Research Article

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Fatigue behaviour of Kevlar/carbon/basalt fibre-reinforced SiC nanofiller particulate hybrid epoxy composite

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Abstract: It is vital to conduct research on the behaviour of natural fibre composites under cyclic loading in order to have confidence in the mechanical durability. During this study, the fabrication of composite laminates will be carried out by the hybridization effect of natural and synthetic fibres. Quantifying the impact that the SiC filler (10, 20, and 30 g) has when combined with the fibre reinforcement and epoxy matrix (275 g) under cyclic loading circumstances and determining the significant sequence of hybrid composites are the goals of this research. The results of the tensile mode were used to determine the input parameters, and based on the tensile strength of the hybrid composite, 70% of the tensile strength was fixed at 3 Hz frequency as the input for fatigue analysis. The life span was then determined for the hybrid composite. The results of this fatigue test showed that increasing the amount of SiC nanofillers produced a very high potential output for the fatigue test. As a result of increasing the amount of silicon carbide fillers from 10 to 30 g, sample S3 was able to significantly tolerate 65% more life. Failure mode can be identified from scanning electron microscope analysis revealing the major porosity, matrix crack, and laminate bonding strength that causes the failure during fatigue analysis.

Keywords: natural fibre, synthetic fibre, silicon carbide, fatigue analysis, Scanning electron microscope morphology

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1 Introduction

Polymer composites can be created by mixing polymers with a variety of continuous and noncontiguous reinforcements/fillers. In addition to their widespread use in industries such as aviation, automotive, the military, and sports, polymer-based composites are increasingly being used in biomedicine, particularly in fields like tissue engineering, wound dressings, drug release, regenerative medicine, dental resin composites, and surgical procedures (1). Fatigue behaviour of numerous chopped-glass- and carbon-fibre-reinforced thermoplastics was investigated. The authors demonstrated that the fatigue behaviour of the composite was determined by the ductility of the matrix, the type of fibre used, and the quality of the interface between the fibre and the matrix. Carbon fibre composites showed a more matrix and interface-dominated reactivity than glass fibre composites (2).

