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REINFORCEMENT OF WOODEN SUPPORTS FOR UNDERGROUND COAL MINES THROUGH FINITE ELEMENT ANALYSIS

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Abstract
Timber is one of the oldest construction materials that remained essential in many industries, including underground mining, where its structural performance was crucial under challenging load conditions. This paper assessed the flexural and uniaxial compressive strength of timber beams reinforced with Sika Wrap-230, Plastic Tie, and Iron Wire using ASTM standards and four-point bending tests. The experimental results, when put together with Finite Element Analysis in ANSYS, established how effective these reinforcements can work to enhance deflection behavior and flexural capacity under timber beams, which means much better performance of timber beams at underground mine supports. The experimental and finite element analysis (FEA) results revealed that the flexural rigidity, strength, and ductility of the timber beam were improved by using Sika Wrap-230 along with Sika Dur. Compared to plastic ties and iron wires, bonding performance was important to be optimized to enhance reinforcement performance. It was suggested to optimized the bonding performance of Sika Wrap-230 by using dedicated adhesives for timber to further enhance reinforcement efficiency. Sika Wrap applied to timber beams placed underground enhanced their strength considerably along with durability in underground mines.

Introduction

Timber is one of the oldest building materials ever used by mankind. Steel and concrete replaced wood as the major building construction material in the 20th century. However, in the 21st century, wood is still being used especially in United States for many short-span bridges[1]. Timber is also used in various constructions such as residential buildings, commercial structures and sport complexes. Timber beams in underground mining support systems are classified by a span-to-cross-sectional area ratio, an important aspect of evaluating the structural performance under underground loads. The declining availability of wood for construction has been one of the greatest impacts of climate change and improved regulations that have specifically dealt with the cutting down of trees as a source of income[2]. The demand for wood, especially in the industry of wood-based panels, increases steadily year after year.

Particleboard leads at around 40% of the overall wood-based panel production while plywood and fiberboard are also emitted[3].Oriented strand boards (OSB) are quite fast-growing products in production, resulting from the growing demand for it in construction and manufacturing[4].

During these last decades wood elements have been reinforced using various techniques, few of which have been successfully commercialized. Nevertheless, some of these techniques have been used to consolidate existent wood beams where it is not possible to operate, for various reasons, a complete replacement of the wood element. In this perspective the introduction of composite materials as reinforcements for wood elements subjected to bending loads [5] or shear loads [6] is of great interest. This interest is enhanced by the continuous progress made in FRP materials, together with their wider availability in different materials and shapes. Elements in wood, due to the nature of the material, can be subjected to a reinforcement intervention for several reasons: increment of dead loads, degradation of the mechanical properties of the element or the reduction of excessive displacements.

Research on studying and developing the techniques for the strengthening of timber structures has been done and still ongoing. Previous researches have contributed significantly in encouraging the usage of FRP and serve as reference for future researchers. Triantafillou and Plevris (1992) bonded a thin unidirectional carbon fiber reinforced sheet to the tension side of wood beams and concluded that the bending strength increased nearly linearly with fiber quantity up to a critical point. It was noted that even a low content of fibers, less than 1% of the cross-sectional area, provided a 60% strength gain. There were higher increases when wood compressive yield occurred[7]. Dolan et al. (1997) have carried out research on prestressed glued-laminated timber beam. This research indicates that both strength and stiffness are increased by using small volumes of pretension Kevlar yarns. [8]. Fiorelli and Dias (2002) had studied the structural behavior of Pinus caribea var. hondurensis wood beams reinforced with GFRP and CFRP. Based on their experimental and theoretical analysis, they found that EI values for the reinforced beams were significantly higher than the theoretical values, thereby improving the safety of the structure. Stiffness gain varied from 15% to 29% for glass and carbon fibre-reinforced specimens[9].

In underground mines, timber support faces strength and load-carrying capacity issues when it deteriorates, is overloaded, or ages. This compromises mining operations in terms of stability and safety, with effective methods being used to maintain the integrity of the support systems. In the last few years, studies have focused on alternative materials for the recovery and reinforcement of structures, and much attention has been dedicated to the use of fibers reinforced with polymer (FRP). This material have high strength, low weight, corrosion resistance and electromagnetic neutrality that make fiber-reinforced plastic (FRP) a suitable candidate in many structural applications, including rehabilitation and strengthening as well as the development of new wood members. This material has been studied in the last ten years in United States and Europe with the objective of to reinforce timber structures. More specific glulam beams. This study consists of an experimental investigation and analytical modeling of timber support for underground mines stringers strengthened with Sika Wrap (FRP), Plastic Tie and Mild Raw Steel Wire. The study investigates the flexural and UCS behavior of timber beams under static loading conditions. Investigation of shear behavior and response to dynamic and impact loading is beyond the scope of this work. Fatigue performance of the reinforced beams and material durability of the GFRP are not included. Based on the results of half-scale and full-scale beam tests and analysis, an analytical model is proposed to predict the flexural capacity of plain and reinforced timber beams.

The research program aims to find a practical solution for strengthening timber supports used in underground mines. Conducted at the Rock Mechanics Laboratory at the University of Engineering and Technology Lahore, the study focuses on enhancing the flexural capacity of timber beams under the maximum legal in-situ stresses in underground mines. The specific objectives include evaluating the impact of different reinforcement materials, such as Sika Wrap-230, Plastic Tie, and Iron Wire, on the overall performance, unconfined compressive strength (UCS), and flexural capacity of the reinforced timber beams. The goal is to improve the structural integrity and durability of timber supports in mining environments. If covering materials such as Sika Dur, Plastic Tie, and Iron Wire are used on timber beams, then the strength and flexural capacity of the beams would increase, enhancing their performance under underground mine stresses.

Materials and Methods

ASTM Wood Standards

ASTM's wood standards are instrumental in the evaluation and testing of the physical and chemical properties of a wide range of wood and wood-based products. Wooden materials covered here include timber, lumber, wood-base fibers, commercial softwoods and hardwoods, wood preservatives, laminated timber, and composite lumber to name a few. These materials are notably used in the fabrication of construction materials such as structural panels and members, construction poles, and log buildings.

Specimen Design

In this study, twenty timber specimens were prepared for each of two tests: the four-point bending flexural test and the Uniaxial Compressive Strength (UCS) test. All specimens had a cross-sectional dimension of 5 cm (width) × 5 cm (depth), with lengths of 80 cm for the flexural test[10] and 12 cm for the UCS test[11]. These specimens were divided into four groups based on reinforcement type. The first group consisted of five unreinforced specimens tested for both flexural and UCS strength. The second group used reinforcement with SikaWrap-230 C, a unidirectional carbon fiber fabric, applied with Sikadur-330 epoxy resin, which serves as a bonding agent. The third group was reinforced with steel bending wires, providing tensile strength and flexibility. The fourth group used plastic ties as reinforcement. The materials included SikaWrap-230 C, a mid-strength carbon fiber fabric supplied in 50-meter rolls with a 600 mm width, and Sikadur-330, a two-part, light grey epoxy resin used to bond the fabric to the specimens. Sikadur-330 was available in both standard (5 kg) and industrial (Part A: 24 kg, Part B: 6 kg) packaging[10].

Procedure

The ASTM D4442 standard defined the procedure to find the moisture content of wood, based on which we dried the samples at 105°C ± 2°C for 24 hours. Similarly, we put our samples in the oven at 105°C for 24 hours, also according to the same standards[12]. To test the samples for both uniaxial compressive strength (UCS) and flexural strength, a Universal Testing Machine (UTM), Shimadzu 200-ton capacity, was utilized. In addition to these testing activities, a dial gauge, Peacock Company, with a minimum count of 0.01 mm, was used for accurate measurement of the displacement of samples during testing. The dial gauge measured accurately the displacement of the samples under load, providing exact readings on deformation while the tests were performed. A total of twenty one timber beams were constructed for four-point bending tests to assess flexural strength. The beams designed for flexural testing measured 5 cm in width, 5 cm in depth, and 80 cm in length, while those for UCS testing had dimensions of 5 cm (width) × 5 cm (depth) × 12 cm (length)[11, 13].The twenty beams were divided into four groups, each with a specific reinforcement configuration. The first group consisted of five beams for UCS and five for flexural testing, which were unreinforced and served as control samples to assess performance without reinforcement. The second group of beams for both UCS and flexural tests were reinforced with SikaWrap® Hex-230 C and an epoxy resin (Sikadur) in a transverse layout. The thickness is approximately 0.8 mm per layer[14]. The third set of specimens was reinforced with plastic ties in a transverse configuration. The **Natural/White Nylon PA 66 Plastic Cable Ties** were typically used for packaging material. The fourth category employed bending iron wires Those wires used in concrete and The ASTM A82 standard provides the requirements for plain steel wire used for concrete reinforcement) as reinforcement in a transverse arrangement[15]. All twenty beams, including those with and without reinforcement, underwent four-point bending tests on the UTM in the Rock Mechanics Lab to determine flexural strength. Additionally, UCS tests were conducted on these beams to measure uniaxial compressive strength. During the tests, a uniform load was applied, and deflections and strains were recorded at regular intervals. A displacement meter was installed at the support points and midspan of each beam to monitor deflection accurately. The readings were carefully noted at the moment cracks or failure occurred in each specimen. Material properties for the wood specimens have been obtained from experimental data as well as from literature. For instance, FEA has been conducted using ANSYS in two wood species, namely, Sufaidaand Kiker under three different conditions, including unwrapped, wrapped with steel wire, and wrapped with plastic tiesA bending test configuration was developed in the software to simulate real-life loading conditions and evaluate the deflection behavior of Sufaidaand Kiker wood samples under three configurations: unwrapped, steel wire-wrapped, and plastic tie-wrapped. The unwrapped samples were taken as the baseline to understand the natural deflection characteristics, and the wrapped specimens were tested for the ability to reduce deformation and improve structural stability. Material properties for the simulations are obtained from experimental data and literature to ensure accuracy. In this analysis, it reveals the mechanical performance of the wood under different conditions and justifies the wrapping as an important factor in enhancing flexural strength. Optimization of mesh density and boundary conditions was made in order to achieve the right balance between computational accuracy and efficiency. This approach enabled the comparative analysis of mechanical responses, hence giving insightful knowledge on how wrapping methods can improve the flexural performance of wood.

Results

Table 1.1: Weight of Small sample before oven and after oven remove moisture in a wood

No. of samples	Sample	Before oven weight	After oven weight	No. of samples	Sample	Before oven weight	After oven weight
4	S	302	289.5	27	S	288	272
5	S	292	281.5	28	S	297	283.5
8	S	283	260	30	S	291	274
12	S	275	259.5	33	S	211	196.5
16	S	284	275.5	34	S	308	193
17	S	299	284	35	S	305	285
22	S	290	272.5	37	S	322	303
23	S	301	281	38	S	287	265.5
24	S	296	277	39	S	264	250
25	S	307	290	40	S	219	202

Table 1.2: UCS of small sample without wrapping

No. of samples	Sample	Load apply (Newton)	Area * 10^{3} (m^2)	UCS (MPa)
35	S	107910	2.5	43.16
27	S	113796	2.5	45.51
20	S	100062	2.5	40.02
28	S	101043	2.5	40.41
38	S	100552.5	2.5	40.22
26	K	120663	2.5	48.26
10	K	119682	2.5	47.87
14	K	116739	2.5	46.69
9	K	127530	2.5	51.01

