FLEXURAL AND FRACTURE ANALYSIS OF POLYMER METAL HYBRID COMPOSITE PANELS REINFORCED WITH NATURAL FIBERS

Aamer KAZI[1]*, Rishi DAM[2], Surya DATTA[3], Gopalan VENKATACHALAM[4], Gopalan RAJAN[5]

The primary objective of this work lies in reinforcing the polymer core of a Polymer Metal Hybrid (Metal/Polymer/Metal) composite panel with natural fibers to progress towards a greener composite. Taguchi's method is used to design the experiment in order to achieve the optimum sample size. The current study uses Aluminium grade AA5052 as face sheets. Three widely used unsaturated polyester resins- Vinyl Ester, General Purpose and Isophthalic resins are used as cores after being reinforced with Banana, Sugarcane and Coir Fibers. The flexural and fracture properties of the composite panels are tested, and the influences of the resins, fiber and fiber percentage are studied. The results are optimized by using the ANOVA statistical analysis and regression equations are obtained for varying parameters.

Keywords: Polymer Metal Hybrids (PMH), Natural Fibers, Flexural and Fracture Analysis

1.0. Introduction

Polymer metal hybrids (PMH) were developed with the purpose of combining the strength of metals with the rigidity and low density of polymers. Their high strength to weight ratio has immense relevance in the automotive, construction and aerospace industries. Polymer cores are often reinforced with fibers as they enhance mechanical properties such as rigidity and stiffness.

Composites are a special class of materials that consist of two or more constituents combined with each other, in order to get an enhanced result. Fiber-Reinforced Polymer composites (FRP) are a type of composite made by reinforcing synthetic fibers such as glass fiber and aramid or natural fibers such as coir with a Polymer Matrix. Metal/polymer/metal composites belong to a certain category of composite materials which consist of a polymer matrix sandwiched

[1] * Vellore Institute of Technology, India, contact author, e-mail: aamerk4716@gmail.com
[2] Vellore Institute of Technology, India, e-mail: dam.rishi@gmail.com
[3] Vellore Institute of Technology, India, e-mail: suryadatta1@gmail.com
[4] Vellore Institute of Technology, India, e-mail: g.venkatachalam@vit.ac.in
[5] Mount Zion College of Engineering, India, e-mail: g.rajan@gmail.com

between two thin but stiff skin sheets of a different material [1]. They can become a culmination of the advantages of these miscellaneous materials when combined with each other, exhibiting properties such as low density, high bending resistance, energy absorption, high load-capacity at low weight [2]. By replacing a flat block of metal with a PMH composite of equal dimensions, cost reduction, weight reduction and an increase in strength to weight ratio is easily attained [1]. The core can be designed in two different ways, namely solid structures or open structures like Polypropylene Honeycomb [3]. Polyester and Vinyl Ester Resins have been extensively used in the composite industry as solid polymer structures for decades and have been the building blocks for composite advancements up till now. These Unsaturated Polyester Resins (UPR) not only offer cost economy and ease of handling but also provide a high strength to weight ratio to create a wide variety of composite parts having countless applications [4].

General Purpose Polyester Resin is a widely used standard economic resin. Isophthalic Resin is paving its way into the market as it provides superior mechanical properties and water resistance, especially relevant in the marine industry. These resins are estimated to be the best value for a balance between performance and structural capabilities [5]. Vinyl Ester Resin is an advanced UPR that combines the ease of fabrication of Epoxies and the speedy curing time of Polyesters. It provides greater corrosion resistance and improved toughness as well [6].

The implicit intention of employing Polymer Metal Hybrids is to combine its constituent parts into making an assembly that surpasses the limitations of each component, when implemented individually. Its first practical application was observed in 1996 when Audi used a hybrid of steel sheet and polyamide to fabricate the front end of the A6 variant. Polymer metal hybrids are replacing metals in the aircraft and automobile industries, being cheaper at low and medium scales of production [7]. The predominantly used methods to join the individual components of a PMH to each other are –mechanical fastening, adhesive bonding and welding processes [8, 9, 10 and 11].

