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Experimental and Numerical Analysis of Woven Bamboo and Jute Fiber Reinforced in Epoxy Composites

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KEYWORDS

FEA;
Bamboo;
Jute;
Stacking;
Tensile;
Flexural;
SEM.

ABSTRACT

Aerospace, transportation, marine, and space applications demand structural materials with low densities yet strong, hard, and high impact strength. Composites are materials that satisfy the needs of recent technology. Composites are flexible materials that meet the demands of modern technologies. Herbal fibers may be processed and need little energy. Using natural fibers as reinforcement in polymer composites to create inexpensive building materials has recently gained popularity. The experimental and FEA analysis of woven bamboo and jute fiber reinforced in epoxy composites is the main emphasis of the current work. Mechanical properties such as tensile and flexural properties are evaluated for various stacking sequences. Also, numerical analysis is done using licensed Hyper mesh software. The S1 stacking sequence's testing findings had the highest tensile strength (47.411 MPa) and tensile modulus (695.44 MPa). Additionally, it has the highest flexural strength and modulus at 80.25 MPa and 9.065 GPa, respectively. FEA results deviate by more than 10%. Excellent mechanical characteristics are achieved with a fiber volume fraction of 10% bamboo, 20% jute, and 70% matrix material. The SEM images showed the composite's interface breakdown between the textiles' layers.

1. Introduction

Natural fibers can be found in abundance in nature(Khalid, Al Rashid, Arif, Ahmed, Arshad, et al. 2021). These fibers often make yarns, ropes, mats, wallets, purses, and wall hangings for high-end products(Satyanarayana et al. 1990). Hybrid structures/laminates made engineers design new materials for specific applications with appreciable properties(Onal and Adanur 2002). The major components of natural fiber composites (NFC) include cellulose, lignin, pectin, and hemicelluloses. Cellulose in composite components has also gained popularity and is used in natural fibers(Khalid, Al Rashid, Arif, Ahmed, and Arshad 2021). The fiber surface is hydrophilic and inadequate for usage with hydrophobic polymers (Doan, Brodowsky, and Mäder 2012). Because of two factors, these natural fibers are frequently combined with synthetic fibers. Due to their hydrophobic nature(Khalid, Al Rashid, Arif, Sheikh, et al. 2021), they first lack the mechanical qualities of fibers like Glass, Carbon, and Kevlar(Khalid, Al Rashid, Abbas, et al. 2021). Concerning to cost and processing methods of natural fibers, these offer an advantage over synthetic fibers. However, these natural fibers have lower mechanical properties than synthetic fibers. Another disadvantage of natural fiber composites is their poor moisture absorption (Ahmed and Vijayarangan 2008).

Outstanding benefits of plastic-based composites are their light weight, strength, chemical resistance, and stability. For example, they are used in medium-range applications for sports, electronics, and aviation(Shankara Reddy, Kumshikar, and Ravikumar 2022). However, these materials' biggest drawbacks include environmental issues, waste management, and non-biodegradability (Defoirdt et al. 2010). Therefore, many researchers have been inspired to use biodegradable, eco-friendly composites (Yada 2018).

Natural fibers are lightweight and easily extracted from plants. Compared to synthetic fibers, natural fibers are economical and abundantly available. They are

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biodegradable,eco-friendly, and easily disposed of(Murali et al. 2014). They have good strength and find many applications today(Khalid, Rashid, Arif, Akram, Arshad, and Márquez 2021). The first application of these fibers was between the years 1920 and 1930. It is used for airplane applications to reduce the weight of the component (Reddy and Kumshikar 2023). Once a product's life cycle is complete, it can either be burned or composted (Biswas et al. 2013). Nearly 98% of composite trash and end-of-life (EOL) elements ended up in landfills, as reported by the UK supply chain composite waste study from 2015 (Khalid et al. 2022).

These NFRPCs, or bio-composites, are classified as complete or partial green composites. Using NFRPCs might result in a weight reduction of 10-30%. Hence, manufacturers can explore expanding the use of NFRPCs in their new products(Khalid, Imran, Arif, Akram, Arshad, Rashid, et al. 2021).

The current study considers bamboo and jute fiber for the composite preparation. Jute fibers, one of the modern natural fiber materials, are frequently employed as reinforcement in hybrid composites (Khalid and Nasir 2020). They have better bonding properties resulting in good mechanical properties. Weaved textiles are produced using these raw extracted fibers. The weaving patterns of these fibers are warp 0^0 and weft 90^0(John and Thomas 2008). These woven fabrics are kept in the 0.1 N sodium hydroxide (NaOH) solution. It is done to improve the adhesive property of polymers with natural fibers that increase the composite material's strength (Reddy, Kumshikar, and Ravikumar 2020). Chemical processes and surface alterations can increase the quality of natural fibers.

Finite element analysis is done using licensed hyper mesh software vesion14. Natural fiber composites are considered to function like orthotropic materials. As a hybrid composite contains layers made of different materials, the material definition in the hypermesh should be accurate to apply it for real problem simulations (Adeniyi et al. 2021). The specification of hybrid composite material properties in the hyper mesh depends on criteria such as lamina thickness, fiber type, fiber orientation, the volume percentage of each fiber, and component matrix in the lamina. As a result, estimated lamina characteristics are important in investigating composite materials using hypermesh (Chinta 2021).

Constituent Material

The materials used for the composite material are as follows:

1.1 Bamboo Fiber

Bamboo fiber (BF) is an environmentally friendly natural material. The bamboo plant grows more quickly than other natural fibers, as shown in Figure 1.1. It absorbs and fixes carbon dioxide in the atmosphere(Rao and Rao 2007). Bamboo fibers are recognized for their tall and persistent growth, ranging in height from 10 cm to 40m. Bamboo plants are classified into more than 70 species and are grown worldwide in various environments(Okubo, Fujii, and Yamamoto 2004). Bamboo fiber is plentiful in Asia and South America. It has evolved as the backbone of the socioeconomic status of society. It is used as a living facility. It shows a high strength-to-weight ratio(Abdul Khalil et al. 2012). It is also less expensive and has a low density. Unlike other natural fibers, bamboo fiber is more fragile. Various procedures are used to extract the fibers. Chemical, mechanical, and steam explosion extraction methods are offered. China is called the "Kingdom of Bamboo" since more than 400 different types of bamboo are grown(Liu et al. 2012). The bamboo industry in China is the largest in the world in terms of the variety of bamboo species, bamboo reserves, and industrial output. Chinese bamboo plantations covered 5.38 million hectares in 2010, growing by 100,000 hectares annually. The extracted raw fiber and woven form of the fiber are shown in Figure 1, 2 and Figure 3.

The presence of carbohydrates in bamboo products affects their durability or lifespan (Sun et al. 2014). Yet, bamboo fiber may already be used extensively in creating green bio-composites due to its appealing qualities, including UV protection, moisture management, anti-bacterial capabilities, durability, and non-harmful features(Prakash 2020).

