

Article - Engineering, Technology and Techniques

Virtual Fatigue Life Prediction of Cellulose Microfibrils Reinforced Polymer Composite

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HIGHLIGHTS

- An attempt to reuse industrial waste for new product development.
- Cellulose microfibrils, an industrial waste were used.
- Fatigue life were simulated for polymer reinforced composite.
- Design of Experiment and optimization were used in the research.

Abstract: Composites are the recent ever-growing trend in the materials field of engineering. They have numerous applications in aerospace and automobile which make composites an inevitable research area. Currently, the research flow pattern centres around making sustainable green composites with accessible and overabundance of assets to contribute towards eco-friendly surroundings and waste management. In this paper, an attempt is made to reinforce natural fibres in polymer composite instead of synthetic fibres which are mostly non-biodegradable. Composite specimens are made with chemically treated cellulose microfibrils as reinforcements and epoxy as a matrix. Fatigue analysis of specimens prepared is carried out using ANSYS. The number of samples is decided based on the Box Behnken design (BBD), a design of experiments (DOE) method. The influences of parameters such as NaOH %, fibre diameter and Wt. % of Fibre on composite's fatigue behaviour are investigated using analysis of variance (ANOVA). Optimised values of the input parameters are found to be 18.08 NaOH %, 250 µm fibre diameter and 3.778 Wt. % of Fibre which yields 1.3×10^6 cycles.

Keywords: Cracks and Cracking; Fibre reinforcement; Life cycle assessment/ life cycle analysis; Response Surface Methodology; Analysis of Variance

INTRODUCTION

The consciousnesses of global warming and pollution have found limelight in this decade and hence manufacturers are exploring more environmental friendly alternatives for the highly non-biodegradable plastics. The advent of sustainable development goals is one of the key drivers for growth in this area to battle the resource depletion crisis [1]. Composites offer a fitting alternative for this problem especially when it is reinforced with naturally biodegradable fibres. Composites are made from an amalgamation of materials with different physical and chemical properties which constitute a new material with desired properties [2]. Fiber-reinforced polymer composite is a type of composite which has fibre as reinforcement in the polymer matrix. Surging prices of petroleum-based synthetic fibres and growing ecological concerns among people laid the way to the adoption of natural fibers as a fitting alternative reinforcement to synthetic fibers. Natural fiber reinforced composite is known to exhibit excellent strength to weight ratio, high specific strength, toughness and stiffness at a lower price. They also have cost and energy advantages over traditional reinforcing fibers such as carbon and glass [3-4]. Natural cellulose fibres are the one obtained from plants like wood bark, cotton kenaf, coir, banana peel, jute etc. It acts as a better reinforcement agent for microfibrils and nanofibrils [5].

Organic fillers, such as lignocellulosic, offer advantages over inorganic fillers which includes renewable nature, wide variety of fillers, minimal cost, low energy consumption, low density, high specific modulus and strength, high sound attenuation and comparatively easy processability owing to its nonabrasive nature and flexibility granting high filling levels [6]. Cellulose found in plant walls and other natural items is of much interest to researchers today owing to its biodegradability and acceptable mechanical properties. Another reason for their popularity as reinforcement agent among researchers is their high modulus of elasticity (MOE) and a good aspect ratio. They exist within the cell wall as high tensile fibrils present in the matrix called lignin. A fibril itself is a chain of crystalline unit. Zimmermann and coauthors, [7] investigated cellulose microfibrils extracted from wood fibers as reinforcement agent for two different polymers i.e. Polyvinyl Alcohol (PVA) and Hydroxypropyl cellulose (HPC). The separation of cellulose was done by mechanical and chemical means. Several parameters such as morphological characterization, chemical characterization and mechanical properties were studied. They finally concluded that the fibril reinforced polymer has a three times increase in Young's modulus and fivefold appreciation in tensile strength in PVA and HPC [7]. Another similar analysis conducted by Pragasam and coauthors [8] involved cellulose extracted from banana fibers. The authors investigated its morphological, chemical and thermal behaviours at various stages of chemical treatment. Banana fiber contains hemicellulose, lignin and α -cellulose which are chemically bonded together. Since, α cellulose has a high modulus of elasticity compared to the other two content and is also a significant factor that decides reinforce ability. It is essential to isolate the α -cellulose by chemical or mechanical methods and increase its percentage. In a composite, various factors influence the mechanical properties and fibers compatibility with the matrix including matrix type, fiber architecture and type, specimen geometry, fiber volume fraction and processing conditions which can ultimately decide the composite's physical and mechanical properties [9]. Thomson [10] studied the influence of fiber diameter on the mechanical properties of glass fiber reinforced polyamide. The authors found a correlation between tensile strength and fiber diameter which revealed that the lesser the fiber diameter the greater is the fatigue strength of the fiber.

Similarly, in a study, two glass fiber reinforced polymer composites with different fiber diameters were tested to find their damping effect. It was found that the fibre with a lesser diameter (18.3 μ m) has a more damping effect than the fibre with a higher diameter (27.2 μ m) [11]. However, the Flexural strength and elastic modulus of fiber reinforced polymer composite increase with increase in diameter [12]. Chemical treatment such as NaOH treatment showed enhancement in mechanical properties and viscoelastic properties. NaOH is used for altering the surface of fibre which provides excellent bonding between fibers and in turn results in better composite properties. NaOH possesses the ability to eliminate impurities and unnecessary content from the fiber. Rajeshkumar and coauthors, [13] conducted a study to find the effect of NaOH treatment on the mechanical properties of Epoxy Composites reinforced with Phoenix fiber. The phoenix fibers were treated with sodium hydroxide NaOH (5, 10, 15 and 20% solution). The results indicated that the sample with a 15% concentration of NaOH has good interfacial bonding and higher static and dynamic mechanical properties than the rest of the concentrations. A similar study was conducted by Khan and coauthors, [14] for banana / epoxy laminates with NaOH concentrations of 0%, 2.5%, 4.5%, and 6.5%. The test result indicated that fiber treatment aids in the improvement of mechanical properties. Moreover, the samples with 4.5% of NaOH solution treated fiber indicated the highest compressive strength and tensile strength. A wide range of polymer matrices is available today based on the need. But the use of epoxy as a matrix dominates the industry. The thermosetting polymer has a plethora of advantages, high mechanical properties, ease of

processing, low shrinkage during the curing and importantly excellent adhesion to all types of fiber reinforcement [15].