Adhesively bonded polymers are widely used since the adhesive layer acts as a buffer zone between the skin and core by absorbing contact stresses and also reduces stress concentration in particular zones [12]. Other advantages of this joining method in comparison to mechanical fastening and welding are allowing bonding of dissimilar materials, improving fatigue resistance, providing sealing, offering weight reduction, good surface finishing, facilitating assembly of thin or flexible substrates and no hole requirements [13].

Polymers are often reinforced with fibers to improve stiffness and various other mechanical properties. While synthetic fibers such as glass, aramid etc. have been extensively used in the past, natural fibers are now being used in an attempt to address several drawbacks posed by synthetic fibers. The abrasive nature of natural fibers is distinctly lesser than glass making them better suited in terms of recyclability and machining purposes [14]. An experimental study determined that natural fibers composites can replace glass fiber composites. In fact, certain properties of natural fibers make them more appropriate for applications that do not require high load bearing characteristics [15]. While cultivating the sources from which natural fibers are derived, carbon dioxide neutrality is maintained as it absorbs the same amount of CO_2 that is produced during combustion at the end of its life cycle [14, 15].

Banana, coir and sugarcane fibers are widely used natural fiber reinforcements and numerous studies have been conducted on their feasibility and their ability to replace synthetic fibers. It was concluded that increasing the percentage of banana fiber in a composite enhances the tensile and flexural properties [16]. Studies on Polymer Concrete (PC) concluded that coir and sugarcane fibers function as excellent reinforcements for PC [17]. Combined with their ease of availability and cost effectiveness, these natural fibers are amongst the most widely used, at present. Even though natural fibers have good mechanical properties, there are certain limitations in using them as a core-reinforcement due their hydrophilic nature. The discord that arises due to the incompatibility of the hydrophilic fiber and hydrophobic matrix is due to the structural composition of the fibers (cellulose, lignin, hemicellulose and other waxy substances). The lignocellulosic fibers are hydrophilic and tend to absorb moisture. When the fibers come in contact with atmospheric moisture, the hydrogen bond breaks and the hydroxyl groups form new hydrogen bonds with water molecules. When hydrophilic fibers are mixed in a hydrophobic matrix, fibers swell within the matrix causing the bond strength at the interface to weaken. This results in dimensional instability, matrix cracking and weakened mechanical properties of the matrix. Hence, it is imperative that the fibers are rendered free of moisture through various chemical treatments that eliminate the hydrophilic hydroxyl groups [18]. The tried and tested chemical modification for treating almost all natural fibers is alkali treatment [19]. Treating banana fibers with 5% NaOH for 1 hour at room temperature, has been proven to enhance adhesion characteristics between fiber and matrix [20]. An experimental study on the effect of reinforcing composites with coir, treated with different concentrations of NaOH concluded that there is no significant impact on the fiber's mechanical properties up to 8% NaOH concentration, beyond which the improved adhesive ability of the fiber was not enough to compensate the loss of fiber strength [21]. A study on the effect of alkali treatment on bagasse fibers concluded that treating bagasse with 10% NaOH for a span of 4hours provides optimum results. [22]

In the current study, Metal/ Polymer/Metal Hybrids (PMH) composite structures are used. The hybrid structure uses Aluminium Grade AA5052 as the face sheets and natural fibers reinforced with a polymer as core. General Purpose, Isophthalic and Vinyl Ester Polyester resins are used as the polymers. The study employs the use of short, discontinuous reinforcement of coconut, bagasse (sugarcane) and banana fibers to reinforce the polymer matrix. The diameter of each fiber used is 1mm. The flexural and fracture properties of the natural fiber reinforced PMH sheets are investigated, and the influences of the type of resin, type of fiber and fiber percentage on said properties are studied.

2.0. Methodology and Experimental Procedure

2.1 Experiment Design:

For determining the number of samples to be prepared for the testing, Taguchi's method is used to design the experiment. Taguchi's method is a partial fraction method of experiment design and provides an optimum set of parameters from a smaller sample size. Since, the variables in this study are types of polymer resins, types of fibers and fiber percentage, the L9 orthogonal array is used. Vinyl Ester, GP and Isophthalic Resins are used as the polymers. The fibers used are Coir, Banana and Sugarcane at weight percentages of 0, 2 and 4%. The array is listed in Table-1.