Fig. 1. Bamboo tree

Fig. 2. Extracted raw bamboo fiber

Fig. 3. Woven bamboo fiber

1.2 Jute Fiber

Jute fibers (JF), one of the most customarily used stem-type herbal fibers, are indigenous to India, Bangladesh, and Nepal. Historically, Jute was only used for ropes, twines, sacks, and hessian fabrics. Bast fibers are now used in the automotive sector for seat backs (Holbery and Houston 2006), interior door panels, trunk liners, and so on (Furtado et al. 2014). As shown in Figure 4, the jute plant may grow to a height of

2.5 m and has a base stem diameter of 25 mm. Jute is a soft, long NF that can be made into solid filaments. India produces the most JFs (1,968,000 tons), followed by Bangladesh (1,349,000 tons) and China (29,628 tons)(Song et al. 2021). Figure 5 shows the extracted raw jute fiber, and Figure 6 shows the woven form of jute fiber. It is purchased from the local market.

Fig. 4. Jute plant

Fig. 5. Raw jute fiber

Fig. 6. Woven Jute fiber

Table 1 shows the chemical compositions of different natural fibers.

Table 1. Chemical compositions of a few natural fibers

Natural Fibers	Cellulose %	Hemicellulose %	Lignin %
Banana	62.60	19	5
Jute	61-72	13-24	12-16
Bamboo	60-73.83	12.46	10.15
Sisal	65-72	12	10-15
Coir	32-43	0.14-0.25	40-46
Areca	-	12	13.2-24
Maize silk	37-42	20-23	10-14

1.3 Epoxy Matrix

The epoxy matrix is a thermosetting resin in the plastics sector(Kumshikar 2023). Initially, it was used for structural applications and later implemented in composite materials. It is also used in the paint industry as a convertible coating.

The following are the characteristics of epoxy resin

1. It has good physical properties like abrasion resistance, toughness, and flexibility.
2. It offers excellent adhesiveness to various substrates.
3. Its low shrinkage during cooling results in good dimensional accuracy.
4. It is chemically resistant.
5. It acts as good electrical insulation.
6. Epoxy resin provides superior performance at elevated temperatures compared to thermoplastics.
7. Low cost and ease of fabrication.

In the present investigation, Lapox L12 and K6 hardener is used. It is purchased from the local market.

Table 2 shows the different material properties of the constituent materials.

Table 2. Material Properties

Property	Bamboo (Munshi and Walame 2017)	Jute (Sabeel Ahmed and Vijayaranga n 2006)	Epoxy (Kashyap, Nath, and Das 2019)
Density (kg/m3)	1.4	1.45	1.2
Tensile strength (MPa)	400-800	393-773	70-80
Poissons ratio	0.3	0.35	0.35
Young's Modulus (GPa)	21	20	3.45
Poisons Ratio	0.3	0.38	0.35
Rigidity Modulus (GPa)	0.582	7.24	1.277

1.4 Rule of Mixture

The analytical equation used for preparing composites with varying combinations of matrix and fiber volume fractions is shown in the equation(Yerbolat et al. 2019).

$$V_c = V_f + V_m \text{----------Eqn (1)}$$

V_f = Volume fraction of Fiber Component

V_m = Volume of Matrix

V_c = Volume of Composite

2. Fabrication Process and Methodology

2.1 Fabrication of Mold

A metallic mold made of mild steel measuring 300 mm x 300 mm x 3.2 mm is fabricated to preparethe required specimens.

2.2 Hand Layup Method

The hand layup technique is simple and easy. It involves less tooling during the process(Elkington et al. 2015). This method is used for laying the resin and fibers with adequate orientations. The preparation of samples is explained below.

2.3 Specimen preparation

1. Natural fibers like bamboo and jute are used as reinforcement, and Lapox 12 is used as a matrix. The orientation of the layers is bidirectional, which proved to produce more strength.
2. On the mold surface, a gel coat is applied. This prevents the specimen from being attached to the mold surface.

3. A single layer of Jute is placed along the x-direction (0^0) over the mold surface.
4. The epoxy resin is placed over the Jute surface in a semi-liquid condition, and then another layer of bamboo is added in the y-direction. (90^0).
5. Repeat steps 2 and 3 for the required fiber volumes and thickness.
6. The details of fabricated specimens (laminates) with different stacking sequences are shown in Table 3. Woven Jute fiber is indicated with J and Woven Bamboo fiber with B.

Table 3. Composition of composites with stacking sequence.

Matrix%	Fiber volume %		Stacking sequence	Name of the Sample
	Jute	Bamboo		
70	20	10	JBJBJBJ	S1
	15	15	BJBJBJB	S2
	10	20	BBJBBJBB	S3
	-	30	BBBBBBBB	S4
	30	-	JJJJJ	S5

3. Experimentations

The following experiments were conducted and analyzed using the FEA technique

3.1 Tensile Test

Tensile test specimens were prepared to the required dimensions as per ASTM D3039 (ASTM 2017). The test is conducted using a Computerized UTM with a capacity of 100kN. The specimen is firmly held in a tensile fixture, and load is applied at a rate of 5mm/min at a room temperature of 25^0C. Readings were recorded, and tensile properties were evaluated. Figure 7 shows the experimental setup and specifications for tensile testing, and Figure 8 shows the specimen dimensions.

Fig. 7. Computerized Universal Testing Machine and specification of the UTM

Specifications of the UTM	
Capacity	1 Ton
Maximum Extension	1000 mm
Cross Head Speed	1 to 800 mm/min

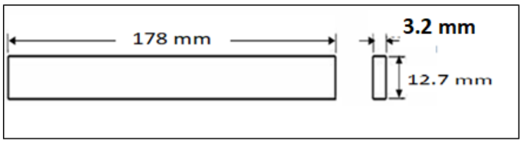

Fig. 8. Tensile Test Specimen dimensions

3.2 Flexural Test

Test samples are prepared to the required dimensions as per ASTM D790(ASTM INTERNATIONAL 2002), as shown in Figure 10. The gauge length of the specimen was set at 50mm. This test is done by fixing the samples in a fixture using a three-point bending condition. The experimental setup is a computerized UTM 100kN capacity, as shown in Figure 9. The crosshead speed was set to 2mm/min for the test. The force needed to bend the specimen or beam under specific loading circumstances is used to assess the flexibility of the test samples. The readings are tabulated, and the flexural characteristics are evaluated.

Fig. 9. Computerized Flexural Testing Machine setup

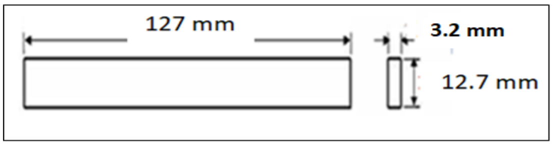

Fig. 10. Flexural test specimen dimensions

3.3 Finite-Element Analysis (FEA)

The FEA pre-processing is an extremely important step. It establishes the standard of the simulation and, thus, the reliability of the outcomes. The process involves the preparation of the geometry, the defining of the material, and the choice of the element and mesh. The loads and constraints are then assigned based on the type of analysis considered(Zhang and Ju 2008). Finite element analysis uses commercial Hyper mesh software (Prasad et al. 2014).

Experiments are carried out to determine the properties of the materials. Using the experimental data, the FEA model is then updated to ensure that the virtual simulation of the composite product performs accurately. The mechanical characterization of the composite materials is employed for identifying all the boundary conditions (Alhijazi et al. 2020). The general procedure of modeling and analysis of the component is shown in Figure 11.