The influence of fibre volume fraction on the mechanical properties of a polyester matrix was studied for bagasse reinforced composite. The result showed that the stiffness and hardness of the composite increase with increase in fiber content whereas strain decreases with an increase in fiber content. Several other Mechanical properties like Ultimate tensile strength and modulus of elasticity show varying dependent nature with a percentage of fiber content concluding that brittleness increases with bagasse fiber content % [16]. Jacob and coauthors, [17] studied the effect of tow size, fiber length and fiber volume fraction on the energy absorption of the chopped carbon fiber polymer composite with two different variables of fiber volume fraction of 40% and 50%. Results showed that composites with higher fiber volume fraction offer higher stiffness and flexural strength. Fiber volume fraction is indirectly proportional to SEA (specific energy absorption) of the composite even though composite with 50% Fiber volume fraction has the highest SEA because of the interaction with other factors like fiber tow size and fiber length. Fiber volume fraction influences interface fracture of the composite. In synthetic fiber, fibre volume fraction and fibre orientation play a significant role in composite properties. In the case of Natural Fiber composite load transfer efficiency is based on the fibre-matrix bond quality. The variation of the fiber volume fraction value in the Natural Fiber composite affects the behaviour of its failure. Fibre Volume Fraction depends on Fibre arrangement within fibrous structure, orientation and spacing between fibers [18]. Volume Fraction not only affects the mechanical properties but also the reinforcing ability and bonding between matrix and fibres [19]. Randomly oriented fibres are isotropic in physical and mechanical properties. Increasing fiber content increases flexural strength [20].

A study conducted by Fotouh and coauthors, [21] on Hemp-fiber–reinforced High-Density Polyethylene (HDPE) composites with untreated 20% and 40 % weight fraction using S-N curves. The results concluded that with increasing hemp fiber content, a minimal increase in fatigue strength was observed though moisture exposure caused overall fatigue strength reduction. This was observed due to the degradation of interfacial fiber matrix bonding strength. At higher stress levels (low cycles), the contribution of fiber is more predominant. The properties of the matrix dominate the fatigue behaviour at higher fatigue life cycles. The fatigue behaviour of metals is known for more than 150 years. It was found in composites that the crack propagation is multidirectional to the tensile load whereas in metal it is perpendicular to the load applied [22]. The damage propagation in composites occurs due to fiber fracture, debonding, matrix cracking, delamination and transversely ply cracking. These together or independently cause fatigue failure in composites. Another finding was that due to the heterogeneous nature of composites, some cracks propagated to the entire area while some were arrested/deflected due to hard filler [23]. The specific endurance limit of composite is greater than that of metals when subjected to cyclic tensile loading. Cyclic compressive loads generate notable damage in composites. With metals, the damage mechanism occurs only on the surface whereas in composites it occurs inside the material as well [24]. The influence of parameters is critical in finding out if the controllable factors affect noncontrollable factors. To find the same, the design of experiments methods is used. Also, analysed the interaction of process parameters (feed rate, spindle speed) on torque and thrust force in drilling operation using RSM and Taguchi approach and compared their result to find out its adequacy. The results revealed that RSM is better than Taguchi because it yields smaller response values in optimising both torque and thrust force for newer materials.

Influence of parameters such as fiber loadings, coupling agents, maleic anhydride and impact modifier on mechanical properties of Abaca fibre reinforced high impact polystyrene (HIPS) composites was studied using box Behnken design, a response surface methodology approach in DOE [25]. Optimisation of CSNL%, fiber volume fraction% and fiber length on tensile behaviour of jute and banana fiber reinforced composite materials was carried out using ANOVA and number of analysis was determined by Taguchi method [26]. So far, the influences of the NaOH%, fiber diameter, fiber volume% were studied for several composites with different fiber reinforcements. In the research carried out by Pragasam and Reddy on the cellulose microfibrils reinforced polymer composite, the effects of input parameters on several mechanical properties were studied [27]. In the study, it was evident that the tensile modulus of the composite is nowhere affected by fibre diameter but it shows variable results in NaOH pre-treatment percentage as it increases initially and then decreases. The effect of fiber diameter and fibre volume % on tensile stress is similar to that of tensile modulus but tensile stress increases with an increase in NaOH treatment. For the flexural stress and flexural modulus, fiber diameter has no effect on it, fiber volume % increases up to a threshold value of 4 and then decreases for both flexural modulus and flexural stress. In the case of NaOH %, it increases and then decreases for flexural modulus and it increases for flexural stress [28].

From the literature review, it is noted that there are few attempts to predict fatigue life for polymer composite. However prediction of virtual fatigue life for cellulose banana micro fibrils reinforced polymer composite is not reported. Here authors predict fatigue life virtually using finite element analysis. Also, authors use statistical techniques to find the influence of controllable input factors on fatigue life leading to optimization of input parameters for maximum fatigue life.

MATERIAL AND METHODS

Material properties, studied by Pragasam and Reddy [27] as shown in Tables 1 and 2, are used for the calculation of fatigue limits. The composite samples are made with epoxy as a matrix and cellulose microfibrils as reinforcement. The specimens were fabricated in accordance with ASTM D3039 standards. Fatigue failure is one of the critical failures commonly occurring in the industry. It is a failure caused by repetitive dynamic loading that forms cracks after a certain period. Many manufacturers prefer materials with a higher fatigue limit. Fatigue performance is specified by the cycles to failure at some specific stress level.

Fatigue test results are plotted as an S-N curve which represents the logarithmic scale curve between alternating stress and life cycles. Fatigue property of the material or composite is completely assessed based on S-N curve. Equations 1-3 shows the mathematical relation for the S-N curve.

$$\log s = (b * \log N) + C \quad (1)$$

$$b = -\frac{1}{3} \log(0.8 * \frac{\sigma_u}{\sigma_e}) \quad (2)$$

$$c = \log(0.8 * \sigma_u)^2 / \sigma_e \quad (3)$$

Here, S represents alternating stress and life cycles are denoted by N, b and c are constants.

The area under the curve where the number of cycles to failure is low called a high fatigue cycle. The stress in this region is high and hence fails early. At a particular stress level, the cycle to failure becomes a flat line and approaches infinity. This condition is known as the endurance limit of the material. Engineering components designed to have alternating stress below the endurance limit have an infinite cycle.

The study of fatigue life for metallic materials has been known for a while now. Recent developments in government policies to reduce the dependency on plastic-based synthetic composites have opened new avenues for adapting natural fiber composites with similar fatigue strength. The fatigue strength of epoxy-based composite reinforced with fly ash, sugarcane fiber and carbon nano tubes was evaluated using the design of experiments method [3]. The present research involves investigating the fatigue behaviour of cellulose microfibrils reinforced polymer composites similarly but stands out in the following ways:

1. Box Behnken model is used for sample preparation. BBD approach is linked with low experimentation cost and reduced complexity.
2. Analysis of Variance (ANOVA), a statistical method, is utilised to study the interaction between the three parameters considered. The results can be used to determine the optimum parameter that is needed to produce composite with maximum fatigue strength.

Epoxy is used as the matrix and cellulose microfibrils as reinforcements. The composite samples are fabricated in accordance with ASTM D3039 standards for tensile testing [28]. Yield strength, UTS and Young's modulus are the output values obtained as a result of tensile testing for the composite samples made according to design of experiments as shown in the Table 2. Epoxy is used as the matrix and cellulose microfibrils as reinforcements. A simulation tool i.e. ANSYS is used to find the virtual fatigue life of the composite. RSM is used to develop the mathematical model and to optimize the process input parameters in order to get the desired outputs. The regression equation for the fatigue life is found and validated with the ANSYS results by finding error percentages between them.

