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Fatigue behaviour of glass fibre reinforced epoxy composites enhanced with nanoparticles

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ABSTRACT

Nanoparticle reinforcement of the matrix in laminates has been recently explored to improve mechanical properties, particularly the interlaminar strength. This study analyses the fatigue behaviour of nanoclay and multiwalled carbon nanotubes enhanced glass/epoxy laminates. The matrix used was the epoxy resin Biresin® CR120, combined with the hardener CH120-3. Multiwalled carbon nanotubes (MWCNTs) 98% and organo-montmorillonite Nanomer I30 E nanoclay were used. Composites plates were manufactured by moulding in vacuum. Fatigue tests were performed under constant amplitude, both under tension–tension and three points bending loadings. The fatigue results show that composites with small amounts of nanoparticles addition into the matrix have bending fatigue strength similar to the obtained for the neat glass fibre reinforced epoxy matrix composite. On the contrary, for higher percentages of nanoclays or carbon nanotubes addition the fatigue strength tend to decrease caused by poor nanoparticles dispersion and formation of agglomerates. Tensile fatigue strength is only marginally affected by the addition of small amount of particles. The fatigue ratio in tension–tension loading increases with the addition of nanoclays and multi-walled carbon nanotubes, suggesting that both nanoparticles can act as barriers to fatigue crack propagation.

1. Introduction

The increased demand of fibre-reinforced polymer composites in recent years on aeronautics, automobile and marine industries, caused an increasing research need in these materials in order to better understand their properties and achieve improved engineering products.

According to Grimmer and Dharan [1] high-cycle fatigue life in aligned glass fibre composites is dominated by fatigue cracking in the matrix, which subsequently propagate and rupture the main load bearing elements, *i.e.*, the fibres. The lower elasticity modulus of glass fibres, when compared to the high-modulus of carbon fibre composites, may impose higher strains in the matrix leading to failure by fatigue. Therefore, the addition of nanoparticles, such as carbon nanotubes (CNTs) or montmorillonite clays (MMTs), is expected to contribute to decrease the scale of damage mechanisms, leading to an increase in the absorption of strain energy through the creation of a multitude of fine nano-scale cracks [1]. Some nanometric particles usually have what is considered to be a high specific surface area (SSA) of more than 1000 m^2/g. According to Gojny et al. [2], this property presents an advantage over micro-scaled fillers, since nanoparticles can act as interface for stress-transfer. These authors also state that single wall carbon nanotubes (SWCNTs) have a higher SSA, around 1300 m^2/g, but present a tendency to form agglomerates (called nanoropes), as well as present difficulties to separate and blend within the matrix. On the contrary, multi wall carbon nanotubes (MWCNTs) have a smaller SSA, but present a better ability to disperse, although lacking in mechanical reinforcement. According to Yasmin et al. [3] MMTs present a SSA around 750 m^2/g. Gojny et al. [4] studied the influence on the mechanical properties of epoxy-based nanocomposites, with several nanofillers, namely single-wall CNTs (SWCNT), double-wall CNTs (DWCNT) and multi-wall CNTs (MWCNT). The most significant improvements were attained with amino-functionalized DWCNTs with 0.5 wt% filler content: 10% on tensile strength, 15% on stiffness and 43% on fracture toughness.

The mechanism of stress-transfer from the matrix to the reinforcements is made by the interface, therefore a chemical

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functionalization of nanofillers could influence this process. Promoting the formation of covalent bonds and/or additional dipole–dipole interactions between CNTs and the polymeric matrix could lead to a strengthened interface [5]. Silva et al. [6] also modified chemically the surface of MMTs, improving intercalation between the particles blended in an epoxy resin, which lead to a tensile strength increase.

Mechanical, rather than chemical, approaches to disperse and exfoliate particles have also being tested in other studies, such as direct mixing and sonication, among others. Gojny et al. [5] sucessfullly used a three-roll mill device to disperse carbon nanotubes without degrading enough their structure to distress their performance. Furthermore, they state that this device is an well established technique to disperse micro-particles in different matrices, such as colour pigments for cosmetics or lacquers.

Yasmin et al. [3] also reported mechanical performance improvement by using a three-roll mill to disperse and exfoliate MMT nanoparticles in epoxy resin. A higher elastic modulus compared to pure resin and almost the same ultimate strength were obtained, with 58 MPa for 3 wt.% of nanoclays blended in the matrix in comparison to 63 MPa for the neat epoxy. To achieve these results a combination of processes were used. To disperse the clays in the epoxy resin a three-roll mill was used. After that, a curing agent was added and the blend was degased for a long period of time and cured in an open mould to help the release of air bubbles. Therefore, a correct combination of chemical and mechanical techniques can lead to the improvement of several mechanical properties of composites.

Fibre orientation in structural components is usually set in the plane (*X* and *Y* direction), leading to fibre dominated material properties in these directions, whereas the *Z* direction remains matrix dominated, which may affect the composite integrity in specific stress conditions. It is expected that applying nanoparticles as a reinforcing phase should increase matrix properties, including in the *Z*-direction, leading to improved interlaminar properties [2].

