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ORIGINAL PAPER

Silane Grafted Nanosilica and Aramid Fibre-Reinforced Epoxy Composite: DMA, Fatigue and Dynamic Loading Behaviour

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Abstract

In this present investigation silane grafted aramid fibre (kevlar) and nanosilica was reinforced into epoxy resin to improve the dynamic mechanical behaviours of steam turbine blade designed and tested. The primary aim of this research was to analyse the failure in aramid fibre-reinforced epoxy composite and prevention measures by incorporating the nanosilica particle. Both the nanosilica and aramid fibre was silane-treated to prevent shear failure under mechanical and thermal loading. The composites were prepared using hand layup method followed by post curing. The composites were subjected to various dynamic-mechanical characterizations and finite element analysis. The dynamic mechanical analysis (DMA) showed that the composite made using silane treated nanosilica and aramid fibre holds higher glass transition temperature and storage modulus. Similarly, the tension-tension fatigue results showed improved life cycle for silane treated composites with higher laminar adhesion. The computational flow dynamics (CFD) results revealed less thermal stress and strain on silane-treated epoxy composite designation N_3. These dynamic loading failure resistance epoxy composites could be used in steam turbine blades, prime movers, automobile body parts and structural applications.

Keywords PMC · Aramid fibre · Nanosilica · Silane treatment · DMA · CFD

1 Introduction

High performance mechanically and thermally stable polymer composites have attracting applications in various engineering applications such as automobile, aircrafts, domestic, defence and structural [1]. Composite materials are often preferred for light weight applications since these materials possess excellent mechanical and thermal properties [2]. The unique advantages such as high strength to weight ratio, economically good, environment friendly and easy processing methods woos its deployment in many engineering application to replace the metallic materials [3]. However, the composites have some noted demerits in their functionally. Under higher thermal condition the fibre delamination from matrix is one of the main drawbacks when these composites aimed for thermal fatigue working conditions [4]. To improve the fibre-matrix interfacial adhesion many research studies are reported by various researchers all over the world. Rajadurai et al. [5] investigated the laminar shear strength and mechanical properties of acid, base and silane treated glass fibre in epoxy resin composite. Authors concluded that the silane treatment on glass fibre improved the strength of composite on compare with acid and base treated fibre in epoxy resin. Prakash VRA et al. [6] have shown the improvement on silane treated iron oxide and glass fibre in epoxy composite. Author concluded that the silane surface-treated glass fibre and iron oxide is seen giving better performance in thermal and mechanical behaviour than composites made using as-received reinforcements. Similarly,

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Arunprakash et al. [7] investigated the effect of silicon coupling grafted ferric oxide and E-glass fibre in thermal stability, wear and tensile fatigue behaviour of epoxy hybrid composite. Authors concluded that the silane treated ferric oxide in glass-epoxy composite is better in fatigue and thermal behaviour. Thus the previous studies proved that the silane treatment is the better process to improve the thermo-mechanical and dynamic behaviour of polymer composites. In many recent studies instead of glass fibre aramid fibre is used when the composite is aimed for high thermal and ballistic loading applications. Usually the kevlar holds high load penetration resistance and toughness. Thus many researchers tuned to invest aramid fibre rather than glass fibre in composites. Khodadadi et al. [8] have done a comparative study on high velocity impact behaviour of Kevlar/rubber and Kevlar/epoxy composites. Authors have done the energy absorption study through ballistic performance to know the effectiveness of kevlar addition in both rubber and epoxy matrixes. Author concluded that the matrix is hugely responsible for maintaining better ballistic performance in composites. The addition of more kevlar fibre in rubber matrix improved the ballistic performance than kevlar fibre in rigid epoxy matrix. The rubber matrix enhances the energy absorption of the fabric by keeping composite flexibility. Similarly, Suthan et al. [9] completed an experimental study on evaluation of mechanical properties of kevlar fibre epoxy composites. Authors have done two forms of composites namely aluminium-epoxy and kevlar-epoxy composites. Authors evaluated the mechanical characteristics like tensile, impact strength and flexural rigidity. With the results obtained it is found that kevlar epoxy composite provides better mechanical characteristics than aluminum. Thus based on the previous studies by various researchers it is found that for ballistic and high energy absorption behaviour kevlar is more suitable than glass fibre. In addition to that the nanosilica particles also providing fine applications with kevlar, glass and natural fibres. The presence of nanosilica would improve the thermal stability and load bearing capability of epoxy composite. There are many research studies are evidenced for this behaviour. Jayabalakrishnan et al. [10] fabricated and characterized acrylonitrile butadiene rubber and stitched e-glass fibre tailored nanosilica epoxy resin composite. According to author's conclusion the inclusion of nanosilica into the glass-epoxy composite improved the energy absorption and reduced the micro crack propagation. Ben et al. [11] researched the visco-elastic, thermal, antimicrobial and dielectric behaviour of areca fibre-reinforced nanosilica and neem oil-toughened epoxy resin biocomposite. The research outcome of this present study confirmed that the silane treated nanosilica particle improved the visco-elastic and antimicrobial behaviour on composite. Similarly, Yu et al. [12] studied the effect of organosilane coupling agents on microstructure and properties of nanosilica/epoxy composites. The study revealed that the ultimate flexural strength of the composites with 4 wt.% of nanoparticle modified by γ-aminopropyltriethoxysilane, γ-glycidoxypropyltrimethoxysilane, and γ-methacryloxypropyltrimethoxysilane are increased by 10, 30, and 8% relative to the unmodified composites. Thus from the previous literatures the role of aramid fibre and nanosilica particle is noteworthy when the composite is aiming for providing high performance in mechanical, thermal and ballistic behaviour. There are more studies presented in kevlar and nanosilica combination in epoxy resin and relative outcomes were also studied. However, the studies related to amino silane treatment on kevlar surface and dynamic analysis is very less. Moreover the finite element study on real time application based studies also fairly quoted. Thus based on this research gap, the present investigation aimed to investigates the effect of silane-treatment on kevlar and nanosilica in dynamic mechanical loading of epoxy composite and finite element analysis of real time steam turbine blade model. Moreover the composites could be prepared using hand layup method since; this method is simple and energy efficient. There is no power requirement to make the composites like other methods such as resin transfer moulding and compression moulding [13].