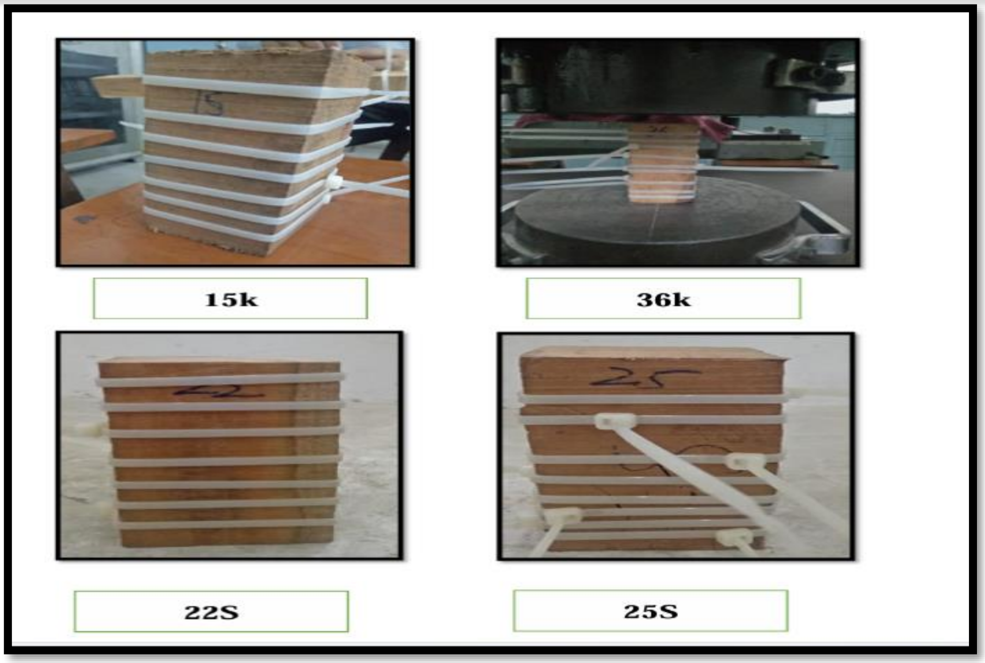

Figure 1: Cracks produced during UCS of small sample without wrapping

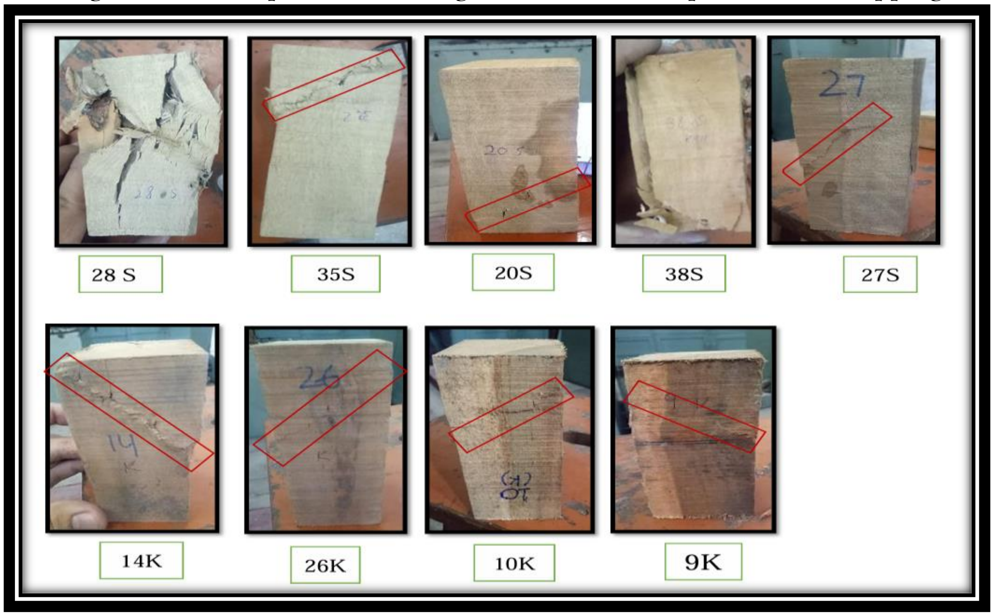

Figure 2 Samples for UCS with wrapping tie plastic

Table 1.3: UCS of small samples of wire tie plastic

No. sample	Sample	Load apply (Newton)	Area of samples $*10^{-3}$ (m^2)	UCS (σ_c = P / A) MPa
22	S	112815	2.5	45.16
25	S	106929	2.5	42.77
36	K	124587	2.5	49.83
15	K	120663	2.5	48.26

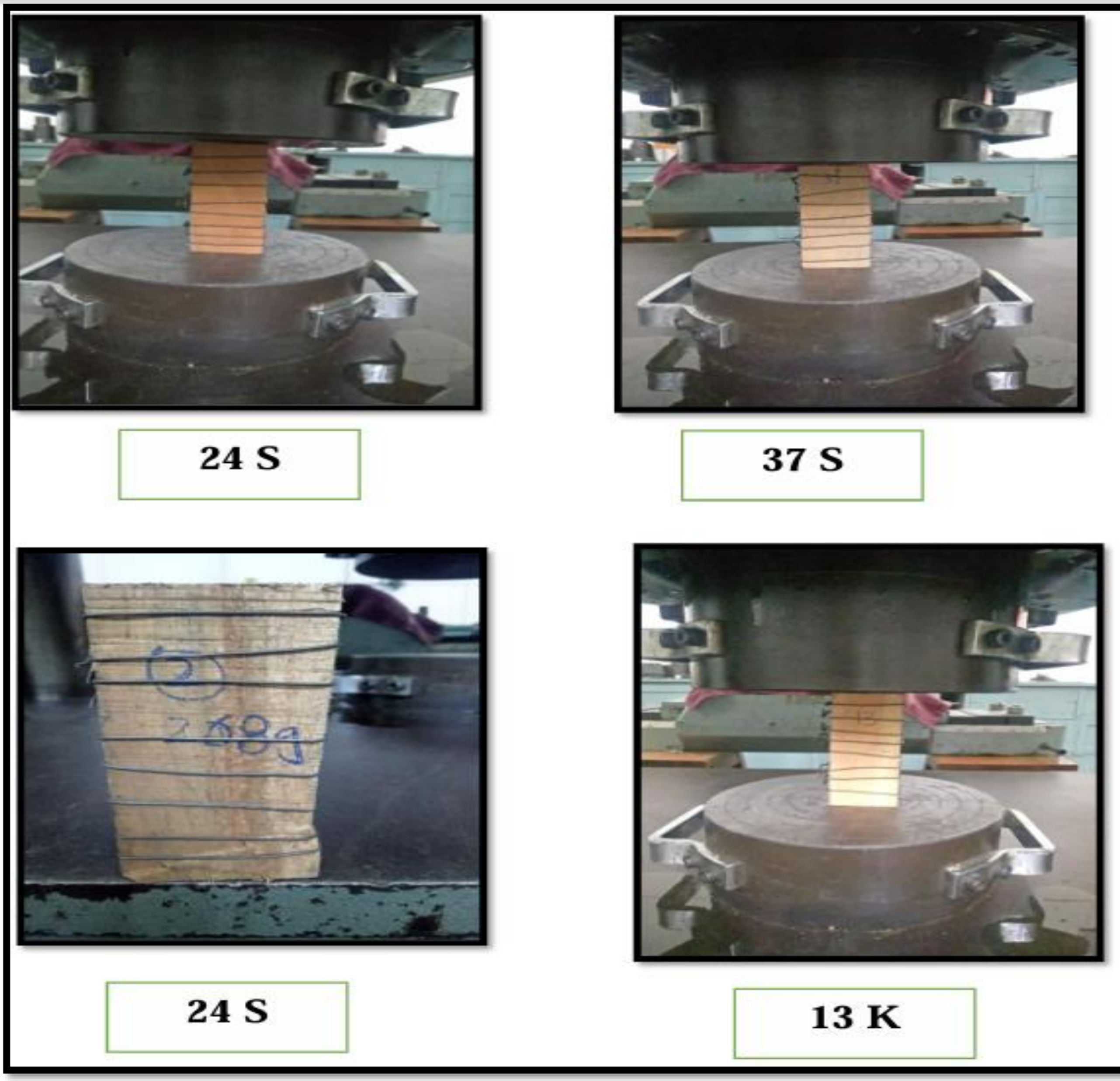

Figure 3: Samples for Before UCS wrapping with iron wire

Table 1.4: UCS of small samples wrapping with Iron wire

No. sample	Sample	Load apply (Newton)	Area of samples * 10^{-3} (m^2)	UCS (MPa)
1	K	109872	2.5	43.94
2	K	129492	2.5	51.79
13	K	120663	2.5	48.26
24	S	109872	2.5	43.94
34	S	117720	2.5	47.08
37	S	119682	2.5	47.87

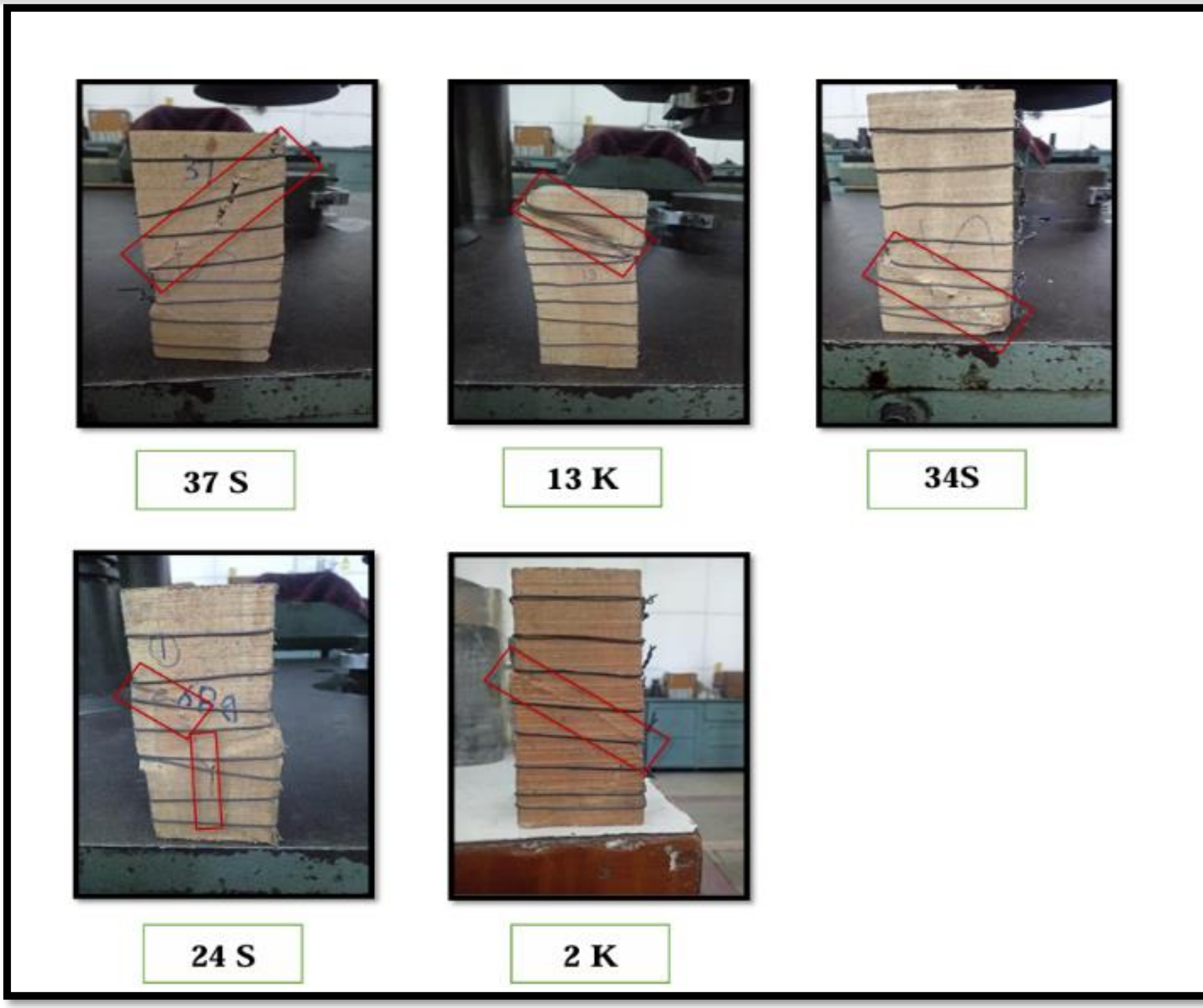

Figure 4: Cracks produced during UCS with wrapping of iron wire

Table 1.5: UCS of small samples of Sika Wrap

No. sample	Sample	Load apply (Newton)	Area *10^{-3} (m^2)	UCS (MPa)
31	K	125568	2.5	50.22
11	K	127530	2.5	51.01
3	K	126549	2.5	50.61
40	S	130473	2.5	52.18
4	S	126549	2.5	50.61
8	S	128511	2.5	51.40

