid of span, expressed by Newton per millimeter square; P – maximum flexural point load, expressed by Newton; L – the span of *Albizia chinensis* wood beam, in millimeters; b and h – respectively, the width and the depth of the specimen, expressed by millimeters.

3. Results and Discussions

Following a comprehensive series of experiments in the materials and structures laboratory, spanning from the preparation phase to the flexural testing, the results and discussions have been derived, and the NSM-reinforced top surface fiber of the Albizia chinensis wood beam is depicted in Figure 6.

3.1. Physical characteristics including density and weight of the specimens

First, regarding the groove, it was generally easy to carve, largely due to the relatively low grade of the wood used. The average width of the groove for the polyester reinforcement matched the intended specification of 3.5 cm. Moreover, no significant defects were observed in the wood as a result of the preparation process. Secondly, the weights of the test specimens—OT, TP, TPR, and TPSE—were recorded as 4.6 kg, 8.1 kg, 11.1 kg, and 12.6 kg, respectively.

3.2. Cracks

The specimens exhibited varying modes of failure and crack propagation patterns under the applied loads. In the first case, the TO specimen experienced pronounced shear cracking at the load point. This likely occurred because the load was entirely borne by the wood, and the longitudinal alignment of the wood fibers further facilitated crack formation. In contrast, the TP specimen showed shear cracking around the beam load location, with noticeable cracks in the tension zone. These cracks initially developed as flexural cracks and subsequently evolved into a shear failure pattern, which meandered due to the influence of the wood fibers in that region, as depicted in Figure 7 (a) and 7 (b).
In Figure 7 (c) and 7 (d), the TPR specimen notably did not exhibit shear cracking at the load location, as observed in the TO and TP specimens. Instead, shear cracking occurred at the support area, particularly in the compression zone, lifting the region where the reinforcement was embedded. This failure mode can be attributed to the absence of shear stirrup reinforcement, which allowed transverse shear

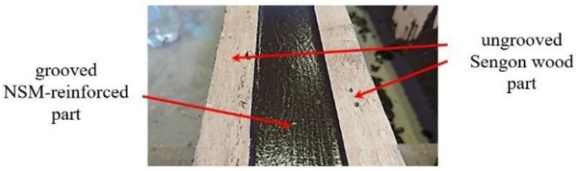


Fig. 6: Polymer concrete poured in the groove of timber or NSM-reinforced

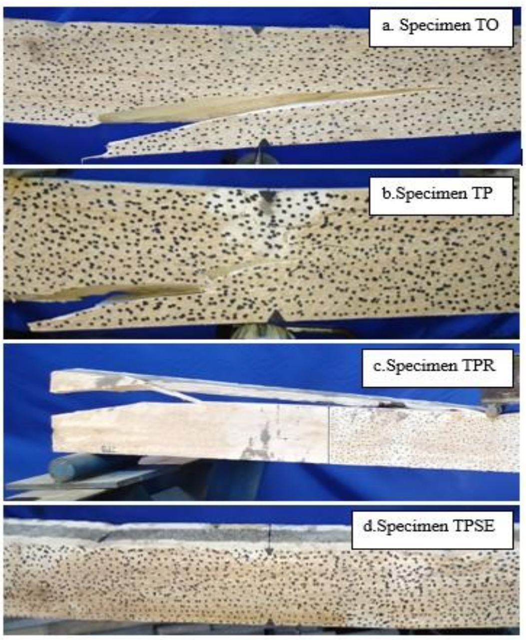


Fig. 7: Different shear cracks and failures occur at peak loading: (a) TO, (b) TP, (c) TPR, and (d) TPSE

forces to lift and displace the outer surface of the polymer containing the reinforcement. In contrast, the TPSE specimen, equipped with additional shear-end stirrup reinforcement, showed no significant cracking. This is likely due to the presence of shear-end stirrup reinforcement, which effectively prevented the shear cracking observed in the TPR specimen.