2 Experiment

2.1 Materials

The matrix material used here was a liquid epoxy of density 1.18 g/cm^3 and molecular mass of 190 g/mol. The curing hardener used for curing the composites are triethelyetetramine (TETA) having 0.4 g/cm^3 and 97.8 g/mol of density and molecular mass respectively. Both the resin and hardener was purchased from HUNTSMAN India Ltd., Mumbai. The aramid fibre (Kevlar-49™) woven mat of 450GSM used in this present study was purchased from Metro composites R&D Centre, Chennai, India. Similarly, the nanosilica of size 20 nm was purchased from Sigma Aldrich, USA. The surface modifier APTMS and other chemicals used for this present investigation was purchased from MERCK India Ltd. All the chemicals are prepared strictly with the user guidelines and process requirements.

2.2 Silane-Treatment of Reinforcements

A 95 wt.% of ethanol and 5 wt.% of water was mixed with gentle stirring to form aqueous solution. The acetic acid of required quantity was added into ethanol-water solution until the pH of solution is tuned between 4.5 to 5.0. The silane substance of 3 wt.% with respect to the amount of reinforcement taken was then added with ethanol–water solution as drop by drop. The Kevlar fiber and nanosilica particle was then briefly dipped into the silane solution for 10 min to perform silanation process. The treated fibre and nanosilica was separated out and heated using hot plate for 10 min at 110 °C to form Si-O-Si structure [14]. The silane grafting on the kevlar and nanosilica surface was confirmed via FT-IR spectral analysis. Figure 1 shows the FT-IR spectral graph of nanosilica particle after silane treatment. The peak at 3474 cm^{-1} indicates the presence of NH_2 functional group. Similarly, peak at 2900 cm^{-1} indicates the presence of C-H stretch, which is from attached propyl group. Moreover the vibrational frequencies at 1465 cm^{-1} and 1060 cm^{-1} were also confirmed the C-H bend which is hailed from pure silane. Finally the peak at 878 cm^{-1} indicates the existence of Si-O-Si structure after the heat treatment of silane treated nanosilica. Thus the process of silane surface grafting induced reactive groups on inorganic nanosilica surface, which may enrich the adhesion behaviour between particle and matrix.

2.3 Composite Preparation

The epoxy resin composite was prepared using hand layup method in this present investigation. First the required amount of nanosilica particle (0.5, 1 and 2 vol.%) in as-received and silane surface treated form was mixed with epoxy resin and stirred continuously using a mechanical stirrer for 10 min. Simultaneously, a composite making mould with lean wax coating was made prior to the composite making process. A required amount of kevlar fiber of 40 vol.% equal to 3 lamina was then laid one by one into the resin. The composites were cured at room temperature for about 24 h and post cured at 120^{o} C for 48 h in a hot oven. Table 1 shows the composition and designation of composites [15]. The prepared epoxy composites were inspected for surface defects and get machined using an abrasive water jet machine (Maxiem water jets, USA) for further characterizations. The machining parameters such as operating pressure of 200 MPa, an abrasive flow rate of 0.30 g/s and nozzle diameter as 0.75 mm were maintained for all composites [16].

