

Experimental Investigation of Natural/Synthetic Hybrid Fiber Reinforced Composites for Optimum Material Selection Using COPRAS Method

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ABSTRACT

The current study conducts an experimental investigation of material selection for specimens prepared from various percentages of weight of sisal fibers (SFs) as natural fibers and glass fibers (GFs) as synthetic fibers with different stacking sequences and fiber directions to select the optimum material with the lowest density and water absorption content and the highest damping, flexural strength, and interlaminar shear strength (ILSS). Eight laminated composite materials comprised of natural fibers such as sisal fibers and synthetic fibers such as glass fibers are created using the hand layup technique. The material selection problem is solved using complex proportional assessment (COPRAS) based on measuring multiple criteria weights using the CRITIC approach. Five competing criteria, including density, water absorption content, damping, flexural strength, and ILSS, are measured to select the optimal laminated composite material. The findings demonstrated that material No. 6 of stacking sequences [RGF/ RGF/BGF/ RGF/BGF/RGF/ RGF] is the best option, whereas material No. 1 of stacking sequences [SF0/SF90/RGF/BGF/RGF/SF90/ SF0] is the worst.

1. Introduction

In a thorough review work, Fasikaw et al. [1] looked at artificial intelligence's potential uses for predicting the mechanical characteristics of various composite materials. The theoretical basis, advantages, and disadvantages of each technique for forecasting various mechanical properties of composites were also discussed. A computer implementation for an efficient selection of composite materials dependent on performance indices to describe the behavior of the material as well as selecting material charts on which the material characteristics could be plotted were also described by Edwards et al. [2]. The algorithm used

bounds to identify the envelope of characteristics attainable to a given material. Garima Tripathi [3] researched the present status of composites use within the industry and moved toward the future trend of composite material with its benefits, drawbacks, and uses in machinery for industry. An outline of the fiber matrix interface and interfacial properties was provided by Huang et al. [4]. The methods for quantifying interfacial characteristics, describing the morphology and chemical makeup of the interface, and running numerical simulations on the FRP interface were then provided. To learn more about the functional differences between naturally aged glass reinforced concrete (GFRC) and polypropylene fiber-reinforced concrete (PPFRC),

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Yuan and Yanmin conducted a study [5]. In comparison to the PPFRC after 28 days of curing, the interfacial bonding between the cement matrix and polypropylene fiber (PPF) showed essentially no change after 3 years of curing. Alamry and Andriyana [6] investigated concepts related to present-day multifunctional composites. According to the study's findings, multifunctional nanoparticle-based composite materials could be utilized to build durable but lightweight airplane wings and electric self-driving car structures. Yellamelli et al.'s [7] study examined the flexural and tensile tests of hybrid synthetic fiber composites made of E-Glass and carbon fibers bound together with epoxy resin. Using a dynamic analysis, natural mode shapes and frequencies for various stacking sequences were discovered. Gupta et al. [8] developed porous asphalt mixtures using five distinct sorts of additions and compared its performance with virgin and polymer-modified bitumen. It came out that bitumen treated with polymers did not perform as well as aramid pulp did, whereas cellulose fiber excelled in the area of sustainability. The physical and mechanical characteristics of short Entada mannii-glass fiber polypropylene hybrid composites, which were created by compressing different ratios of Entada mannii fiber (EMF) to glass fiber (GF), were examined by Oluwayomi et al. [9]. All hybrid composites had significantly improved tensile, compressive, impact, and hardness properties. Rikards and Chate [10] proposed a numerical-experimental planning technique for determining the mechanical properties of laminated polymeric composites based on experimental results. The calculation of the identification function could be significantly reduced as compared to typical minimizing methods. An overview of recent developments in the dynamic as well as static sensitivities of composite structures to quasi-static loads and low velocity impacts was given by Azzam and Li Wei [11]. High-performance fiber composites' impact response was assessed. Through the use of both mathematical and experimental methods, Kastratović et al. [12] examined the mechanical characteristics of glass fiber strengthened epoxy composite pieces with different fiber orientations. A Finite Element (FE) model had been built. An excellent basis for upcoming improvements to the FE model was given by the strong agreement across experimental and numerical data. Djordjevic et al. [13] examined the use of multi-criteria decision making (MCDM) to select materials for shafts that

were made from composites. Incorporating hybrid materials, besides improving performance, might complicate material selection decisions. Giridharan [14] used epoxy resin, ramie fibers, and E-glass to build composite materials using hand layup method. Two weight percentages were hybridized in fiber-reinforced composites. The hybrid fiber strengthened epoxy composites outperformed the individual samples in terms of mechanical performance. A brief beam shear bending test was performed by Selmy et al. [15] to examine the interlaminar shear performance of epoxy hybrid composites supplemented with random (R) and unidirectional (U) glass fiber. Five plies ([R]₅ and [U]₅) were utilized to construct hybrid as well as non-hybrid laminates using hand layup. As compared to [R]₅ composites, the results indicated that [U]₅ had a greater ILSS. Moreover, the ILSS of hybrid composites was higher than that of random composites. Dipen et al. [16] conducted a review of the current status of synthetic fibres in various reinforced composites. The classifications, uses, and properties were largely determined by their physical and mechanical qualities, as well as the synthesis method. For the purpose of solving the material selection problem, Seyed and Alireza [17] presented an easy and comprehensive MCDM-based framework. After reviewing over 100 scholarly works, COPRAS and TOPSIS were selected to address the material selection problem in general.