Box Behnken design model is used to develop a model at three different levels with coded values of -1, 0 and 1. Three factors / Three levels BBD model is utilized to study the influence of NaOH %, fiber size and **Wt. % of Fibre** on fatigue strength of cellulose micro fibrils reinforced polymer composites. The three levels of the parameter taken are shown in Table 1. "Wt% of fiber" refers to the weight percentage of fibers relative to the total weight of the composite. The term "wt% of fiber diameter" is intended to convey the distribution of fibers by diameter within the total fiber content.

Table 1. coded values with respect to parameter values

Levels	-1	0	1
Wt. % of NaOH	15	17.5	20
Wt. % of Fibre (weight percentage of fibres)	2	4	6
Fibre Diameter (µm)	250	375	500

Table 2. Samples obtained and their mechanical properties.

Sample Number	Wt.% of NaOH		Wt.% of Fibre		Fibre Diameter		Yield Stress	Ultimate Stress	Youngs Modulus
	Actual	Coded	Actual	Coded	Actual	Coded	MPa	MPa	MPa
1	20	1	375	0	6	1	33.68	36.08	6848.7
2	15	-1	375	0	2	-1	26.12	27.98	5249.27
3	17.5	0	375	0	4	0	36.26	38.85	10527.24
4	15	-1	250	-1	4	0	36.59	39.20	8176.21
5	20	1	500	1	4	0	35.8	38.36	8169.82
6	17.5	0	500	1	2	-1	25.42	27.23	6239.62
7	17.5	0	500	1	6	1	28.71	30.76	8510.55
8	17.5	0	375	0	4	0	36.26	38.85	10527.24
9	17.5	0	250	-1	2	-1	40.78	43.69	6618.06
10	17.5	0	250	-1	6	1	35.55	38.09	8311.05
11	15	-1	375	0	6	1	25.37	27.18	5505.91
12	20	+1	375	0	2	-1	37.69	40.38	7243.13
13	17.5	0	375	0	4	0	36.26	38.85	10527.24
14	20	+1	250	-1	4	0	41.48	44.44	9734.19
15	15	-1	500	1	4	0	28.69	30.74	7054.35
16	0	0	0	0	0	0	32.04	34.33	4337.98

RESULTS AND DISCUSSION

The calculation of fatigue limit can be done using three different criteria Soderberg, Goodman, and Gerber equations. The main advantage of using Soderberg criteria for the calculation of fatigue limits is that Soderberg is more conservative and safer than the other two equations. A comparative study of fatigue factor of safety was conducted between Soderberg and German standard DIN743 for shafts and axes [29]. They concluded that the Soderberg method is more conservative than DIN 743 for any given case as it presents lower safety factors. Therefore, the Soderberg factor of safety is selected for this study. The interaction of mean and alternating stresses on the fatigue life of a material is quantified by Soderberg equation. The equation is given in Equation 4.

According to the guidelines of the ASM handbook volume 19, the values of $\sigma_{\min}$ and $\sigma_{\max}$ are taken to be 80% and 40% of the σ_{yt} yield stress, respectively.

$$\left[\frac{\sigma_m}{\sigma_{yt}} + \frac{\sigma_a}{\sigma_e} \right] = 1 \quad (4)$$

Where,

σ_{yt} – yield Stress,

σ_e – Fatigue Limit,

σ_m – Mean Stress = $\frac{\sigma_{\max} + \sigma_{\min}}{2}$,

σ_a – Stress Amplitude = $\frac{\sigma_{\max} - \sigma_{\min}}{2}$,

$\sigma_{\min}$ – Minimum Stress = $0.4 * \sigma_{yt}$

$\sigma_{\max}$ – Maximum Stress = $0.8 * \sigma_{yt}$

Values of b and c are found using the equations 2 and 3. From the S-N curve equation, one gets the life cycles and alternating stress of every sample. The values of 7 alternating stresses are taken to be $0.6 * \sigma_{yt}$,

$0.7 \cdot \sigma_y$, $0.8 \cdot \sigma_y$, $0.9 \cdot \sigma_y$, $0.96 \cdot \sigma_y$, $0.98 \cdot \sigma_y$ and σ_e . Respective 7 life cycles are found for every 15 samples. With the use of life cycles and alternating stresses, S-N curve is plotted for every sample. Figure 1 represents the consolidated S-N curves of all 15 samples. The nature of the curve depicts highly varying behaviour between stress and cycles up to $0.6 \cdot \sigma_y$. Below a certain stress level i.e. endurance limit, the fatigue cycles become constant and approach infinite.

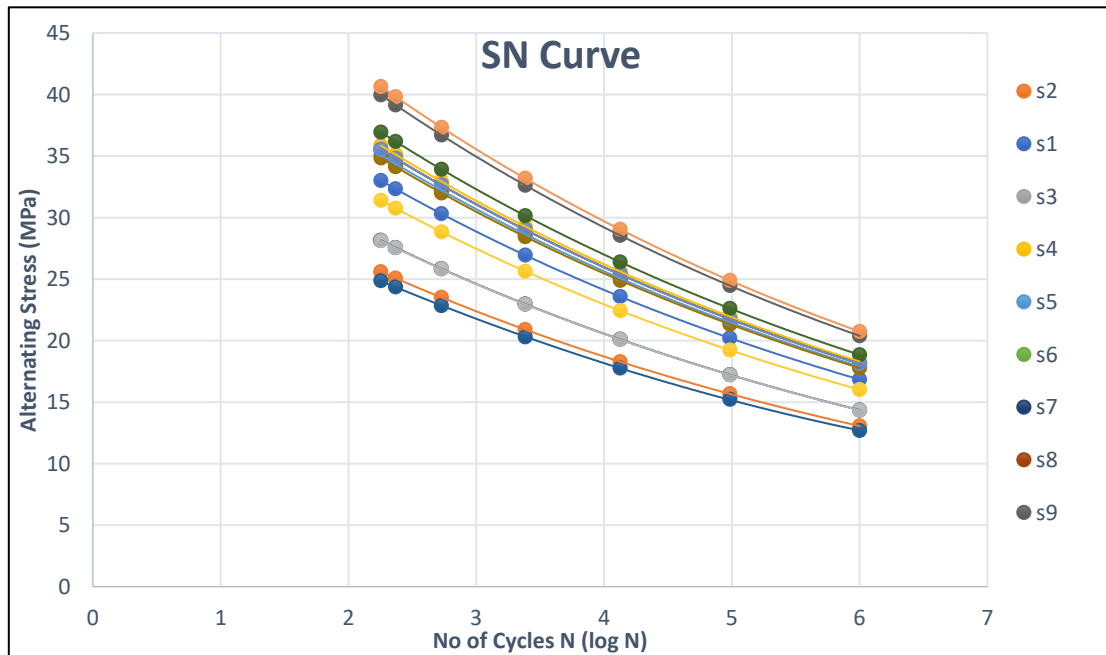


Figure 1. Consolidated S-N curve.