3 Characterization

3.1 General

The visco-elastic properties such as storage modulus, loss factor and glass transition temperature have been evaluated using a DMA analyzer (SEIKO, DMS EXSTAR 6100, USA) in accordance with ASTM D 4065 as temperature sweep mode. These properties were tested to understand the ability of composite material to store and dissipate energy during a loading cycle and heat energy required to convert the rigid form of composite to soft nature. The test sample used in this investigation was having length of 50 mm, width of 12.7 mm and thickness of 2 mm. The temperature variation applied here was between 30^{o}C to 240^{o}C at a constant frequency of 1 KHz with dual form cantilever fixtures with a heating rate of 50^{o}C/min. From the test results, the storage modulus and loss factor values were calculated. Similarly, the tension-tension fatigue behaviour of epoxy and its composites were tested using a load frame (MTS Landmark 370, USA) in-

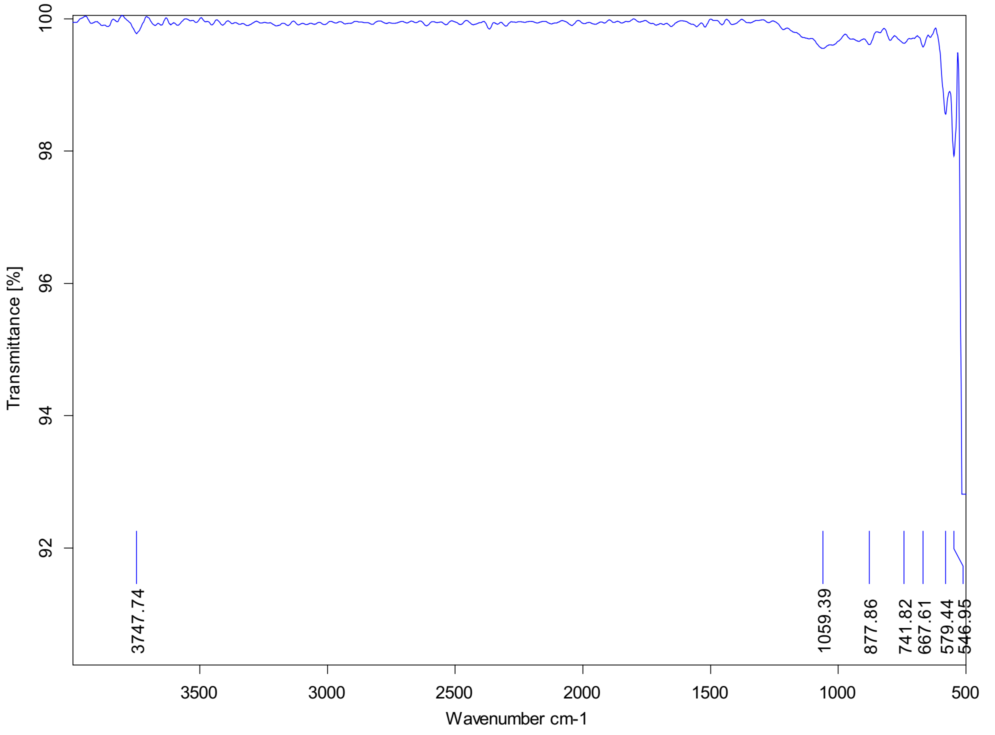


Fig. 1 FT-IR spectral peaks of silane treated nanosilica

Table 1 Designations of epoxy composites with compositions

Composite Designation	Epoxy (vol.%)	kevlar Fibre (vol.%)	Nanosilica (vol.%)
N_0	100	–	–
N_1	59.5	40	0.5
N_2	59.0	40	1.0
N_3	58.0	40	2.0

Table 2 FEA Input parameters

Parameter	Value
Mass flow rate (kg/s)	1.8
Steam temperature (^oC)	120
Density of steam (g/cm^3)	0.022
Mach Number	0.25
Steam velocity	25 m/s

accordance to ASTM D 3479. The ultimate stress of 50% is fixed as input stress with stress ratio of R = 1 and frequency of 5 Hz. Figure 2 shows the ASTM test specimens (a) DMA and (b) fatigue with dimensions.