In spite of the structural benefits provided by synthetic composites such as carbon fibre composites and glass fibre composites, these materials have several limitations, such as high cost of the raw materials, and they create an end-of-life negative effect on the environment, as the synthetic composites cannot be recycled and do not degrade (3). The fatigue behaviour of thermoplastic composites reinforced with natural fibres was experimentally investigated, and a novel semi-analytical model was constructed to account for this phenomenon. Based on the loading situation, fibre fraction, and moisture absorption, this model may estimate the fatigue life of various materials. Natural fibre composites' fatigue behaviour was investigated and modelled using fatigue stress-life (S–N) curves (4). As an alternative to high-strength aluminium alloys, hybrid composite laminates known as glass aluminium-reinforced epoxy have been used, particularly for aircraft structures. These laminates consist of different layers of unidirectional glass-fibre reinforced plastic laminate and thin aluminium alloy sheets (5). It was observed that the fatigue behaviours of the hybrid composites were greatly enhanced with the addition of alumina nanoparticles, rubber micro-particles, and silica nanoparticles. When subjected to tension–tension, compression–tension, and tension–compression fatigue loading, the fraction of carbon fibres present in hybrid glass/carbon composites has a considerable impact on the fatigue lifetime of the composites (6). The fatigue behaviour and damage mechanism of composites based on high-performance carbon fibres or graphite fibres for reinforcement, and carbon or graphite for matrix, were related to many parameters, such as experimental conditions. These conditions included a variety of load types, loading frequencies, and stress ratios. An experimental study on the fatigue behaviour of woven flax fibre hybridized with woven glass fibre, with the epoxy matrix serving as the substrate was carried out (7). The findings of the study indicated that there is a possibility of increasing the fatigue strength and fatigue life of laminate structures using materials that contain natural fibres. The fatigue behaviour of carbon, Kevlar-49, and epoxy hybrid composites was investigated. Under repeated tension–tension and compression–tension loads, and with various stress ratios, S–N graphs were plotted for both unidirectional and hybrid laminates (8). The term endurance limit or fatigue limit refers to a limit that most engineering materials have, which is a safe zone for the stress level below which failure can never occur, even after being subjected to an infinitely high number of loading cycles. This level of stress can be precisely determined with regard to metals. On the contrary, fibre-reinforced polymer matrix composites typically do not have a fatigue limit. This is due to the fact that the complex damage patterns that are observed in composite materials consist of matrix cracks, fibre fractures, fibre/matrix interface debonding, inter-ply delamination cracks, and the various interactions between these damage patterns (9). As a result, the majority of research efforts are concentrated on establishing a connection between the observed damage or a damage parameter and the mechanical properties of the laminates (10). When contrasted with the large number of static tests on composite materials clearly specified, the fatigue testing of laminates is much less restrictive. In order to prevent failures in the vicinity of the grip jaws, it is essential to have accurate alignment and proper grasping (11). Additionally, in order to prevent buckling during tests that involve compressive loads, high lateral stiffness is absolutely necessary. Because of the effects of friction, using some of the anti-buckling guides that are designed for static testing in cyclic testing can be troublesome. This fact should be brought to your attention (12). Now fatigue testing software is available that can monitor the temperature of the test specimen and intelligently modify the test frequency in order to shorten the test length while simultaneously ensuring that the specimen does not become too hot. When a composite material has failed a fatigue test, monitoring any damage that occurs throughout the test is not a simple task. Monitoring the change in specimen stiffness as the test progresses is a standard method for tracking damage, although de-lamination damage has very little impact on tensile stiffness (13). Poly-para-phenylene terephthalamide is the name of the chemical component used in the production of the man-made material known as Kevlar. Kevlar, also known as para-aramid, is a type of synthetic fibre that is both strong and resistant to heat. It is a synthetic fibre that can withstand high temperatures and is quite robust (14). Compared to other synthetic and natural fibres, Kevlar possesses more desirable properties, which places it in an advantageous position for use in a variety of load-bearing applications. It has a high tensile strength-to-weight ratio, which indicates that, in comparison to a typical material, it possesses a higher tensile strength at a lower weight (15). This is the most essential characteristic it possesses. Although Kevlar is resistant to most chemical conditions, it is still subject to degradation. When subjected to the action of certain aqueous acids, bases, or sodium hypochlorite. A carbon fibre is made up of a chain of carbon atoms that are linked to one another (16). The fibres are utilized in various processes to produce high-quality building materials due to their exceptional rigidity, strength, and lightweight. Carbon fibre material is available in a wide variety of raw building blocks, such as yarns, unidirectional, weaves, and braids. These raw building blocks are then utilized in the process of fabricating carbon fibre composite parts (17). There are a great number of specialized subcategories contained within each of these larger categories. The strength of carbon fibre is unmatched. In the field of engineering, it is a common practice to evaluate the usefulness of a material in terms of its strength-to-weight ratio and its stiffness-to-weight ratio. This practice is especially common in structural design, where an increase in weight may result in increased lifecycle cost or less-than-satisfactory performance (18). The modulus of elasticity is a measurement used to determine the rigidity of a material. Basalt is a naturally occurring substance that can be found in rocks generated by the solidification of lava. Basalt fibre is made from broken-up pieces of basalt rock, which are then placed in a furnace and heated to temperatures between 1,500°C and 17,000°C before being melted into a silk-like consistency using a platinum-iridium alloy leaky plate (19). Since its discovery in 1923, basalt fibre has also been put to use in a variety of military applications. In the field of armour protection, basalt fibre outperforms typical bullet-proof fibres such as glass fibre, aramid fibre, and ultra-high molecular weight polyethylene fibre (20). The chemical composition of basalt fibre is identical to that of glass fibre; it consists of SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3, and FeO. However, basalt fibre is more resistant to the effects of strong alkalis than glass fibre. On the basis of the results of the mechanical testing, the percentage of weight that is composed of sisal fibre in the Sisal/polypropylene (PP) composites has been optimized to be 42 wt%. In order to improve the tribological and mechanical performance of sisal fibre-reinforced polypropylene composites for use in automobile and construction applications, sisal fibres were hybridized with recycled glass and carbon fibres (21). This was done in order to improve the tribological and mechanical properties of the composites. Despite this, much effort and progress have been made to improve the mechanical properties of natural fiber polymer composites, such as through the hybridization process or the addition of nanofillers in order to achieve performance that is comparable to that of synthetic polymer composites (22). The fatigue behaviour of hemp-reinforced high-density polyethylene (HDPE) was studied. Hemp fibre inclusion increased the overall fatigue strength of the polymer matrix but had no effect on the sensitivity of the generated fatigue life curves. Although the unreinforced HDPE showed ductile-brittle fatigue failures, the composites consistently showed brittle failures (23).