ANSYS Results

The sample is modelled in SOLIDWORKS as per ASTM D3039 standards with dimensions 250x25x2.5 mm³ in Figure 2.

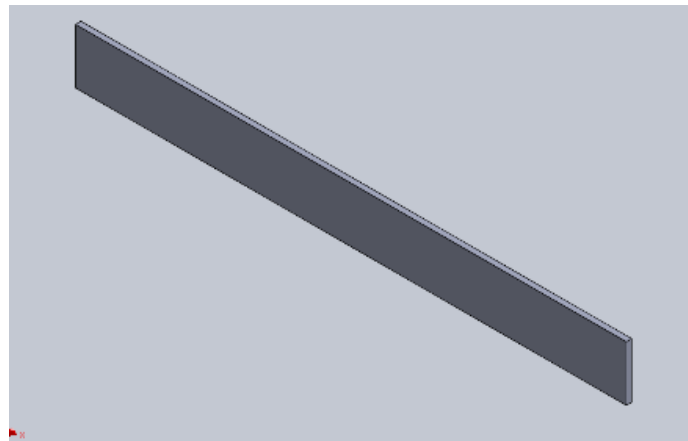


Figure 2. Three-dimensional image of specimen.

The fatigue behaviour of the Notched cantilever beam was validated in Ansys [30]. In their model, Equivalent alternating stress, life and factor of safety were studied and compared with reference values. The results were validated with less error percentage [30]. Similarly, Ansys is used in the present approach for finding the alternating stress and life. Material properties, calculated stress and cycle values are the input required for ANSYS analysis. Built-in Fatigue tool with Mean stress theory following the Soderberg criterion is utilized to run the analysis. The model is fixed on one end and a cyclic load of 825 N is applied on the opposite end in Figure 3. The load is found concerning the sample with the lowest yield strength corresponding to maximum alternating stress in the result. The same load is applied to all 15 samples in Figure 4 and 5. The results i.e. life and alternating stress are shown in Table 3.

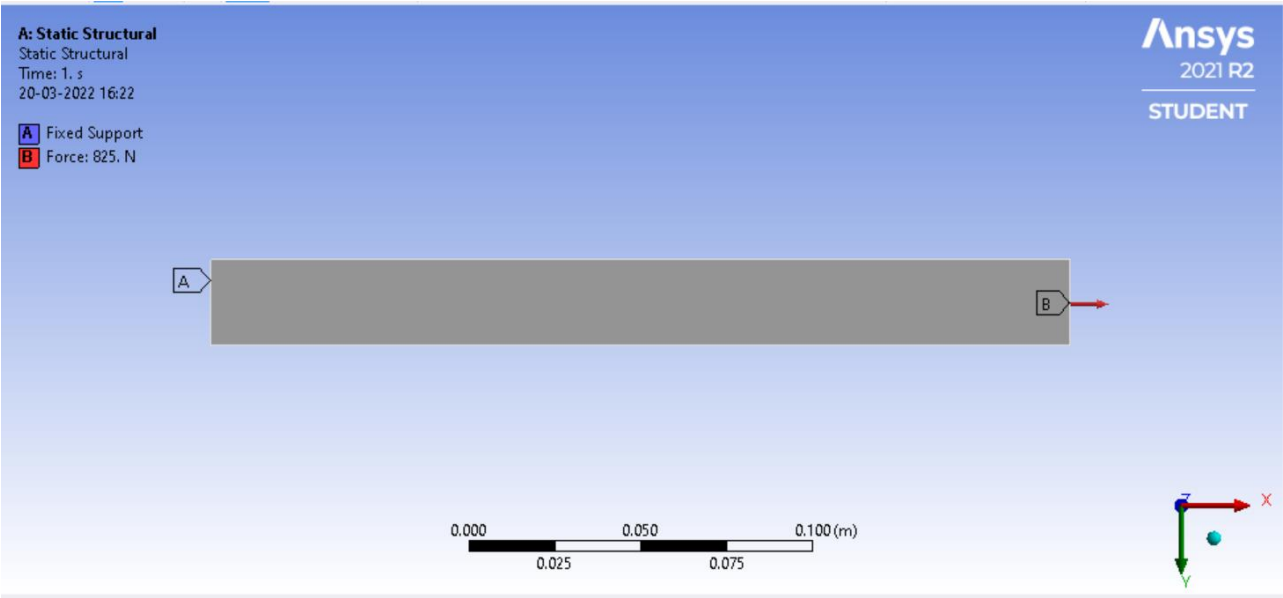


Figure 3. Loading Conditions.

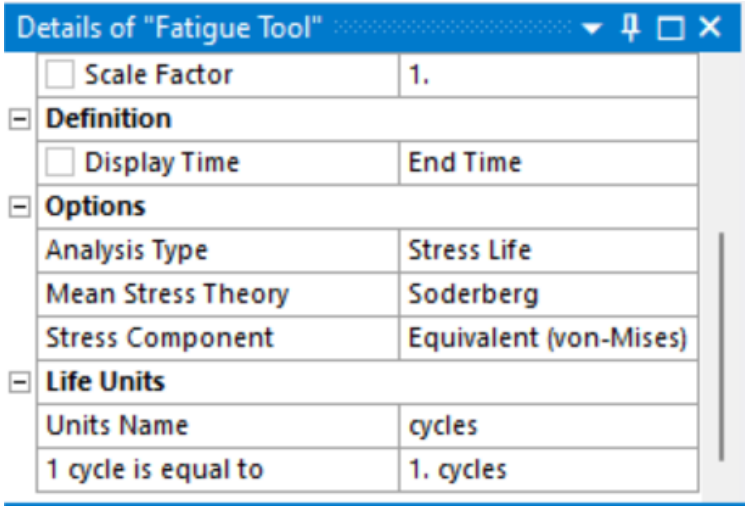


Figure 4. Fatigue tool Conditions.