Huang and Hongxia [18] created laminates composed of glass fibre textiles and unsaturated polyester. After being submerged in water at a temperature of around 30°C for various amounts of time, the composites' tensile strength decreased significantly, while their bending strength increased. To guarantee a decent dispersion of rice straw, Ali-Eldin et al. [19] created a new mat of random rice straw fiber. Rice straw fiber mat was used to strengthen polyester in the creation of hybrid composites. By alternating four layers of the generated rice straw fiber mats with random glass fiber layers of varying areal densities, six distinct stacking sequences were created. These hybrid composites' tensile, flexural, shear, impact, and water absorption characteristics were examined. The inclusion of the glass fibers enhanced the composites' mechanical qualities. A sheet of random rice straw fiber was created by Megahed et al. [20]. The polyester matrix was reinforced with these sheets of rice straw. Polyester composites reinforced with glass fibers and sheets of rice straw were synthesized and examined. Random glass fiber mats with varying areal densities were used to create a number of novel

stacking configurations. These composites' particular mechanical characteristics were examined. According to experimental results, rice straw fiber composites have superior specific tensile and flexural stiffness compared to glass fiber composites. Advanced analytical methods for the thorough characterization of synthetic (polymeric) and natural (cellulose-hemicellulose-lignin) fibers were reviewed by Zafar et al. [21]. The significance of an integrated strategy employing a range of analytical techniques for thorough fiber characterization was underlined by their review. The combined application of cutting-edge techniques yielded a more comprehensive understanding of fiber properties, but traditional wet chemical procedures gave few benefits. The suitability of asparagus bean stem (ABS) for reinforcement in polymer matrices was examined by Tengsuthiwat et al. [22]. After extraction using a water-retting method, a 5% alkali solution was used for treatment. Following chemical treatment, the fiber density rose to 1.13 g/cm³ and the cellulose content was increased to 65 weight percent. Increased surface roughness and impurity reduction were revealed by morphological examination. The study's main goal was to show that ABS is a good substitute raw material for composite reinforcement that can be used to create lightweight structural applications. Eggshells were investigated by Ogundipe et al. [23] as a filler to improve the mechanical, thermal, and physical characteristics of the natural fiber-reinforced epoxy composite. In order to determine the impact of fillers on the overall properties of the composite, the properties of natural fiber-reinforced composites were examined both with and without fillers. Because of its availability, affordability, biodegradability, and ability to reduce landfill pollution, eggshell was chosen as a filler material. The tensile strength of carbon fiber, jute fiber, and carbon fiber composite hybridization was examined by Maithil et al. [24]. Their main goal was to increase the tensile strength of composite materials by mixing synthetic and natural fibers. To evaluate the tensile performance, a hybrid polymer composite reinforced with carbon and jute fiber was numerically built. It was discovered through experimental analysis of the composite laminate of the various materials that surface treatment of the fiber might enhance the binding between the fiber and matrix. The results show that the hybrid fiber-reinforced composite material has a higher tensile strength than jute fibers. Using a sandwich-type composite of bamboo and jute fibers, Surappa et al. [25] created, examined, and evaluated the tensile behavior of a composite material. The outcomes were examined and contrasted with the bamboo fiber and epoxy resin

composite. According to the experimental results, hybrid composites had values that were noticeably higher than those of monolithic composites. The work's main goal was to determine how jute fiber affected the tensile characteristics of a hybrid composite reinforced with jute and bamboo. Using the representative volume element used in ANSYS, Gupta et al. [26] created a hybrid laminate of glass fiber and jute with polyester resin. A variety of glass and jute fiber volume fractions were used to construct the composite material's three-dimensional microstructure. Following that, the simulation-based effective elastic property was confirmed by the results of the current experiment, which demonstrated good agreement, and the effective elastic properties of glass fiber/polyester, jute fiber/polyester, and hybrid jute/glass fiber and polyester as matrix were assessed. Their research would provide valuable insight into how incorporating glass fiber into jute fiber could improve its mechanical qualities. Faridul et al. [27] compared the morphological characteristics of natural hemp-woven fabrics and synthetic glass-woven fabrics before and after tensile stresses. Additionally, the items' better mechanical performances were demonstrated by their mechanical tensile qualities (both flexural and tensile). Using TGA (thermogravimetric analysis) and DTG (derivative thermogravimetry) analysis, the products' thermal stability was also evaluated. It was discovered that glass fiber reinforced composites were more stable than hemp. The outcomes of the composite materials that were created amply demonstrated the notable distinctions between the two kinds of woven textiles. In their publication, Dias et al. [28] aimed to demonstrate the latest developments in the study of nanoclay-infused natural/synthetic hybrid composites, as well as the diverse manufacturing methods tried by various academic authors, their results, and test-driven conclusions. It became clear from their review that a range of sectors may use composite materials loaded with nanoclay. Because they are more lightweight and durable than standard metals or composites, these nanoclay-infused materials may eventually replace them. The hand lay up method was used by Wagh et al. [29] to create the laminated composite material. The reinforcement ingredients were glass fiber, jute fiber, hemp fiber, and sisal fiber, while the matrix material was epoxy resin with a hardener. The specimen was made using varying percentages of matrix and reinforcing components in accordance with ASTM specifications. Additionally, the mechanical characteristics of water absorption, tensile, flexural, and impact strength were

determined. A superior outcome was obtained by the specimen made from glass and jute fibers.