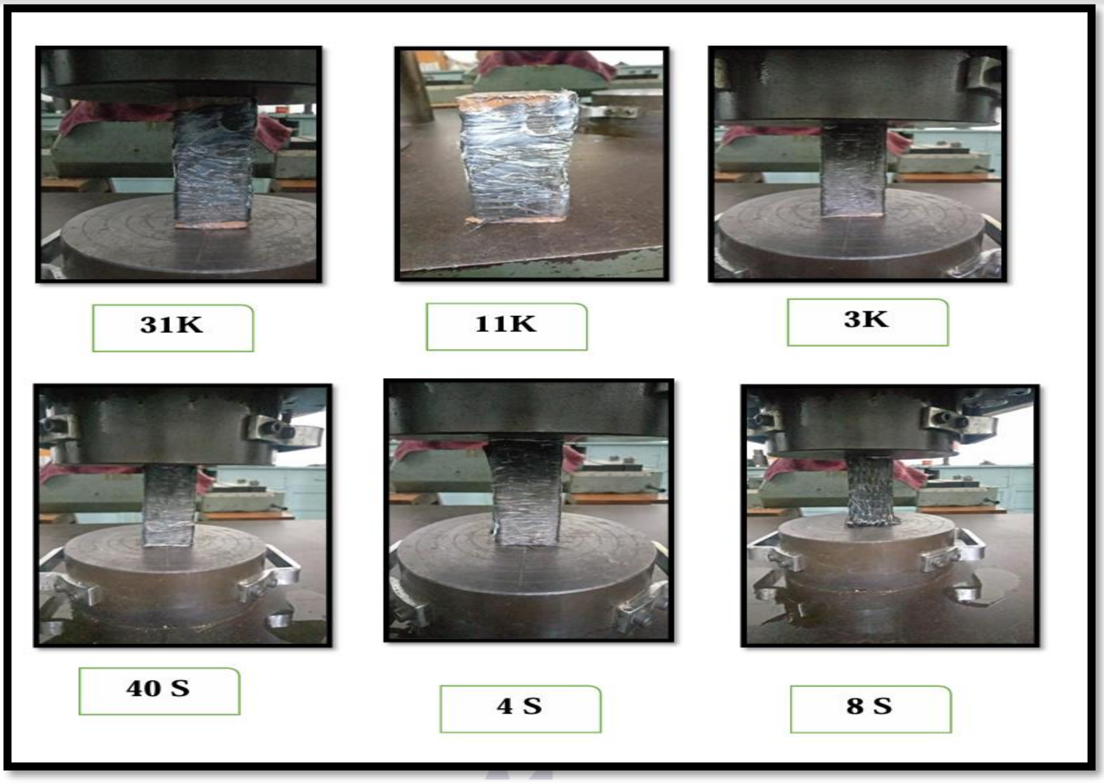

Figure 5: Covering Samples with Sika Wrap-230 for UCS

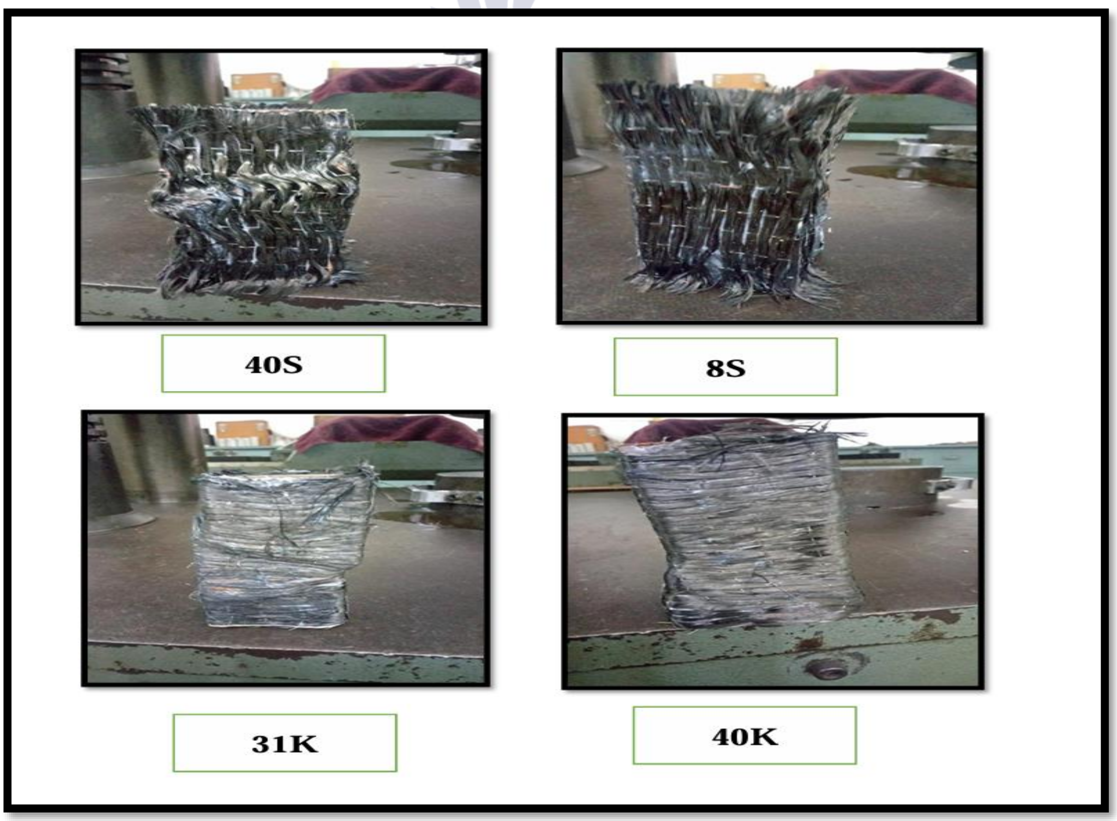

Figure 6: After UCS cracks are produced in samples covered with Sika Wrap-230

Flexure Testing of Samples

Table 1.6: Flexure testing of timber beams without wrapping

No. of sample	Sample	Area * 10^{-3} (m^2)	Flexure strength (Newton)	Modulus of Elasticity (MPa)	Modulus of Rupture (MPa)	Displacement (▲) (m)	Numerical Results using Ansys (m)
5	s	2.5	5689.8	5462.738106	30.72	0.0139	0.012942 (figure 9)
3	s	2.5	6082.2	5803.432500	32.84	0.0162	0.014933
11	s	2.5	5787.9	5488.740138	31.25	0.0163	0.015928
2	k	2.5	7700.85	7988.985831	41.58	0.0122	0.01196
10	k	2.5	7651.8	7730.568529	41.31	0.0153	0.014701
13	k	2.5	7749.9	7778.836315	41.84	0.0154	0.015478

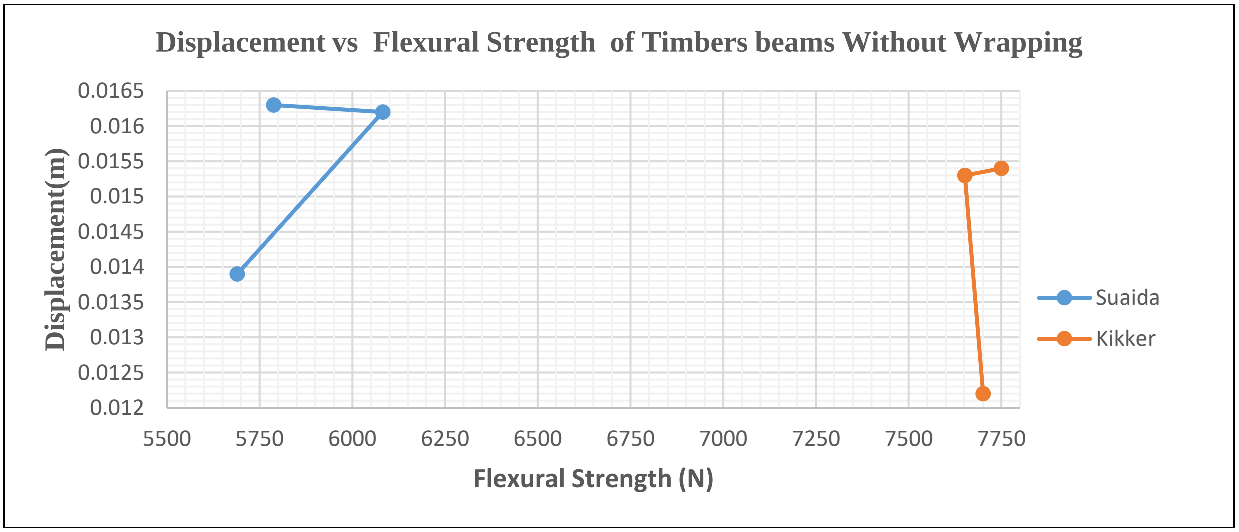

Figure 7: Displacement vs Flexural Strength of Timbers beams Without Wrapping

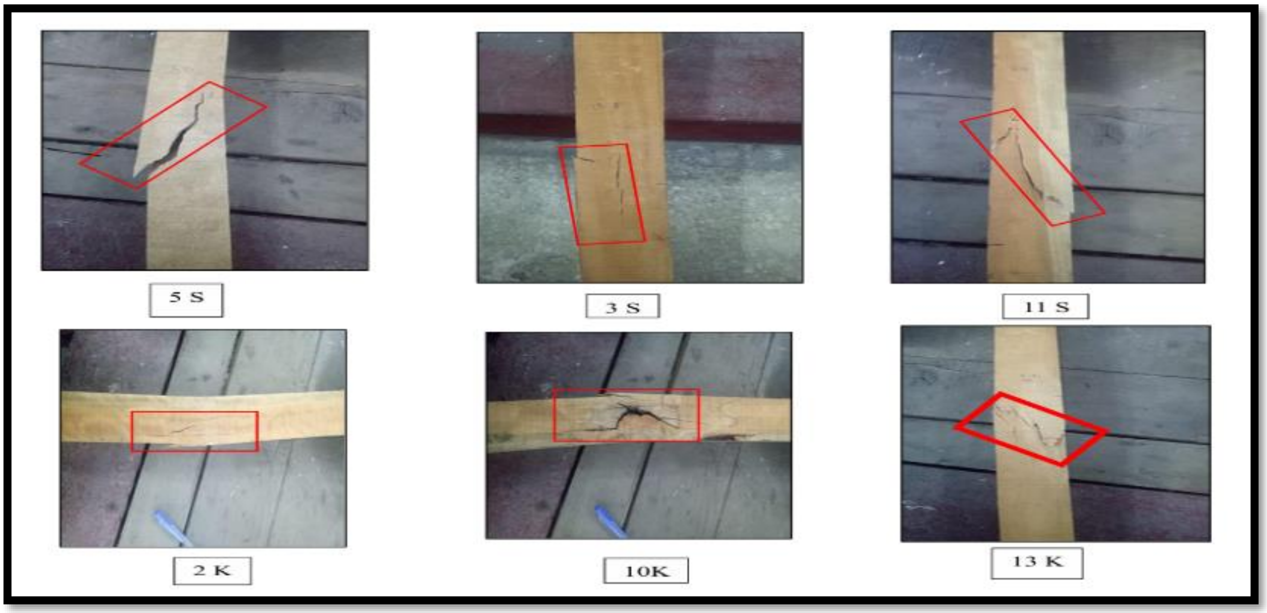

Figure 8: Cracks are produced during the flexural strength Test on the wooden sample

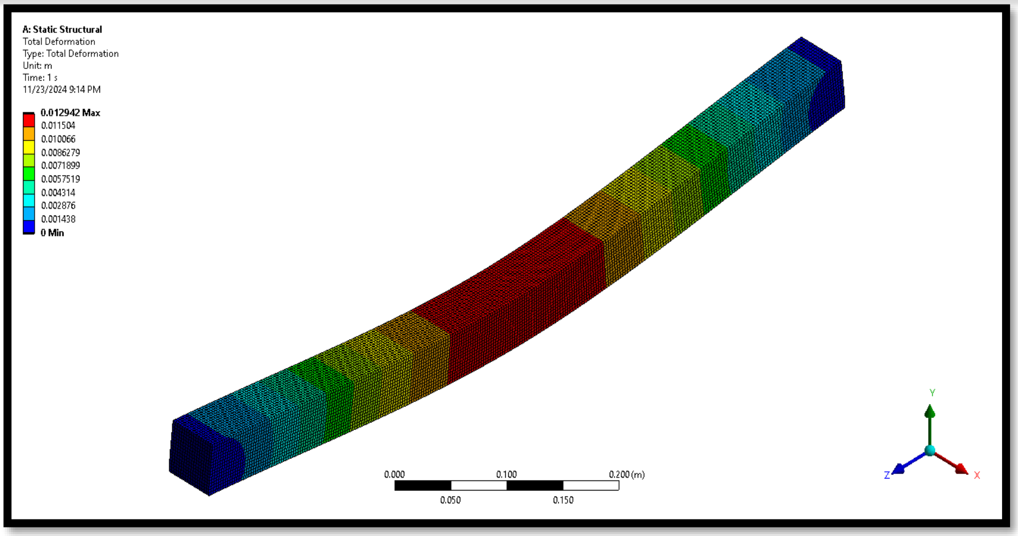

Figure 9: Simulation results of sample no. 5S through Ansys.