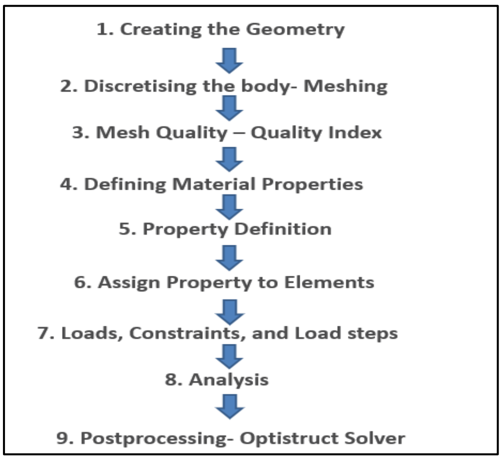

Fig. 11. General procedure of modeling and analysis in Hypermesh

Jute and Bamboo fiber-reinforced composite materials are modeled in hyper mesh, and analysis is done in an Opti struct solver. The material is assumed to be orthotropic, and using element type MAT8, the properties of the material are assigned. The mechanical properties were studied.

The elastic constants used for the hybrid fiber composites are taken from Table 2. The thickness of the jute fiber ranges from 4mm to 4.5mm, and bamboo fiber ranges from 3mm to 3.5mm.

3.4 Steps Involved in the Numerical Analysis of the Tensile Test for the S1 Stacking Sequence

The steps involved in the FEA are preprocessing, solving, and post-processing. The procedure is shown in Figure 18.

1. Pre-processing is the first step which involves Creating the geometry as per ASTM standards, as shown in Figure 12.
2. The discretization process was carried out using MAT 8 element type. Assuming as an orthotropic material. 144 elements were generated with 189 nodes, as shown in Figure 13.
3. The element properties like warpage, aspect ratio, minimum length, maximum length, skew, angle, etc were maintained as per the element standards and shown in Figure 14.
4. Considering the stacking sequence S1, i.e., JBJBJBJ, 13 plies were generated. The epoxy matrix is introduced as a bonding material between every ply. Figure 15 and Figure 16 show the different plies for the S1 sample.
5. After assigning all the material properties, the model is constrained, and all the boundary conditions are applied, as shown in Figure 17.
6. The next step is to solve the problem using an Opti struct solver.
7. The post-processing is done, and results are obtained.

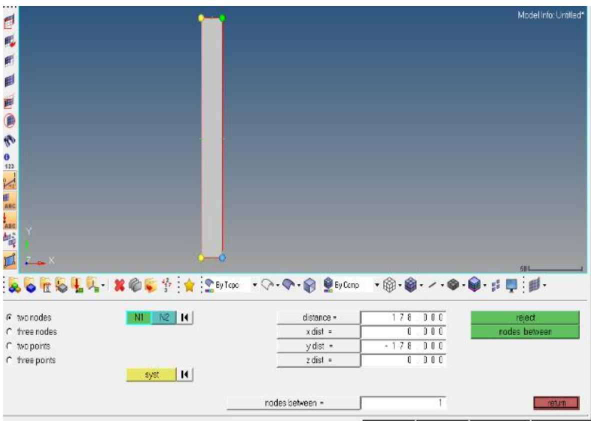

Fig. 12. Specimen as per ASTM standards

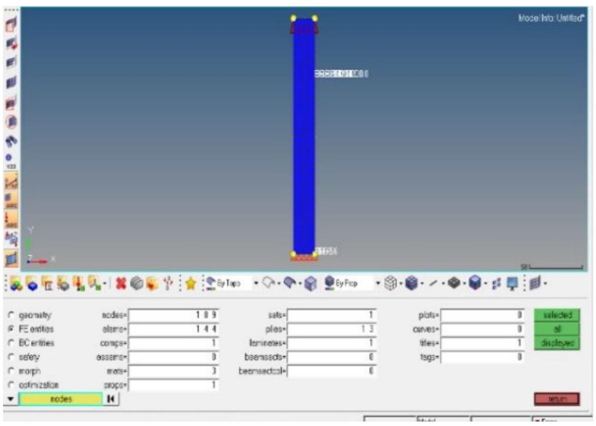

Fig. 13. Discretization process: number of elements: 144, number of nodes: 189

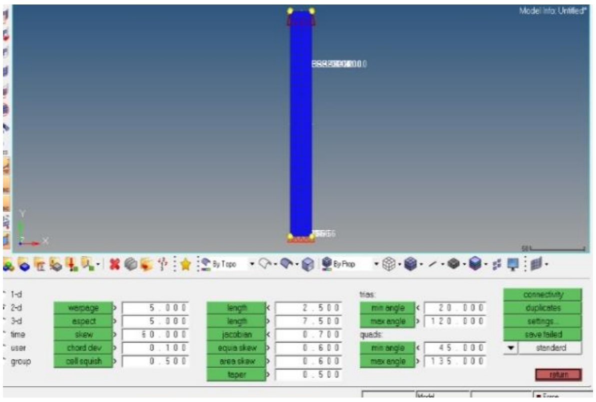

Fig. 14. Properties of an element

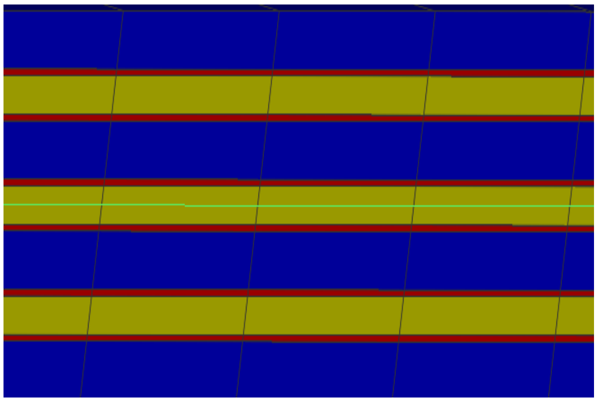

Fig. 15. Creating 13 plies for the S1 Stacking sequence

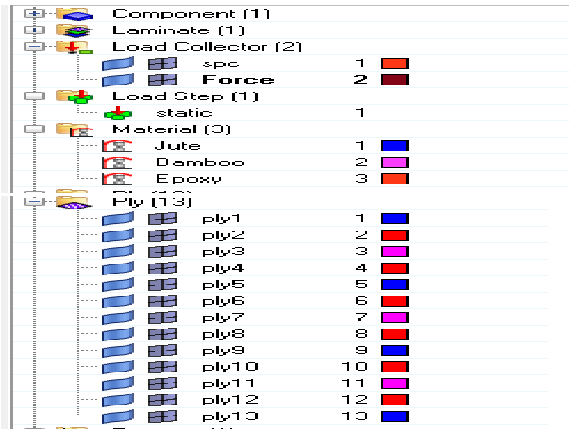

Fig. 16. Creating 13 plies for the stacking sequence S1

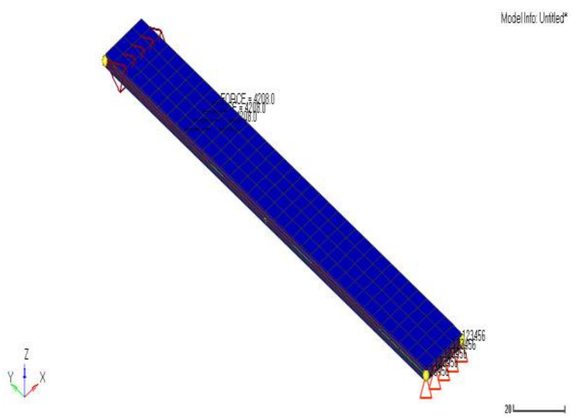

Fig. 17. Applying all the boundary conditions

Fig. 18. Pre-processing Process

3.5 SEM Analysis

It is a powerful investigating tool. The highly focused beam of electrons produces complex and large magnification images of the specimens to study fractured surface topology.

