Advanced Composite Letters, 22, 2013, 52-56

Fatigue behavior of a hybrid particles modified fiberglass/epoxy composite under a helicopter spectrum load sequence

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ABSTRACT

The fatigue life of a glass fiber reinforced plastic (GFRP) hybrid composite containing 9 wt.% of rubber microparticles and 10 wt.% of silica nanoparticles in the epoxy matrix, under a standard helicopter rotor spectrum load sequence was determined and observed to be about three times higher than that of GFRP with unmodified epoxy matrix. The underlying mechanisms for the observed improvements in spectrum fatigue life of GFRP-hybrid composite are discussed.

1. INTRODUCTION

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Fiber reinforced polymer (FRP) composites are increasingly being employed in various structural applications such as airframes, wind turbines, ship hulls, etc. Such composites experience various types of static and fatigue loads in service. Hence, from a safety and certification view point of these engineering structures, polymer composites should possess high fatigue-durability and fracture toughness.

Efforts have been made in recent times to improve the fatigue resistance of polymer composites by incorporation of second phase fillers. Improvement in the fatigue life and a reduction in the fatigue crack growth rate (FCGR) of epoxies containing rubber particles have been well established [1-4]. Similarly, epoxy polymers containing silica nanoparticles have been shown to exhibit improved fatigue life [5-6] and reduced FCGR [7]. Presence of small amounts of carbon nanotubes [8] and carbon nanofibers [9] also enhance the fatigue properties of epoxies.

Use of filler modified epoxies in FRPs has been shown to improve the fatigue properties of the FRPs as well. The addition of 1wt.% of carbon nanotubes to the polymer matrix of a GFRP composite laminate improves the high-cycle fatigue strength [10]. Carbon nanofiber reinforced composites have been shown to possess improved fatigue properties compared to their unmodified counterparts and fatigue life improvements of 150–670% have been observed in fully compressive, tensile and tensile-dominated loadings [11]. The addition of silica nanoparticles [5,12] and nanoclay [13] into an epoxy matrix has also been shown to enhance the fatigue properties of FRP composites.

Recently, we have observed that the hybrid GFRP composite containing 9 wt. % of micron-rubber and 10 wt. %of nano-silica particles in the epoxy matrix exhibit enhanced constant amplitude fatigue life by about eight to ten times over that of GFRP composite with unmodified epoxy matrix [14]. Also, spectrum fatigue life under a wind turbine load sequence was observed to be improved by four to five times [15]. The aim of this investigation was to study the fatigue behavior of this material under a helicopter rotor spectrum load sequence.

2. EXPERIMENTAL

2.1 Materials and Processing

The complete details of materials used and the processing employed to manufacture the GFRP composites can be found in Manjunatha et al [14]. Briefly, the epoxy resin used was diglycidyl ether of bisphenolA (DGEBA) resin, LY556. The silica (SiO_2) nanoparticles were obtained as a colloidal silica sol with a concentration of 40 wt.% in LY556. The reactive liquid rubber was a carboxyl-terminated butadiene-acrylonitrile (CTBN) rubber, obtained as a 40 wt.% CTBN-LY556 epoxy adduct. The curing agent was an accelerated methylhexahydrophthalic acid anhydride, HE600. The E-glass fiber cloth was a non-crimp-fabric.

The required quantity of the neat epoxy resin, the calculated quantities of silica nanoparticle-epoxy resin and CTBN-epoxy adduct, to give 10 wt.% of nano-silica and 9 wt.% of CTBN rubber in the final resin, were all individually weighed, degassed and mixed together and a stoichiometric amount of curing agent. The atomic force microscope (AFM) phase image of the particles modified bulk epoxy polymer is shown in Fig 1[14]. The rubber particles were evenly distributed and had an average diameter of about 0.5 to 1 μm. The silica particles of about 20 nm in diameter were somewhat agglomerated to give a ‘necklace-type’ structure with an average width of about 1 μm.