From the previous literature review, it has been noted that there is a lack of research work concerning hybrid natural/synthetic fibers. Therefore, composite materials composed of hybrid natural/synthetic fibers exhibit greater variety in characteristics, necessitating further investigation. Therefore, the present work represents an experimental investigation of material selection for specimens manufactured by hand layup process. The manufactured specimens are prepared from various percentages of weight of SFs and GFs with different stacking sequences and fiber arrangement in order to select the optimum material with the lowest density and water absorption content and the highest damping, flexural strength, and ILSS. To choose the best laminated composite material, five competing factors are evaluated: density, moisture content, damping, flexural strength, and interlaminar shear strength. The material selection problem is solved using COPRAS, which measures several criteria weights using the CRITIC technique.

2 Methodology

2.1 CRITIC Weight Measurement Method

CRITIC approach is to be used to calculate the objective weights of the relative relevance of replies in MCDM settings. When selecting weights, both contrary intensity and conflict, which are included in the structure of the choice problem, are taken into account. A multi-attribute decision-making (MADM) issue is designed to generate a decision matrix represented by Eq. (1) by comparing each alternative to a specified set of n attributes. [30]

$$[U]_{m \times n} = (u_{ij})_{m \times n} = \begin{bmatrix} u_{11} & u_{12} & \dots & u_{1n} \\ u_{21} & u_{22} & \dots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{m1} & u_{m2} & \dots & u_{mn} \end{bmatrix} \quad (1)$$

Eqs. (2, 3, 4 and 5) are used for calculating the weights of responses utilizing CRITIC method as reported in Ref. [31]. Using Eqs. (5 and 6), the defined decision matrix u_{ij} is first normalized to produce all responses that change in the ranges between 0 and 1.

$$\rho_{ij} = \frac{u_{ij} - u_j^{worst}}{u_j^{best} - u_j^{worst}} \quad i = 1, 2, \dots, m; j = 1, 2, \dots, n \text{ for beneficial attributes} \quad (2)$$

$$\rho_{ij} = \frac{u_j^{best} - u_{ij}}{u_j^{best} - u_j^{worst}} \quad i = 1, 2, \dots, m; j = 1, 2, \dots, n \text{ for non beneficial attributes} \quad (3)$$

The symmetric matrix ($m \times m$) is developed through C_{jk} (the correlation between the responses) as indicated in Eq. (4). Then to calculate the weight of the criteria, Eq. (5) is used

$$C_{jk} = \frac{\sum_{i=1}^m (\rho_{ij} - \bar{\rho}_j)(\rho_{ik} - \bar{\rho}_k)}{\sqrt{\sum_{i=1}^m (\rho_{ij} - \bar{\rho}_j)^2 \sum_{i=1}^m (\rho_{ik} - \bar{\rho}_k)^2}} \quad j, k = 1, 2, \dots, n \quad (4)$$

$$w_j = \frac{\beta_j}{\sum_{k=1}^n \beta_k} \quad (5)$$

Where,

$$\beta_j = \sigma_j \sum_{k=1}^n (1 - C_{jk}); j = 1, 2, \dots, n \text{ and } \sigma_j = \sqrt{\frac{\sum_{i=1}^m (\rho_{ij} - \bar{\rho}_j)^2}{m}} \quad (6)$$

It is commonly recognized that the standard deviation σ_j indicates the degree of contrast between responses.

2.2. Multi Criteria Decision Making (MCDM) Methods

Multi-objective optimization is the process of optimizing two or more conflicting criteria (objectives) simultaneously under specific limitations. In this work, eight laminated composite materials selection problems are answered using COPRAS, which is based on measuring the different criteria weights utilizing the CRITIC methodology. To choose the best laminated composites, five conflicting criteria were measured: density, water absorption content, damping, flexural strength, and interlaminar shear strength (ILSS).

2.2.1 COPRAS Method

COPRAS preference ranking approach was developed by Zavadskas et al. [32]. In this procedure, the impact of maximizing and minimizing criteria on the evaluation outcome is addressed independently. The greatest alternative is chosen after analyzing both perfect and anti-ideal answers. The COPRAS method's primary process consists of multiple steps [33].

Step 1: Set the initial decision matrix, U.

The initial decision matrix was presented previously in Eq. (1).

Step 2: Apply Eq. (7) to normalize the choice matrix. the equation that follows:

$$[R] = [r_{ij}]_{m \times n} = u_{ij} / \sum_{i=1}^m u_{ij} \quad (7)$$

Step 3: The following equation should be used to determine the weighted normalized decision matrix, or D:

$$[D] = [y_{ij}]_{m \times n} = r_{ij} \cdot w_j, i = 1, \dots, m, j = 1, \dots, n \quad (8)$$

where w_j is the weight of the j -th criterion determined using the CRITIC weight technique, and r_{ij} denotes a normalized performance value for the i -th alternative on the j -th criterion. Every criterion's weight is always equal to the total of its weighted normalized values:

$$\sum_{i=1}^m y_{ij} = w_j \quad (9)$$

Step 4: In this stage, the following equations are used to obtain the sums of weighted normalized values for both the favorable and non-beneficial criteria:

$$S_{+i} = \sum_{j=1}^n y_{+ij}, S_{-i} = \sum_{j=1}^n y_{-ij} \quad (10)$$

where the weighted normalized values for the non-beneficial and beneficial criteria are, respectively, y_{+ij} and y_{-ij} .