In this test, the Hitachi SU3500 SEM analyzing machine was used. It involves a low aberration objective lens. It offers a better bias function, providing a greater emissions current at low kV.

4. Results and Discussions

4.1 Experimental Results of Mechanical Properties

Fabricated woven hybrid bamboo and jute fiber composite specimens were subjected to a series of tensile and flexural tests.

The following results were obtained, and graphs were plotted.

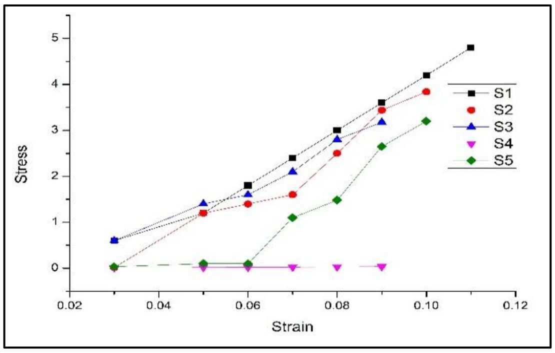

Fig. 19. Stress Vs.Strain curves for tensile test

Figure 19 shows the stress vs. strain curves of all stacking sequences of the tensile test. It is indicated that the S1 stacking sequence shows the highest stress and strain curves than theother. As the percentage of bamboo fiber decreases, the strength of the hybrid composite increases. The pure bamboo fiber composite shows the least strength compared to different sequences.

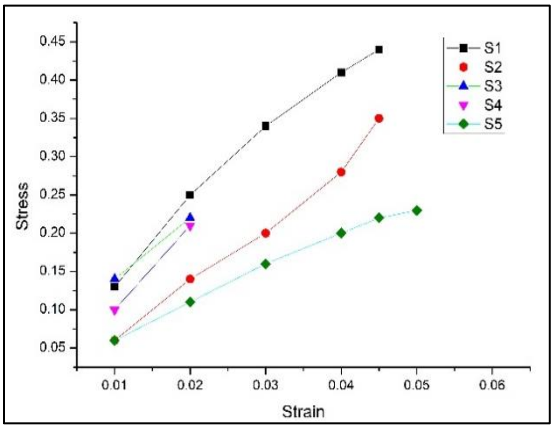

Fig. 20. Stress Vs. Strain curves for flexural test

Figure 20 shows the stress vs. strain curves for the flexural test. S1 sample flexural strength is more than that of the others. As the percentage of Jute fiber increases, the strength of the composite material increases.

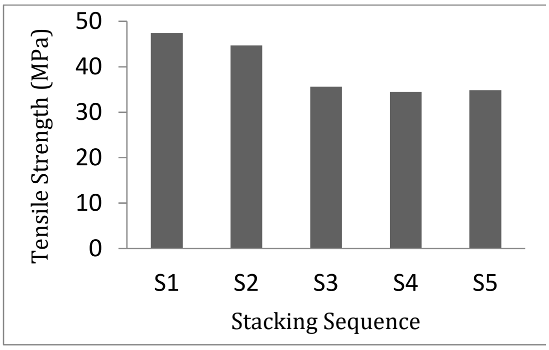

Fig. 21. Variation in specimen tensile strength with regard to stacking sequence

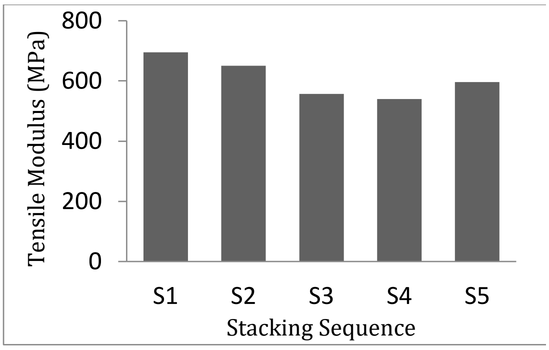

Fig. 22. Variation of tensile modulus of specimens with respect to stacking sequence

Figures 21 and 22 show how the composite specimens' stacking order impacts their tensile strength and modulus. It was observed that a substantial improvement in tensile strength and modulus in the combined sequence of Jute and Bamboo fibers in specimens S1, S2, and S3 in comparison with sequences of pure Bamboo and Jute in samples S4 and S5, respectively. A higher percentage of Jute fibers has shown an enhanced improvement in tensile strength, tensile modulus, ductility, and toughness in specimen S1 compared to all other hybrid composite specimens. It is observed that S1 offers the highest values of tensile strength (47.411MPa) and tensile modulus (695.44MPa) among all the composites. This is due to the alternative arrangements or positioning of the Jute and Bamboo fibers.

Figures 23 and 24 show the variation of flexural strength and flexural modulus with respect to the stacking sequence of composite specimens. The highest flexural strength value is 80.25MPa, and flexural modulus 9.065 GPa is found for hybrid composite S1. The lowest flexural strength values are 58.19MPa and flexural modulus 6.75 GPa found in S4 and S5 specimens that are pure bamboo and Jute fiber composites. This is due to the position of Jute fibers at the ends, and as the percentage of Jute fibers increases, the flexural strength and flexural modulus increase. As the percentage of bamboo fiber increases, there will be poor resistance to flexural load.

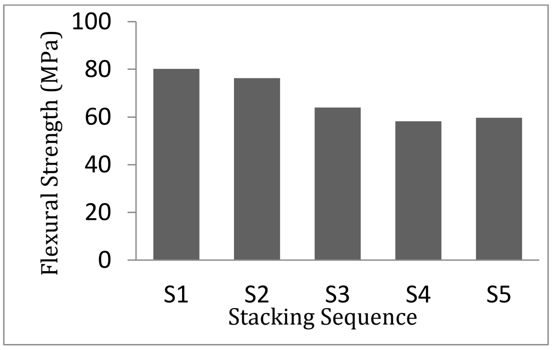

Fig. 23. Flexural strength of specimens varies according to the stacking order.

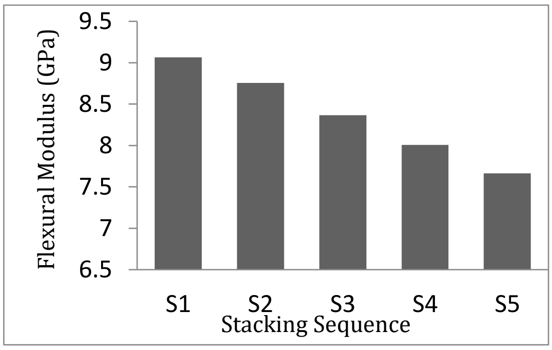

Fig. 24. Variation of specimen flexural modulus with reference to stacking patterns

4.2 FEA Analysis of Tensile Test For All Stacking Sequences

Figure 35 indicates the post-processing results of the composite. The maximum stress for all the stacking sequences is represented in Figures 25, 27, 29, 31, and 33. The numerical analysis was carried out for the maximum experimental loading conditions, and the results were obtained. Maximum displacement for all the stacking sequences is shown in Figures 26, 28, 30, 32, and 34. The results were tabulated.