3.2 Finite Element Analysis

The deformation during the live test was analysed using finite element steam turbine blade model with epoxy composite properties and run by using ANSYS CFX, version 2019, R2. The maximum number of nodes used here was 1 L with dynamic loading condition. In this present study the MAT 54/55 code was used and the failure criterion used here was Chang–Chang criterion with 1 L node category. Initially the 2-D design of standard steam turbine blade was drawn using Pro e, PTC wildfire 5.0 and imported into the Ansys platform. In this version the results can be post-processed live in Ansys CFD-Post using GPU-accelerated animations. The tool is capable of making single row blade flutter and inlet disturbance cases, single disturbance harmonic analysis solutions and single-stage TBR cases using Fourier Transformation or Time Transformation pitch change. Table 2 shows the input parameters for the finite element analysis done.

4 Results and Discussions

4.1 Dynamic Mechanical Analysis

Tables 3, 4 and 5 presents the values of storage modulus, loss factor and glass transition temperature of epoxy and its composites. It is observed that the pure epoxy resin gives the storage modulus and loss factor of 2.26GPa and 0.42 with glass transition temperature of 63°C. This lower storage modulus, loss factor and Tg is the reason of high brittleness of epoxy resin, which could keep absorbs energy until the molecules getting crystalline. Since the epoxy resin as brittle the molecules are rigid enough and trying to align with respect to the energy applied. But due to the covalent bond reactions during the curing process the molecules could not able to align and fractured. Similarly, the loss factor of 0.42 is observed due to the rigid and tight molecular structure, which couldn't response to the repeated loading. When the loading is continues with specific interval the amount of plastic strain stored in the high cross linked epoxy structure increases and produced plastic deformation. The degree of energy release is very less thus the fracture happened at early stage itself [17].

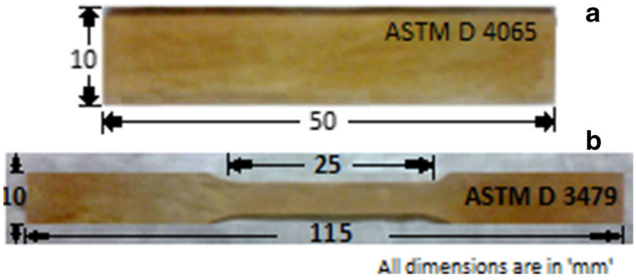


Fig. 2 DMA test specimen

It is further noted that the addition of as-received and silane treated kevlar fibre of 40 vol.% and nanosilica of 0.5 vol.% into epoxy resin further improved the storage modulus and loss factor. The improvement of 20% and 41% was observed in storage modulus and 64% and 83% of improvement in loss factor for as-received and surface modified composite designation N_1. This significant improvement is because of presence of high energy absorbing kevlar fibre and nanosilica particle. The presence of nanosilica particle do absorbs the energy and reduces the rotation of attached secondary molecules of epoxy resin. Thus the Tg is improved thereby increasing the storage modulus. Similarly, the improved toughness of matrix by the addition of high toughness kevlar fibre smoothly dissipates the stored energy at the time of load removal. The accumulation of plastic stress and strain is reduces thereby increased the energy release rate [18]. It is observed that the

Table 3 Storage Modulus of epoxy composites at 1KHz

Composite Designation	As-received (GPa)	Surface-modified (GPa)	Improvement (%)
N_0	2.26		–
N_1	2.72	3.18	17
N_2	3.94	4.25	8
N_3	4.18	4.38	5

Table 4 Loss factor of epoxy composites at 1KHz

Composite Designation	As-received	Surface-modified	Improvement (%)
N_0	0.42		–
N_1	0.69	0.77	12
N_2	0.54	0.84	56
N_3	0.50	0.79	58

further addition of nanosilica of 1 and 2 vol.% into aramid fibre-epoxy composite improved the storage modulus of composite. The highest storage modulus of 4.38GPa was observed for surface modified composite designation N_3, which is near 94% of improvement on compare with neat epoxy resin. This improvement is because of presence of silane-treated nanosilica particle of large volume (up to 2), which improved the energy absorption due to its high inherent specific heat capacity and incremental in density. The increment in density facilitates the epoxy molecules to admit lots of energy to freely rotate about their axis. This nature improved the glass transition temperature of N_1, N_2 and N_3 composites [19]. The improvement of 14%, 21%, 37% and 22%, 41%, 46% were observed for as-received and surface modified composite designations N_1, N_2 and N_3 on comparing with pure epoxy resin N_0. This improvement in glass transition temperature led further improvements in storage modulus.