Step 5: Use the following equation to get the relative significances of the options, Q_i :

$$Q_i = S_{+i} + \frac{S_{-min} \cdot \sum_{i=1}^m S_{-i}}{S_{-i} \cdot \sum_{i=1}^m (S_{-min}/S_{-i})}, i = 1, \dots, m \quad (11)$$

where S_{-min} represents the lowest value of S_{-i} .

Step 6: Use the following equation to calculate the quantitative utility, or Z_i , for the i -th alternative:

$$Z_i = \frac{Q_i}{Q_{max}} \quad (12).$$

where Q_{max} stands for the highest value of relative significance. Utility ratings range from 0 to 1 for candidate alternatives. The alternative is given greater priority the higher its value (Z_i).

3 Experimental Work

3.1. Fabrication of composite materials

The hand lay-up approach is the most basic form of composite processing. This method likewise requires minimum infrastructure. Figure (1) depicts natural fibers (sisal fibers) and synthetic fibers (glass fibers) as reinforcing phases in laminated composite materials. First, an open wooden mold measuring 200 mm x 150 mm x 12 mm is made for stacking and putting up seven piles of sisal and glass fibers to achieve a thickness of 12 mm. In the present work, the hand layup methodology is used to produce laminated composite plate of dimensions of 200 x 150 x 12 mm from which different specimens with different dimensions are utilized in static, dynamic and physical tests. The Random Glass Fibers (RGF) woven mat and bidirectional plain-woven glass fibers (BGF) are cut into dimension of 200 mm x 150 mm. Every used ply has its weight measured. Over the open wooden mold's surface, the fabrication is done. To make the laminate easier to remove after curing, polishing wax is initially applied to the flat surface.



Figure (1): Natural fibers (Sisal Fibers) and Synthetic fibers used in fabrication laminated composite materials

The liquid polyester resin is completely mixed with a prescribed hardener (curing agent) and poured onto the surface of the first layer of RGF woven mat, bidirectional plain-woven glass fibers, or Sisal fibers that has previously been inserted in the mold. The polyester is distributed evenly with a brush. After applying the second layer to the polymer surface, any leftover polymer and trapped air are gently pushed through the mat-polymer layer with a roller. This process is repeated for every layer until all required layers are stacked to create the final 200 x 150 x 12 mm laminated plate. After 24 hours of drying at room temperature, the formed composite part is removed from the mold and sliced into various specimens of varying sizes for further testing.. Table 1 shows the various stacking sequences and composite ingredient weight percentages for the eight laminated composites manufactured. Figure (2) depicts the steps involved in the hand layup method while Figure (3) shows the eight laminated composite plates soon after they were removed from the mold. Table 2 and Table 3 lists the different properties and specifications of the composites' constituents and the composite materials taking into consideration the weigh fraction of glass fibers, sisal fibers and polyester resin and using mixture ruleTable 2 and Table 3 lists the different properties and specifications of the composites' constituents and the composite materials taking into consideration the weigh fraction of glass fibers, sisal fibers and polyester resin and using mixture rule.

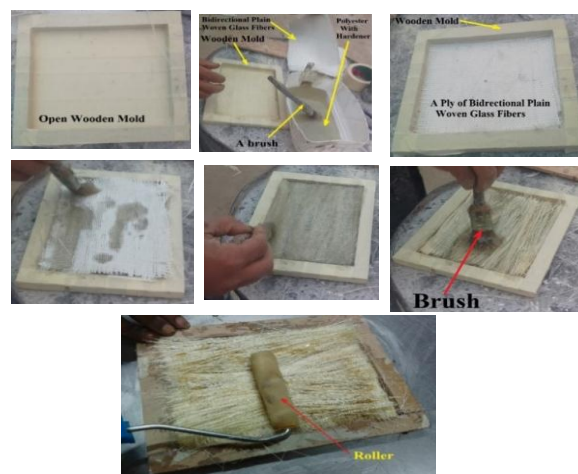


Figure (2) Procedures of Hand Layup Method



Figure (3) Eight Laminated composite plates Manufactured by hand layup methodology

Table 1: composite laminates with the specified stacking sequences

Alternatives (Materials)	Stacking Sequences	Sisal Fiber (SF) wt.% content	Glass Fiber (GF) wt.% content	Polyester wt.% content
M 1	[SF ₀ /SF ₉₀ /RGF/BGF/RGF/SF ₉₀ / SF ₀]	8.511	9.574	81.915
M 2	[BGF /SF ₀ /SF ₉₀ / SF ₀ /SF ₉₀ /SF ₀ / RGF]	11.628	6.977	81.395
M 3	[BGF/RGF/SF ₀ /SF ₉₀ /SF ₀ /RGF/BGF]	6.897	13.793	79.31
M 4	[SF ₀ /SF ₉₀ /SF ₀ /RGF/SF ₀ /SF ₉₀ /SF ₀]	12.632	3.158	84.211
M 5	[RGF/SF ₀ / RGF/RGF/ BGF/SF ₀ / RGF]	4.938	18.519	76.543
M 6	[RGF/ RGF/BGF/ RGF/BGF/RGF/ RGF]	0	25	75
M 7	[BGF/BGF/RGF/SF ₀ /RGF/RGF/BGF/]	2.062	18.557	79.381
M 8	[SF ₀ /SF ₉₀ / SF ₀ /SF ₉₀ / SF ₀ /SF ₉₀ / SF ₀]	17.5	0	82.5

Table 2: Properties of composite constitutes

Fibers and polyester	Density, gm/cm ³	Poisson Ratio	Modulus elasticity, Mpa	Tensile strength, Mpa	Fractur strain
Glass fibres (GF)	2.58	0.2	72500	2975	0.034
Sisal fibres (SF)	1.46	0.32	8060	323.32	0.0494
Polyester (PE)	1.09	0.33	3300	40	0.01