Preliminary work of the authors showed that the fatigue strength of MMT nanoclays blended within epoxy resin presents a small tendency to decrease with the increase of nanoclay content as consequence of some particle agglomerates, which promote easier fatigue crack initiation [7]. Manjunatha et al. [8] found that by adding silica nanoparticles, fatigue life of a glass fibre reinforced polymer composite (GFRP) was increased by three to four times. Böger et al. [9] also obtained a fatigue improvement when performing fatigue tests on GFRP composites modified with fumed silica and MWCNT in tensile, alternating and compression loadings.

Fibre-reinforced composites fatigue tests are generally made in uniaxial tension–tension, tension–compression [1,8–13] and compression–compression loadings [9]. The number of studies using these loading modes is considerable, since for tension–tension loading there is even an internationally accepted standard (ASTM D3479). On the other hand, bending fatigue tests do not have an international standard to be followed, which can eventually justify the lower number of works published. Despite this, there is some research using bending fatigue tests, e.g. [14,15]. In comparison to tension–compression tests, this type of loading presents interesting advantages, namely, bending loads regularly appear during service conditions, there are no problems associated with buckling and loads needed to perform the tests are significantly lower [14].

The main objective of this work was to study the fatigue behaviour of glass-reinforced composites based on epoxy resin. Three types of matrix compositions were analysed, namely neat epoxy resin, as well as epoxy resin enhanced with nanoclays, MMTs, or multi wall carbon nanotubes, MWCNTs. Moreover, two types of fatigue loading modes, namely three point bending and tension–tension loadings, were used.

2. Materials and experimental procedure

The materials used were glass-reinforced composites based on epoxy resin. The glass reinforcement was a glass fibre tri-axial mat, designated as ETXT 450, supplied by Saapi, with their three plies displaced in 0°/±45° orientations. The thermosetting epoxy resin used was a Biresin® CR120 combined with the hardener CH120-3, both supplied by Sika. The nanoparticles used as reinforcements were the commercially available organo-montmorillonite, Nanomer nanoclay I30 E, provided by Nanocor Inc, and also multiwall carbon nanotubes (MWCNTs) with 98% in carbon, supplied by Sigma–Aldrich.

The nanoclays and the multi wall carbon nanotubes were blended in the resin using the same method. The desired amount of nanoparticles was dispersed into the epoxy resin using a high rotation technique (8000 rpm) during 1 h. Then, the mixture was degassed under vacuum for 15 min, followed by the addition of the hardener agent. Degasification was needed since during the blend processing air bubbles erupted from the mixture.

Composites were manufactured by moulding in vacuum with five different matrix formulations as listed in Table 1. Fibres and resin were hand placed in a mould with all fibre layers oriented in the same direction and subjected to low compression. Fibreglass layers and resin were applied alternately, while ensuring the complete impregnation of the fibres until achieving a stack of ten layers. The mould was put into a vacuum bag as illustrated in Fig. 1, at room temperature for 8 h. The post-cure process was performed in an oven initially at 55 C during 16 h, then at 75 C during 3 h and finally at 120 C during 12 h.

For the glass-reinforced composite series presented in Table 1, NC stands for nanoclays and CNT for carbon nanotubes. Obviously, the numbers identify the amount of nanoparticles in weight percentage dispersed within the resin. The indicated amounts were chosen in order to facilitate the blend within the epoxy resin, since the viscosity of the mixture increases with further increase addition of nanoparticles, which affect the nanoparticle dispersion and fibre impregnation, and consequently the mechanical properties of the composite [1–3,16].

Samples were prepared in an ultramicrotome for ultrathin sectioning EM FCS, Leica Company. Morphological analyses were realised in an Ultra-high resolution Field Emission Gun Scanning Electron Microscopy (FEG-SEM), NOVA 200 Nano SEM, FEI Company, using a Scanning Transmission Electron Microscopy (STEM) detector and an acceleration voltage between 15 and 18.4 kV to obtain the micrographs. Fig. 2 shows the typical observation for 1% nanoclays filled epoxy matrix composite, indicating good dispersion and clay exfoliation. However, poor dispersion was obtained for the glass fibre reinforced epoxy composites enhanced with multi wall carbon nanotubes.

Both uniaxial static and fatigue tests were performed under tension and three point bending (3PB) loadings. Fig. 3 depicts the specimens used in the tests. A referential is also superimposed in the figure to illustrate the considered fibre orientation. The tests performed under tension loading were performed using grooved specimens with the same geometry and dimensions (Fig. 3a) that have been used by other authors [16–19]. Fig. 3(b) shows the

Table 1
Matrix of the glass fibre composites composition (wt%).

Material	Epoxy	Nanoclay	MWCNT
GFRP	100	–	–
GFRP + 1% NC	99	1	–
GFRP + 3% NC	97	3	–
GFRP + 0.5% CNT	99.5	–	0.5
GFRP + 1% CNT	99	–	1

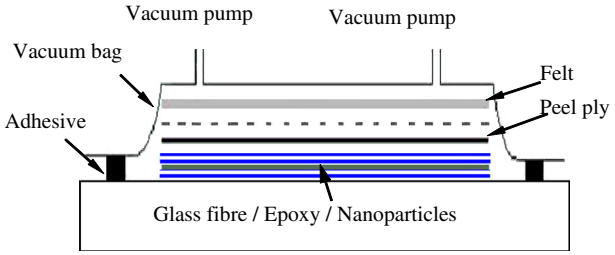

Fig. 1. Schematic view of the vacuum in mould curing process.