Table 1

Taguchi's L9 array

TYPE OF RESIN (X)	TYPE OF FIBER (Y)	FIBER PERCENTAGE (Z)
X1	Y1	Z1
X1	Y2	Z2
X1	Y3	Z3
X2	Y1	Z2
X2	Y2	Z3
X2	Y3	Z1
X3	Y1	Z3
X3	Y2	Z1
X3	Y3	Z2

X1: Vinyl Ester
X2: GP resin
X3: Isophthalic resin

Y1: Coir 1mm fiber
Y2: Banana 1mm fiber
Y3: Sugarcane 1mm fiber

Z1: 0% fiber
Z2: 2% fiber
Z3: 4% fiber

2.2 Experimental Procedure:

The samples are prepared according to ASTM C393 non-standard configurations for the flexural test. The dimensions of the sample are 250x25x5 (in mm), with the span length being 200mm. For the fracture test, the dimensions are in accordance with ASTM E399. To improve adhesion, Coir Fibers are treated with 5% NaOH for 4 hours. Banana fiber is treated with 5% NaOH for 1 hour and Sugarcane is treated with 10% NaOH for 4 hours as per aforementioned citations.

The samples are prepared by pouring the resin-fiber mixture into a mould, which is dimensioned to match the ASTM standards. The mixture is allowed to cure for 24 hours. The cured sample is then sanded to get an even finish and any dimensional inaccuracies are fine tuned.

The aluminium face sheets are developed according to the dimensions as using foot shearing machine, BOSCH Angle grinding tool, and adhesively bonded to the cured composite by using Araldite, an Industrial grade Epoxy adhesive. The sample is cured for 24 hours under uniformly loaded weights to ensure strong bonding between the layers. The final sample is shown in Fig. 1.

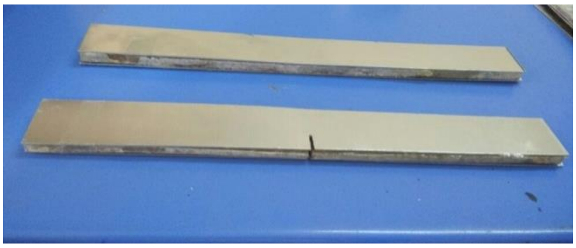

Fig 1: PMH composites after fabrication

2.3 Mechanical tests performed:

Flexural tests: Nine samples are tested in the INSTRON machine for maximum flexural stress at a constant feed rate of 6mm/min. The specimens are monitored for deformation under the applied load.

Fracture tests: After notches of 7.5 mm are made in the samples, the values of fracture stress and fracture modulus are determined using the INSTRON machine at constant feed rate of 2mm/min.

In order to determine the stress rate near the tip, stress intensity factor is used. This theoretical concept provides a criterion for failure of brittle materials and is typically used for linear and homogenous elastic materials.

Stress intensity factor is evaluated using the formula:

$$K_{1c} = \sigma\sqrt{a\pi} \quad (1)$$

Here, ‘σ’ is fracture stress and ‘a’ is the notch length.

3.0. Results and Discussions:

3.1. Flexural Testing:

The Flexural Testing is performed on the samples in accordance with Taguchi’s L9 array. Table 2 represents the Flexural Stress values in MPa of all 9 samples.

Table 2

Flexural Stress results

S. No.	Type of Resin (X)	Type of Fiber (Y)	Fiber % (Z)	Flexural Stress (MPa)
1	Vinyl Ester	Coir	0	22.90
2	Vinyl Ester	Banana	2	26.10
3	Vinyl Ester	Sugarcane	4	32.82
4	GP Resin	Coir	2	25.07
5	GP Resin	Banana	4	29.38
6	GP Resin	Sugarcane	0	21.62
7	Isophthalic Resin	Coir	4	29.68
8	Isophthalic Resin	Banana	0	22.78
9	Isophthalic Resin	Sugarcane	2	26.54

3.1.1. Anova:

Analysis of Variance (ANOVA) is carried out to determine the regression equation for the flexural test. The regression equations provide us with the levels of variability beyond the 9 sample parameters.