Table 3: Properties and specifications of composite materials

Composite materials	Density, gm/cm ³	Poisson Ratio	Modulus elasticity, Mpa	Tensile strength, Mpa	Fractur strain
M1	1.2641	0.3167	10330.6383	345.1230	0.0157
M2	1.2370	0.3198	8681.3953	277.7116	0.0163
M3	1.3210	0.3114	13173.1034	464.3669	0.0160
M4	1.1838	0.3246	6086.5263	168.4720	0.0157
M5	1.3842	0.3054	16349.8765	597.5096	0.0164
M6	1.4625	0.2975	20600.0000	773.7500	0.0160
M7	1.3741	0.3057	16239.3814	590.4808	0.0153
M8	1.1548	0.3283	4133.0000	89.5810	0.0169

3.2 Static Tests

3.2.1 Three-Point Flexural Test

A composite's flexural strength is the highest tensile stress it can endure while bending before breaking. In the bending flexural test, a specimen is put under uniaxial bending stress (tension and compression) to gain information on material bending behavior. Flexural strength, for example, is measured during a bending test. A standardized specimen is installed on the two supporting pins of a universal testing machine to accomplish this according to ASTM D2344. As the load increases, a loading pin positioned centrally bends the specimen. The three-point flexural test, named after the three pressure points at the pins, determines the flexural strength ($\sigma_{bending}$) in MPa of all test specimens using Eq. (13) [34].

$$\text{Flexural Strength}(\sigma_{bending}) = \frac{3P_{max}L}{2bt^2} \quad (13)$$

where Pmax is the maximum load (N), L is the specimen's span length (mm), b is its width (mm), and t is its thickness (mm). The test specimens are 200 × 30 × 12 mm in size. The cross-head speed of 10 mm/min and the span length of 180 mm are kept constant. The three-point bend test is performed on all composite samples using a computer-controlled electro-hydraulic servo universal testing equipment (Model WAW 600) at the college of engineering, Benha University, Egypt. The Experimental setup for three-point bending test is shown in Figure (4). The flexural strengths of several composite materials are presented in Table 4. According to the flexural strength results and with the help of Eq. (13), material No. 6 has the maximum flexural strength (606.25 MPa), whereas materials No. 1 and No. 2 have the lowest and equal flexural strengths (500 MPa).

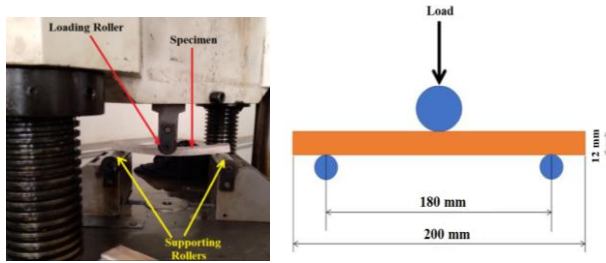


Figure (4) Experimental setup for three-point bending test

Table 4: Flexural strengths of composite materials

Alternatives (Materials)	P _{max} , Newton	Flexural Strength ($\sigma_{bending}$) MPa
M 1	8000	500
M 2	8000	500
M 3	9650	603.125
M 4	9600	600
M 5	8800	550
M 6	9700	606.25
M 7	9050	565.625
M 8	8500	531.25

3.2.2. Interlaminar shear strength (ILSS) test

The ILSS of laminated composites was determined using the short-beam method. The ILSS of laminated composites is determined using Eq. (14), which is based on beam theory [35].

$$ILSS(\tau_{max}) = \frac{3P_{max}}{4bt} \quad (14)$$

The ILSS, or short beam shear strength (MPa), is represented by τ_{max} in this equation, along with the highest force recorded during the test P_{max} , b, the specimen width (mm), and t, the specimen thickness. Test specimens with dimensions of 200 × 30 × 12 mm were employed according to ASTM D2344. Both the cross-head speed of 10 mm/min and the span length of 110 mm are holding steady. This test is carried out on all composite samples at Benha University's engineering faculty utilizing a computer-controlled electro-hydraulic servo universal testing machine (Model WAW 600). Figure (5) depicts the experimental configuration for short beam shear strength testing. The ILSS is an important parameter and a primary designation that characterizes the interlaminar property of composite laminates. Because composite failures frequently occur at the interface, increasing interface bonding strength

becomes an important demand. Table 5 shows how the interlaminar shear strengths of various composite materials differ. According to the flexural strength values and using Eq. (14), material No. 7 has the highest interlaminar shear strength (23.13 MPa), whereas material No. 1 has the lowest interlaminar shear strength (16.46 MPa).