The previous research served as the foundation for the present work, which focuses on the fabrication of hybrid composites using carbon, Kevlar, and basalt fibre reinforcement with silicon carbide used as a filler blended with epoxy resin as the matrix material. Furthermore, the fatigue behaviour of this composite is investigated, and the impact of fibre sequence and filler material on this composite is identified.

2 Materials and experimental method of hybrid composite

In this study, three different fibres were used to reinforce Kevlar. The carbon fibres were supplied by SM Composites, Chennai, India and Go Green Pvt Ltd, Chennai, India. Polyepoxides LY1564 epoxy resin, Araldite (HY951), and silicon carbide filler materials were provided by Zhengzhou Xinli Wear-Resistant Materials Co., Chennai, India.

2.1 Experimental process

The standard hand layup process was used to fabricate hybrid composite laminates because it was the most cost-efficient method, and a diverse range of materials were utilized in the fabrication of this composite (24). In this process, the resin is applied with brushes and rollers in order to minimize the formation of air bubbles. The chemical reaction that occurs during the mixing process can either involve the hardener as a reactant or as a catalyst, depending on the ratio of the hardener to an epoxy resin used. The hybridization of reinforcement, filler, and matrix was utilized in the composite fabrication process. The hybridization of the composite was done through the use of the traditional hand layup procedure, and the mild stainless-steel mould was used for the fabrication process (25). The first step was to apply liquid wax as a mould releasing agent on a 25 cm × 25 cm steel mould. Next, a predefined 40% epoxy resin was blended with hardener at a 10:1 ratio using a hand electric stirrer for 5 min continuously (25). After that, 10% SiC filler was applied to the matrix, and the hand layup process commenced (26). Fabrication of a hybrid composite by reinforcing natural and synthetic fibres and varying the weight fraction of three separate samples of carbon, Kevlar, and basalt fibres was carried out. The ratios of 45% filler, 5% filler, and 50% epoxy matrix were used to quantify the effect of hybrid composites. Following the completion of the fabrication process, the mould is subjected to room temperature compression with 15 kg of weight for up to 48 h in order to complete the curing process of the hybrid composite. Following that, the press consolidation method was utilized to prepare hybrid composite laminates without air bubbles. For better curing, the hybrid composite laminates were placed in a hot furnace at 175°C for 1 h, after which the laminates were removed from the mould without defects and the composite plate for the fatigue test samples was cut to have dimensions of 150 mm × 200 mm × 5 mm, as specified by the ASTM standards (27). The weight ratios of composite laminates are given in Table 1.