Similar effects were observed in loss factor also. The highest loss factor of 0.84 was observed for surface-modified aramid-nanosilica epoxy composite (N_2). On compare with epoxy resin this is almost 100% of improvement. This improved loss factor is the cause of low acquisition of plastic strain during every cycles of loading. The presence of high toughness kevlar and nanosilica particle never let the matrix to store large plastic strain thus the dissipation of heat in every loading is smoothly increased. Moreover the effective void filling of nanosilica in epoxy resin reduces the free voids in the matrix. This phenomenon reduces the molecular stretching and acquisition of plastic strain in the cross linked matrix; thus improved the loss factor [20].

Table 5 Glass transition temperature of epoxy composites

Composite Designation	As-received (°C)	Surface-modified (°C)	Improvement (%)
N_0	63		–
N_1	72	77	7
N_2	76	89	17
N_3	86	92	7

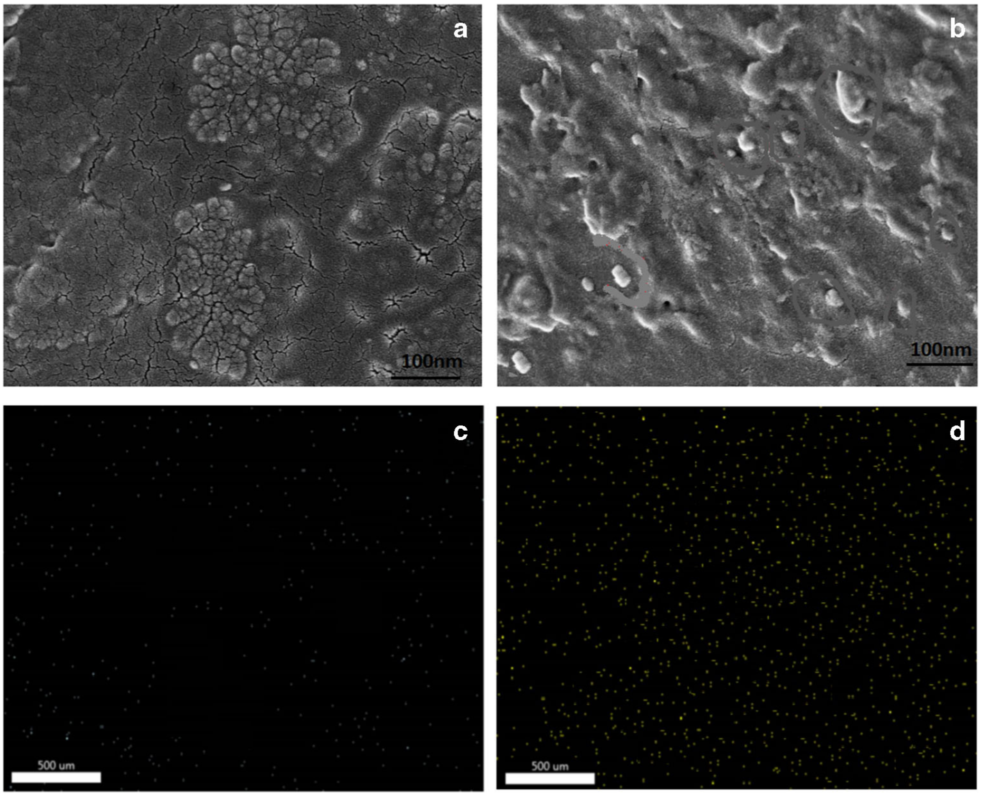
It is noted that in all composite designations the silane-treated nanosilica and kevlar fibre gives improved storage modulus. The improvement of 17%, 8% and 5% were noted for surface-treated epoxy composites N_1, N_2 and N_3. Similarly, improvement of 12%, 56% and 58% also were observed at loss factor for N_1, N_2 and N_3 composite designations. This improvement is the cause of two mechanisms. Firstly the silane treated nanosilica disperses on the matrix as more uniform. The functionally activated nanosilica particle chemically reacts with free OH molecules of epoxy resin thus, uniform dispersion is achieved. Thus the particle-particle attraction and agglomeration on matrix is significantly reduced. Moreover, the silane treatment never alters the actual cross section of fibre and particle. There is no surface leaching takes place. The silane substance just covers the reinforcement as a cap and provides reinforcement effect to the matrix via functional group reaction. But in other surface treatments like acid, base and plasma the surface molecules washes away thereby reduction is cross section is occurred, which resulted subsequent failure in load bearing effect [21]. Second, the silane-treated nanosilica and kevlar fibre chemically reacts with epoxy resin thus the interfacial adhesion between the matrix and reinforcement is high. Thus the load sharing effect between matrix and reinforcement is smooth and there is no stress intensity zone around the fibre-matrix interface observed. Thus the stress intensity factor on the crack tip of inbound micro cracks are nominally less, which in turn improves the storage modulus of epoxy composite. Figure 3 shows the scanning electron microscopy image of nanosilica dispersion in epoxy matrix. Figure 3(a) shows the as-received nanosilica in epoxy. The particles are agglomerated and hinder the uniform dispersion. But in Fig. 3(b) the silane-treated nanosilica particle shows uniform dispersion on matrix. There is no cluster due to the surface coverage by amino silane. The same effect was confirmed using elemental mapping technique too.