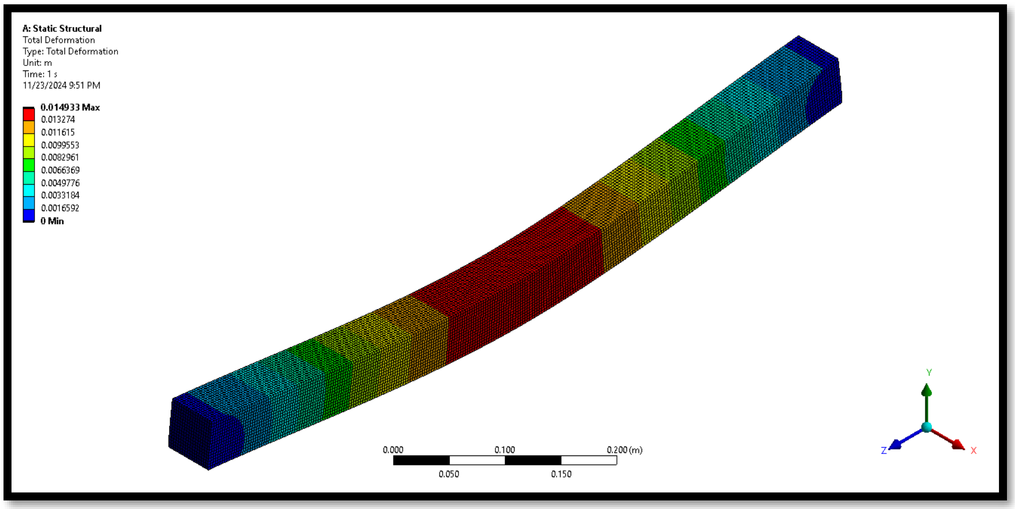

Figure 10: Simulation results of sample no. 3S through Ansys.

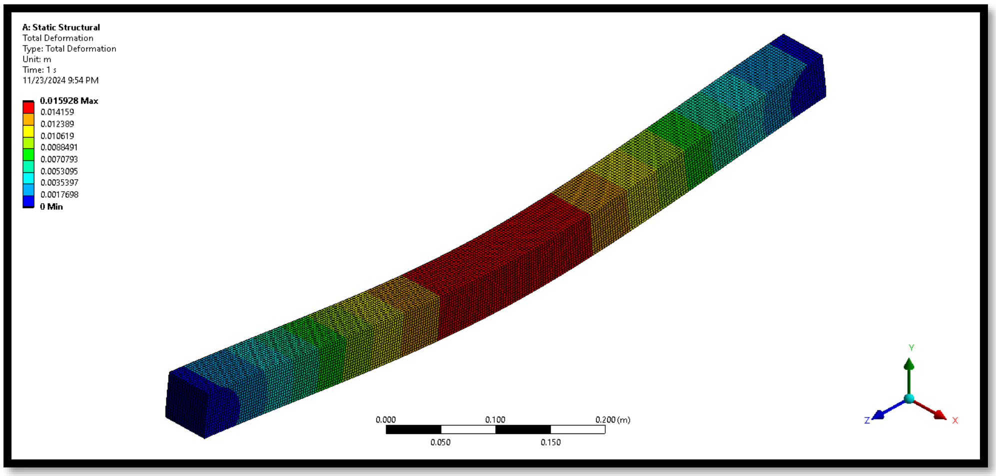

Figure 11: Simulation results of sample no. 11S through Ansys.

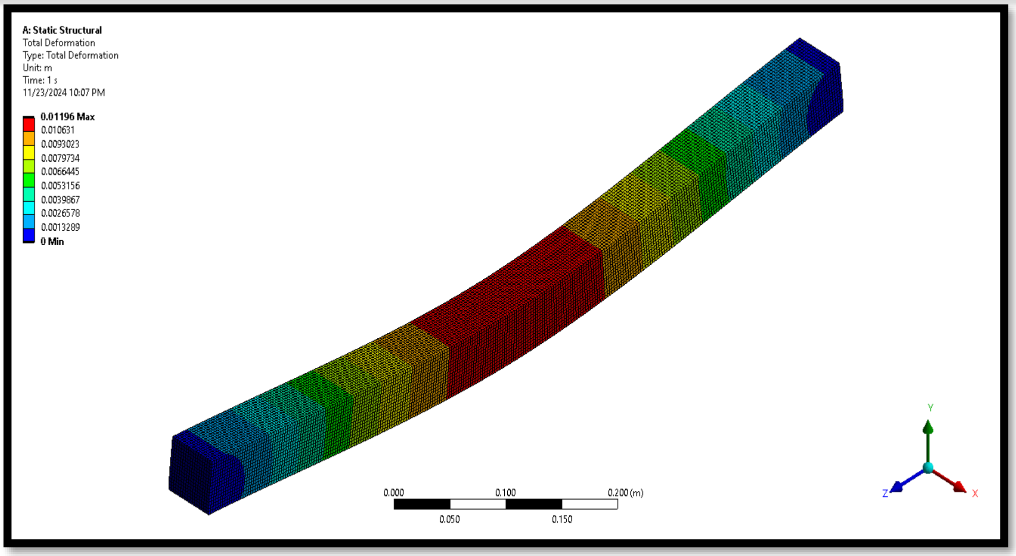

Figure 12: Simulation results of sample no. 2K through Ansys.

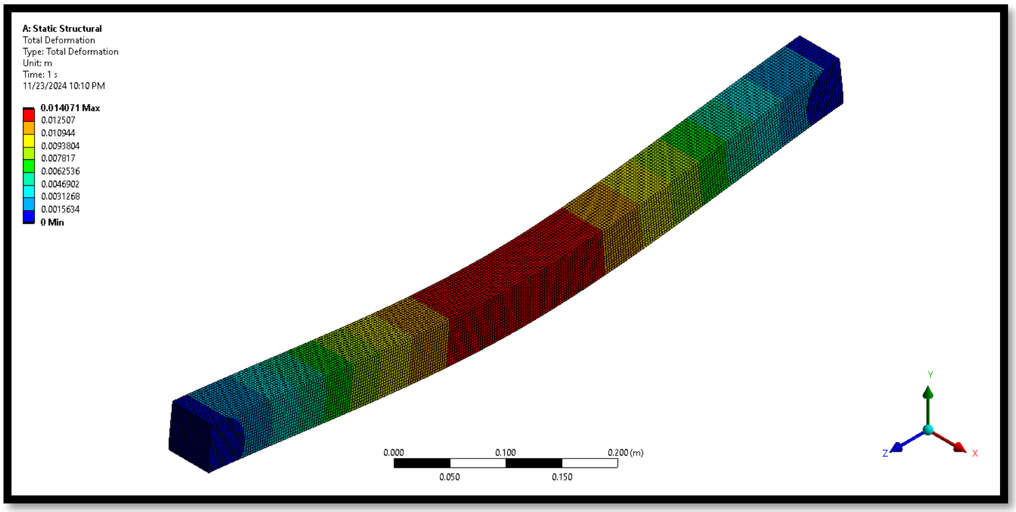

Figure 13: Simulation results of sample no. 10K through Ansys.

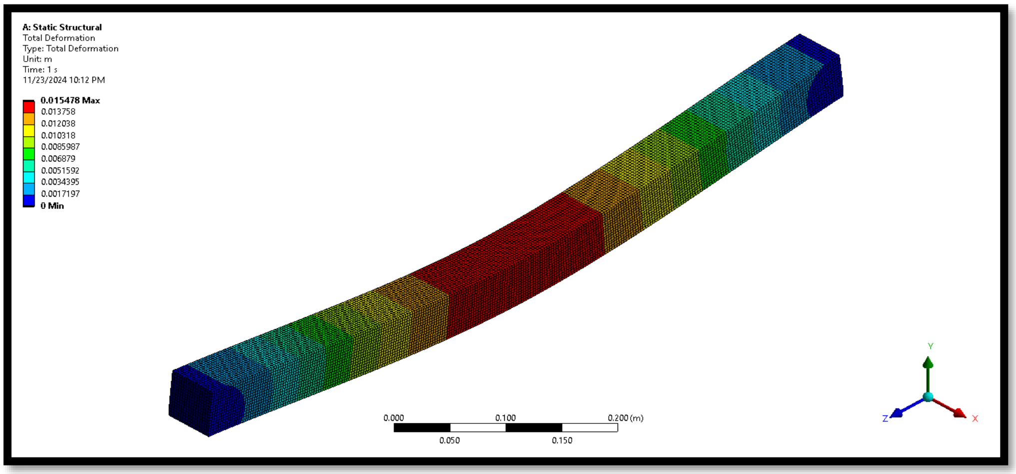

Figure 14: Simulation results of sample no. 13K through Ansys.

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Table 1.7: Flexure strength with wrapping of plastic wire

No. of samples	Sample	Area *10^{3} (m^2)	Flexure strength (Newton)	Modulus of Elasticity (MPa)	Modulus Of Rupture (MPa)	Displacement (▲) (m)	Numerical Simulation by ANSYS (m)
15	S	2.5	4905	1895.475938	26.48	0.048	0.046425
4	S	2.5	4414.5	1664.320335	23.83	0.045	0.043772
17	K	2.5	4905	1579.563281	26.48	0.041	0.04119
7	K	2.5	5886	2021.841000	31.78	0.040	0.039793

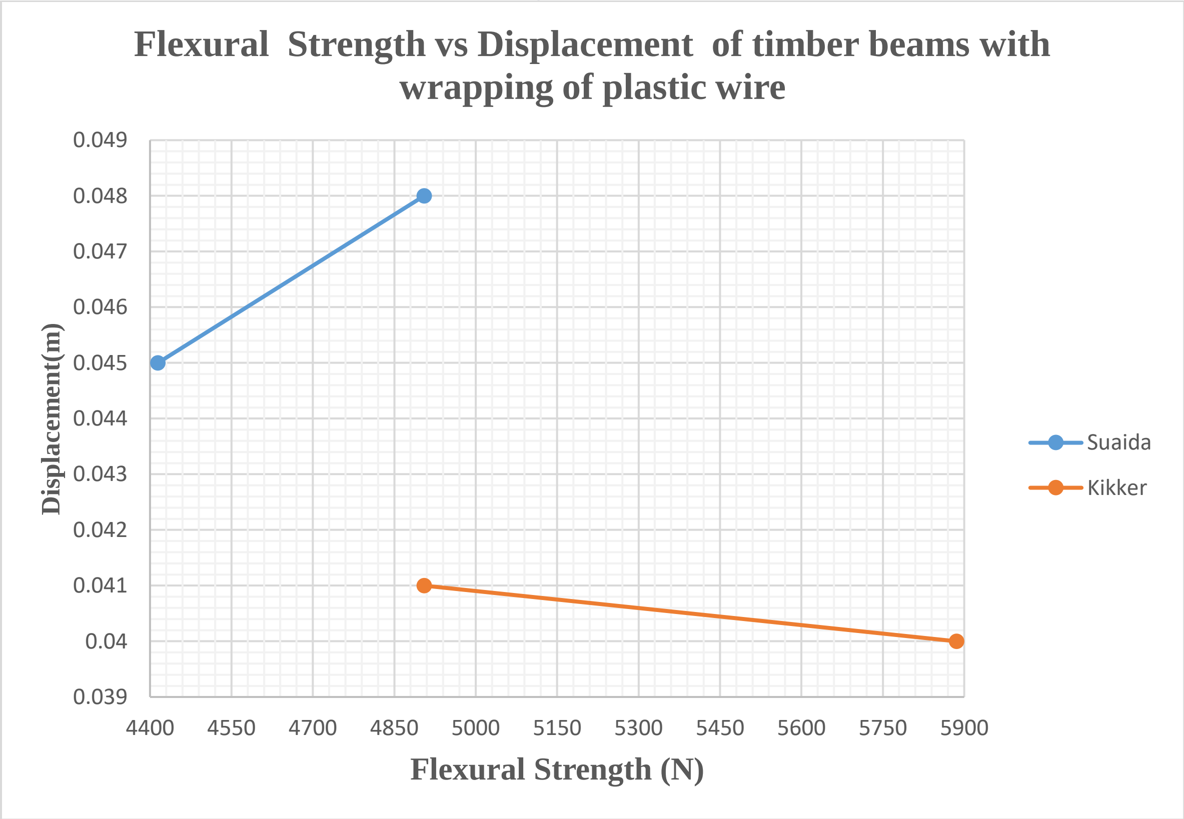

Figure 15: Flexural Strength vs Displacement of timber beams with wrapping of plastic wire