3.3. Flexural test: load vs deflections

The bending test uses a four-point bending scheme, referring to ASTM D 7264[38] to find out the bending strength and deflection that occurs in the specimens. The specimens were divided into four distinct types. The first type was a pure timber beam or timber only (TO). The second type, timber polymer (TP), and the third type, timber polymer rebar (TPR), both had longitudinal grooves on the top and bottom surfaces of the beam. The difference between these two types is that the second type involved only timber and polymer, whereas the third type included timber, polymer, and rebars. The fourth type, timber polymer rebars with shear end stirrup rebars (TPSE), was similar to the third variant but with the addition of vertical reinforcement at both ends of the beam, necessitating extra grooves. In this test, the relationship between the magnitude of the force given and the deflection that occurs has been reviewed, The load-displacement relationship graphs of the four test objects can be compared in Figure 9. The first is the TO specimen whose load and deflection increase almost linearly up to a loading of 16 kN and then deflection occurs more easily until it failure at 18 kN. Then the second is the TP specimen which failure at a load of 10 kN with a maximum deflection of 26,2 mm.

Interestingly, is that the TP specimen, which is a wood specimen given NSM polymer, does not have a flexural strength as strong as TO, which does not have polymer. This finding aligns with observations that reported that insufficient bonding between reinforcement and timber can lead to premature debonding and poor load transfer. In the TP specimen, the absence of mechanical confinement provided by grooves likely allowed early slippage of the polyester layer, resulting in ineffective stress redistribution and higher local deformation, ultimately reducing overall stiffness despite the presence of reinforcement. This reduction is attributed to insufficient bonding and ineffective load transfer between the reinforcement and the surrounding wood matrix due to poor resin confinement[7,8].

The third specimen is TPR, which is a variant like TP but given iron reinforcement.

This specimen rises quite linearly until it is loaded with 27 kN, then rises slopingly to 28 kN (and this is the maximum) with a deflection of 26,1 mm. Then, it drops again to 22 kN and rises again until it experiences failure at a load of 25 kN with a deflection of 46,2 mm. The maximum load that can be held far exceeds the TP specimen without reinforcement. Thus, it proves that the installation of reinforcement in NSM beams can effectively increase resistance to bending.