2.2 Fatigue test and scanning electron microscope (SEM) analysis of hybrid composite

The ability of a material to withstand cyclic fatigue loading conditions can be determined using a fatigue test. A material is chosen specifically to meet or surpass the service loads expected in fatigue testing applications. This decision is made during the design phase. The fatigue test is used to estimate the remaining useful life of a material after it has been subjected to cyclic loading. In addition, the fatigue strength and crack resistance of the material are frequently sought for values. The fatigue life of a material is defined as the total number of cycles that it can withstand while still maintaining its integrity under a particular loading scheme. A fatigue test is also used to determine the maximum load that a sample is capable of withstanding for a predetermined number of cycles. This is done by repeatedly subjecting the sample to the same load. Any sector of the economy in which the substance in question is subjected to variable rather than continuous influences necessitates the existence of all these qualities. This particular experiment used strain-controlled low cycle fatigue tests, which typically entail plastic deformations in accordance with the ASTM standard. The ASTM 3479 standard for fatigue testing was followed, and the tests were carried out in load control mode while subjected to a tension–tension sinusoidal cycle. Each type was evaluated using three different samples. During the fatigue test, the highest load applied was equal to 70% of the load of the material's ultimate tensile strength (UTS), and the minimum load applied was equal to 10% of the maximum load applied. Since this was the case, the loading ratio was 0.1. During cyclic loading, the minimum applied load was used to define the loading ratio, and the highest applied load was used to define the loading ratio (fatigue test). The term "loading frequency" refers to the number of fatigue cycles that are completed each second. The loading frequency was kept at 3 Hz throughout the fatigue tests. Because composite materials have a tendency to generate heat when subjected to cyclic loading, particularly in tension–tension mode, the frequency was kept low (less than 5 Hz) in order to decrease the influence of self-heat generated by the material (28). SEM testing includes sweeping an electron beam over a sample in order to generate a magnified image that can then be analysed. Microanalysis and failure analysis of solid inorganic materials are two of the most common applications for this technique, which is also known as SEM analysis and SEM microscopy. Both terms refer to the same entity. High magnifications are used in the electron microscopy technique, resulting in high-resolution images and accurate assessment of very small features and objects. The resolution is 0.6 nm at 15 kV, 0.7 nm at 1 kV, 1.0 nm at 0.5 kV, and 3.0 nm at 5 kV. The probe current is 5 nA, the working distance is 10 mm, and the electron gun is a lens Schottky combined with a field emission (FE) gun (29). The JSM-7900F is a flagship model in the present SEM region of an FE-SEM that aims to assist research and technological advances for future generations. These developments are intended to benefit future generations. The JSM-700F successfully combines ultrahigh-resolution analysis with increased usability. Figure 1 shows fatigue testing, sample analysis, and SEM analysis of the hybrid composite.

3 Results and discussion

3.1 Fatigue behaviour

The ability of a material to withstand cyclic fatigue loading conditions can be determined using a fatigue test. This approach has a manufacturing limit as well, which is determined based on the level of complexity of the aircraft (30). This technique can be applied to any material, such as carbon or basalt fibre, and in any shape (continuous fibre, chopped fibre, woven, etc.). A material is chosen specifically to meet or surpass the anticipated service loads in fatigue testing applications. This decision is made during the design phase. The tensile properties of the S1, S2, and S3 specimens are 63, 90, and 128 MPa, respectively, which match to the testing conditions for the frequency of 3 Hz with three tensile properties. During composite testing, load cycles are divided into measurements for the half, stable, and final loads. The findings of the tests show that specimen S3 has a higher score than the other two specimens, each of which has a lower score than the previous level. The results of fatigue tests (fatigue life, high cycles to failure) at a loading frequency of 3 Hz to a mean fatigue life for Kevlar, carbon, and basalt within the three samples S1,

Table 1: Weight ratio of composite laminates

Sample	Weight of matrix (g)	Weight of filler (g)	Weight of Kevlar (g)	Weight of carbon (g)	Weight of basalt (g)	Weight of composite laminates (g)
S1	275	10	78	64	78	505
S2	275	20	78	64	78	515
S3	275	30	78	64	78	525

Figure 1: Testing of the hybrid composite.