4.3 Comparative Study and Analysis of Tensile Test Results

The properties were obtained experimentally and validated by conducting FEA analysis on each specimen S1 to S5. The experimental and FEA analysis results were tabulated in Table 4. Figure36 compares the tensile strength results from experimental and numerical analysis, and Figure37 plots the displacement curves for various stacking sequences.The study showed that the FEM results differed by more than 10% from the experimental results. This deviation is due to several reasons. The weaving nature of the reinforcements leads to nonuniform property distribution. Since the hand layup method is adopted for the fabrication process, it is difficult to achieve consistent epoxy dispersion, and microvoids may be developed.

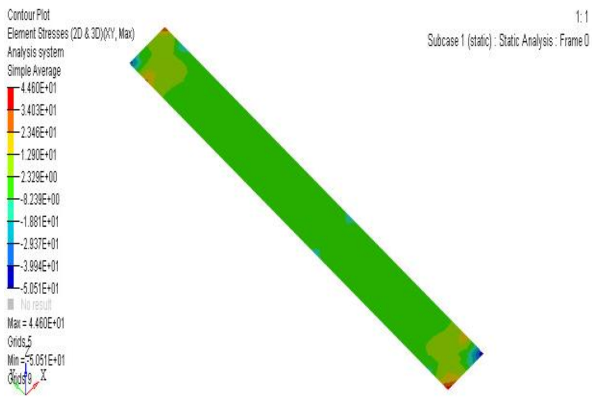

Fig. 25. Maximum stress in XY for the S1 Sample

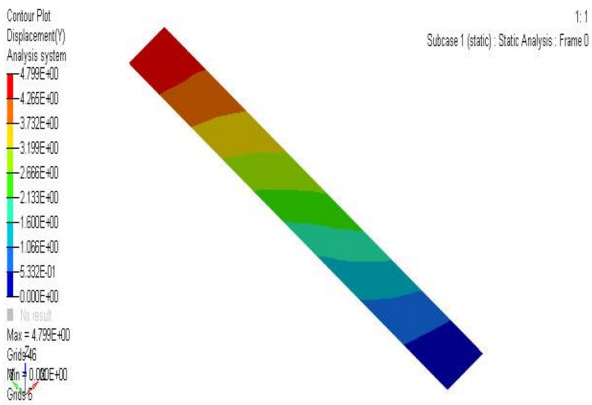

Fig. 26. Maximum displacement in the Y direction for the S1 sample

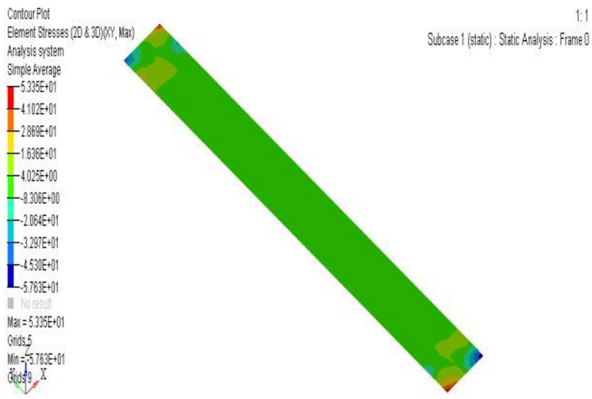

Fig. 27. Maximum stress in XY for the S2 Sample

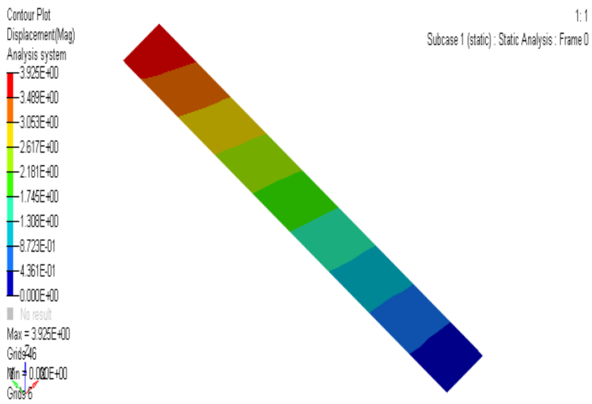

Fig. 28. Maximum displacement in the Y direction for the S2 sample

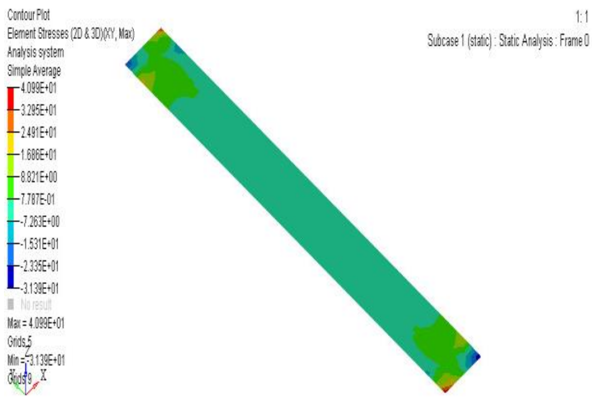

Fig. 29. Maximum stress in XY for the S3 Sample

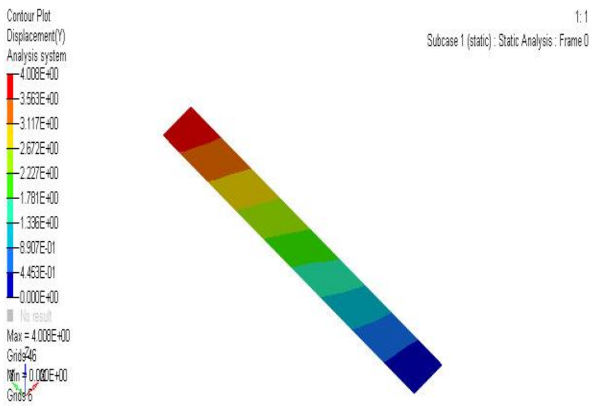

Fig. 30. Maximum displacement in the Y direction for the S3 sample

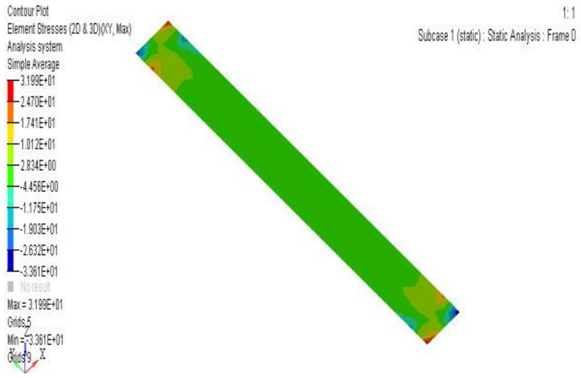

Fig. 31. Maximum stress in XY for the S4 Sample

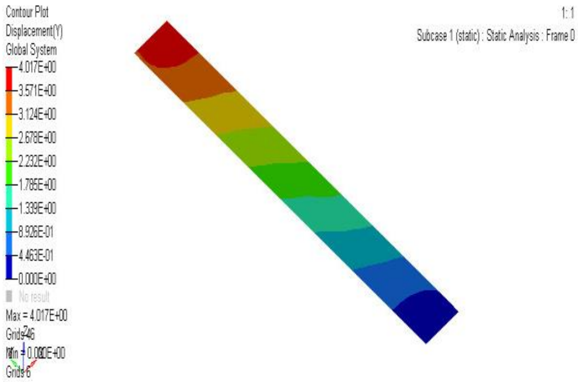

Fig. 32. Maximum displacement in the Y direction for the S4 sample

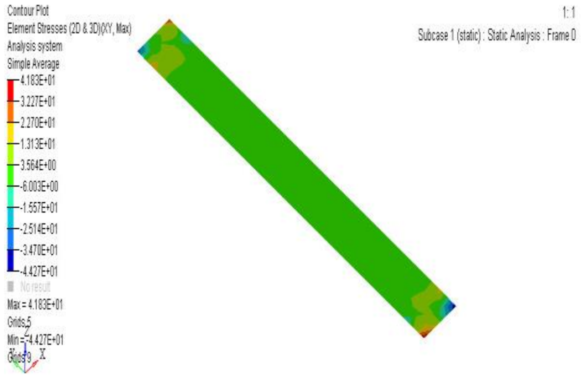

Fig. 33. The maximum stress in XY for the S5 Sample

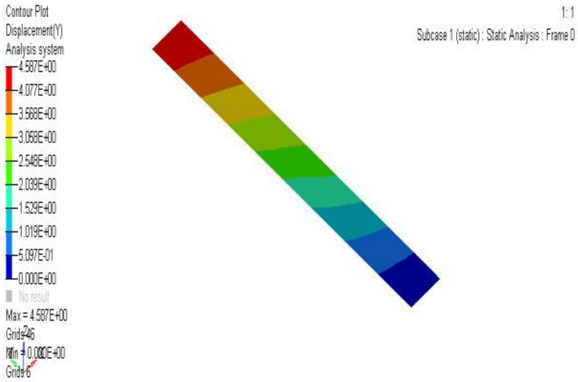

Fig. 34. Maximum displacement in the Y direction for the S5 sample

Fig. 35. Post-processing results of tensile testof all the stacking sequences

Table 4. Experimental and numerical analysis results

Sample Number	Stress MPa			Displacement mm		
	Experimental	FEA	% error	Experimental	FEA	% error
S1	47.411	44.6	5.93	4.99	4.79	4.01
S2	44.68	53.35	19.40	4.82	3.92	18.67
S3	35.63	40.99	15.04	4.625	4.06	12.22
S4	34.5	31.99	7.28	4.34	4.01	7.60