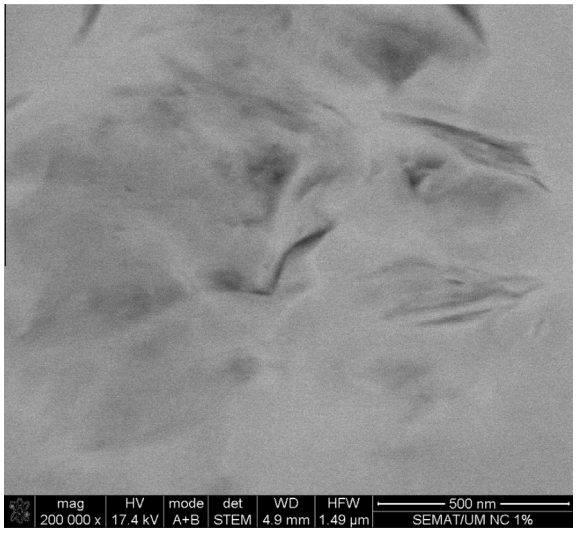

Fig. 2. TEM observation of a composite with the epoxy matrix reinforced with 1% of nanoclay content.

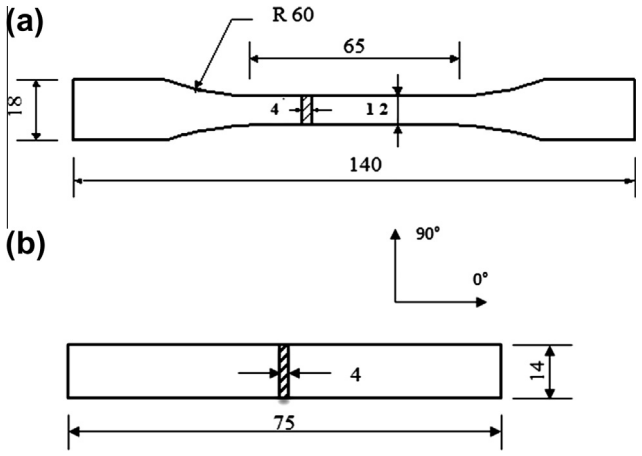

Fig. 3. Specimen's geometry (dimensions in mm): (a) tension and (b) bending.

specimen dimensions used for tests performed under three point bending loading. Specimens were extracted from plates of hybrid composites manufactured according to the compositions indicated in Table 1, and subsequently machined to the desired dimensions, grinded and polished.

In order to obtain the static strength of the material, both in tensile and under 3PB loading, a batch of four specimens for each configuration listed in Table 2 was produced. For fatigue tests, at least fifteen specimens were used for each material. The static tensile tests were performed in an Instron 4206 testing machine, with 100 kN of load capacity, using a constant rate of 2 mm/min and 3 mm/min at room temperature, for tensile and 3PB tests, respectively.

Table 2
Ultimate strength obtained for the glass fibre composites.

Composite	Ultimate tensile strength, σ_{uts} (MPa)	Ultimate bending strength, σ_{ubs} (MPa)
GFRP	332.5 ± 21.6	373.1 ± 28.2
GFRP + 1% NC	321.3 ± 17.6	364.9 ± 15.8
GFRP + 3% NC	305.4 ± 15.5	319.6 ± 12.4
GFRP + 0.5% CNT	318.8 ± 4.90	360.9 ± 38.5
GFRP + 1% CNT	309.8 ± 14.7	370.5 ± 9.70

Fatigue performance of nanoparticle modified glass fibre composites was analysed following part of the procedure presented in [21]. At least fifteen specimens for each composite architecture, both in tension–tension and three point bending loadings, were tested until final failure. The fatigue tests were carried out at constant amplitude loading using a servo hydraulic Instron testing machine using a sinusoidal wave load with a load ratio $R = 0.05$ and a frequency of 8 and 10 Hz for bending and for tensile loading, respectively. All tests were carried out at room temperature.

The stress levels used in both bending and tensile fatigue tests were in the range 0.4–0.7 of the ultimate strength. During the tests the number of cycles to failure was registered, as well as the maximum and minimum displacements. The results were analysed in terms of stress range versus the number of cycles to failure, *i.e.*, by representation of data as *S–N* Wohler curves. The temperature rise at the specimen surface was also monitored at the middle point of the specimens using type K thermocouples.

3. Results and discussion

3.1. Static loading

Fig. 4 depicts the typical tensile stress versus displacement curves obtained for the composites under static three point bending loading. The presented curves clearly show that the specimens do not fail immediately at maximum load, keeping some residual strength until final failure. A similar behaviour was also observed under static tensile loading.