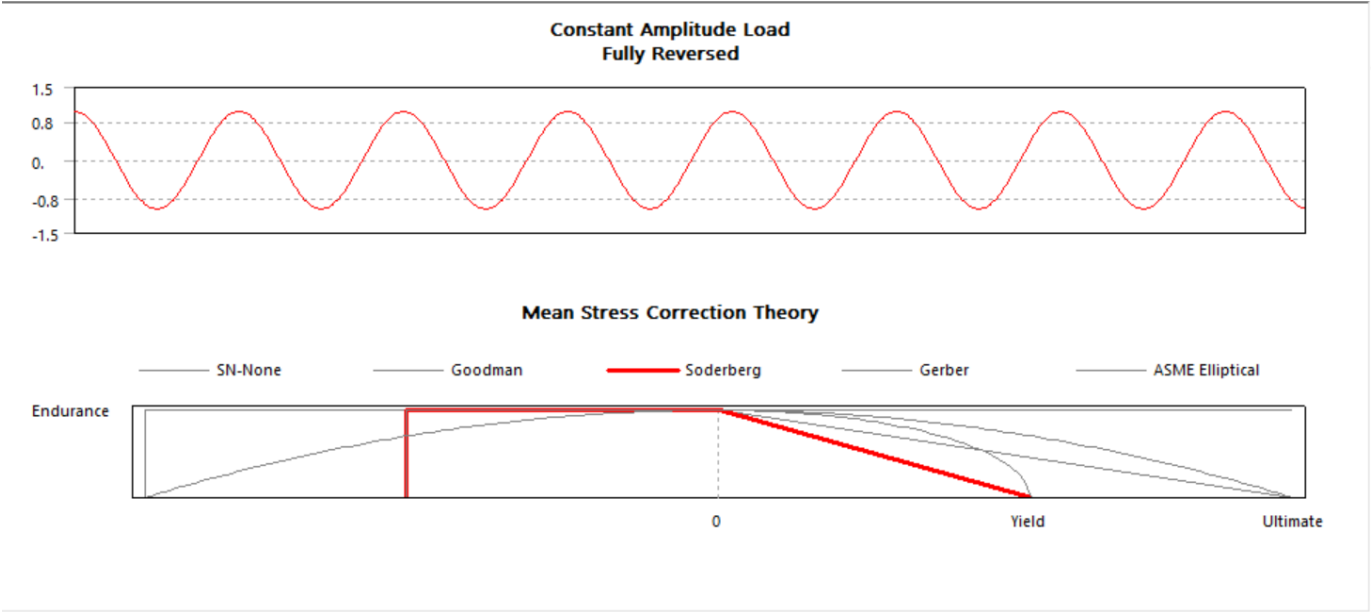


Figure 5. Loading and Fatigue criteria graph.

Table 3. ANSYS results for different combinations

Sample Number	Alternating stress MPa	Fatigue Life cycles(minimum)
1	17.67	5.62E+05
2	17.53	2.37E+04
3	17.67	1.00E+06
4	17.67	1.00E+06
5	17.53	1.00E+06
6	17.67	1.47E+04
7	17.81	6.45E+04
8	17.53	1.00E+06
9	17.67	1.00E+06
10	17.53	1.00E+06
11	17.81	1.29E+04
12	17.53	1.00E+06
13	17.67	1.00E+06
14	17.53	1.00E+06
15	17.81	6.40E+04
16	17.67	3.00E+05

The no of experiments in BBD is determined by Equation 5.

$$N = [2 * f * (f - 1)] + C \quad (5)$$

Where,

N – no of experiments, f-factors, C-central points.

Here, a three-factor / three-level model with three central points is taken and hence

$$N = [2 * 3 * (3 - 1)] + 3 = 15.$$

So, 15 samples are obtained for our analysis. In order to validate the regression equation obtained from the BBD model, the fatigue limit values are compared with values obtained from the Soderberg equation and their error percentages are found (Table 4). From the error %, it is noticeably clear that the regression equation holds good as all the error percentages are below 1%.

Table 4. Error percentage

Sample Number	Fatigue limit by current model (MPa)	Fatigue limit by Soderberg (MPa)	Error %
1	17.6735	17.67	0.02
2	17.621	17.67	-0.27
3	17.7965	17.81	-0.07
4	17.603	17.67	-0.38
5	17.849	17.81	0.21
6	17.6735	17.67	0.02
7	17.796	17.81	-0.08
8	17.6205	17.53	0.51
9	17.638	17.67	-0.18
10	17.6735	17.67	0.02
11	17.586	17.53	0.32
12	17.5505	17.53	0.11
13	17.604	17.53	0.42
14	17.5865	17.67	-0.47
15	17.551	17.53	0.12
16	17.6735	17.67	0.02

Regression Equation

ANOVA is used here to analyze the interaction between the three parameters NaOH%, Wt. % of Fibre , fiber diameter on fatigue life cycles. The results from ANSYS software are used for the ANOVA test carried out in statistical software called Minitab. The fatigue life cycles obtained from ANSYS and the corresponding actual values for each parameter are input to the Minitab.

$$\begin{aligned} \text{Fatigue limit} = & 15.38 + 0.238 \text{ NaOH} + 0.00126 \text{ Fiber Diameter} + 0.044 \text{ Wt. \% of Fibre} - \\ & 0.0056 \text{ NaOH} * \text{NaOH} - 0.000112 \text{ NaOH} * \text{Fiber Diameter} - 0.007 \text{ NaOH} * \text{Wt. \% of Fibre} + \\ & 0.00028 \text{ Fiber Diameter} * \text{Wt. \% of Fibre} \end{aligned} \quad (6)$$

Since the model is validated using fatigue limit, it is decided to proceed to find out the influence of parameters on the fatigue life cycle using the same model.

Table 5. ANOVA table

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	2.80254E+12	3.11393E+11	7.96	0.017
Linear	3	5.50499E+11	1.83500E+11	4.69	0.065
NaOH	1	93615276608	93615276608	2.39	0.183
Fiber Diameter	1	1.21862E+11	1.21862E+11	3.11	0.138
Wt. % of Fibre	1	2.92321E+11	2.92321E+11	7.47	0.041
Square	3	7.39971E+11	2.46657E+11	6.30	0.038
NaOH*NaOH	1	1.15825E+11	1.15825E+11	2.96	0.146
Fiber Diameter*Fiber Diameter	1	11949000577	11949000577	0.31	0.604
Wt. % of Fibre* Wt. % of Fibre	1	6.61629E+11	6.61629E+11	16.90	0.009
2-Way Interaction	3	2.65342E+11	88447312212	2.26	0.199
NaOH*Fiber Diameter	1	2.19026E+11	2.19026E+11	5.60	0.064
NaOH* Wt. % of Fibre	1	45694833932	45694833932	1.17	0.329
Fiber Diameter* Wt. % of Fibre	1	621230700	621230700	0.02	0.905
Error	5	1.95720E+11	39143943120		
Lack-of-Fit	3	1.95720E+11	65239905200	*	*
Pure Error	2	0	0		
Total	14	2.99826E+12			

The F-value of the model is 7.96 as depicted in Table 5. Higher F-Value depicts the importance of the model. The squared term of Wt. % of Fibre has the highest F-Value i.e. 16.90 and hence has the most influence on the response. A P-Value of less than 0.05 is considered a significant term corresponding to a high F-value. One can find most terms are significant. Terms like 'Fiber Diameter * Wt. % of Fibre' have a P-Value greater than 0.10 and hence are regarded as insignificant.

Pareto chart (Figure 6) gives us a clear picture that Wt. % of Fibre plays a vital role in deciding the fatigue life cycle of the composite compared to other parameters i.e. NaOH% and fiber diameter. Meanwhile, fiber diameter has the least influence among others. A regression equation is used to calculate the virtual fatigue life of the fiber reinforced composite and the same is given in Equation 7.