The resin mixture was used to prepare the GFRP composite laminate by the ‘Resin Infusion under Flexible Tooling’ (RIFT) technique [16]. Glass fiber fabric pieces were cut and laid up in a quasi-isotropic sequence $[(+45/-45/0/90)_s]_2$. The resin mixture was infused into the glass-cloth lay-up and cured at 100°C for 2 hours and post-cured at 150°C for 10 hours. Two types of GFRP composites were fabricated i.e., (i) GFRP with unmodified epoxy matrix (GFRP-neat) and, GFRP with modified matrix (GFRP-modified) containing 9 wt.% of rubber microparticles and 10 wt.% of silica nanoparticles in the epoxy matrix. The mechanical properties of both GFRP-neat and GFRP-modified composites are shown in Table 1 [15].

2.2 Fatigue Testing

Fatigue tests on both the GFRP-neat and GFRP-modified composites were conducted under a standard helicopter rotor spectrum load sequence, HELIX-32 shown in Fig 2 [17]. This particular load sequence was considered in the present investigation since GFRP composites are used in the construction of helicopter rotor blades and are therefore expected to experience such spectrum loads. In Fig. 2, the normalized stress is plotted against the peak/trough points of the load sequence. One block of the HELIX-32 load sequence consists of 2,91,725 load reversals at 31 different stress levels. The actual stress sequence for experiments was obtained by multiplying all the peak/trough points in the entire block with a constant reference stress, σ_{ref}.

Spectrum fatigue tests were performed on GFRP composites with different reference stress levels ranging from 125 MPa to 200 MPa. The spectrum load sequence block with specific reference stress was repeatedly applied to the test specimens until failure and the fatigue life, expressed as the number of blocks to failure, was determined. The test specimens of size 150 mm x 12 mm x 2.6 mm with end-tabs were employed for the spectrum fatigue tests. All the tests were conducted using a computer controlled 25 kN servo-hydraulic test machine. When the specimen failed in-between any block, the fraction of the block completed was determined as the ratio of the number of reversals applied until then to the total number of reversals in the block.

The stiffness variation of the specimen subjected to spectrum fatigue loads was determined during the test as a function of the number of applied load blocks. Whenever stiffness measurement data were required, the fatigue test was intermittently stopped, a load cycle with σ_{max} = 0.5 σ_{ref} and stress ratio R=σ_{min} / σ_{max} = 0 was applied, the load, displacement data was obtained and analyzed. Considering the large number of load cycles in one block, insertion of this one cycle was assumed not to alter the fatigue damage in the material significantly. For the purpose of comparison, the normalized stiffness of the specimen was defined as the ratio of measured stiffness at any given time to the initial stiffness (obtained before application of the first spectrum load block). For one particular test with σ_{ref} =160 MPa, the specimens were dismounted at the end of the application of one complete load block and photographs showing matrix cracks were obtained, as explained in Manjunatha et al. [14].

3. RESULTS AND DISCUSSION

The spectrum fatigue life determined for both the GFRP-neat and GFRP-modified composites under the HELIX-32 load sequence at various reference stresses is shown in Fig 3. The fatigue life was observed to increase with reduced reference stress in both GFRP composites, a similar trend was observed earlier in a GFRP composite under spectrum loads [18]. However, for a given reference stress, the GFRP-modified composite exhibits an enhanced fatigue life compared to the GFRP-neat composite by about three times. This spectrum fatigue life enhancement is observed over the entire range of reference stress levels investigated in the present work.

The variation of the normalized stiffness with the spectrum load blocks, evaluated for the fatigue test with σ_{ref}= 160 MPa, for both GFRP composites is shown in Fig 4. In general, both the GFRP-neat and GFRP-modified composites exhibit a typical stiffness reduction trend as previously observed in FRP composites [19-22]. It may be noted that the stiffness reduction rate in ‘stage I’ and ‘stage II’ are quite steep and significant in the GFRP-neat composite when compared to the GFRP-modified composite.