Except for the 3% nanoclay GFRP, the hybrid composites present similar bending strength in comparison with the neat matrix GFRP one. Moreover, the 1% nanoclay glass fibre reinforced composite

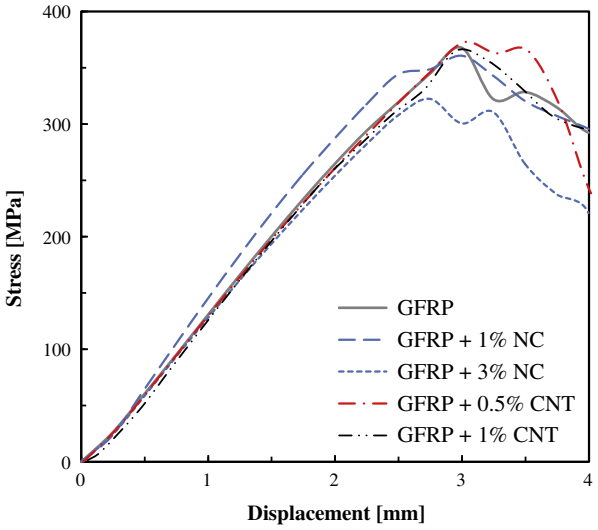

Fig. 4. Typical stress–displacement curves for three point bending static tests.

presents an increase in rigidity, while the 3% nanoclay filled epoxy matrix composite has a slightly lower one in comparison to the unfilled composite. Both carbon nanotube enhanced and neat epoxy matrix composites have similar rigidity. Below approximately 0.5 mm of displacement, all curves show a progressive increase of rigidity, stabilizing almost linearly over the rest of the course until maximum strength is reached. This particular behaviour can be explained by contact accommodation of the specimens to the rollers of the three-point experimental setup used in the tests.

Table 2 summarises the average and standard deviation values of the ultimate strength for each composite composition, being noticeable the difference obtained between the two distinct loading modes. Bending tests show higher static strength for all materials. Moreover, nanoparticles added to the resin matrix seem to failed in improving the static strength in both types of loading modes, being the resistance decrease higher in tensile mode loading where the epoxy filled composites show approximately 3–8% lower strength than the neat epoxy matrix composites, when analysing the respective average values. However, it is important to notice that due to the relatively high standard deviation of the results, a definitive conclusion is beyond experimental uncertainty.

Under both loading modes, composites with nanoclay addition present lower ultimate static strength than the ones with the epoxy matrix enhanced by carbon nanotubes. The 3% nanoclay GFRP composite has the higher amount of nanoparticles added into the matrix, but presents the lower mechanical properties. This may indicate that, contrary to the observed for the 1% nanoclay GFRP composite, the particles were not well dispersed, since nanoclays have a high propensity to agglomerate, leading to premature failure. This behaviour is in agreement with the results of Manfredi et al. [20] which, after XRD analyses, observed that high clay contents tend to form an intercalated structure within the epoxy resin not allowing complete exfoliation.

3.2. Three point bending fatigue loading

The fatigue results obtained under three point bending loading, analysed in terms of the stress range of the load cycle against the number of cycles to failure, are depicted in Figs. 5 and 6 for glass fibre reinforced polymers (GFRPs) with addition of nanoclays or carbon nanotubes into the epoxy matrix, respectively. The fatigue life for neat epoxy matrix glass fibre reinforced composite is superimposed in both figures for comparison.

Fig. 5 shows that there seems to be a very slight increase in the fatigue strength of 1% nanoclay GFRP composites only for lives lower than approximately 20.000 cycles, while 3% nanoclay GFRP composites present always a significant lower fatigue resistance in comparison to neat composites. The adverse effect of the nanoclay particles on the majority of the fatigue life decreases the fatigue strength at 10^6 cycles in approximately 4% and 14% relatively to the neat GFRP epoxy matrix, for 1% and 3% nanoclay glass fibre reinforced composites, respectively. This behaviour is in agreement with the decrease of the mechanical strength. Indeed, the 3% nanoclay GFRP composites presented the lower static strength of all the analysed composites, due to a lower adhesion between filler and matrix combined with the natural tendency to particle agglomeration. The presence of agglomerates, inhomogeneities and porosity points induce greater sensitivity to the initiation of fatigue cracks due to stress concentration in these regions, which may explain the observed fatigue behaviour.

Fig. 6 clearly shows a fatigue life increase of GFRP with 0.5% of MWCNTs, being more significant for short lives and reaching approximately the same fatigue strength at 10^6 cycles in comparison to the neat glass fibre reinforced composite. The *S–N* curve obtained for GFRP composites with addition of 1% of carbon nanotubes is relatively close to the neat composite one at very short lives. However, as fatigue life increases the higher slope of the *S–N* curve results in an inferior performance under flexural fatigue loading, reaching a fatigue strength decrease at 10^6 cycles of approximately 10% relatively to the GFRP with neat epoxy matrix. Both Figs. 5 and 6 clearly show that less fatigue resistance is achieved by the laminate composite with increasing percentage of nanoparticles added to the epoxy matrix. Moreover, only 0.5% carbon nanotube GFRP composites achieved a somewhat higher resistance in bending fatigue in comparison to neat matrix composites.

The tolerance to fatigue can also be analysed using the fatigue ratio, which is defined as the ratio between the loading stress range and the respective static strength. Fig. 7a and b presents the comparison between the fatigue ratio of neat glass fibre reinforced polymer (GFRP) with nanoclays and carbon nanotubes GFRP composites, respectively. Obviously, the static strength is the ultimate bending strength (σ_{ubs}) of the correspondent material.