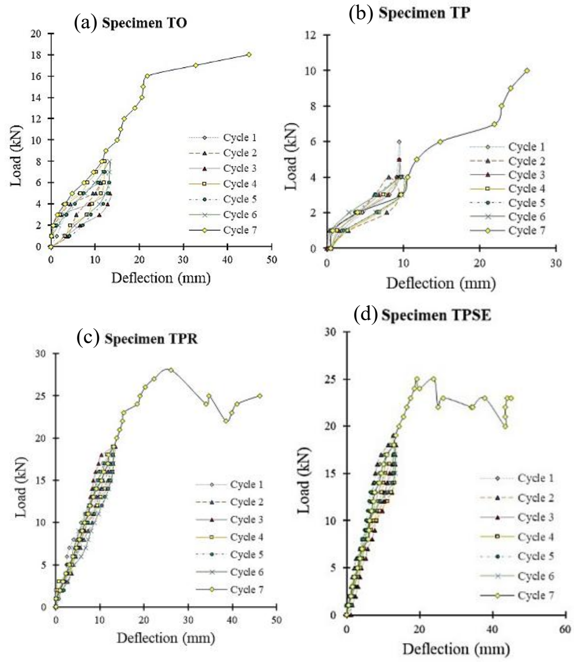


Fig. 8: Loads versus deflections: (a) TO, (b) TP, (c) TPR, and (d) TPSE

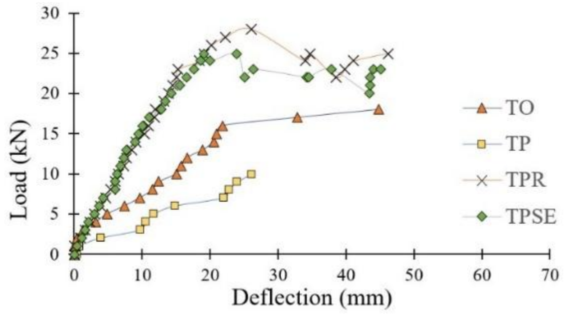


Fig. 9: Load vs Deflection of four specimens

The last specimen is TPSE, which is a variant like TPR but with shear reinforcement at the ends of the beam. Load and deflection increase quite linearly until the load is 25 kN (and this is the maximum) with a deflection of 19,28 mm. Then it fluctuates down to the lowest at 20 kN with a deflection of 43.4 mm. Then it increases until the specimen can no longer accept the load, which occurs at a load of 23 kN with a deflection of 45,1 mm. In this specimen, the test object did not experience major physical cracks, but several times a cracking sound was heard, namely at deflections of 19 mm and 38 mm.

Although TPSE specimens had more grooves than TPR, the performance improvement was not as significant. This counterintuitive outcome is likely due to inconsistent groove geometry or bonding effectiveness. As noted in studies by Lu[19] and Sena-Cruz et al[32], the efficiency of NSM reinforcement strongly depends not only on the number of grooves but also on their depth, alignment, and quality of adhesive bonding. In TPSE, the presence of multiple grooves may have led to local stress concentrations or ineffective force transfer if the installation was not perfectly uniform. Initially, both TPSE and TPR exhibited similar stiffness and load response; however, as the loading progressed, the TPR specimen displayed a more stable and higher ultimate load capacity. This improvement is atttributed to the optimized groove position and more effective force distribution in TPR.

In flexural testing, the load-to-deflection relationship graph obtained from the 4-point bending test shows a clear trend that the specimens with polyester NSM reinforcement experienced increased load capacity and stiffness compared with the control specimens. In particular, the TPR specimen (with two strips of polyester NSM) showed the best performance with an increase in maximum load of more than 30% compared to the TO specimen (without reinforcement). In addition, the deflection graph also indicates that the use of polyester as a filler in the NSM grooves is able to withstand deformation longer before reaching failure. This shows the contribution of polyester in significantly increasing the flexural stiffness.

In Figure 8 shows the results of the cyclic loading test performed on the specimen to evaluate the resistance performance against repeated loading. From the graph, it can be observed that the TPR specimen maintains its stiffness better from cycle to cycle, although there is a slight stiffness degradation. This indicates that the use of polyester NSM reinforcement is able to increase the resistance of the beam to repeated deformation. Narrow hysteresis behavior indicates that there is low energy dissipation, but the deformation that occurs is elastic and can recover to a large extent. These results provide an indication that the reinforcement system with polyester NSM not only increases static capacity but also has the potential to improve performance against dynamic or cyclic loads.

It is important to note that the results were derived from single specimens for each test group (TO, TP, TPR, TPSE). Therefore, statistical variability such as standard deviation or confidence intervals could not be established. The results should be interpreted as preliminary findings, and further studies with repeated specimens are recommended for statistical validation.

3.4. Flexural test: maximum bending stress

The maximum bending stress on the test specimen is calculated using the equation in ASTM D7264, which has been discussed in the previous chapter. L (span from support to support) is 1700 mm. Then for b and d cross-sections, each average is 75 mm and 115 mm, respectively. So, after being entered and processed using the formula, it was found that the results of the mid-span stress of TO, TP, TPR, and TPSE were 23,14, 12,90, 35,99, and 32,14 MPa, respectively, as depicted in Table 2.

Table 2: Bending strength and failure type

Specimen	Bending Strength (MPa)	Maximum loads (kN)	Failure type
TO	23,14	18	Shear crack on the mid-span
TP	12,85	10	Shear crack on the mid-span
TPR	35,99	28	Shear crack on the support
TPSE	32,14	25	No major crack

These results are closely related to the previous section, which discussed the relationship between load and deflection. The reason the maximum stress of TP is lower than TO, even though TP has reinforcement, is that TP fails first due to the tensile part of the beam, which has NSM polymer without reinforcement, resulting in brittleness, which accelerates failure. Then the TPSE specimen, which has shear reinforcement, does not actually experience large cracks on the surface of the beam compared to TPR, which has large shear cracks around the beam support area.