Figure 3(c and d) shows the nanosilica distribution in the epoxy matrix. It is evidenced that the as-received nanosilica formed clusters (grey dots) while the silane-treated nanosilica explicit uniform dispersion. This nature improved the dynamic mechanical behaviour of epoxy composite at greater level. Thus the silane treatment on reinforcements facilitates improvement in adhesion and dispersion quality of nano elements in high denser matrix medium. This phenomenon may improve the dynamic mechanical behaviour of epoxy composites [22].

4.2 Fatigue Behaviour

Table 6 shows the fatigue life cycle of epoxy and its kevlar fibre reinforced nanosilica toughened composites. It is noted that the pure epoxy resin gives the fatigue life cycle of 371. This lower fatigue life cycle is the reason of high brittle nature

Fig. 3 SEM and elemental mapping of nanosilica dispersion in matrix (a & c) as-received and (b & d) silane-treated



of bare epoxy molecules, which could not stretch when the repeated load is applied. The energy dissipation during the repeated loading is literally hampered due to the inelastic nature of matrix material, thus storage of plastic strain in the material is very high. But it is further noted that the addition of nanosilica particle of 0.5, 1.0 and 2.0 vol.% along with 40 vol.% of kevlar fibre improved the fatigue life counts. Moreover the silane surface treated kevlar fibre and nanosilica particle greatly improved the fatigue life counts. The improvement of 10, 12 and 13% were recorded for composites made using silane surface treated reinforcements. This improvement is the reason for effective load sharing ability and improvement of toughness. The presence of kevlar and nanosilica particle effectively absorbs the repeated load and reduces impend of crack propagation [23 and 24]. The high toughness of kevlar fibre improves the energy storage and release, while the nanosilica particle presents in the free space of matrix and suppress the initiation of micro cracks and flaws to grow further. The presence of nanosilica in the crack tip hinders the propagation of cracks to grow further, thus larger energy is required to makes the cracks open [25]. It is further observed that the silane treated kevlar fibre and nanosilica particle combo provided improved fatigue life cycle. This improvement is the outcome of increased adhesion of fibre to resin and uniform dispersion of nanosilica particle in epoxy matrix. The NH_2 functional group in the grafted nanosilica and kevlar fibre enhances the adhesion and dispersion behaviour. The interfacial delamination resistance between the fibre-matrix phases is improved and stable for higher loading cycles. Similarly, the uniform dispersion of nanosilica particle greatly suppresses the crack initiation by reducing lumpy clusters of nanosilica in high denser epoxy resin matrix. Thus the stress intensity factor in the crack tip becomes less thereby improved the fatigue life cycle. Figure 4 shows the scanning electron microscope images of fatigue fractured as-received and silane surface treated N_3 composite designation. It is observed that in Fig. 4(a) the fibre pullout is seen and it is because of poor bonding strength of fibre with matrix. Thus when the tensile load is applied, the fibre separated from matrix phase and makes early delamination. However in silane surface-treated kevlar fibre the fibre pullouts were not seen. The matrix and fibre has the broken surfaces at the same point. The fibre is

Table 6 Tension-tension fatigue life cycle of epoxy composites

Composite Designation	As-received (counts)	Surface-modified (counts)	Improvement (%)
N_0	371		–
N_1	32,284	35,617	10
N_2	36,633	40,881	12
N_3	35,738	40,967	15