At longer fatigue lives nanoclay GFRP and neat GFRP composites present similar normalised fatigue strength, implying that the fatigue resistance trends previously observed are mainly due to the

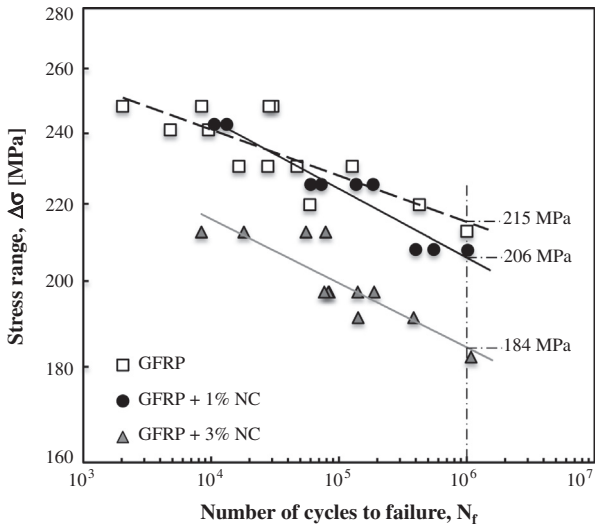

Fig. 5. Effect of nanoclay addition on GFRP composites under three point bending fatigue loading.

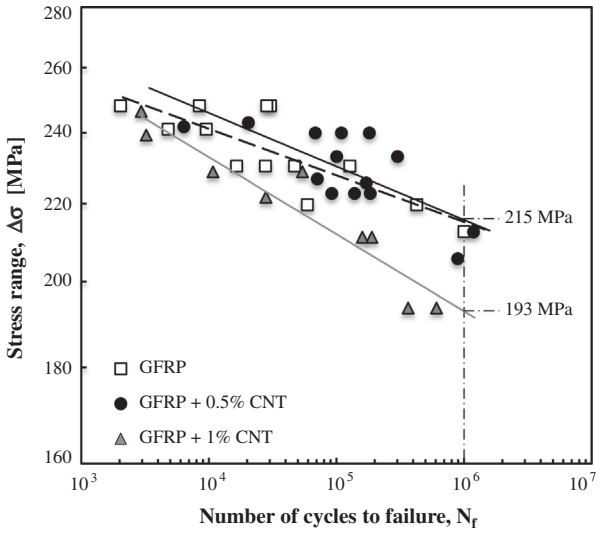

Fig. 6. Effect of carbon nanotubes addition on GFRP composites under three point bending fatigue loading.

static strength variations. However, at shorter fatigue lives GFRP with nanoclay addition show higher fatigue ratios than neat matrix GFRP, indicating less fatigue sensibility and more resistance to fatigue crack delamination.

The glass fibre reinforced epoxy composite with addition of carbon nanotubes present a different fatigue behaviour. For 0.5% carbon nanotubes GFRP composites, reasonable nanoparticle dispersion into the epoxy matrix will be expected. Therefore, the normalised fatigue strength will be higher than for the neat matrix GFRP at all fatigue life, as indeed observed in Fig. 7b, which indicates than the addition of small quantities of CNTs increases fatigue crack delamination resistance. On the other hand, the normalised fatigue resistance of 1% carbon nanotubes GFRP composites is always lower than for neat matrix GFRP one, probably due to poor dispersion with agglomerate formation, consequent increase of local stress concentration and correspondent fatigue strength reduction.

3.3. Tension–tension fatigue loading

The fatigue results obtained under tension–tension loading, analysed in terms of the stress range of the load cycle against the number of cycles to failure, are depicted in Fig. 8a and b for glass fibre reinforced polymers with addition of nanoclays or carbon nanotubes into the epoxy matrix, respectively. The fatigue life for neat epoxy matrix glass fibre reinforced composites is once again superimposed in both figures for comparison.

A close proximity is observed between the *S–N* curves of the neat matrix glass fibre reinforced epoxy composite and of nanoparticle enhanced composites, suggesting that under tension–tension fatigue loading the particle addition does not affect significantly the performance of the resulting composites since the mechanical resistance is mainly due to the fibres disposed in the loading direction. Differences are clearly negligible for the composites with the lower content of both nanoclays and carbon nanotubes. However, it is still noticeable that in terms of average values the higher amounts of nanoparticles added composites display a slightly lower fatigue resistance. Indeed, for both the 3% nanoclay and 1% carbon nanotube enhanced GFRP composites the fatigue strength at 10^6 cycles decreases approximately 3% relatively to the neat epoxy matrix GFRP. On the other hand, Fig. 8 clearly shows approximately the same fatigue strength at 10^6 cycles as the one achieved by the neat glass fibre reinforced composite for both 1% nanoclay and 0.5% MWCNT enhanced GFRP composites.