To assess the effect of these variables, the software MINITAB is used to obtain the results. These results are also illustrated in the form of main effect and contour plots.

From the main effects plot shown in Fig. 2, the influences of type of resin, fiber type and fiber percentage on the flexural strength of the tested samples can be observed. One can conclude that polymer metal hybrid samples with Vinyl Ester as their core has a higher flexural strength compared to samples with Isophthalic and GP resin cores. It is to be noted that *sugarcane has the best flexural strength*. Maximum flexural strength is observed at 4% fiber reinforcement. Flexural strength increases almost linearly with an increase in fiber content.

Contour plots are indicators of the variation of multiple variables at a time, in the same study. In Figs. 3-5, flexural stress is compared with the parameters, taken two at a time, i.e. Resin type, Fiber type, and Fiber percentage. In fig. 3, the contour plot shows the variation of flexural stress with the type of resin and percentage of fiber. The highest value is noted for resin 1 or Vinyl Ester at 4% reinforcement. Fig. 4 displays the change in flexural stress by varying resin and fiber type. Maximum flexural stress is observed for fiber 3, i.e. sugarcane when used with resin 1, Vinyl Ester.

Fig. 5 contrasts the variation of flexural stress with fiber type and percentage. The highest value of flexural stress is observed when polymeric cores reinforced with sugarcane at 4% reinforcement.

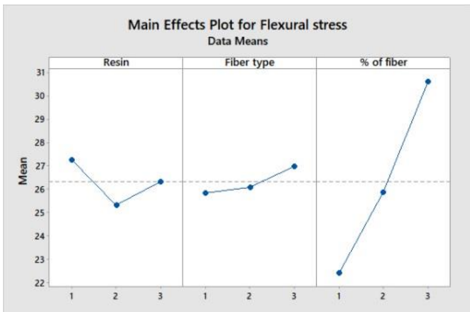

Fig. 2 – Main effects plot for flexural stress

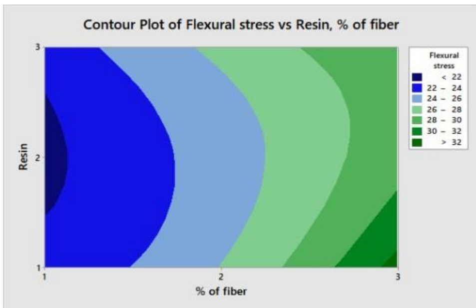

Fig. 3 – Contour plot of flexural stress against type of resin and fiber percentage

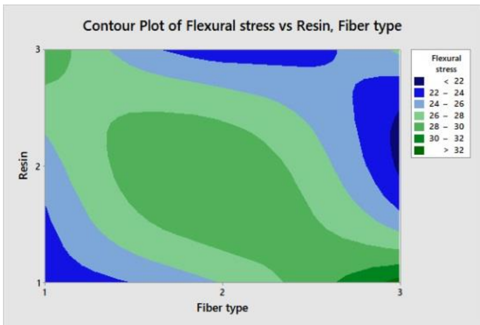

Fig. 4 – Contour plot of flexural stress against type of resin and fiber

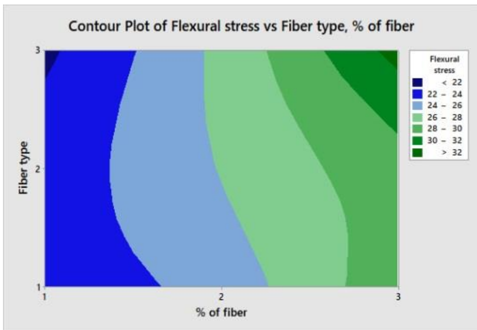

Fig. 5 – Contour plot of flexural stress against fiber type and fiber percentage

3.1.2. Regression Equation:

ANOVA analysis is used to determine the Regression equation. This equation mathematically represents all the parameters involved along with the weightage of each parameter and their influence on the flexural stress. It is possible to obtain the numerical value of flexural stress for various combinations of the independent variables through ANOVA analysis and regression equation.