Photographs of the matrix cracks observed on the surface of the top 45° layers of the composites subjected to one complete load block of the HELIX-32 spectrum load sequence with σ_{ref} = 160 MPa are shown in Fig 5. Similar observations of the initiation and growth of such matrix cracks under cyclic fatigue loads in a GFRP composite have been reported by others [23,24]. The GFRP-neat composite exhibits more severe cracking than the GFRP-modified composite (Fig 5). Thus, suppressed matrix cracking is clearly observed in GFRP-modified composite under the HELIX-32 load sequence.

The fatigue failure mechanisms under cyclic loads in polymer composites involve [19-22] (i) initiation and growth of matrix cracks, (ii) initiation of disbonds and delaminations due to coalescence of primary and secondary matrix cracks, and (iii) subsequent growth of cracks/ delaminations to lead to final failure. In an earlier investigation [25] it has been observed that the fatigue crack growth rate of the bulk epoxy containing both micron-rubber and nano-silica particles is over an order of magnitude lower than that of the neat epoxy. Further, it has been shown that the use of such particles to formulate a modified epoxy matrix in a GFRP composite material enhances the constant amplitude fatigue life due to suppressed matrix cracking, delayed initiation of delamination and reduced crack / delamination growth rate [14].

The stiffness loss in ‘stage I’ and ‘stage II’ results primarily from matrix cracking [14,19,21,23]. Once the matrix crack density saturates and attains the characteristic damage state (CDS), the disbonds and delaminations created due to the coalescence of primary and secondary matrix cracks grow, and this leads to a further loss in stiffness, i.e. ‘stage III’ [22]. The present results show that when both composites are subjected to the same number of spectrum load blocks, the crack density is lower in the GFRP-modified composite compared to the GFRP-neat composite (see Fig. 5). Thus, the stiffness loss curves shown in Fig. 4 indicate the underlying mechanisms, i.e. suppressed matrix cracking, delayed initiation of delamination, and reduced crack / delamination growth rate [25] which lead to an improvement in the spectrum fatigue life of the GFRP-modified composite.

It is to be noted that the fatigue life enhancement is about eight to ten times under constant amplitude loads at stress ratio, R =0.1[14]. However, it is observed to reduce with increasing stress ratio [15]. Also, under a wind energy spectrum load sequence, the enhancement factor has been observed to be about four to five times [15]. The fatigue life enhancement factor in the present investigation is about three times. Since the HELIX spectrum load consists of load cycles with various R ratios, it is indeed to be expected that the total enhancement of fatigue life under spectrum load is lower than the one observed at R = 0.1. It may also be noted that load interaction effects in composites may affect the fatigue lives significantly [26-28] which may lead to different enhancement factors under different spectrum load sequences. Hence, detailed investigations on the effect of load sequence on fatigue life are necessary to further understand the observed variations in enhancement factor in GFRP-modified composite.

4. CONCLUSIONS

Based on the results obtained in this investigation the following conclusions may be drawn:

1. The addition of 9 wt.% rubber micro-particles and 10 wt.% of silica nano-particles to the epoxy matrix of a GFRP composite (i.e. to give the GFRP-modified material) enhances the fatigue life under the HELIX-32 spectrum load sequence by about three times.

2. The stiffness degradation of the GFRP-neat composite is more severe than that of the GFRP-modified composite during the fatigue loading. The suppressed matrix cracking and reduced crack and delamination growth rate in the modified epoxy matrix of the GFRP-modified composite enhances the fatigue life under spectrum load sequence.

ACKNOWLEDGEMENTS

The authors from CSIR-NAL wish to thank Mr. Shyam Chetty, Director and Dr. Satish Chandra, Head, Structural Technologies Division, CSIR-National Aerospace Laboratories, Bangalore, India for their constant support and encouragement during this work. The authors also wish to thank the technical support staff members of the Department of Mechanical Engineering and the Composites Centre of the Aeronautics Department, Imperial College London, and the Materials Evaluation Lab, STTD, NAL, Bangalore for their assistance in the experimental work.