S5	34.805	41.83	20.18	4.69	4.58	2.35

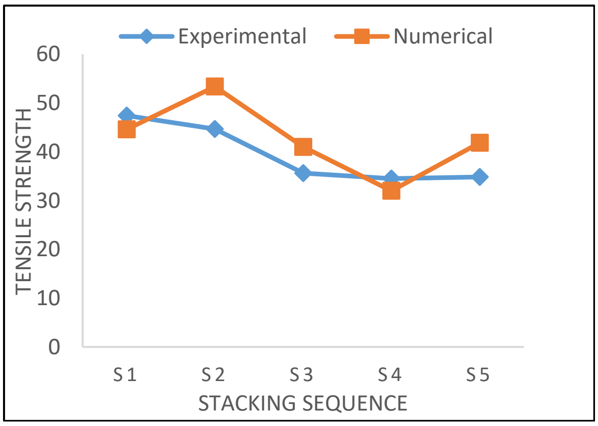

Fig. 36. Comparative study of tensile strength results with respect to stacking sequences.

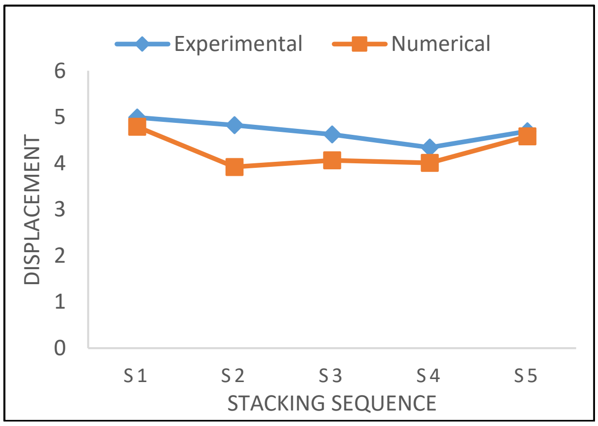

Fig. 37. Comparative study of displacement results with respect to stacking sequences.

4.4 SEM Analysis of Tensile Fracture Specimens

Tensile fractured surfaces of the composite specimens S1, S2, and S3 are analyzed through SEM analysis and are shown in Figures 38, 39, and 40, respectively. It was found that surfaces indicate some defects and fiber pull-out due to improper bonding.

As the percentage of the matrix increases, i.e., S1 stacking sequence with 70% matrix, the resin is uniformly distributed, and defects are less compared to S2 and S3.

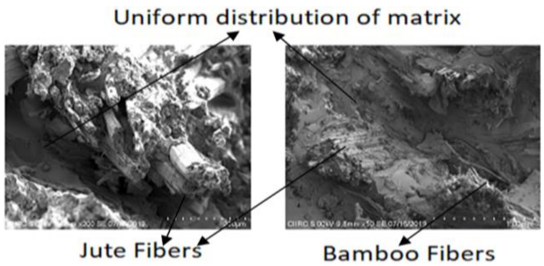

Fig. 38. Tensile test fractured SEM images of S1 specimen (10% B and 20% J)

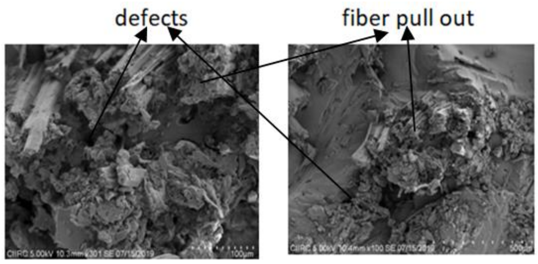

Fig. 39. Tensile test fractured SEM images of S2 specimen (15% B and 15% J)

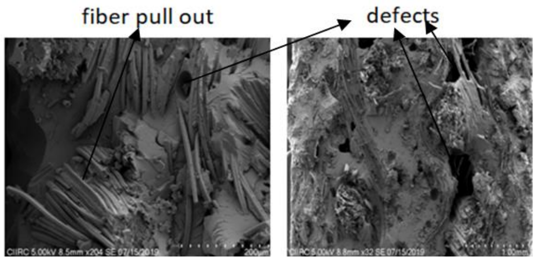

Fig. 40. Tensile test fractured SEM images of S3 specimen (20% B and 10% J)

4.5 Flexural Test Analysis

Similarly, the flexural test is carried out using the commercial software Hypermesh 14. The fundamental material properties of composites would be experimentally assessed through material or mechanical characterization. The general procedure is already explained, and the same methodology is adopted for the flexural test. The same type of element and material properties are used for the analysis. The flexural load obtained experimentally is applied. The contour plot results are shown in Figure51.

The von Mises stresses are one of the most important factors in the FEA model, and they were analyzed as shown in the Figures. It depicts the intricate stress distribution for the composite material, fiber, and interphase. It shows the level of stress in the fiber matrix regions. Figures 41, 43, 45, 47, and 49 show each stacking sequence's von Mises stress generated. For all the stacking sequences, the maximum displacement is found at the center of the applied loading condition, as shown in Figures 42, 44, 46, 48, and 50.