From the Regression equation, it is concluded that the percentage of fiber has the most significant influence on the flexural stress of the PMH composite. The fiber type has a weaker relative influence compared to fiber percentage, but more relevant than the resin type. The Regression equation obtained is as follows:

$$\textit{Flexural Stress} = 17.93 - 0.469 \times X + 0.566 \times Y + 4.097 \times Z \quad (2)$$

A comparison is conducted between experimental data and the values determined through the regression equation 2. The percentage errors of flexural stress are tabulated in table 3.

Table 3

Flexural stress error comparison

Experimental Data (MPa)	Calculated data (MPa)	Error %
22.9017	22.124	3.39
26.1003	26.787	-2.63
32.6202	31.45	4.17
25.0035	25.752	-2.99
29.3869	30.415	-3.49
21.6282	22.787	-5.35
29.6865	29.38	1.03
22.78163	21.752	4.51
26.5403	26.415	0.47

3.2. Fracture testing:

The INSTRON machine is used to determine fracture stress, and stress intensity factor is evaluated using equation (i) and gives us a good understanding of the fracture attributes. The magnitude of stress intensity factor depends on sample geometry, size and location of crack, magnitude and distribution of load. The results are tabulated as given in table-4, along with the main effects and contour plots:

Table 4

Fracture test results

S.No	Resin (X)	Fiber (Y)	Fiber % (Z)	Fracture Stress (MPa)	Stress Intensity factor, K_{1c} (MPa $\sqrt{}$mm)
1	Vinyl Ester	Coir	0	83.94	407.53
2	Vinyl Ester	Banana	2	103.45	502.25
3	Vinyl Ester	Sugarcane	4	132.78	644.65
4	GP Resin	Coir	2	101.67	493.61
5	GP Resin	Banana	4	118.29	574.30
6	GP Resin	Sugarcane	0	80.26	389.66
7	Isophthalic Resin	Coir	4	129.22	627.36
8	Isophthalic Resin	Banana	0	81.01	393.26
9	Isophthalic Resin	Sugarcane	2	106.56	514.63

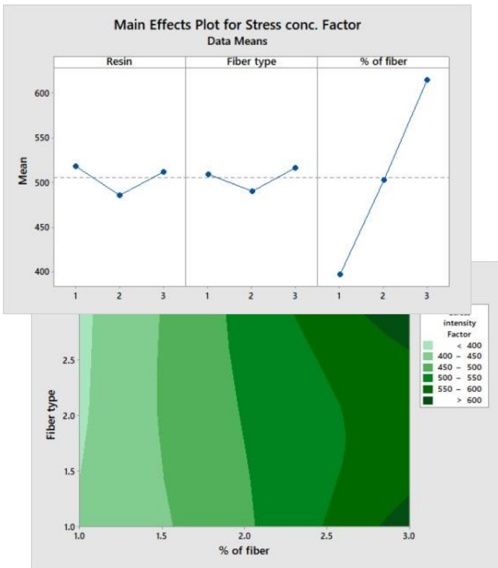

Fig. 8 – Contour plot of stress concentration factor against fiber type

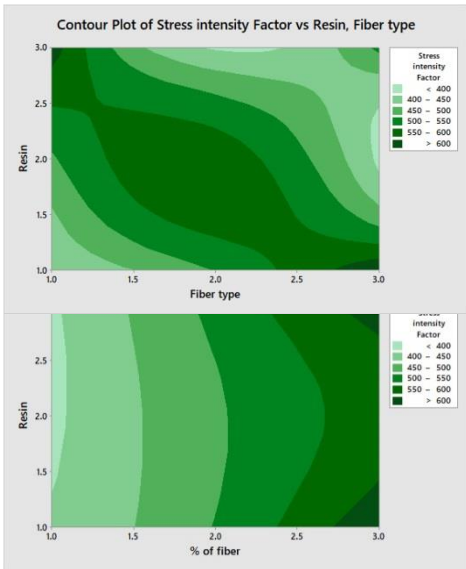

Fig. 9 – Contour plot of stress concentration factor against type of resin

3.2.1. ANOVA:

Following the same procedure as flexural testing, ANOVA is employed using Minitab software to obtain contour plots and regression equations. It helps to understand the correlation of the variables and their influence on stress intensity factor. From the main effects plot in Fig. 6, the influences of the type of resin, fiber type and fiber percentage on the stress intensity factor of the tested samples can be observed. Polymer metal hybrid samples with Vinyl Ester as their core, closely followed by Isophthalic resin, has a higher stress intensity factor compared to samples with GP resin cores. It is observed that polymeric cores reinforced with sugarcane have the highest stress intensity factor. Maximum stress intensity factor is observed at 4% fiber reinforcement. Stress intensity factor increases linearly with an increase in fiber percentage.