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TABLE

Table 1 Mechanical properties of the GFRP composites [15]

Type of test	Mechanical Property	Material	
		GFRP-neat	GFRP-modified
Tension	σ_{UTS} (MPa)	365	386
	E_T (GPa)	17.5	15.9
Compression	σ_{UCS} (MPa)	355	356
	E_C (GPa)	21.3	21.1

FIGURES

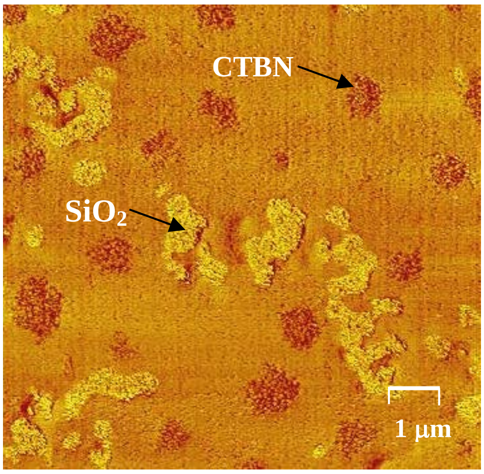


Fig. 1. Atomic force microscope phase image of the modified bulk epoxy polymer [14]

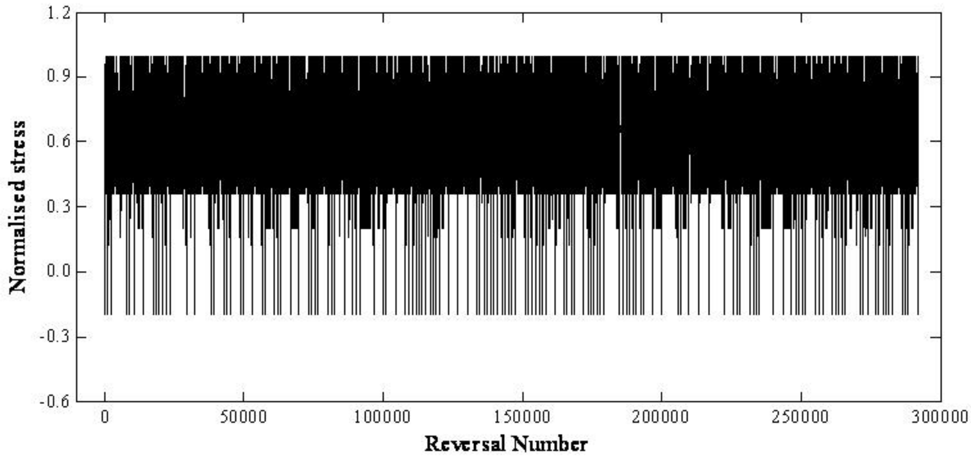


Fig. 2. The HELIX-32 spectrum load sequence [17]

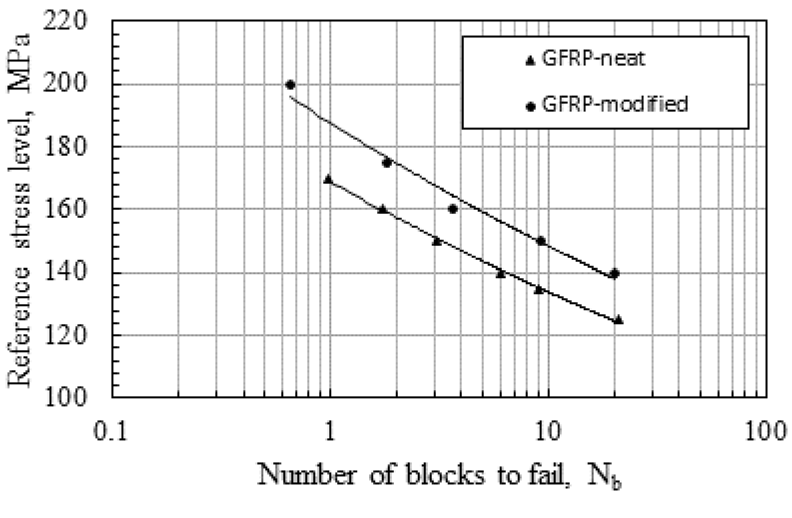


Fig. 3. Experimental fatigue lives of the GFRP composites under the HELIX-32 spectrum load sequence