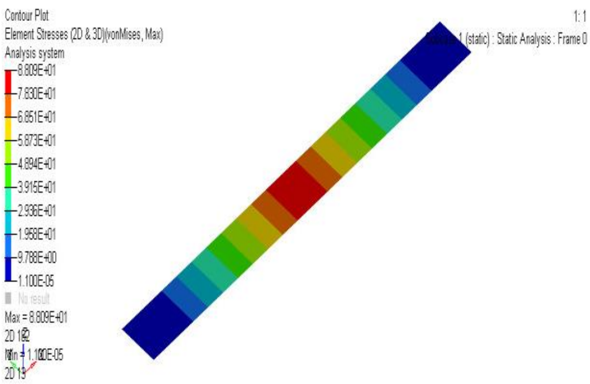

Fig. 41. Maximum Von Mises stress for the S1

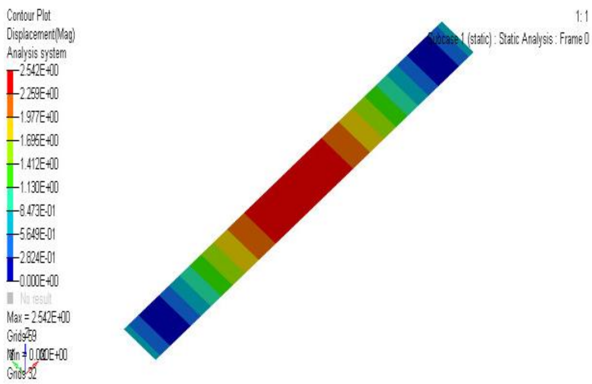

Fig. 42. Maximum displacements for the S1 Sample.

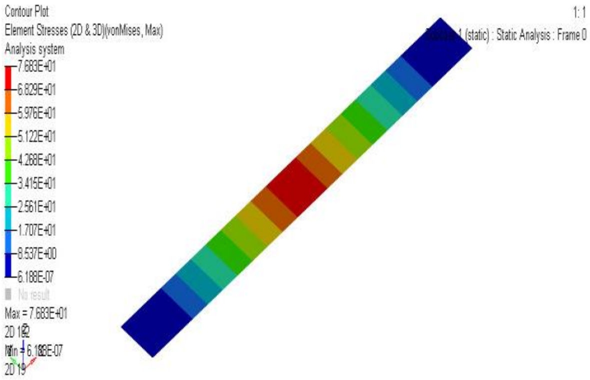

Fig. 43. Maximum von Mises stress for the S2 Sample.

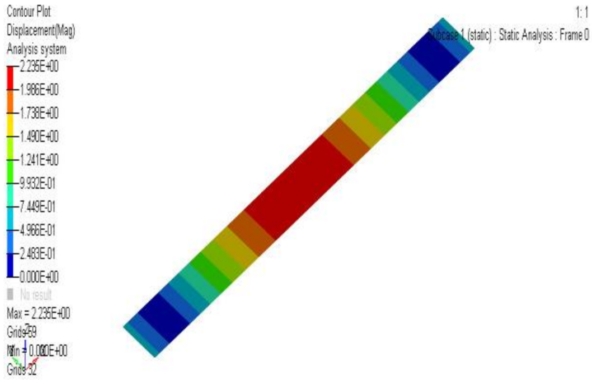

Fig. 44. Maximum displacements for the S2 Sample.

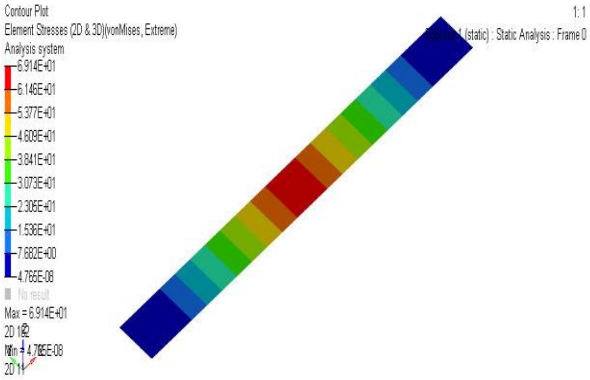

Fig. 45. Maximum von Mises stress for the S3 Sample.

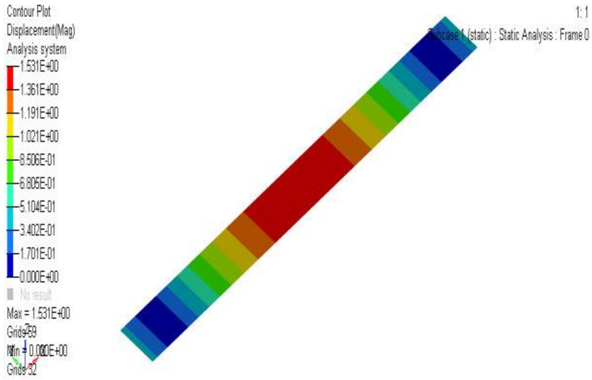

Fig. 46. Maximum displacements for the S3 Sample.

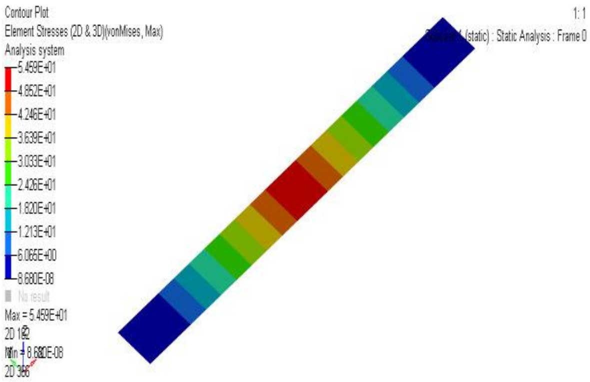

Fig. 47. Maximum von Mises stress for the S4 Sample

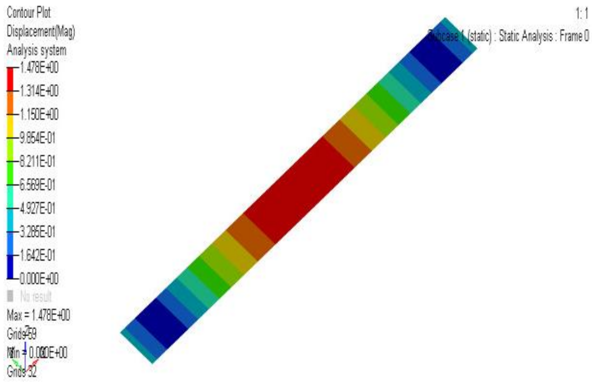

Fig. 48. Maximum displacements for the S4 Sample.

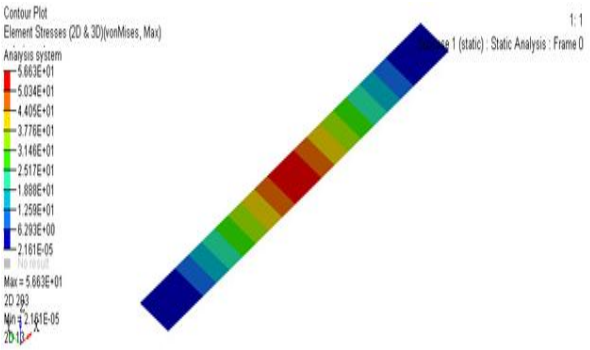

Fig. 49. Maximum von Mises stress for the S5 Sample.