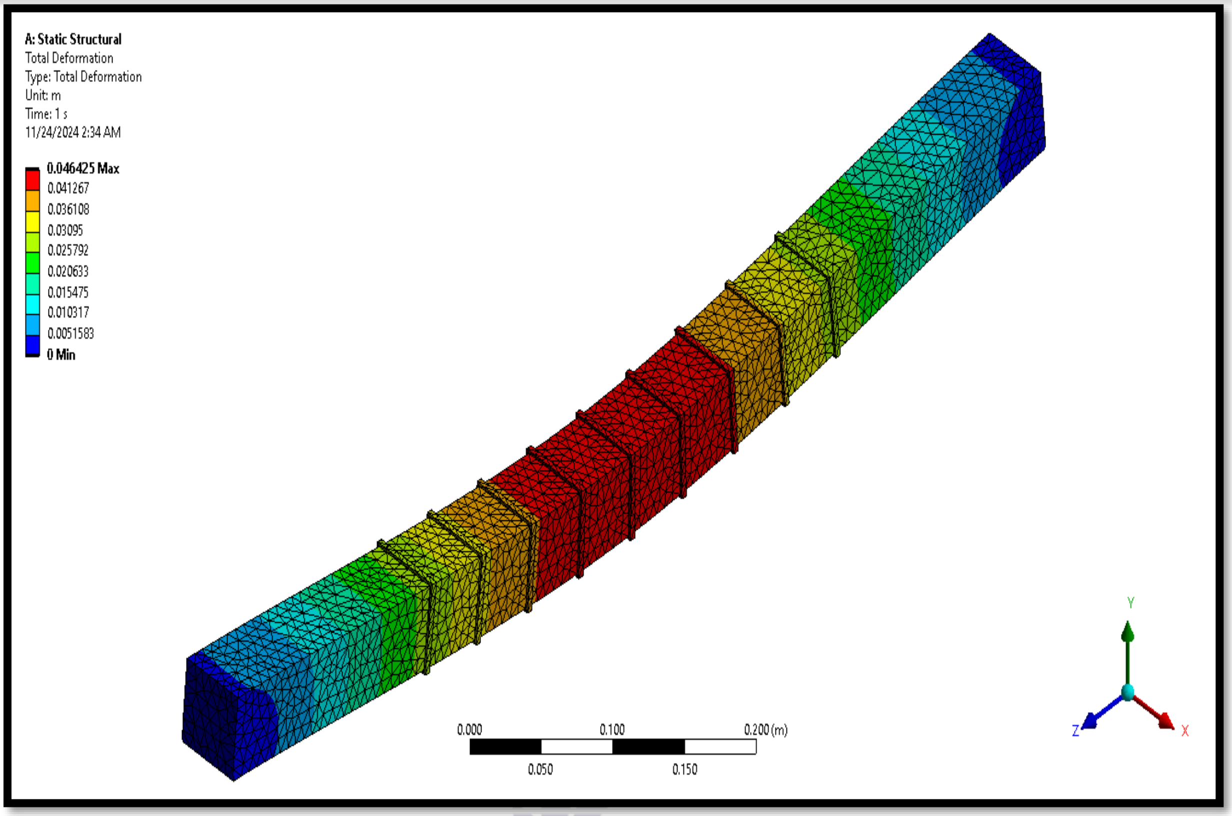

Figure 16: Simulation results of sample no. 15S through Ansys

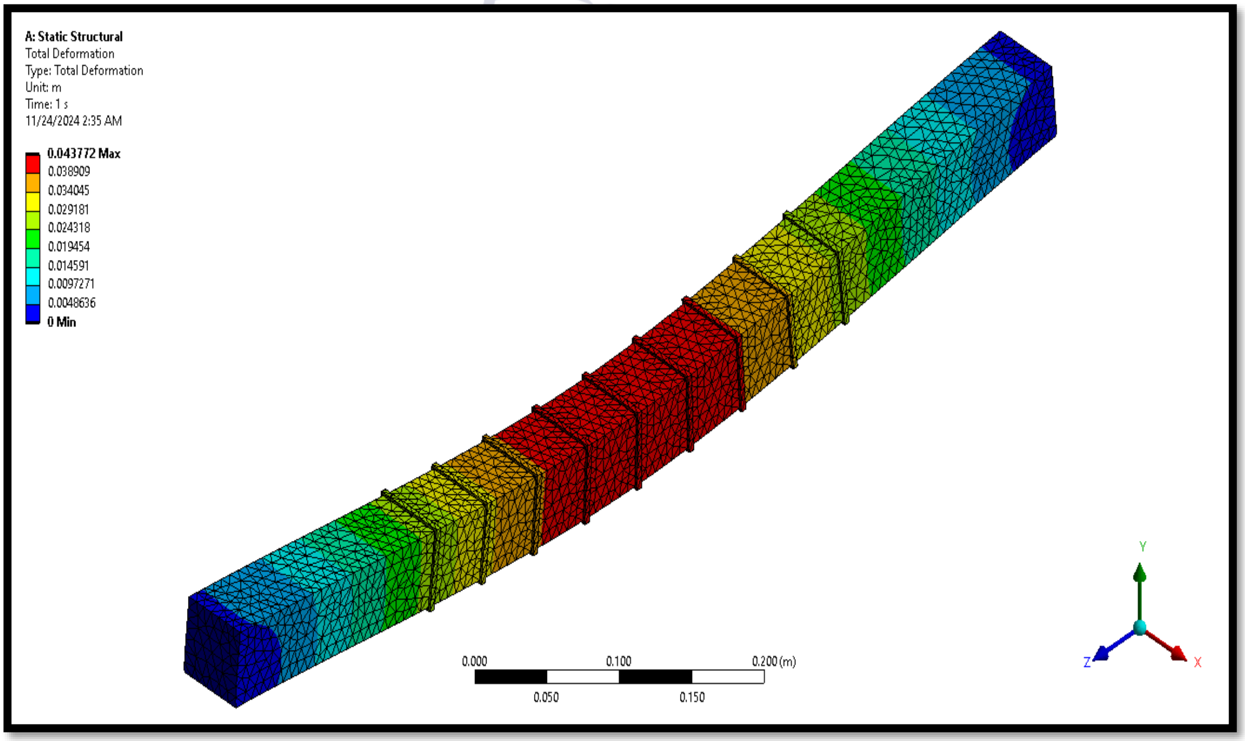

Figure 17: Simulation results of sample no. 4S through Ansys

Figure 18: Cracks produced during flexural testing samples covered with plastic tie

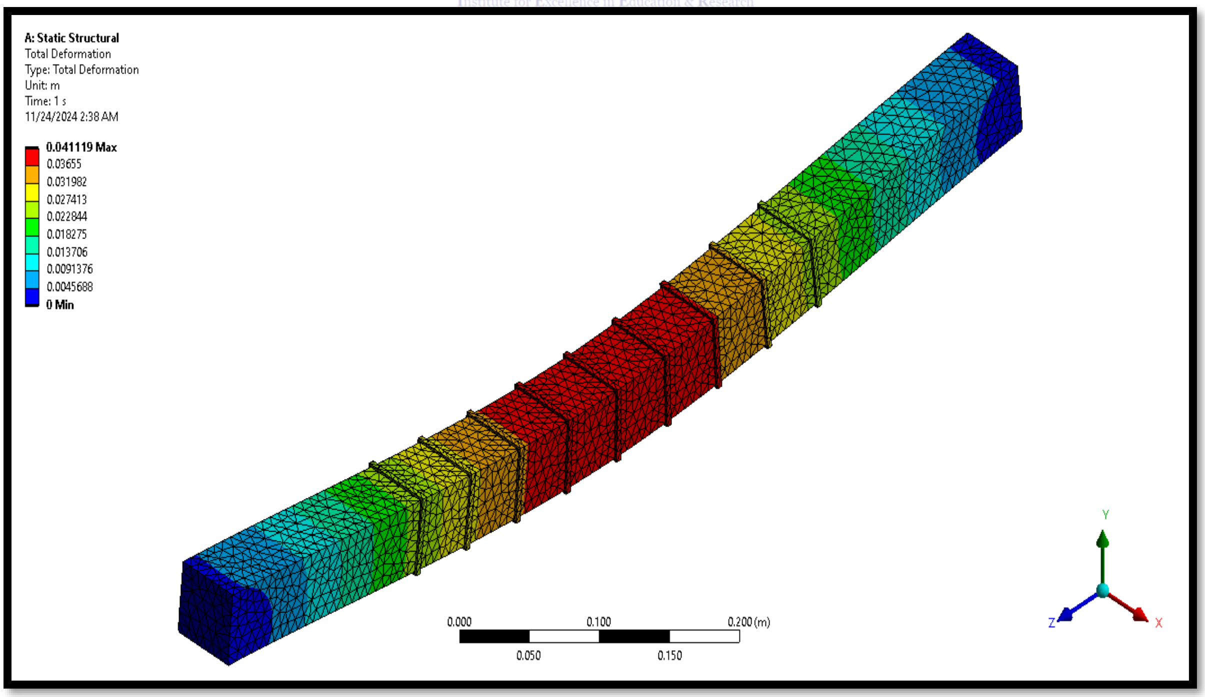

Figure 19: Simulation results of sample no. 17K through Ansys.