This study is limited to short-term flexural testing of small-scale *Albizia chinensis* wood beams. The long-term durability of the polyester reinforcement, including performance under moisture exposure, thermal variation, and biological degradation, was not assessed. Additionally, fire resistance and behavior under high-temperature conditions were not examined. The results are also constrained by the scale of the specimens; extrapolation to full-size structural members may require adjustments in groove configuration and reinforcement anchorage.

3.5. Theoretical Validation of Experimental Results

The formulation used is based on general timber design principles, such as those outlined in Eurocode 5 (EN 1995-1-1) and recommendations by Raheem[39], which defines flexural strength in terms of section modulus and material properties. To validate the flexural test results, an estimation of the theoretical flexural strength was conducted using the maximum bending moment (M_{max}) calculation approach for homogeneous beams:

$$M_{max} = f_{m,k} . W / \gamma_M \quad (3)$$

Where:

$f_{m,k}$: characteristic flexural strength of *albizia chinensis* wood (e.g., 32 MPa)

γ_M : partial safety factor (e.g., 1.3)

W : section modulus $W = b.h^2/6$

As an example, for a beam with dimensions of 50 mm × 100 mm:

$$W = 50.100\text{^}2/6 = 83.333{,}33 mm^2 \quad (4)$$

$M_{max} = 32 \times 83.333{,}33/1{,}3 = 2{,}05 \times 10^6 N.mm =$

$$2,05 kN.m \tag{5}$$

This value is reasonably close to the experimental maximum moment values for the TO specimen (~1,95 kN.m), TPSE (~2,20 kN.m), and TPR (~2,60 kN.m), thereby confirming that the experimental results do not significantly deviate from basic theory. The slight differences are attributed to the natural variability of wood as a material and the contribution of polyester resin in transferring internal forces. This simple validation further shows that the use of NSM polyester not only provides empirical mechanical improvement but also aligns with theoretical expectations.

4. Conclusion

Based on the discussion from the series of preparation processes, casting, and flexural testing, it is evident that the incorporation of polymer fly-ash and steel reinforcement significantly enhances the strength, stiffness, and ductility of *Albizia chinensis* wood specimens (TPR and TPSE) when compared to the TO and TP specimens. Unsaturated polyester resin forms a strong adhesive bond with *Albizia chinensis* wood, integrating the wood and reinforcement into a unified monolithic structure; however, it significantly increases the weight of the beam. The addition of shear-end stirrup reinforcement at the support region of the TPSE beam provides significant resistance to shear forces, therefore effectively preventing the initiation and propagation of progressive shear cracking. However, it should be noted that the TP specimen, which lacks reinforcement, was unable to transfer the load effectively due to its brittle nature. Overall, the reinforcement with the Near Surface Mounted (NSM) technique for *Albizia chinensis* wood beams is strongly recommended, especially with reinforcement, to effectively resist tensile forces. Furthermore, the experimental results obtained in this study were found to be consistent with theoretical predictions based on basic flexural design principles. This agreement reinforces the credibility of using NSM polyester reinforcement not only as a practical strengthening technique but also as one that aligns well with established structural mechanics theory.

In addition to its application on flexural timber members such as beams, the NSM polyester reinforcement technique has potential for use in other structural elements. For instance, it can be applied to columns to enhance the axial load capacity or to timber joints to improve the stiffness and load transfer at the connections. Its adaptability and ease of installation also make it suitable for retrofitting purposes in wall panels, floor diaphragms, or even truss members where additional shear or tensile reinforcement is needed. Due to the lightweight and cost-effective nature of the polyester composite, makes it particularly promising for the rehabilitation of timber structures in rural or low-income settings.

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