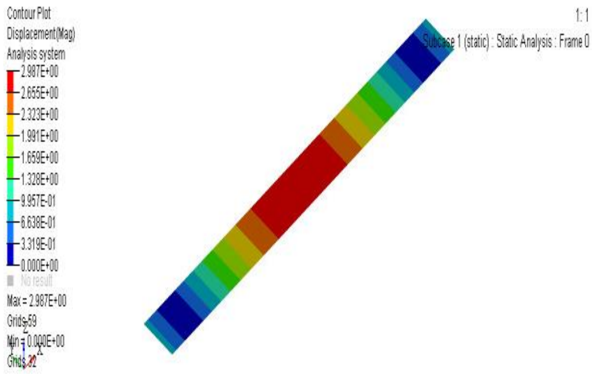

Fig. 50. Maximum displacement for the S5 Sample.

Fig. 51. Contour plots of the flexural test for all the stacking sequences.

4.6 Comparative Study of Flexural Test Results

The experimental and numerical analysis results were tabulated in Table 5. A comparison of von Mises stress results is presented in Figure 52, and the displacement curves for different stacking sequences are plotted in Figure 53.

The properties obtained experimentally are validated by conducting FEA analysis on each specimen S1 to S5. Comparing the experimental and numerical results, it is observed that both are in close proximity with a slight deviation of FEA results.

The experimental results and the FEM simulations diverged by more than 10%. The weaving nature of reinforcements, microvoids caused by the hand layup manufacturing method, and the potential for delamination in an actual experimental model were the causes of this discrepancy. Epoxy was manually distributed using a roller during hand layup, making it hard to create an even distribution of epoxy.

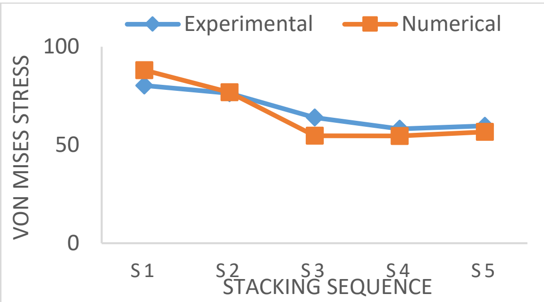

Fig. 52. Comparative studies of Von Mises stress results

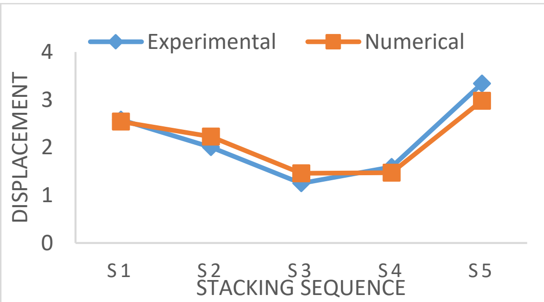

Fig. 53. Comparative studies of displacement results

4.7 SEM Analysis of Bending Test Specimens

SEM analysis of flexural tested composite specimens S1, S2, and S3 are shown in Figures 54, 55, and 56, respectively. Again, surface defects and fiber pull-out due to improper bonding were observed.

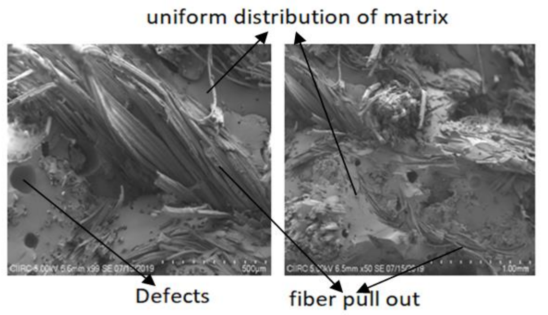

Fig. 54. Flexural test fractured SEM images of S1 Specimen (10% B and 20% J)

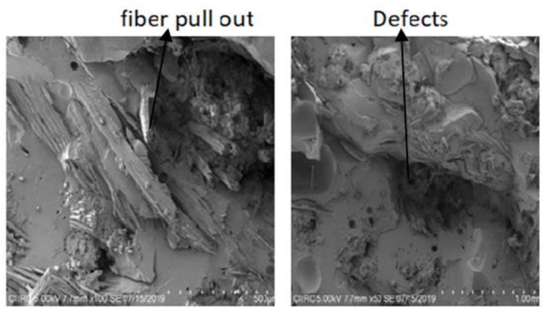

Fig. 55. Flexural test fractured SEM images of S2 Specimen (15% B and 15% J)

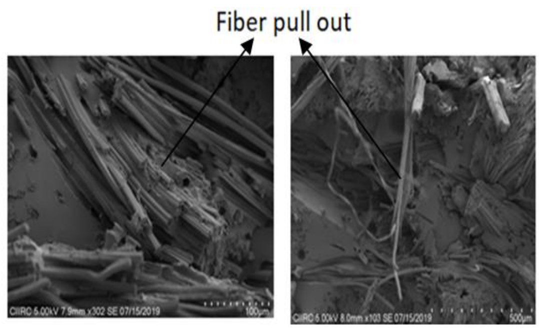

Fig. 56. Flexural test fractured SEM images of S3 Specimen (20% B and 10% J)

Table 5. Experimental and numerical analysis results

Sample Number	Stress MPa			Displacement mm		
	Experimental	FEA	% error	Experimental	FEA	% error
S1	80.25	88.09	9.77	2.58	2.54	1.55
S2	76.25	76.83	0.76	2.01	2.23	10.95
S3	64.00	54.75	14.45	1.25	1.46	16.80
S4	58.19	54.59	6.19	1.59	1.47	7.26
S5	59.75	56.63	5.22	3.34	2.98	10.78

5. Conclusions

The effect of stacking sequences with different hybrid configurations was investigated experimentally and numerically. In this study, it can be proved that the mechanical properties of hybrid composites can be improved by changing the stacking sequences of the laminates of the hybrid composite.

The study has drawn the following conclusions:

- Hybrid fibers treated with NaOH solution exhibit significant improvement in fiber-matrix adhesion.
- The tensile strength of composite with stacking sequence S1 exhibits the highest value compared to S2, S3, S4, and S5 laminates.
- The maximum Modulus of elasticity found in the S1 sample is 695.44Mpa.
- Further, the bending strength of the S1 sequence specimen was higher compared to the other S2, S3, S4, and S5 laminates stacking sequences.
- The highest flexural modulus was found to be 9.065GPa in S1 laminate.
- FEA study reveals that there is a need to have certain assumptions for perfect bonding.
- Comparing experimental and numerical results, it was observed that both are near a slight deviation of FEA results with experimental values.
- SEM investigation revealed the composite's interface breakdown between the textiles' layers.
- The S1 stacking sequence composition can be employed for car body parts. Construction helmets, army helmets, car helmets, skateboards, etc.
- In the future, the Fracture toughness properties can further be evaluated for better application suggestions
- It can also be extended for more applications in the aerospace and automobile industries.

Nomenclature

FEA	Finite Element Analysis
NaOH	Sodium Hydroxide
BF	Bamboo Fiber
JF	Jute Fiber
UTM	Universal Testing Machine
ASTM	American Society for Testing and Materials
NFC	Natural Fiber Composites

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Conflicts of interest

The authors have no conflicts of interest to declare.

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