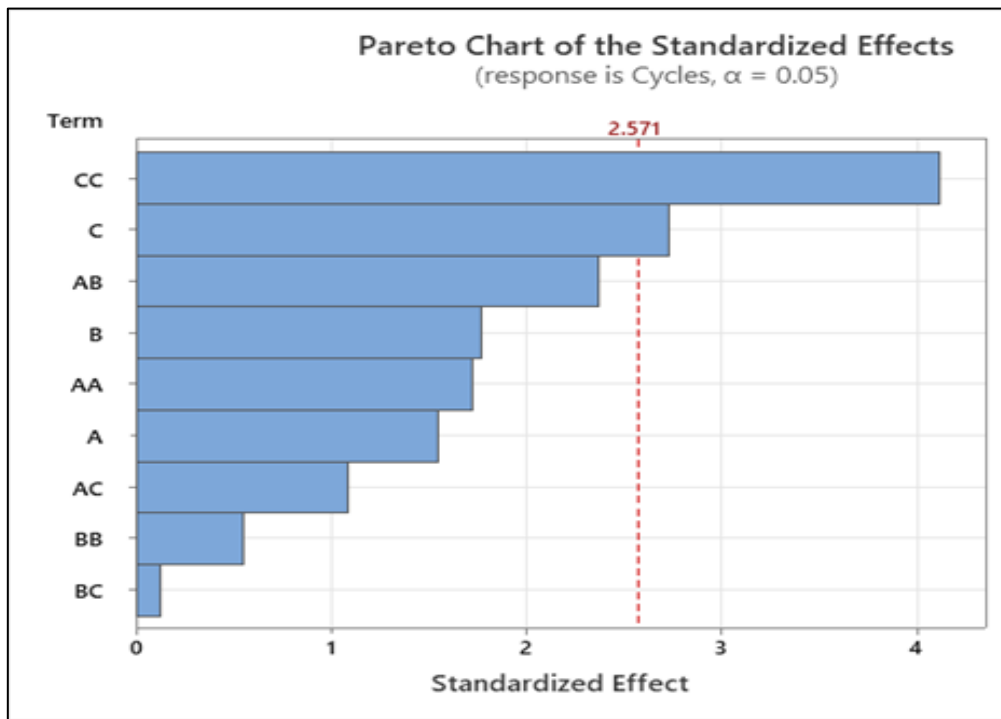


Figure 6. Pareto chart.

Regression Equation

$$\begin{aligned} \text{Lifecycles} = & -7373740 + 919597 \text{ NaOH} - 13430 \text{ Fiber Diameter} + 1177063 \text{ Wt. \% of Fibre} - \\ & 28338 \text{ NaOH} * \text{NaOH} - 3.64 \text{ Fiber Diameter} * \text{Fiber Diameter} - 105827 \text{ Wt. \% of Fibre} * \text{Wt. \% of Fibre} + \\ & 749 \text{ NaOH} * \text{Fiber Diameter} - 21376 \text{ NaOH} * \text{Wt. \% of Fibre} + 50 \text{ Fiber Diameter} * \\ & \text{Wt. \% of Fibre} \end{aligned} \quad (7)$$

The contour plot shows the effect of the interaction of parameters on the response. In Figure 7, the parameters taken are fibre diameter and NaOH.

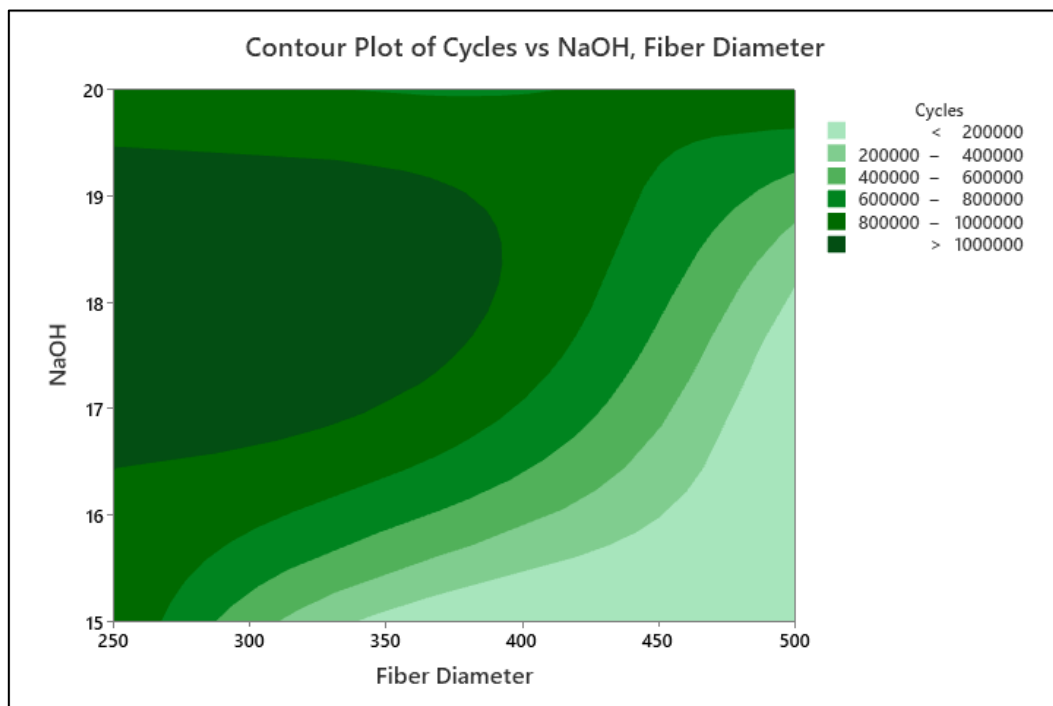


Figure 7. Contour plot of cycles vs NaOH, Fiber Diameter.

The plot (Figure 7) figures out that a higher fibre diameter and lower value of NaOH% interaction results in minimum cycles whereas the lower fibre diameter and value of NaOH% around 18 gives the composite maximum life cycles. In Figure 8, the interaction between NaOH% and fibre volume is studied. This plot depicts that higher NaOH% gives maximum cycles and Wt. % of Fibre of around 4 yields maximum cycles whereas the highest and lowest values of Wt. % of Fibre give only a minimum number of cycles. Figure 9 shows the interaction of fibre diameter and Wt. % of Fibre and it concludes that minimal fibre diameter and value of Wt. % of Fibre around 4 gives higher life cycles.