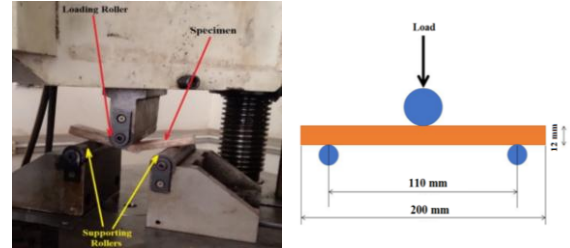


Figure (5) Experimental setup for short beam shear strength testing

Table 5: ILSS of composite materials

Alternatives (Materials)	P _{max} , Newton	ILSS (τ_{max}) Mpa
M 1	7900	16.46
M 2	9000	18.75
M 3	10850	22.60
M 4	9500	19.79
M 5	9450	19.69
M 6	11000	22.92
M 7	11100	23.13
M 8	8800	18.33

3.3. Experimental modal analysis (Dynamic Test)

The traditional strike approach is utilized for experimental modal characterization of degraded composites in order to retrieve modal characteristics from test materials. Figure (6) depicts the experimental setup, which includes a piezoelectric impact hammer, an accelerometer, and a data gathering system/software. The specimen has dimensions of 200 mm x 50 mm x 12 mm for free-free boundary condition. Elastic strings hold the test specimen to the fixture. An accelerometer that is placed at the specimen's center of geometry and wax-sealed to the specimen observed the response to the composite specimen being awoken at its center of geometry using a piezoelectric impact hammer. The accelerometer is coupled to a data collection system. The observed response is interpreted by data acquisition software to yield frequency, mode shapes, and damping values. To ensure that there are no errors in the experiment, the sample is excited five

times, and an average value is noted each time. The modal analysis software is used to study the frequency response function (FRF).

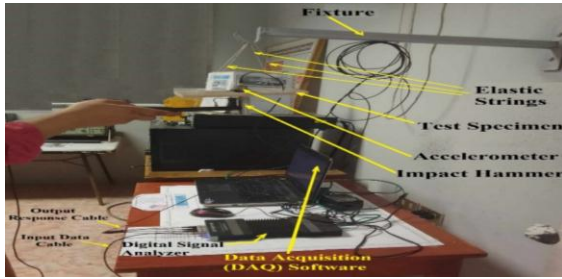


Figure (6) Experimental setup for modal testing

The modes found from modal analysis of composite laminates for the Free-Free boundary condition are the structure's inherent qualities. Modal parameters include natural frequency (ω_n), mode shape, and damping ratio (ξ). In the current study, the modal damping ratios and natural frequencies for the first four modes are calculated using the frequency response function of the modal testing findings, as shown in Figure (7). Figure (8) depicts the coherence function derived from modal testing for specimen No. 3, as an example. The coherence function shows a strong correlation between input and output signals as it approaches unity, implying trustworthy measurements of modal parameters. Table 6 demonstrates the changes in damping ratios for the first four modes of the eight laminated composite specimens. Concerning the first mode, which is an important mode indicating the structure's dynamic behavior, it is noted that material No. 8 has the largest damping ratio (6.78%), while material No. 7 has the lowest (2.6%).

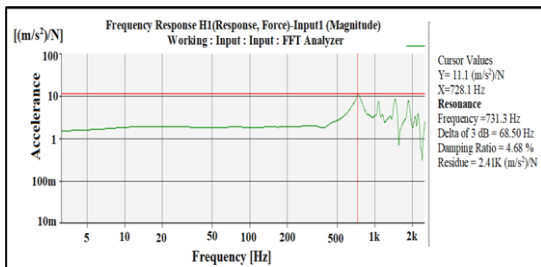


Figure (7). magnitude of FRF versus frequency

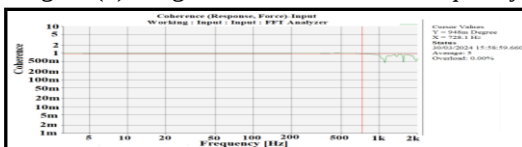


Figure (8): coherence function versus frequency

Table 6: Damping ratios for the first four modes of composite laminates

Alternatives (Materials)	Damping Ratio(ξ), %			
	ξ_1	ξ_2	ξ_3	ξ_4
M1	5.2	4.56	8.43	2.37
M2	4.85	3.82	3.35	1.874
M3	4.68	1.94	2.75	2.13
M4	4.54	6.67	3.5	2.02
M5	2.97	8.38	1.83	1.51
M6	6	5.7	1.98	2.08
M7	2.6	6.35	1.95	3.24
M8	6.78	5.98	2.14	3.89

3.4 Physical Tests

3.4.1 Water Absorption Test

Water absorption experiments are carried out on laminated composites, and the specimens' weights are determined prior to immersion in normal water. Following 49 days, the specimens were weighed. After removing the specimens from the damp surroundings, every trace of moisture was wiped away with a fresh, dry cloth. Within 1 minute of withdrawing the specimens from the damp environment, they are weighed again to the nearest 0.0001 g using a digital balance. Moisture absorption testing is used to determine the required quality of a composite specimen. As seen in Fig. (9), the moisture absorption test represents a gravity test technique that calculates the total mass change of a specimen subjected to a damp environment over time. The moisture content (%) of each test specimen is determined employing Eq. (15) [36].

$$\text{Moisture Content (\%)} = \left[\frac{m_2 - m_1}{m_1} \right] \times 100 \quad (15)$$

Where m_1 and m_2 represent the specimen's mass before and after immersion in water, respectively. Table 7 indicates the water absorption percentages of the eight laminating composite specimens throughout a 49-day period. Material No. 2 has the highest moisture percentage content, whilst material No. 6 has the lowest.