Jen et al. [22] also achieved a small improvement in the fatigue resistance with 1% content of SiO_2 nanoparticles. Bortz et al. [23]

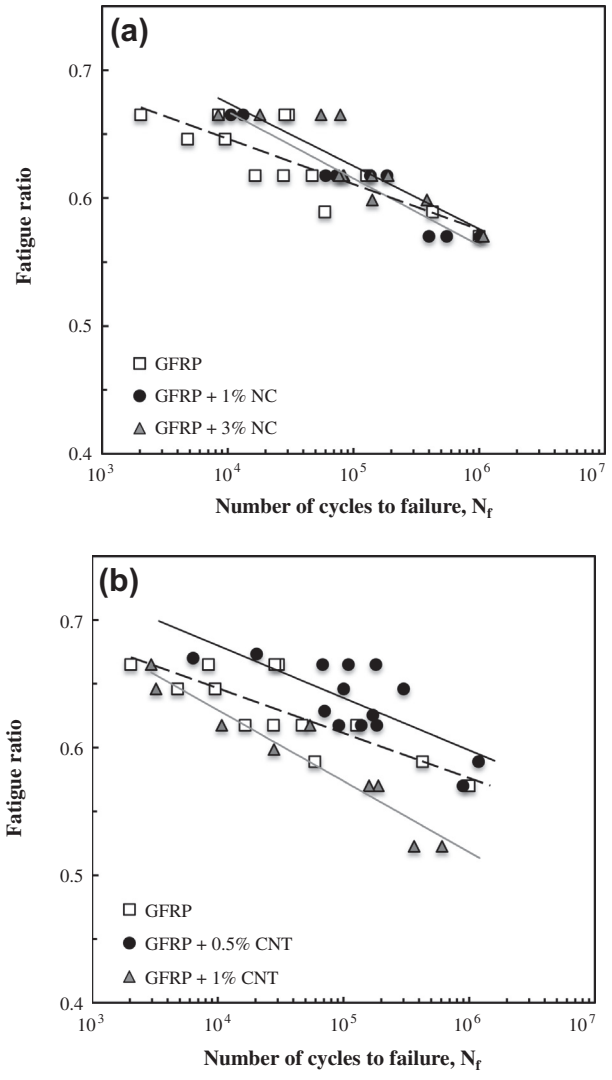

Fig. 7. Fatigue ratio against the number of cycles to failure under 3 PB loading: (a) nanoclay filled GFRP and (b) carbon nanotube enhanced composite.

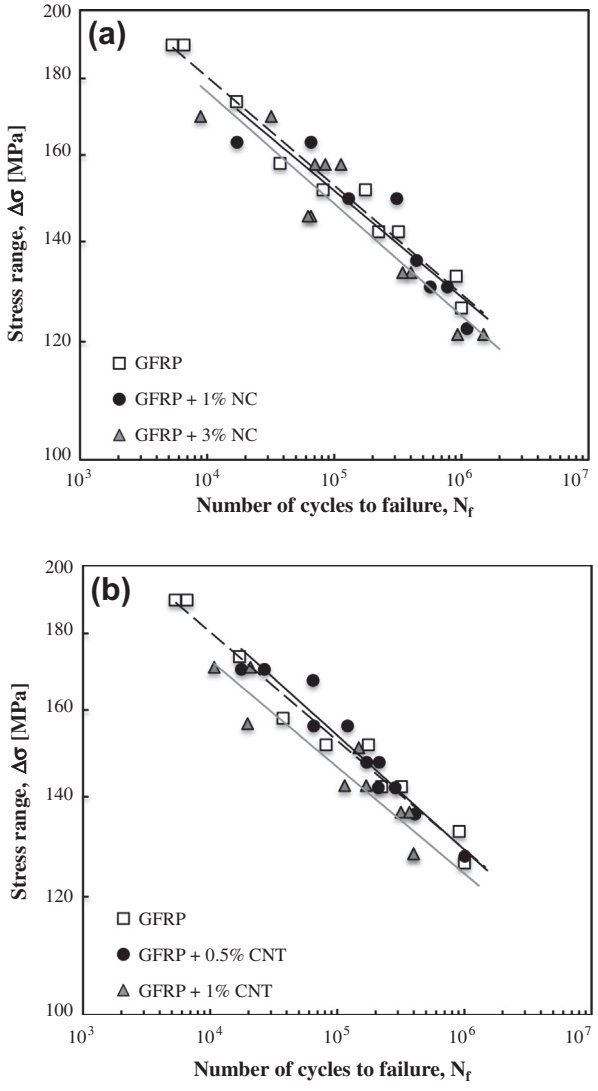

Fig. 8. Effect of nanoparticle addition on GFRP composites under tension–tension fatigue loading: (a) nanoclay particles and (b) carbon nanotubes.

studied the effect of the addition of carbon nanofibres in epoxy resin on the fatigue life under tension–tension loading, obtaining much flatter *S–N* curves for the carbon nanofibres composites. Increased fatigue life was obtained by the addition of carbon nanofibres for the high-cycle fatigue life, *i.e.*, for low stress amplitudes, which increased approximately 180% and 365% over the control material with the addition of 0.5 and 1.0 wt.% of carbon nanofibres, respectively. By the other hand, for high stress amplitudes the addition of carbon nanofibres did not improved the fatigue resistance.