S2, and S3 in different sequences of hybrid composite materials were found to be 0 cycle to 30,900 cycles, respectively. These results were found for a series of hybrid composite materials. Standard deviation in fatigue life for and hybrid composites was found to be that the S1 sample began with 3 Hz of frequency and reached values of 10,801 cycles, the S2 sample began with the same 3 Hz of frequency and reached values of 21,060 cycles, and the S3 sample began with the same 3 Hz of frequency and reached values of 30,900 cycles, which is the sample considered to be high performed among the other samples S1 and S2, respectively. The standard deviation in fatigue life for and hybrid composites were found to be S3. According to the findings, sample S2 hybrid composites displayed a fatigue life comparable to sample S1 and sample S3 hybrid composites. The addition of 30 g of silicon carbide nanofillers in S3 composites increased fatigue life, which was greater than in the other two samples. In another work, the fatigue limit of a Ramie fibre composite was tested at a loading frequency of 3 Hz in order to select fatigue limits close to 45% of UTS. The purpose of this experiment was to determine the impact of loading frequency on fatigue life, and it was carried out at three distinct loading frequencies (3, 5, and 10 Hz). With more frequent loading, the fatigue threshold was observed to gradually decrease. In addition, an experimental method was used to separate two types of damage energy during cyclic loading and determine the primary damage energy responsible for the decrease in fatigue limit with increasing loading frequency (31). Additionally, in the previous test, the tensile test, sample S3 with the highest output value among other samples as the given lower frequency that in our composite materials are also attained. While the tensile modes of sample composites S1 and S2 were almost similar in fatigue at different frequency levels, the flexural modes of the samples were relatively different. Because of the presence of a high quantity of nanofiller, the fatigue life of S3 was very long (in terms of the number of cycles necessary to fail). Therefore, the bonding between the fibre laminates is greater when the addition of filler material has a significant response while subjected to cyclic loading. Because the bonding between the fibres and matrix is robust and filler materials are used to stabilize the load transfer between the fibre laminates, hybrid composites have a significant material life. This is due to the fact that the hybrid composites allow for significant load transfer between the fibre's laminates (32). The value of fatigue analysis is shown in Figure 2.

In a separate piece of research, it was found that the fatigue behaviour of an interaction carbon/Kevlar-reinforced epoxy hybrid composite subjected to static and cyclic stress (6,000 cycles) at a frequency of 10 Hz was shown to be

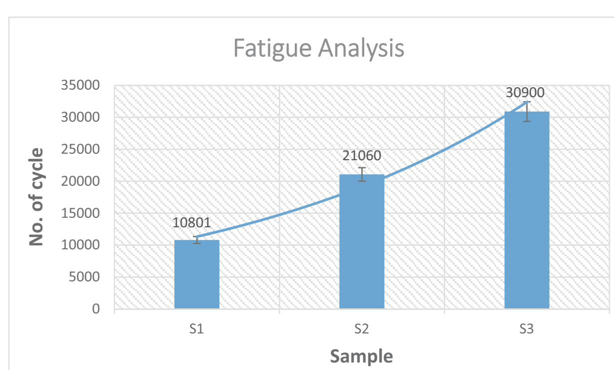

Figure 2: Fatigue behaviour chart.

Table 2: Parametric analysis of fatigue in hybrid composite specimen

Parameter	Specimen					
	S1		S2		S3	
	Test cycles					
	I	II	I	II	I	II
Peak stress (MPa)	90.2	90.4	128.3	128.1	183.7	183.8
Stress valley (MPa)	38.7	38.5	65.16	65.10	84.46	84.37
Stress range (MPa)	40.6	40.6	67.55	67.60	87.49	87.43
Calculated peak strain (mm·mm^{-1})	342.8	339.5	287.51	291.54	272.15	273.25
Calculated strain valley (mm·mm^{-1})	178.04	177.2	134.62	138.85	111.898	111.77
Calculated strain range (mm·mm^{-1})	164.78	162.2	152.88	152.68	160.25	161.47
Unloading modulus load control (MPa)	0.051	0.058	0.0483	0.0425	0.045	0.039
Loading modulus load control (MPa)	0.0409	0.059	0.0384	0.044	0.0386	0.0486

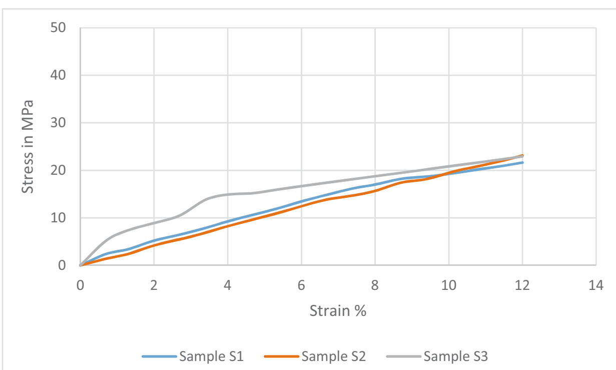

Figure 3: SN curves of fatigue analysis.

significantly dependent on the fibre characteristics (33). When compared to these composites, we used a lower frequency of 3 Hz, resulting in the highest cyclic loading (30,900 cycles). This was made possible by including 30 g of filler particles in the sample. These particles contributed significantly to the stiffness of the gaps between the fibres. Table 2 represents the parametric fatigue analysis in the hybrid composite specimens. Figure 3 depicts the output values of fatigue behaviour as represented by SN plots.