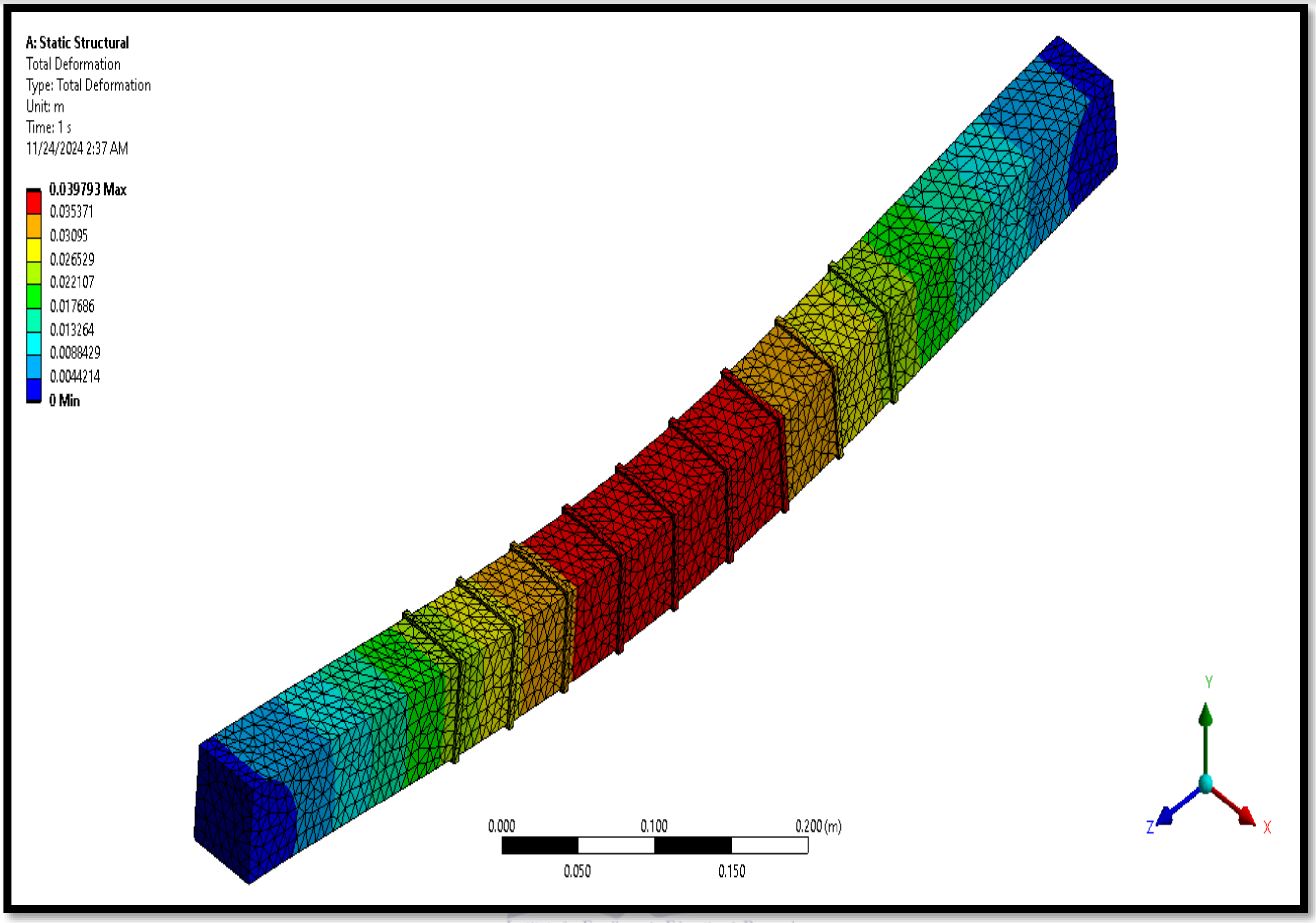

Figure 20: Simulation results of sample no. 7K through Ansys.

Table 1.8: Flexure strength testing with wrapping of Iron wire

No. of samples	sample	Area * 10^3 (m^2)	Flexure strength (Newton)	Modulus of Elasticity (MPa)	Modulus of Rupture (MPa)	Displacement (▲) (m)	Numerical Simulation by Ansys (m) Maximum
4	K	2.5	10300.5	6689.915074	55.62	0.0238	0.023022
18	K	2.5	10791	6836.142725	58.27	0.0244	0.024173
19	K	2.5	8829	5547.734451	47.67	0.0246	0.023597
10	S	2.5	5395.5	4459.943382	29.13	0.0187	0.018417
16	S	2.5	3924	3314.493443	21.18	0.0183	0.017842
17	S	2.5	3924	3278.661081	21.18	0.0185	0.018417

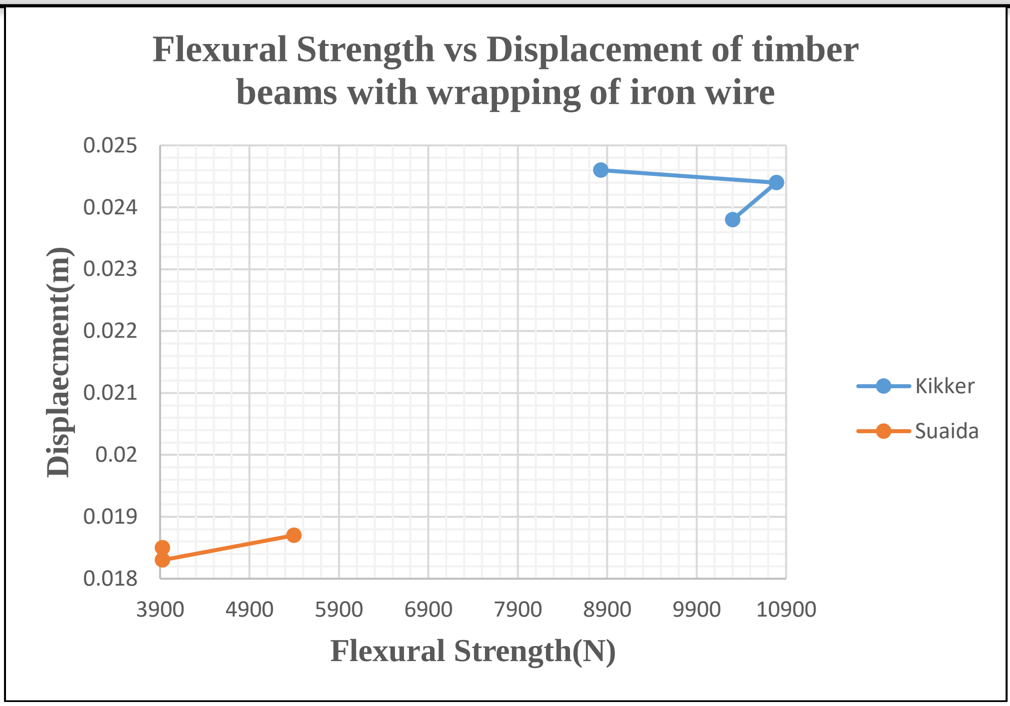

Figure 21: Flexural Strength vs Displacement of timber beams with wrapping of iron wire

Figure 22: Cracks produced during the fractural test of sample wrapped with iron wire, (19S, 18S, and 18K), and (1K) sample is wrapped with sika 230

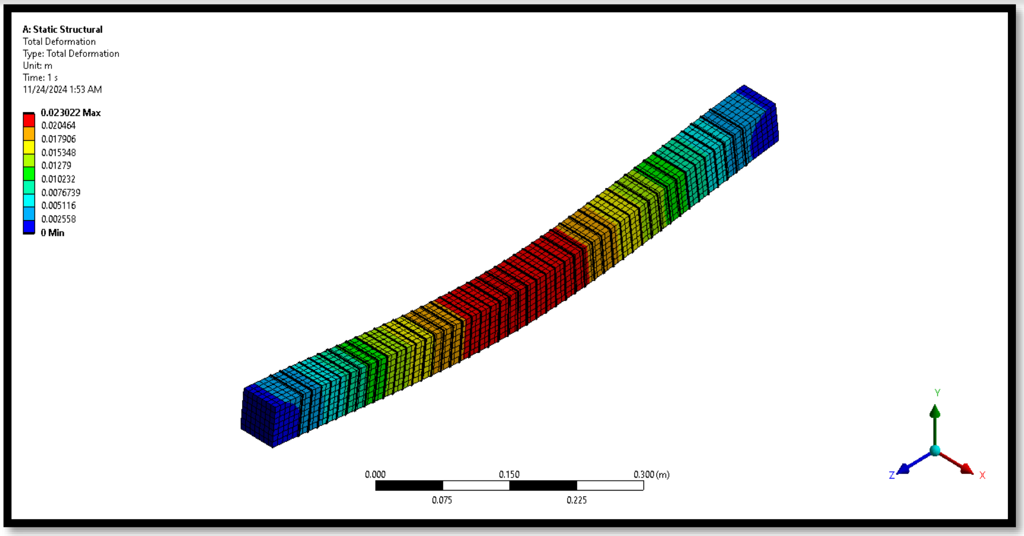

Figure 23: Simulation results of sample no. 4K through Ansys.

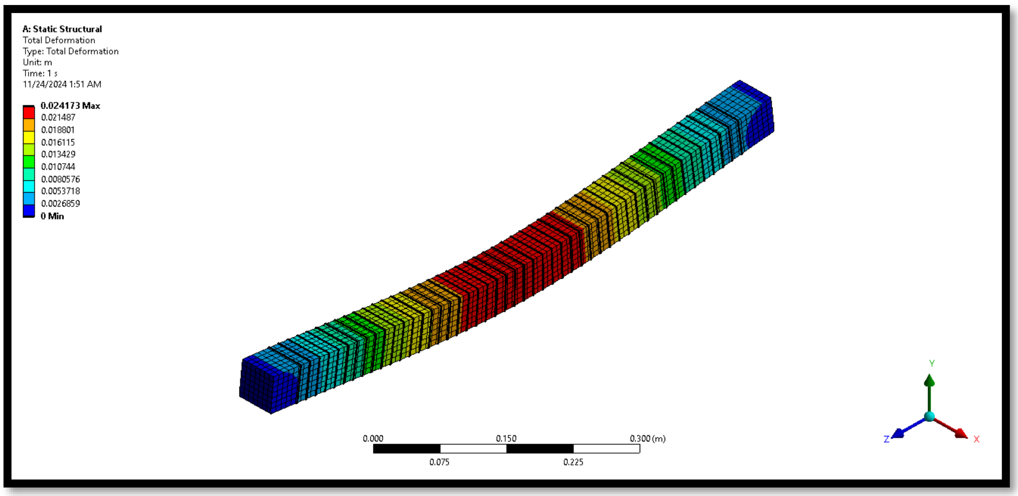

Figure 24: Simulation results of sample no. 18K through Ansys.

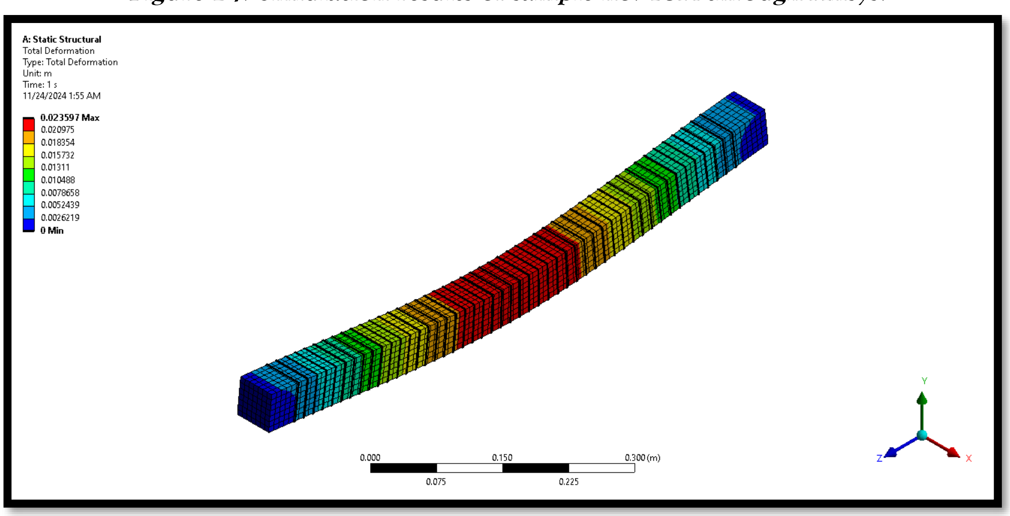

Figure 25: Simulation results of sample no. 19K through Ansys.

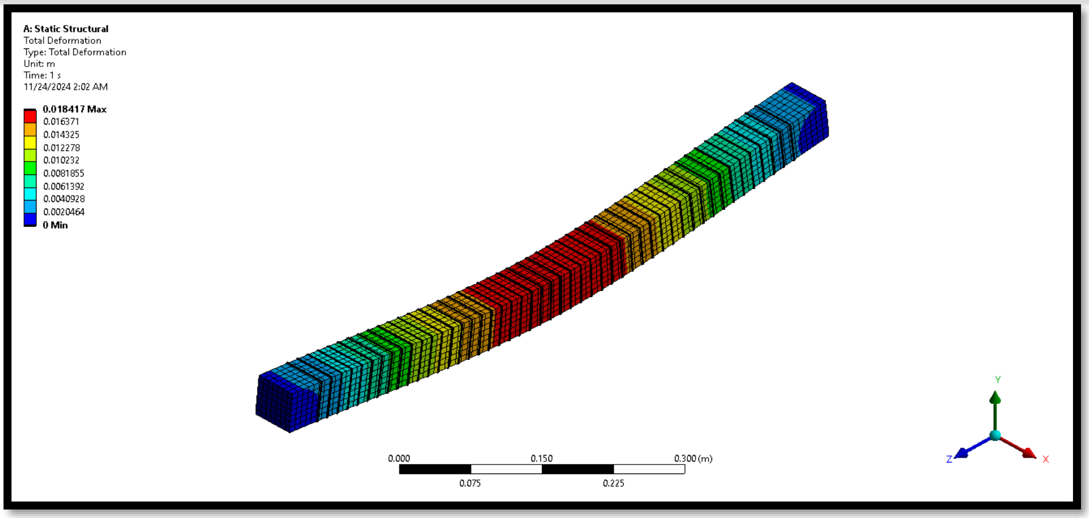

Figure 26: Simulation results of sample no. 10S through Ansys.