Fatigue results analysed in terms of the fatigue ratio for nanoclay and MWCNT enhanced GFRP composites are plotted in Fig. 9a and b, respectively. The analysis of these figures indicates that nanoclay addition makes the material less sensitive to fatigue damage and that this effect increases with the amount of nanoclays. Moreover, in the case of GFRP with MWCNTs the composite with 0.5% of nanoparticles is the most tolerant to fatigue damage. Contrary to the observed under 3 PB, under tension–tension loading the GFRP with 1% MWCNTs also presents higher fatigue ratio than the neat matrix glass fibre reinforced epoxy composite, indicating that even for this percentage of particle addition the nanotube agglomerates do not have a very detrimental effect on the fatigue strength.

As already mentioned, in order to control and prevent the possible degradation of the polymer matrix due to the increases of the sample temperature during the fatigue tests, the temperature was monitored at the middle point of the specimen's surface. Fig. 10 depicts the typical temperature rise during cyclic loading, at several stress ranges, against the number of loading cycles. Initially the temperature increases for the earlier fatigue cycles, then grows smoothly for most of the test and finally, nearly the final failure a more intense increase occurs. The value of the stable temperature in the intermediate stage is basically independent of the matrix composition but increases significantly with the stress range, remaining always below 25 °C. Therefore, the degradation of the matrix is not to be expected once the maximum temperature is below the glass transition temperature.

The compliance of the specimens during the fatigue tests was calculated using the monitored maximum and minimum values of both load and displacement. The compliance was quantified by using the following equation,

$$C = \frac{\delta_{max} - \delta_{min}}{P_{max} - P_{min}} \quad (1)$$

where C is the current compliance, δ_{max} and δ_{min} are the maximum and minimum displacements, respectively, P_{max} and P_{min} are the maximum and the minimum loads, respectively. The normalised compliance is quantified by the ratio C/C_0, where C_0 is the initial value of compliance. It is important to notice that an earlier and/or higher compliance increase corresponds to higher fatigue damage.

Fig. 11 shows the typical normalised compliance against the number of cycles for the neat glass fibre reinforced epoxy matrix composite under several stress ranges of the loading cycle. As expected, the stress range increase promotes earlier fatigue damage, higher damage rate and lower fatigue life. It was also observed that the fatigue damage just before failure, quantified in terms of the normalised compliance (C/C_0), increases with the stress range.

In order to analyse the effect of the matrix composition in the normalised compliance, Fig. 12 presents the comparison of the C/C_0 ratio evolution with the number of loading cycles between the neat glass fibre reinforced epoxy matrix composite, 1% nanoclays GFRP and 1% MWCNTs GFRP composites, tested in tension–tension loading, using as stress range half of the tensile ultimate static strength.

For this loading mode the fatigue damage in terms of stiffness loss starts at a similar number of loading cycles for the three matrix

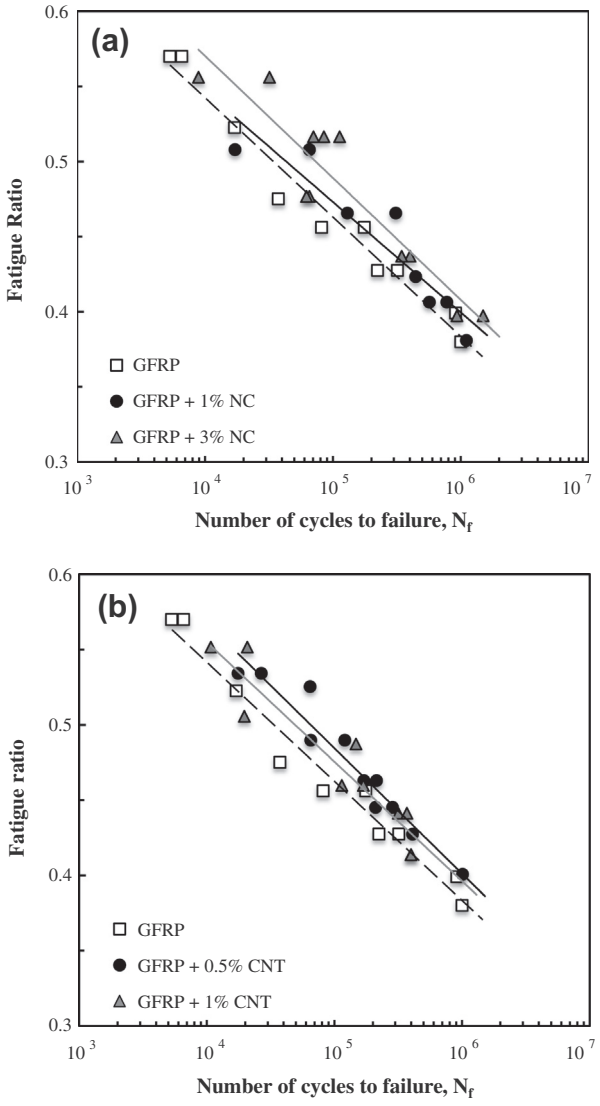

Fig. 9. Fatigue ratio against the number of cycles to failure under tension–tension loading: (a) nanoclay filled GFRP and (b) carbon nanotube enhanced composite.