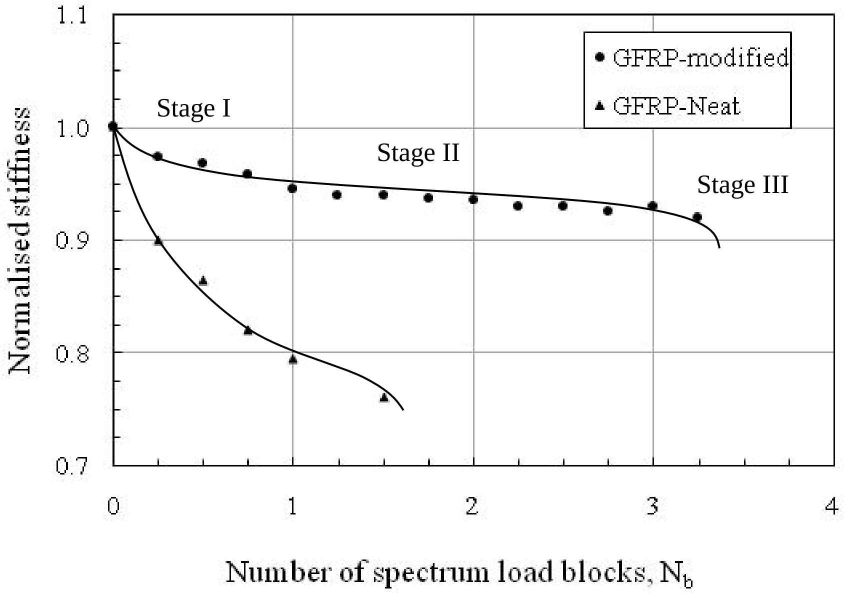
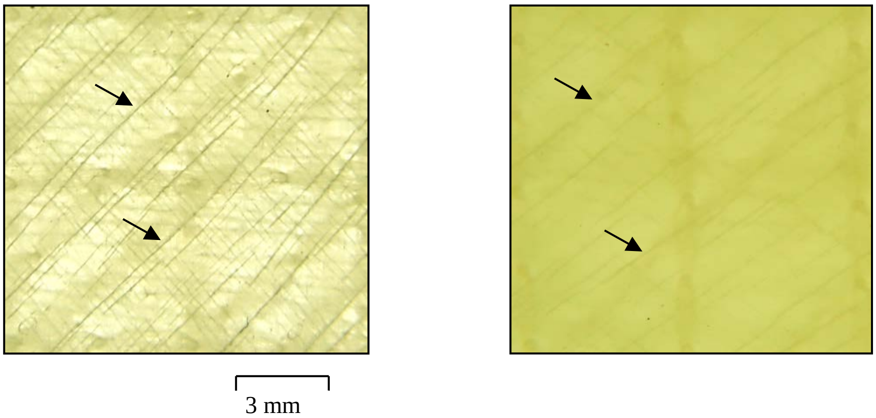


Fig. 4. Normalized stiffness variation curves for the GFRP composites determined under the HELIX-32 spectrum load sequence with σ_{ref} = 160 MPa



(a) GFRP-neat composite (b) GFRP-modified composite

Fig. 5. Photographs showing matrix cracks (indicated by arrows) in GFRP composites ubjected to one complete HELIX-32 spectrum load block with $\sigma_{ref} = 160$ MPa