Figs. 7-9 illustrate the influences on stress intensity factor as result of variations in the parameters taken two at a time. Fig. 7 marks the change of stress intensity factor with respect to variation in resin and fiber type. Fig. 8 denotes the influence of fiber type and concentration on the stress intensity factor. Sugarcane and banana at 4% reinforcement display high magnitudes of K_{1c}. Fig. 9 shows the effects of resin type and fiber percentage on stress intensity factor. PMH reinforced with Isophthalic resin and Vinyl ester resin cores exhibit the highest values of K_{1c} at 4% reinforcement.

3.2.2. Regression equation:

The regression equation is obtained using ANOVA. From the value of the coefficients, it is evident that the percentage of fiber has an overwhelming influence on the stress intensity factor. The type of natural fiber has a greater influence than the polymeric core used.

$$K_{1c} = 285.9 - 3.08 \text{ x } X + 3.41 \text{ x } Y + 109.36 \text{ x } Z \quad (3)$$

The values derived from regression equation 3 are compared to experimental data and the percentage errors of stress concentration factor are tabulated in table 5.

Table 5

Stress concentration factor error comparison

Experimental K_{1c} (MPa)	Calculated K_{1c} (MPa))	Error in %
407.5321887	395.59	2.97
502.2540496	508.36	-1.21
644.6524186	621.13	3.58
493.6120756	501.87	-1.67
574.3028664	614.64	-7.02
389.6656358	399.33	-2.48
627.3684707	608.15	3.06
393.2632216	392.84	0.10
514.6392606	505.61	1.75

4.0. Conclusions

In the current study on Polymer Metal Hybrids, the maximum flexural strength of the composite has been deduced using the flexural test, and stress intensity factor (K_{1c}) has been used to understand the fracture toughness of the samples. ANOVA (Analysis of Variation) is employed to obtain contour plots and regression equations, to understand the relationship between the different parameters and the flexural and fracture characteristics of the samples. The main inferences from the study are as follows:

1) The percentage of fiber has the maximum influence on the flexural and fracture properties of the Polymer Metal Hybrid Composite Panel. Increasing the percentage of fiber causes an almost linear increase in the flexural and fracture strengths.
2) The type of fiber used has a greater influence on the flexural and fracture behaviour of the composite panel when compared with the type of resin used.

3) Vinyl Ester and sugarcane proved to be the best core material and reinforcement respectively, amongst the core and reinforcement materials tested in this study. Hence, a PMH panel with a Vinyl Ester core reinforced with sugarcane at 4% is the ideal combination.
4) As the fabricated specimens have thicknesses of 5mm, they can be considered as sheets and can replace sheet metal in automobile structures, such as the roof, in order to attain weight reduction.

R E F E R E N C E S

[1]. *Chiara Colombo, Adele Carradó, Heinz Palkowski, Laura Vergani*; 2015," Impact behaviour of 3-layered metal-polymer-metal sandwich panels", Composite structures, **Vol 133**, pp 140-147

[2]. *Librescu L, Hause* T, 2000, "Recent developments in the modelling and behaviour of advanced sandwich constructions: a survey", Composite Structures, **Vol 48**, Issues 1-3, pp 1-17

[3]. *Wang B., Yang M.*, 2000, Damping of honeycomb sandwich beams, Journal of Materials Processing Technology, **Vol 105**, issue 1–2, pp 67–72

[4]. *V. Sarath Kumar, P. Prakash, M. Abdul Rahuman, R. Deepak Joel Johnson, V.Arumugaprabu A,* 2017, Review on natural fiber reinforced polyester and vinylester composites, International Conference on Automotive systems, Agricultural Equipments and Manufacturing, Kalasalingam University, Tamil Nadu, India