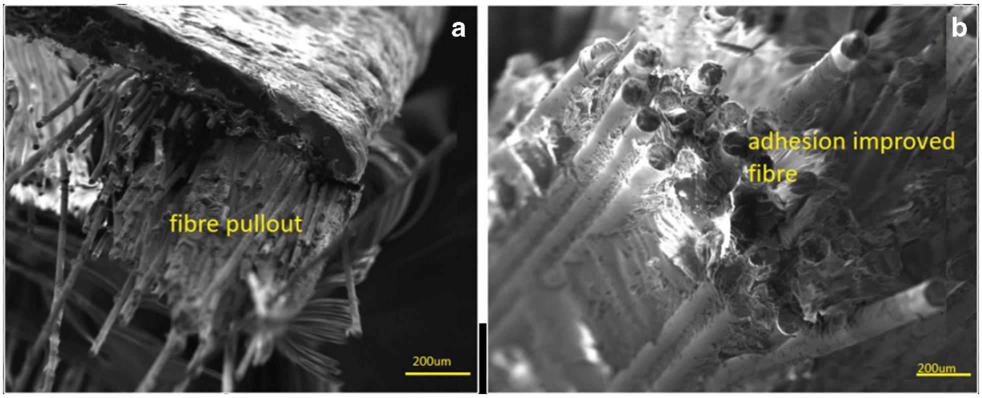


Fig. 4 SEM fatigue fractograph of (a) as-received and (b) silane treated N_3 composite designation

finely mangled as pieces and having the trace of epoxy matrix on their surface after fracture. Thus the process of silane treatment improved the adhesion and dispersion of reinforcements in the matrix and presented high fatigue strength in terms of life cycles.

4.3 Finite Element Failure Analysis

Figure 5 shows the finite element analysis model of aerofoil turbine blade tested using fluid flow analysis. It is observed that the pure epoxy resin (Fig. 5a) N_0 control group gives highest deformation under the hot steam stream line. The blade suffered with maximum deflection at the root and minimum deflection at the tailing edge. This higher deformation under the action of dynamic load is the reason for poor thermal conductivity and load bearing capacity of epoxy resin. The continuous supply of hot steam converts the resin as soft and created the notable deformation. The deformation gradually reduces towards the tailing edge from the root and made the blade to deflect more. This gradual decrement is the reason for effective cooling and reduction in velocity of steam. When the steam hits the blade the entire momentum transformed to the blade's surface thus produced higher deflection at the root on comparing with the tailing edge. However the addition of high toughness kevlar fibre and nanosilica particle increased the rigidness [26]. Fig. 5b shows the deformation image of N_1