Figure (9) Measuring the mass of the laminated composite specimens using digital balance

Table 7: Results of Water Absorption Test of laminated composite specimens

Alternatives (Materials)	Mass before immersion (m ₁), gm	Mass after immersion (m ₂), gm	Moisture content (%)
M 1	26.6226	27.393	2.894
M 2	22.9466	23.7111	3.332
M 3	27.7591	28.3342	2.072
M 4	27.693	28.3522	2.380
M 5	20.4843	20.9551	2.298
M 6	22.0665	22.1902	0.561
M 7	29.4279	29.7124	0.967
M 8	22.3408	22.9783	2.854

3.4.2 Density Measurement

The specimen is first weighed in the air before being immersed in normal water at 23°C. Archimedes' principle states that the weight of the water displaced by the volume of the solid equals the difference in weights [37]. Eqs. (16 and 17) are used to compute specific gravity and density, respectively

$$SG = \frac{m_a}{(m_w - m_a)} \quad (16)$$

$$\text{Density of Specimen}(\rho) = \frac{SG}{\rho_L} \quad (17)$$

Where m_a and m_w denote the mass of the specimen in air and water, respectively. SG is the specific gravity of the immersed liquid in a consistent unit, while ρ_L is the density of the immersed liquid, which in this case is water with a density of 1 gm/cm³.

The mass of a specimen in air and water is measured using a digital balance in the chemical lab at Menoufia University's Faculty of Engineering, Shebin El-Kom. Figure (10) depicts the samples prepared for measuring the density. The densities of the eight specimens are listed in Table 8. It is revealed that material No. 6 has the highest density and material No. 2 has the lowest density.



Figure (10) Samples prepared for measuring the density

Table 8: Measured densities of laminated composites using buoyancy principle of Archimedes

Alternatives (Materials)	Mass in air (m _a), gm	Mass in water (m _w), gm	Density (ρ), gm/cm ³
M 1	6.4609	1.2398	1.2375
M 2	5.074	0.9053	1.2172
M 3	3.9796	0.8756	1.2821
M 4	8.4092	1.5537	1.2266
M 5	5.6906	1.2846	1.2916
M 6	8.6257	2.1351	1.3290
M 7	7.6175	1.7852	1.3061
M 8	6.0514	1.106	1.2236

4 Implementation of MCDM Methods for Analysis of the Results

4.1 Determination of Attributes' Weights by CRITIC Method

The following section demonstrates the application of the CRITIC method that considers the evaluation of eight alternatives (eight laminated composite specimens) in relation to 5 measured criteria namely density, water absorption content, damping, flexural strength and ILSS.

Step 1: Normalization of the initial decision matrix.

Firstly, the initial decision matrix of all measured criteria is represented and tabulated in Table 7. Since damping, flexural strength and ILSS criteria are maximized and termed as beneficial attributes, Eq. (2) is employed for normalizing the elements of the initial decision matrix while density and water absorption content criteria are minimized and termed as non-beneficial attributes Eq. (3) is employed for normalizing elements the initial decision matrix Therefore, the overall normalized decision matrix is presented in Table 8.

Step 2: Calculation of standard deviation of the elements of the normalized decision matrix using Eq. (6). We arrived at standard deviation for criteria as σ_j = (0.3855, 0.3464, 0.3389, 0.4162, 0.3662)

Step 3: Matrix of linear correlation between the three investigated responses is formulated using Eq. (4) and tabulated in Table. 9. Finally, the individual weight of each criterion is calculated using Eq. (5) and listed in Table 10

4.2 Implementation of COPRAS Method

Stage 1. Construction of Decision Matrix

First of all decision matrix is constructed from measuring all criteria namely density, water absorption content, damping, flexural strength and

interlaminar shear strength (ILSS). Decision matrix of all investigated criteria was previously tabulated in Table 8.

Stage 2. The Normalization of Decision-Making Matrix

In order to transform performances of considered alternatives into comparable dimensionless values, normalization procedure is used. For normalization in COPRAS method, Eq. (7) is employed as shown in Table 12. tabulating the normalized decision matrix.

Stage 3. Determining of Weighted Normalized Decision-Making Matrix

After forming normalized decision making-matrix, the next stage is to determine weighted normalized decision-making matrix constructed using Eq. (8) and listed in Table 12.

Stage 4. Calculation of Maximizing and Minimizing Index for Each Alternative

In this phase each alternative is categorized as maximizing index (S+i) and minimizing index (S-i) as stated in Eq. (10) and listed in Table 13.

utility values of the candidate alternatives range from 0 to 1 as shown in Table 16. The greater the value of Z_i , the higher is the priority of the alternative. Based on alternative's utility values a complete ranking of

Step 5: Determination the relative significances of the alternatives (Q_i)

the relative significance of the alternatives or relative weight of each alternative is estimated with the help of Eq. (11) as listed in Table 14 for the eight composite materials(alternatives)

Step 6: Calculation of the quantitative utility (Z_i) and Ranking

The Performance Index or quantitative utility (z_i) value for each alternative is calculated with the help of Eq. (12) as listed in Table 15. It is noted that the competitive alternatives can be obtained. Therefore, it is observed that material No. 6 whose quantitative utility is of the largest value (1) is the optimum material resulting in compromising solution of the least values for density and water absorption content and the largest values for damping, flexural strength and ILSS. On the other hand, and according to the smallest value of quantitative utility (0.7526), Material No.1 is the worst material resulting in compromising solution of the largest values for density and water absorption content and the least values for damping, flexural strength and ILSS

Table 9: Initial Decision Matrix

Alternatives (Materials)	Non-beneficial attributes			Beneficial attributes		
	Density(ρ), gm/cm ³	Water content	Absorption	Damping Ratio (ξ)	Flexural Strength (σ_{bending}), MPa	ILSS, MPa
M1	1.237	0.0289		0.0520	500.000	16.458
M2	1.217	0.0333		0.4850	500.000	18.750
M3	1.282	0.0207		0.0468	603.125	22.604
M4	1.227	0.0238		0.0454	600.000	19.792
M5	1.292	0.0230		0.0297	550.000	19.688
M6	1.329	0.0056		0.0600	606.250	22.917
M7	1.306	0.0097		0.0260	565.625	23.125
M8	1.224	0.0285		0.0678	531.250	18.333