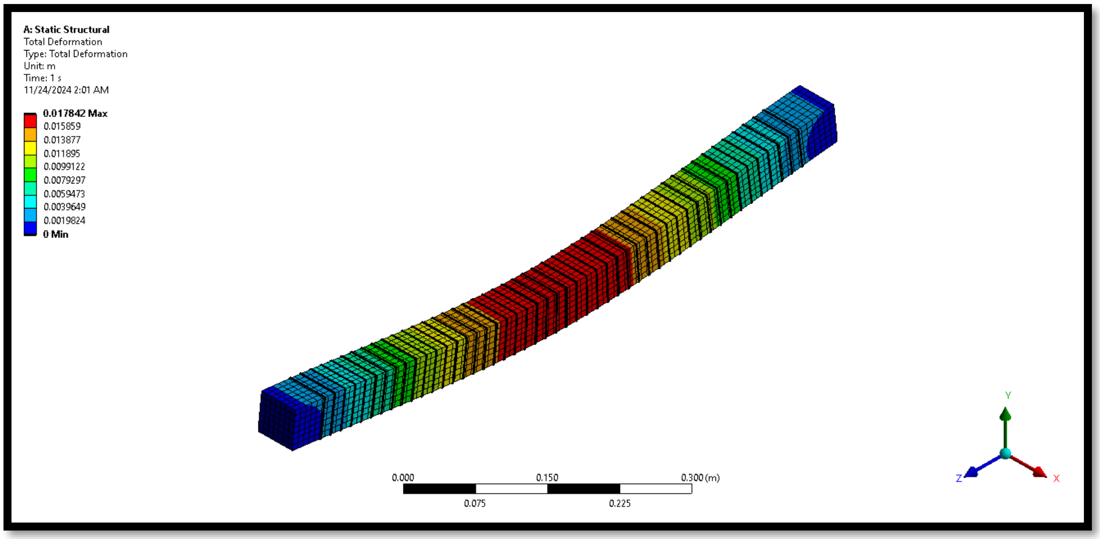

Figure 27: Simulation results of sample no. 16S through Ansys.

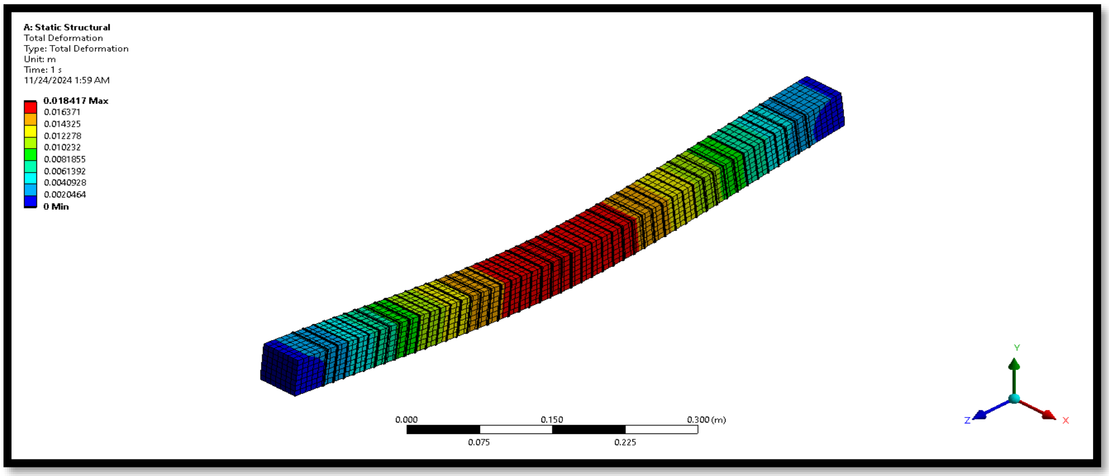

Figure 28: Simulation results of sample no. 17S through Ansys.

Table 1.9: Wrapping of Sika wrap for (SIKA Wrap-230) flexure testing

No. of samples	Sample	Area* 10^3 (m^2)	Flexure strength (Newton)	Modulus of Elasticity (MPa)	Modulus of Rupture (MPa)	Displacement (▲) (m)	Numerical Simulation by Ansys (m) (Maximum)
12	S	2.5	3924	3243.595187	21.18	0.0187	0.016719
14	S	2.5	4414.5	3833.546840	23.83	0.0178	0.017416
20	S	2.5	4905	4143.116803	26.48	0.0183	0.018113
1	K	2.5	10791	5692.897014	58.27	0.0293	0.029259
9	K	2.5	11772	6545.528417	63.56	0.0278	0.027866
16	K	2.5	9810	5377.236702	52.94	0.0282	0.028562

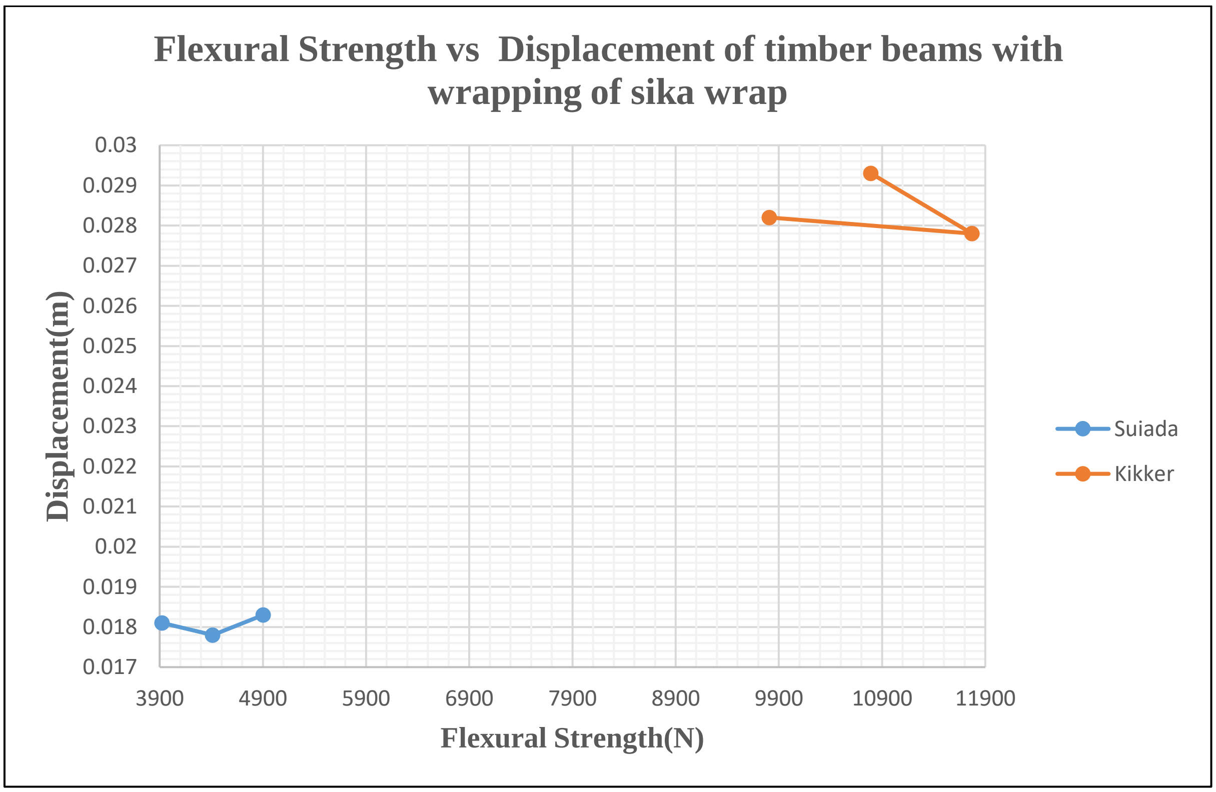

Figure 29: Graph between Flexural Strength vs Displacement of timber beams with wrapping of sika wrap.

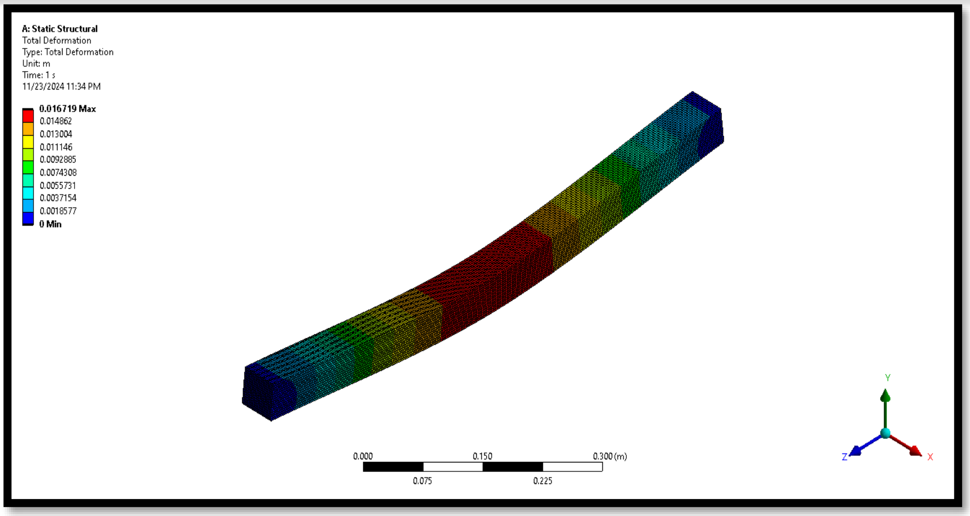

Figure 30: Simulation results of sample no. 12S through Ansys.

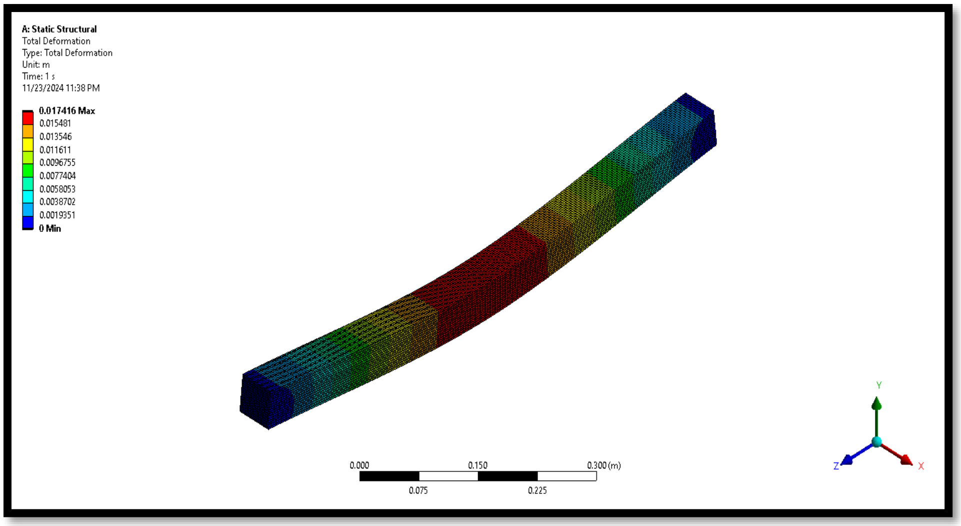

Figure 31: Simulation results of sample no. 14S through Ansys.