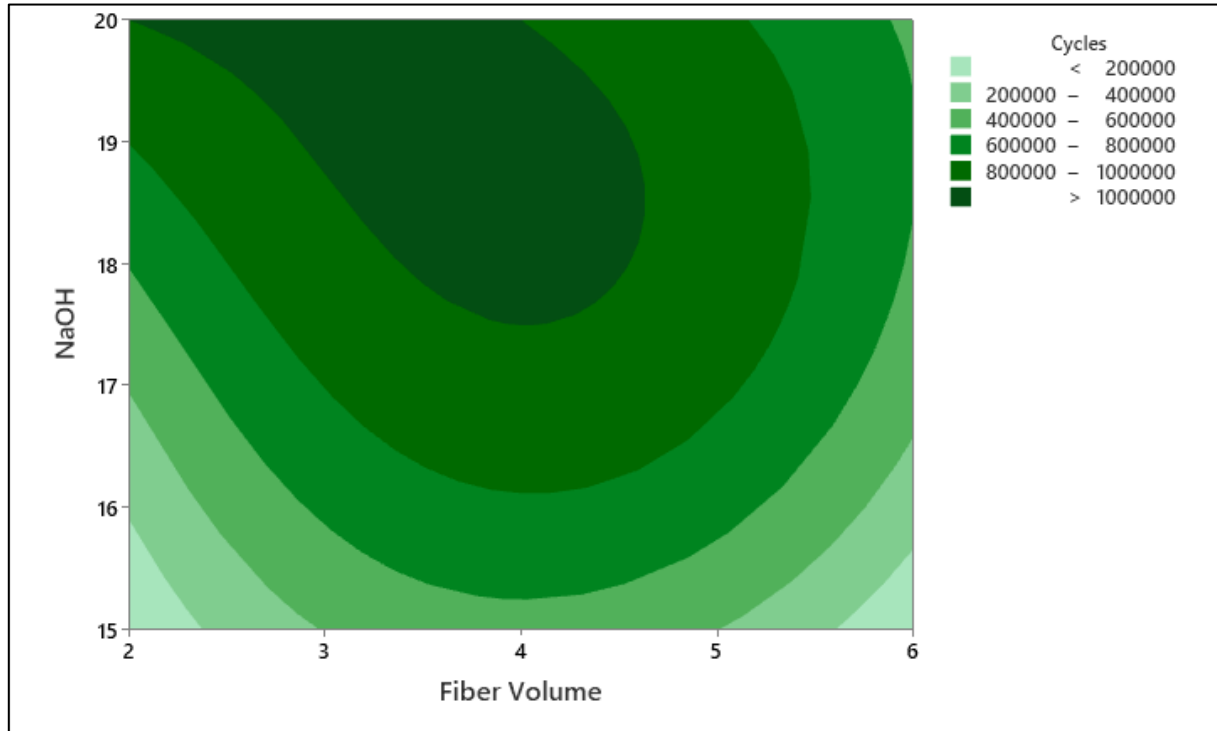


Figure 8. Contour plot of cycles vs NaOH, Wt. % of Fibre

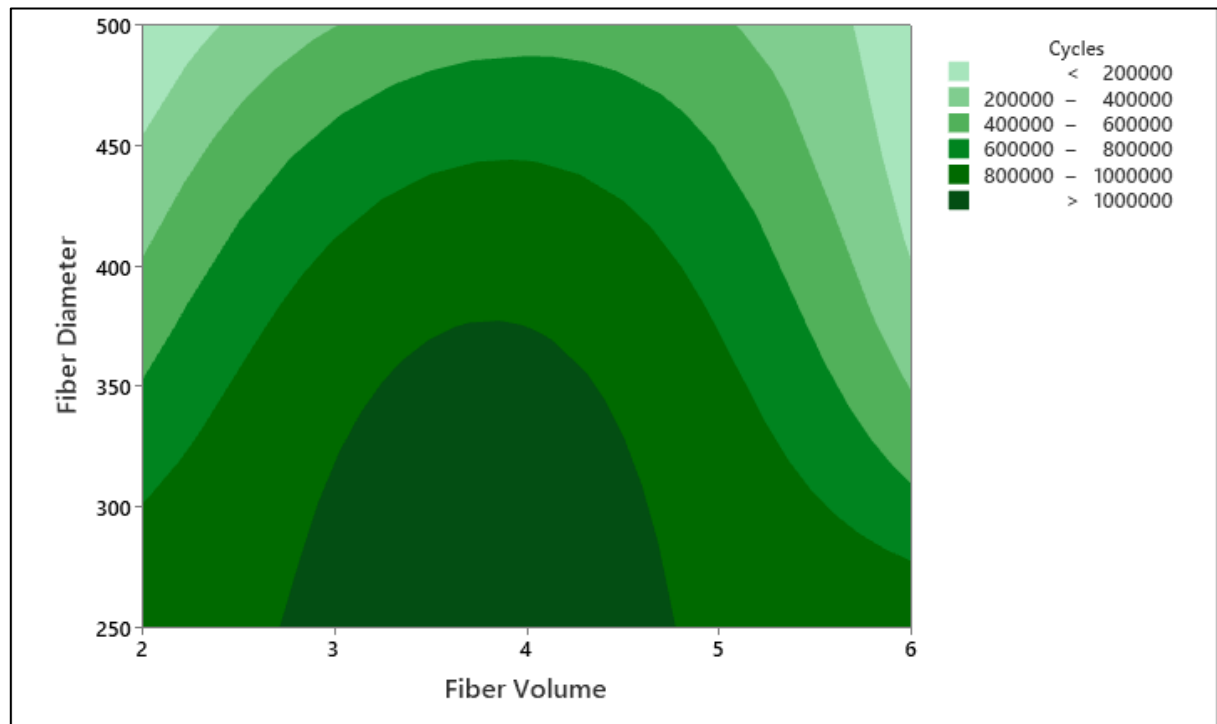


Figure 9. Contour plot of cycles vs Wt. % of Fibre , Fiber Diameter

The main effect plot (Figure 10) depicts the individual effects of parameters on the response i.e., fatigue life cycles. It is found a steep increase in cycles when NaOH% is increased from 15% to 17.5% and a meagre

increase after 17.5%. Fiber diameter has a negative correlation with life cycles. Life cycles decrease as the diameter increases from 250 to 500 μm . The Wt. % of Fibre positively impacts the life cycles up to 4% and anything beyond has a decreasing effect on life cycles.