Table 10: Normalized Decision Matrix

Alternatives (Materials)	Normalized non-beneficial attributes			Normalized beneficial attributes		
	Density(ρ)	Water content	Absorption	Damping Ratio (ξ)	Flexural Strength (σ_{bending}),	ILSS
M1	0.818	0.158		0.057	0.000	0.000
M2	1.000	0.000		1.000	0.000	0.344
M3	0.419	0.455		0.045	0.971	0.922
M4	0.915	0.343		0.042	0.941	0.500
M5	0.335	0.373		0.008	0.471	0.484
M6	0.000	1.000		0.074	1.000	0.969
M7	0.205	0.853		0.000	0.618	1.000
M8	0.942	0.173		0.091	0.294	0.281

Table 11: Linear correlation matrix between responses

Criteria	Density(ρ)	Water Absorption content	Damping Ratio (ξ)	Flexural Strength (σ_{bending}),	ILSS
Density(ρ)	1.000	-0.907	0.470	-0.586	-0.797
Water Absorption content	-0.907	1.000	-0.506	0.711	0.850
Damping Ratio (ξ)	0.470	-0.506	1.000	-0.525	-0.268
Flexural Strength (σ_{bending}),	-0.586	0.711	-0.525	1.000	0.794
ILSS	-0.797	0.850	-0.268	0.794	1.000

Table 12: Weights of attributes determined by CRITIC method

Attributes	Density(ρ)	Water Absorption content	Damping Ratio (ξ)	Flexural Strength (σ_{bending}),	ILSS
Weight	0.282	0.167	0.205	0.188	0.157

Table 13: Normalized matrix of responses

Alternatives (Materials)	Normalized non-beneficial attributes		Normalized beneficial attributes		
	Density(ρ)	Water Absorption content	Damping Ratio (ξ)	Flexural Strength (σ_{bending}),	ILSS
M1	0.1224	0.1667	0.0640	0.1122	0.1018
M2	0.1203	0.1920	0.5968	0.1122	0.1160
M3	0.1268	0.1194	0.0576	0.1353	0.1398
M4	0.1213	0.1371	0.0559	0.1346	0.1224
M5	0.1277	0.1324	0.0365	0.1234	0.1218
M6	0.1314	0.0323	0.0738	0.1360	0.1418
M7	0.1291	0.0557	0.0320	0.1269	0.1430
M8	0.1210	0.1644	0.0834	0.1192	0.1134

Table 14: Weighted normalized matrix of responses

Alternatives (Materials)	Weighted normalized non-beneficial attributes		Weighted normalized beneficial attributes		
	Density(ρ)	Water Absorption content	Damping Ratio (ξ)	Flexural Strength (σ_{bending}),	ILSS
M1	0.0344	0.0279	0.0131	0.0211	0.0160
M2	0.0339	0.0321	0.1226	0.0211	0.0182
M3	0.0357	0.0200	0.0118	0.0255	0.0220
M4	0.0341	0.0230	0.0115	0.0254	0.0192
M5	0.0360	0.0222	0.0075	0.0233	0.0191
M6	0.0370	0.0054	0.0152	0.0256	0.0223
M7	0.0364	0.0093	0.0066	0.0239	0.0225
M8	0.0341	0.0275	0.0171	0.0225	0.0178

Table 15. Maximizing and Minimizing Index Values

Alternatives (Materials)	Maximizing Index S_{+i}	Minimizing Index S_{-i}
M1	0.0503	0.0624
M2	0.1620	0.0660
M3	0.0593	0.0557
M4	0.0561	0.0571
M5	0.0499	0.0581
M6	0.0631	0.0424
M7	0.0530	0.0457
M8	0.0574	0.0616

Table 16: Relative significance of each alternative

Alternatives (Materials)	Relative Significance (Q_i)
M1	0.6869
M2	0.7565
M3	0.7722
M4	0.7512
M5	0.7332
M6	1.0000
M7	0.9229
M8	0.7017

Table 17. Performance Value Index and Ultimate Ranking of Alternatives

Alternatives (Materials)	quantitative utility (Z_i)	Rank
M1	0.7526	8
M2	0.8595	3
M3	0.8235	4
M4	0.8105	5
M5	0.7863	6
M6	1.0000	1
M7	0.9412	2
M8	0.7692	7

5 Conclusions

In the present work, an investigation was carried out on composite specimens prepared from various wt.% of sisal fibers (SF) and glass fibers (GF) with different stacking sequences and fiber orientations and manufactured using the hand layup method to select the optimum material with the lowest density and water absorption content and the highest damping, flexural strength, and ILSS. The following findings are achieved using the CRITIC weight-based COPRAS approach as an MCDM method:

- 1- Material No. 6 of stacking sequences [RGF/RGF/BGF/RGF/BGF/RGF/RGF], with the highest quantitative utility value (1), is the best option for balancing low density and water absorption with high damping, flexural strength, and ILSS values.

- 2- Material No.1 of stacking sequences [SF0/SF90/RGF/BGF/RGF/SF90/ SF0] has the lowest quantitative utility (0.7526) and has the highest density and water absorption content, but lower damping, flexural strength, and ILSS values.

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