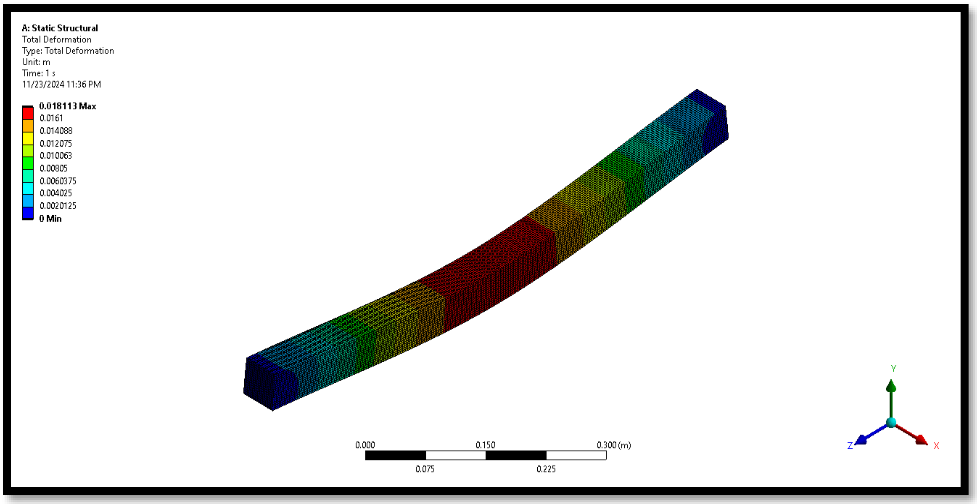

Figure 32: Sample No. 20 S Simulation result

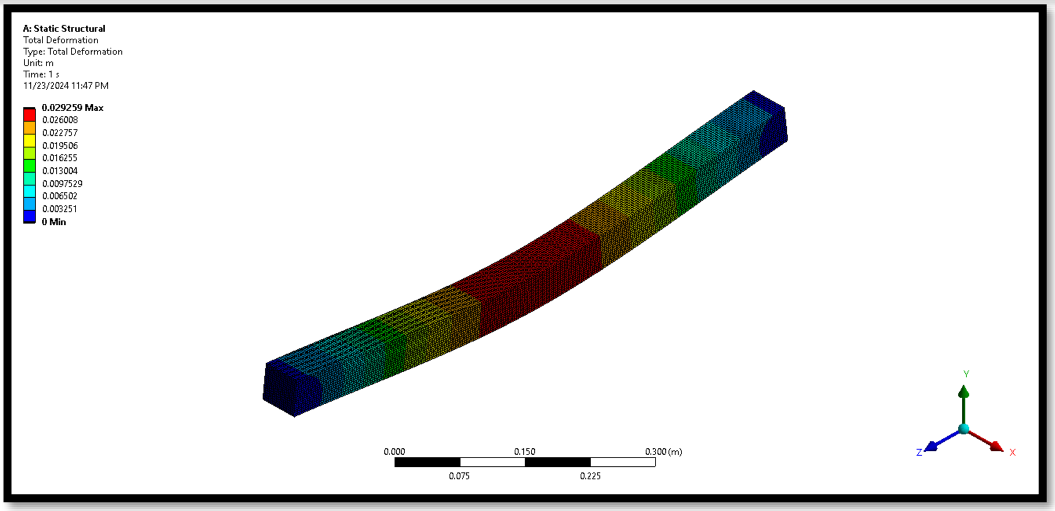

Figure 33: Simulation results of sample no. 1K through Ansys.

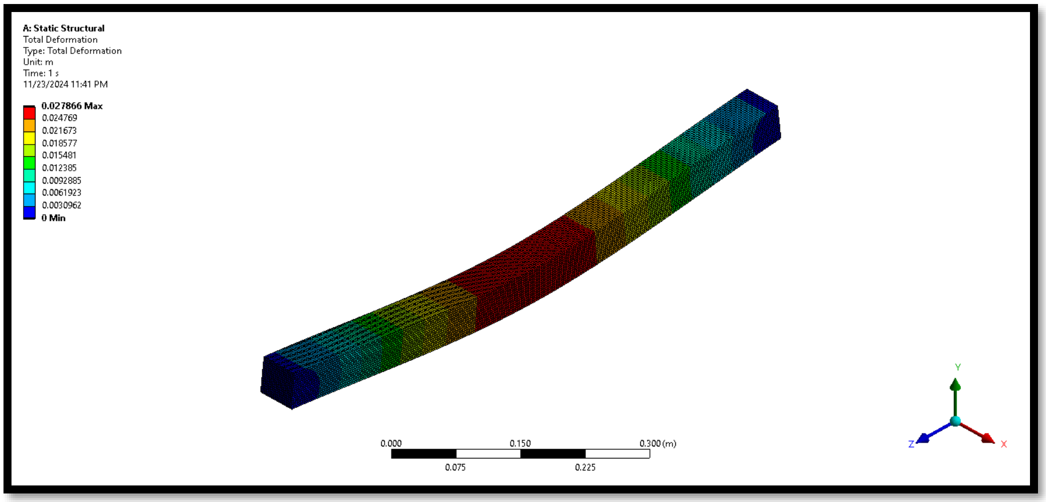

Figure 34: Simulation results of sample no. 19K through Ansys.

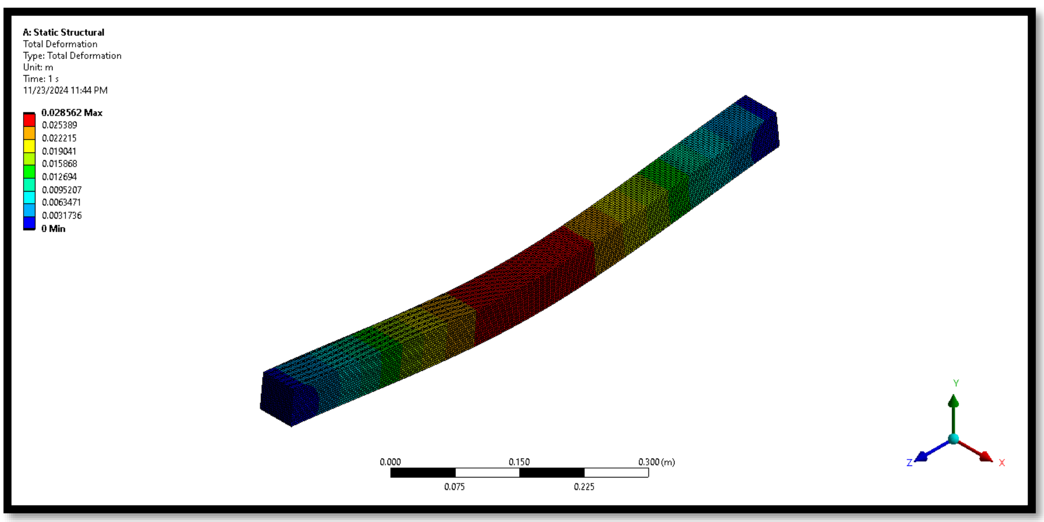

Figure 35: Simulation results of sample no. 16K through Ansys.

Observations

This study gives an all-rounded assessment of the reinforcement methods of timber beams using Sika Wrap-230, plastic ties, and iron wire as potential uses in underground mining. By complementing the experimental results with Finite Element Analysis (FEA) simulation results, it was revealed that Sika Wrap-230 used in combination with Sika Dur epoxy resin is the most efficient method for increasing the mechanical properties of the timber beams. The flexural rigidity, bearing capacity, and overall structural integrity of the timber beams were significantly enhanced with this rebar method. The reduced deflection and stress along the length of the beam were thus very evident in the application of Sika Wrap-230, a factor that depicts its superiority compared to other methods of reinforcement. However, while the Sika Wrap-230 method showed the significant improvements, the study also revealed that some challenges related to the bonding process. The Sikadur epoxy resin used in the reinforcement, although effective to a certain extent, was not a specifically designed for use with the timber and Sika Wrap-230. This mismatch resulted in detachment issues observed in the later stages of testing, especially in areas with high stress concentrations. Such observations emphasize the need for maximizing bonding agents used in conjunction with reinforcement materials such as Sika Wrap-230. Detachment observed during the experiments means that a scope remains for improvement, such that higher quality adhesion would result in the more reliable and long-lasting reinforcement.
On the other hand, plastic tie and iron wire reinforcements had reasonably low performance. Though the two methods slightly relieved deflection as well as stress, they limited the overall strength, rigidity, and load-bearing capability. Plastic ties were less effective to maintain stability when loaded with high loads and so are not desired for such applications that require great strength as well as durability. Iron wire reinforcement showed moderate improvement, but it still lagged behind Sika Wrap-230 in terms of overall performance, particularly for underground mining applications.

The simulations carried out through FEA in ANSYS were nearly in agreement with the experimental results, and thus, both the techniques validated each other. Further, FEA showed that, in both stress distribution and deflection reduction, Sika Wrap-230 performed better as compared to the experimental results. Further, several potential regions of stress concentrations were observed, which may cause bonding failure, thereby supporting the requirement of improvement in adhesives and bonding. The full utilization of the potential offered by Sika Wrap-230 in the reinforcement of timber beams requires future research efforts on the specialized adhesives developed for timber and bonding with Sika Wrap-230. The bonding strength and durability of the adhesives need to be further improved so that the performance of the reinforcement system will not be affected by time.This also requires extensive in-situ, real-world field testing in the underground mining environments in order to confirm the results drawn in the laboratory and evaluate their practical applicability in these methods of reinforcement. It would really provide invaluable insights into how timber beams behave under the real mining conditions so that the refining of the reinforcing techniques can be finalized for ensuring practical effectiveness in boosting the safety and stability of wooden supports.
In conclusion, it is evident that Sika Wrap-230 can be the strongest reinforcement method and thus requires continuous research into how adhesives can be improved and field tests conducted to attain the full benefits of implementing it in the underground mining application. Based on the investigation, there lies a future for improved timber reinforcement where bonding and optimizing materials are imperative for the further demands of this industry and an increase in the endurance and safety performance of underground support structures.

Discussions

Due to the impact of different aspects like moisture changes, fungi and insect attacks, timber beam elements can be damaged and resulting in lower capacity and larger deformations. High stresses exceeding the strength limits can also lead to different types of failure cases, like bending, compression, and tension or shear failure. The analyses of experiments and their assessment shows that most damaged timber beams present cracks in the grain direction due to any of the aforementioned cases. In all of these circumstances, retrofitting and reinforcement of the beams can extend the life of the wooden underground support structure.

The available reinforcement methods to repair or enhance the structural performance of timber beams. The choice of reinforcement method is based not only on the ability of the reinforcement to provide adequate strengthening of the structure but will be constrained by other factors such as aesthetics, need for reversibility, access for repair, and available expertise. Approaches to the design of the reinforcement are presented where available. Old underground support structures of mines need special attention. FRP composites find an easier, more practical and constitutive solution. They are offering a vast range of possibilities therefore, considering the numerous combinations and their great variation, the choice of materials and methods will be up to the designer, for each particular strengthening case. Plastic Tie and Mild Raw Steel Wire can also strengthen timber beams up to some extent. Both are cheap methods of reinforcement of wood.

For us, to record progress, both as individuals and as a community, new ways of improving underground support are to be searched for. No matter the domain or the impossibility of an idea, progress must be encouraged but there should be no possible image of the future without the mark of the past. To keep this mark means to protect our miners. To achieve this, measures have already been taken but enhanced methods, all following this same goal, are looked for every day.

While some aspects are well understood, additional research is required particularly related to the long-term behavior of reinforced beams, and the influence of fluctuating temperature and moisture conditions on the performance. In the latter case, different thermal expansion and moisture absorption properties of the timber element and the reinforcement may lead to additional thermal or moisture-induced stresses. Guidance on how these stresses may be quantified for design purposes should form the basis of future research.

Conclusion

From the experimental study, Sika Wrap-230 requires adhesively bonding timber mechanically for improving their bonding performance with a view to obtaining actual reinforcement effectiveness. Long-term durability testing in simulated fluctuating moisture-temperature environments may well lead to adequate acceptability in belowground applications. For that matter, field implementation, including pilot test application under on-site mine environments should therefore be undertaken. Many other reinforcement techniques are admirably adapted for underground conditions but considerably differ in cost, with some being moderately inexpensive while others are relatively expensive, depending on the specific application and environment. Finite element analysis can also be applied to enhance efficiency to optimize the pattern of reinforcements and material usage. Finally, the development of standardized guidelines on the application of reinforcement techniques in underground mining is critical for safety, sustainability, and practical adoption.

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