3.2 SEM analysis of hybrid composite

SEM analysis of the composite specimen after the fatigue load applied, which is revealed clearly the matrix was broken, this types of failure is produced by inappropriate bonding between the matrix and the reinforcement (27). This proves that fibre breakage, matrix fracture, fibre debonding, and fibre pull-outs can be observed after a tensile test on either composite. The presence of fibrous material on the fracture surface can be seen quite

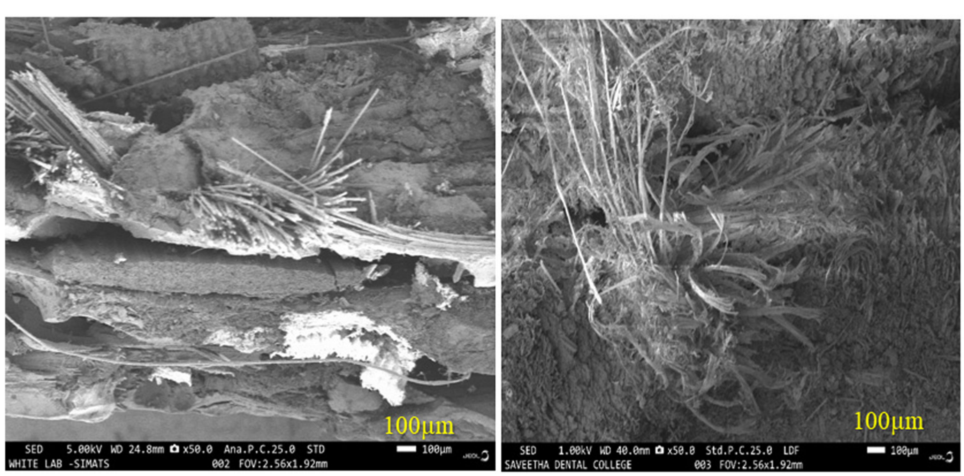

Figure 4: SEM image of hybrid composite.

naturally in the images. Lower fibre content will result in poor mechanical properties because there are fewer fibres available to support the load transferred from the matrix. Another study found that adhesion, abrasive, and adhesive wear mechanisms exist in hybrid fibre-reinforced PP composites using confocal and scanning electron microscopy. It has been observed that increasing the amount of sisal fibre content leads to increased fibrillation as well as larger transfer films on surfaces that have been worn (2). The effect of the SEM image reveals that the fibres, fillers, and epoxy resin bonding are significantly used to withstand the mechanical loading on this hybrid composite. Figure 4 shows the morphological surface of the hybrid composite.

4 Conclusion

As a result of this study's findings, fatigue can be evaluated under cyclic loading, and the collected data are used to discuss and finalize the significant sample. During this fatigue analysis, the mode of failure of the significant sample was determined. Each sequence comprises three basalt layers, two carbon layers, and three Kevlar layers. The increase in silicon carbide particles has caused the most significant change in all of the test results. Thirty grams of silicon carbide particles were discovered in sample 3. In comparison to the other samples, this shows that increasing the amount of silicon carbide particles used as filler results in an increase in the material's strength. When adding 2% more SiC filler to this composite S1, the number of cycles it can withstand is 10,801 cycles. Adding 4% and 6% more SiC filler to samples S2 and S3 increases the number of cycles they can withstand to 21,060 and 30,900 cycles, respectively. It demonstrates that there is a 65% difference in output fatigue life between S1 and S3 as a result of the presence of nanofillers, which work to lower the failure rate and increase the material's resistance to cyclic loading conditions.

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