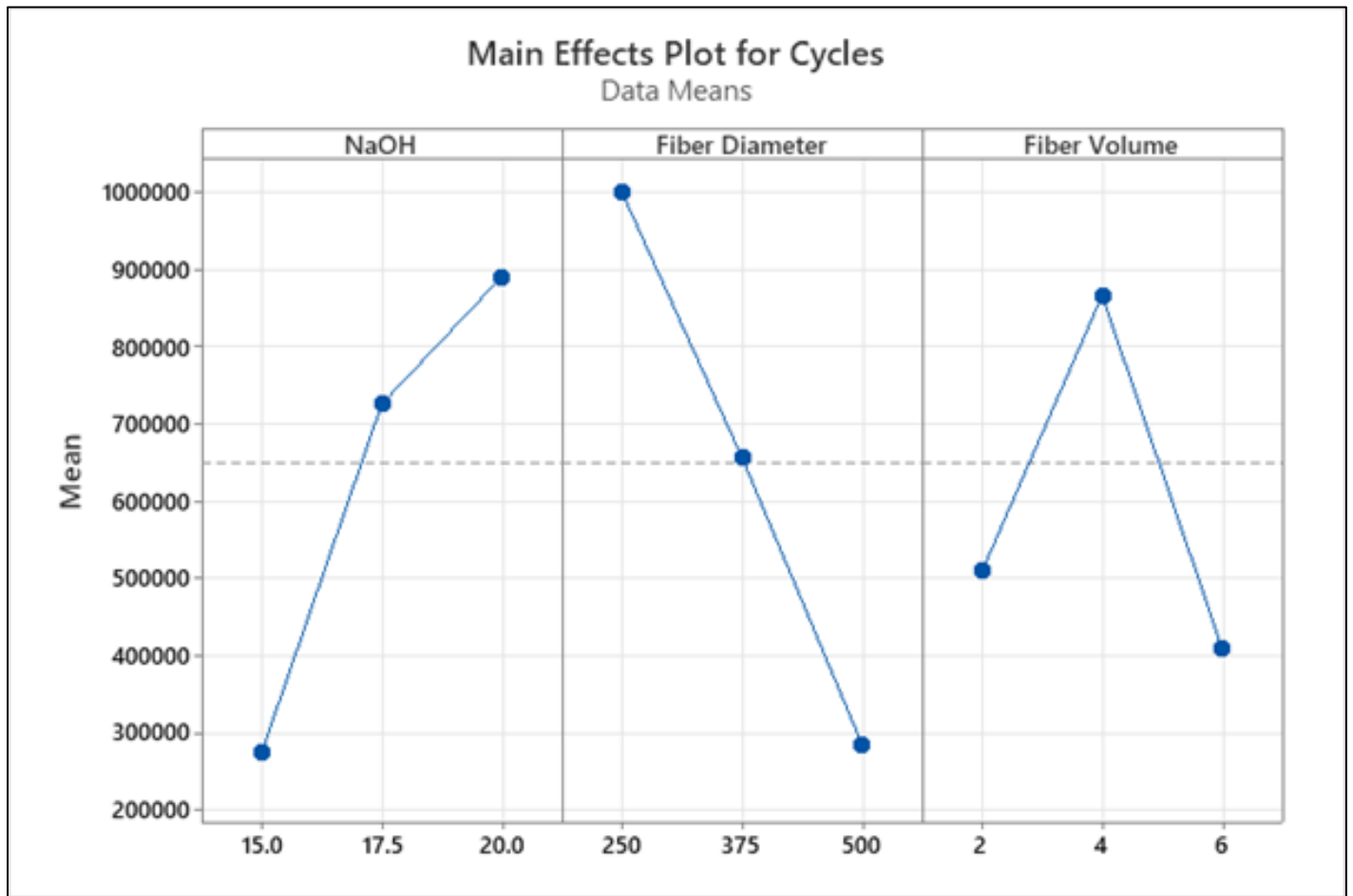


Figure 10. Main effects plot for cycles

Optimisation

Optimised results are found using response optimisation in Minitab. In this case, the response i.e., fatigue life cycles are required to be maximum is shown in Figure 11. For the parameter NaOH%, the optimum concentration for fatigue life cycles to be maximum is 18.08. Similarly, one can find fibre diameter of 250 μm yields maximum fatigue life. Finally, the Wt. % of Fibre at 3.77% provides a maximum fatigue life cycle is mentioned in Table 6.

Table 6. Optimization table

Parameters					
Response	Goal	Lower	Target Upper	Weight	Importance
Cycles	Maximum	12917	1000000	1	1
Solution					
Solution	Fiber Diameter(μm)	NaOH %(w/w)	Wt. % of Fibre	Cycle Fit	Composite Desirability
1	250	18.0808	3.77778	1312233	1

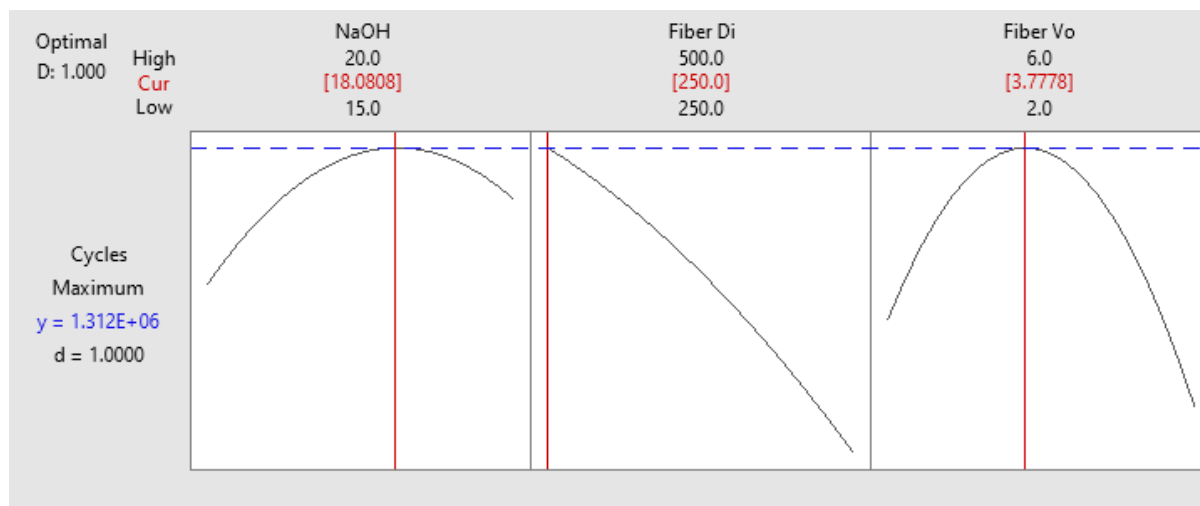


Figure 11. Optimization graph

CONCLUSION

In this study, the authors explore the development of sustainable green composites by reinforcing natural fibers into a polymer matrix, aiming to replace synthetic / non-biodegradable fibers. The composites are prepared using chemically treated cellulose microfibrils as reinforcements and epoxy as the matrix. The virtual Fatigue life of cellulose microfibrils reinforced epoxy polymer matrix composite is investigated using ANSYS with Soderberg criterion. Response surface methodology (RSM), a DOE model, is utilised to find out the influence of parameters such as NaOH%, fibre diameter Wt. % of Fibre and number of samples on fatigue life cycle based on box Behnen design (BBD). The results, obtained from ANSYS, are undergone. ANOVA test using Minitab software. Various charts such as Pareto, main effect plot, contour plot and surface plots are used to describe the interaction between the parameters and their influence on the fatigue life of the composite. These findings underscore the potential of natural fiber-reinforced composites in various engineering applications, particularly in the aerospace and automotive industries, where fatigue resistance is critical. By leveraging the abundance and renewability of natural fibers, this research contributes to the development of eco-friendly materials that promote sustainable practices and effective waste management. Finally, the response optimizer is used to arrive optimum combinations that provide the maximum fatigue life cycles.

The following observations are made from the study:

1. The optimum values for attaining maximum fatigue life are 18.08 NaOH %, 250 μ m fiber diameter and 3.778 Wt. % of Fibre . The maximum fatigue life obtained is 13,12,223 cycles.
2. The life cycles have a positive correlation with the concentration of NaOH% whereas it has a negative correlation with fiber diameter. It is interesting to note that in the case of Wt. % of Fibre , the life cycles increase up to 4% and then decrease.

The optimization of the input parameters not only enhances the performance of the composite materials but also paves the way for future research focused on further improving the mechanical properties and environmental benefits of natural fiber-reinforced composites.

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