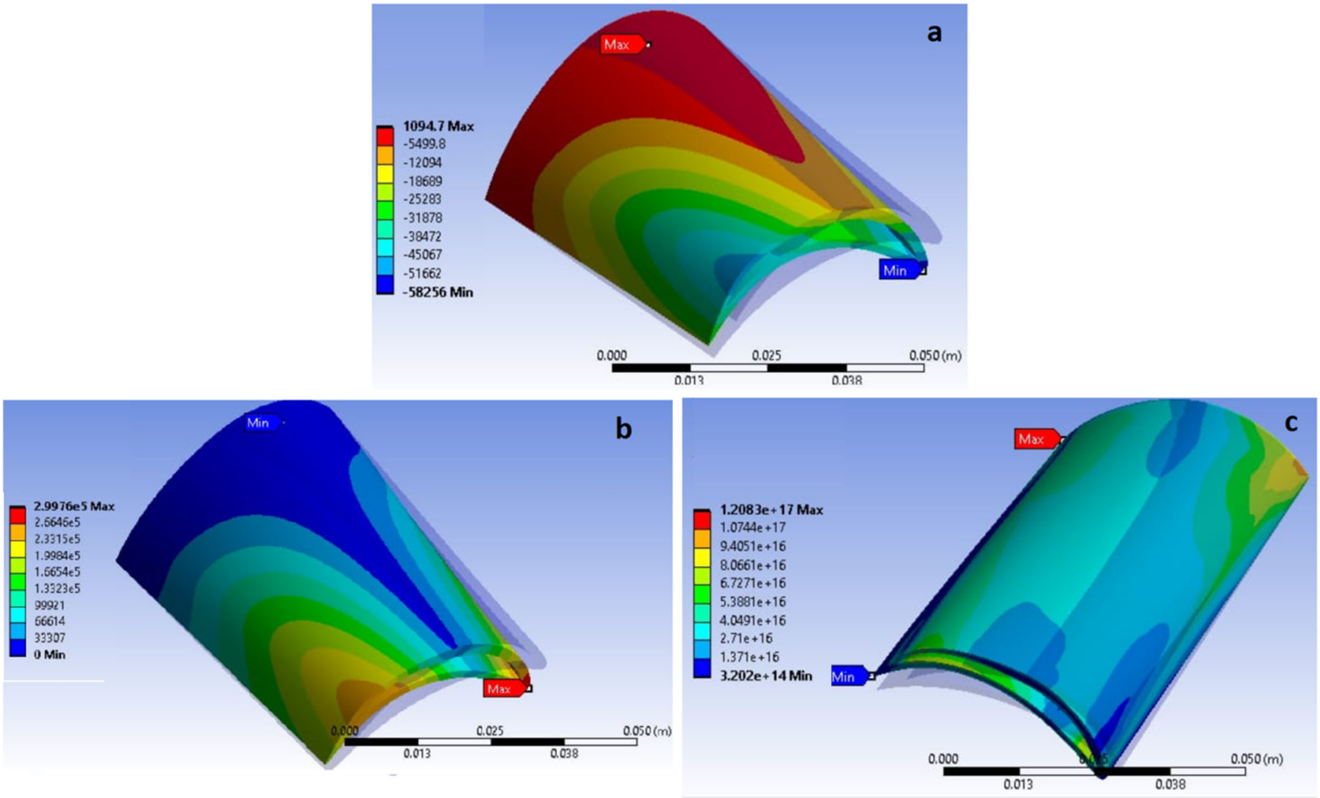


Fig. 5 Finite element analysis of composite blade

designated composite aerofoil blade, which is made using 40 vol.% of kevlar fibre. The blade retains minimum deformation on comparing with N_0 at the root portion. This improvement in load bearing effect is the reason for high energy storage behaviour of kevlar fibre. The addition of kevlar fibre uniformly shares the load throughout the matrix. Thus the stress intensity in the matrix phase reduced, which in turn increased the load bearing effect [27].

Similar effects were noted in the Fig. 5c. The blade made using both kevlar fibre and nanosilica particle (N_3) possesses high impact toughness and load bearing effect against the hot steam and produces very minor deformation. The deformation is almost negligible in the root area and the top surface of the blade. The blade tip at the root is posses with very marginal stress builds up thus there is red colour portion in the blade tip. This stress is the possibility of turbulent creation in the blade tip due to the velocity of hot steam. The internal cooling effect provided in the aerofoil blade further improves the cooling effect, which improves the dimensional stability of composite blade [28 and 29]. The lowest deformation of $3.202E^{+14}$ is observed at the tailing edge of the blade. This remarkable increment in the load bearing effect and temperature stability is the reason for presence of high heat capacity nanosilica particle. These particles absorb the heat and made the composite to withstand against the hot steam. Thus the fluid flow analysis of steam turbine blade model indicates the composite, which posses with high toughness kevlar fibre and nanosilica particle are having great potential to be serve as the working material for prime mover applications [30].

5 Conclusions

High dynamic loading stable aramid fibre-reinforced nanosilica toughened epoxy composite was prepared and tested for dynamic mechanical and finite element analysis. The composites were prepared using hand layup method using surface-treated reinforcements. The 3-D image of aerofoil steam blade was designed as per the standard dimension and involved into the deformation analysis. The specific outcomes of this present investigation are as follows.

1) The silane surface treatment was successfully done using simple aqueous solution method with effective surface functionalization index.
2) The aramid fibre of 40 vol.% produced good quality composites with uniform filling of resin. Higher volume of laying beyond this level may reduce the reinforcing effect and quality of composite making.
3) The silane treated nanosilica particle dispersed in epoxy matrix more uniform than as-received nanosilica particle.
4) The addition of aramid fibre and nanosilica particle improved the storage modulus and glass transition temperature. The increase of glass transition temperature was attributes to the increase in nanosilica content.
5) The addition of kevlar fibre and nanosilica into the epoxy resin improved the loss factor. However adding more volume beyond 1 vol.% reduces the loss factor. A highest loss factor of 0.84 was observed for silane surface treated composite designation N_2.
6) The silane surface treated kevlar fibre and nanosilica addition into the brittle epoxy resin improved the fatigue life counts. However dose of nanosilica beyond 1.0 vol.% affects the fatigue life.
7) The finite element model of steam turbine blade model reveals improvement in deformation resistance on comparing to the N_0 control group. The highest deformation resistance was observed for epoxy composite made of 2 vol.% of nanosilica particle. The presence of silane-treated kevlar improved the toughness and the nanosilica improved the thermal stability.
8) The thermally affected zones on blade surface are very less. There is no deformation exist in steam leaving edge of blade too. Thus the combined effect of aramid fibre and nanosilica produced significant improvement in thermo-mechanical behaviour of composites.
9) Hence these thermo-mechanically toughened epoxy composites could be a suitable replacement for steam turbine conventional blades, where low inertia of composite blades required for producing high efficiency.

Availability of Data and Material No data available to deposit as private. There are no rights.

Authors' Contributions All have done equal contribution.

Declarations Yes this article compliance with ethical standards of journal.

Consent to Participate Yes. All permission granted.

Consent for Publication Yes. All permission granted.

Conflicts of Interest/Competing Interests There is no conflict of interest by any form for this manuscript.

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