[5]. *M. Tuttle*, 2004, "Introduction". In: Structural analysis of Polymeric Composite Materials, University of Washington, 0-82474-717-8, pp 1-40

[6]. *F. Mathews, R. Rawlings*, 1994, Polymer Matrix Composite, In: Composite Materials: Engineering and sciences, The Alden Press, Oxford, 0-41255-960-9, pp 168-205

[7]. *Erica R.H. Fuchs, Frank R. Field, Richard Roth, Randolph E. Kirchain*, 2008, "Strategic materials selection in the automobile body: Economic opportunities for polymer composite design"', Composites Science and Technology, **Vol 68**, Issue 9, pp 1989-2002

[8]. *D. Grewell and A. Benatar*, 2007, "Welding of plastics- fundamentals and new developments", International Polymer processing, **vol 22**, issue 1, pp 43-60

[9]. *M.C.-Y. Niu*, 2001, "Composite Airframe Structures", Practical Design Information and Data, 3rd ed., Aeronautical Journal,New Series- **Vol 105** issue 1050, pp-459

[10]. *R.W. Messler Jr.*,2000, Assembly Automation, 20, pp 118-128

[11]. *R.W. Messler Jr.*,2004, "Joining composite materials and structures: some thought provoking possibilities" in: J. Thermoplastic Composite. Materials, pp 51-75

[12]. *M. Grujicic a, V. Sellappana, M.A. Omar a, Norbert Seyr , Andreas Obieglo ,Marc Erdmann, JochenHolzleitner,* 2008, "An overview of the polymer-to-metal direct-adhesion hybrid technologies for load-bearing automotive components", Journal of materials processing technology, **Vol- 197**, issues 1-3, pp 363-373

[13]. *S.T. Amancio-Filho, J.F. dos Santos*, 2008, Joining of Polymers and Polymer–Metal Hybrid Structures: Recent Developments and Trends, Polymer Engineering and Science, **vol-49**, pp 1461-1476

[14]. *A.K. Bledzki, J. Gassan*, 1999, "Composites reinforced with cellulose based fibers", Progress in polymer science, **Vol 24**, Issue no 2, pp 221-274

[15]. *Paul Wambua, Jan Ivens, IgnaasVerpoest*, 2003, "Natural fibers: Can they replace glass in fiber reinforced plastics?", Composites Science and Technology, **Vol 63**, Issue 9, pp 1259-1264

[16]. *M. Ramesha, Sri Ananda Atreyaa, U. S. Aswina, H. Eashwara, C. Deepa*, 2014, "Processing and Mechanical Property Evaluation of Banana Fiber Reinforced Polymer Composites", Procedia Engineering, **Vol-97**. pp 563-572

[17]. *J.M.L. Reis, 2005*, "Fracture and flexural characterization of natural fiber-reinforced polymer concrete", Construction and Building Materials, **Vol 20**, Issue 9, 673-678

[18]. *M.M. Kabir, H. Wang, K.T. Lau, F. Cardona*, 2012, "Chemical treatments on plant-based natural fiber reinforced polymer composites: An overview", Composites: Part B, **Vol-43**, issue-7, pp 2883-2892

[19]. *E. Bisanda*, 2000, "The Effect of Alkali Treatment on the Adhesion Characteristics of Sisal Fibers", Applied Composite Materials, **Vol. 7**, Issue 5 pp: 331-339

[20]. *H. Dodiya* and *G. Venkatachalam*, 2016,"Dynamic Analysis of Banana Fiber Reinforced Hybrid Polymer Matrix Composite Using ANSYS and Optimization of Design Parameters", Applied Mechanics and Materials, **Vol. 852**, pp. 3-9;

[21]. *Huang Gu*, 2009, "Tensile behaviour of the coir fiber and related composites after NAOH treatment", Materials and design, **Vol 30**, Issue 9, pp 3931-3934;

[22]. *JuilianaAnggono, SuwandiSugondo, SanjayaSewucipto, HariyatiPurwaningsih* and *Steven Henrico*, 2017, "The use of sugarcane bagasse in PP matrix composites: A comparative study of bagasse treatment using calcium hydroxide and sodium hydroxide on composite strength", AIP Conference Proceedings 1788, 030055