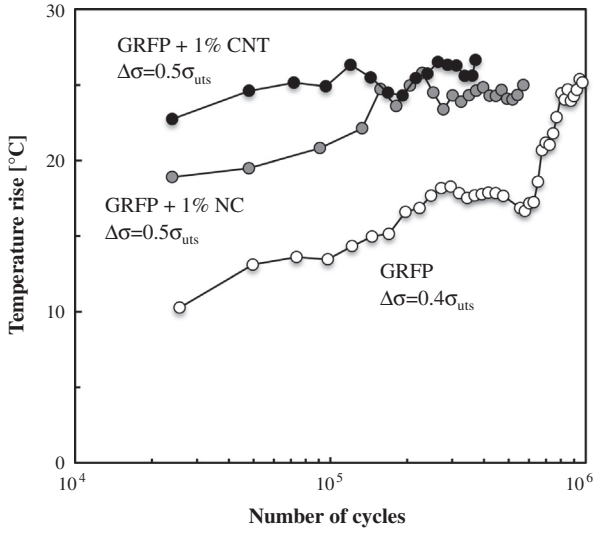

Fig. 10. Temperature rise during tension–tension fatigue loading.

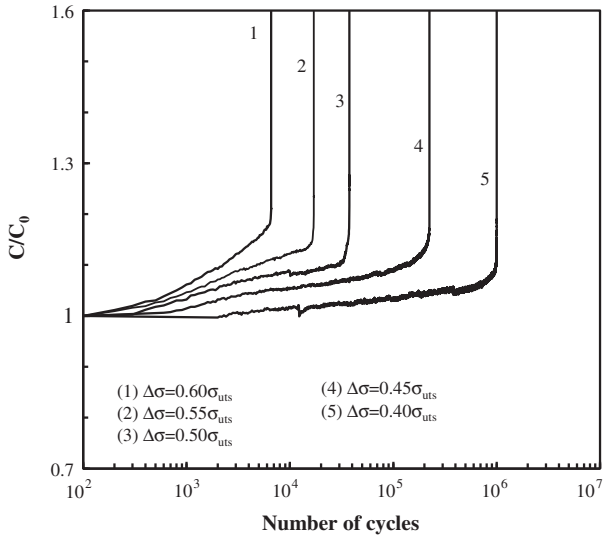

Fig. 11. Normalised compliance for neat epoxy matrix GFRP composite at several stress ranges of the loading cycle.

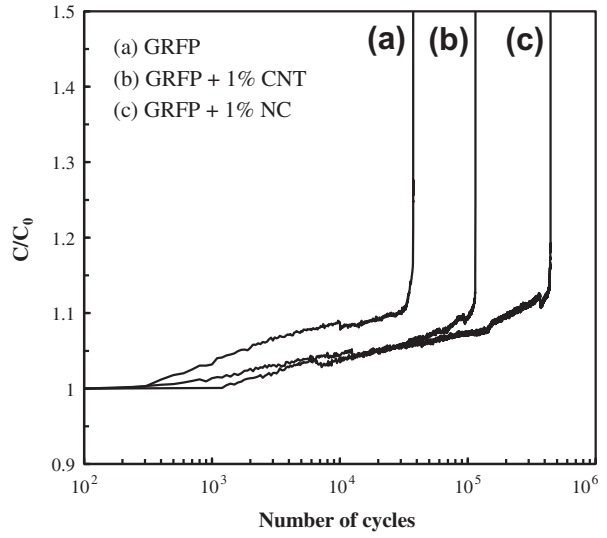

Fig. 12. Normalised compliance for several GFRP matrix compositions. $\Delta\sigma = 0.5\sigma_{uts}$.

compositions, of about three hundred cycles. Afterwards, until near the final failure, increases progressively with nearly constant damage rate for each composite. The intermediate damage rate decreases and fatigue live increases significantly for both the nanoparticle filled composites. The lower damage rate for the GFRP composite with the matrix enhanced by 1% MWCNTs, and particularly with 1% nanoclays, promotes a significant higher number of cycles to failure than for the neat matrix GFRP composite, suggesting that nanoparticles can act as barriers to fatigue crack propagation.

This possibility is in agreement with the work reported by Grimmer and Dharan [24]. These authors concluded that the addition of small volume fractions of multi-walled carbon nanotubes into the matrix of glass fibre composites significantly reduces cyclic delamination crack propagation rates, justified by the experimental evidence that the incorporation of CNTs improved fatigue life by a factor of two to three in in-plane cyclic loading. Khan et al. [25] also observed that the incorporation of nanoclays into CFRP composites improves the fatigue life for a given cyclic load level, delays the delamination damage growth and reduces the corresponding fatigue damage area.

4. Conclusions

In the present study the effect of the addition of small amount of nanoclays and multi-walled carbon nanotubes into epoxy matrix on the fatigue behaviour of glass fibre composites was analysed. The following main conclusions can be drawn:

- Good dispersion into the matrix was achieved for 1% nanoclays, while for higher content and for MWCNTs nanoparticles the dispersion technique was apparently ineffective. Moreover, independently of the efficiency of particles dispersion, both bending and tensile static strength were not improved by the nanoparticles addition.
- The fatigue strength, both under 3 point bending as well as under tension–tension loadings, for the composites with matrix filled with only a small amount of nanoparticles (0.5% MWCNTs and 1% nanoclays) is similar to the obtained for the neat glass fibre reinforced epoxy matrix composite. However, for composites with addition of higher percentage of nanoparticles a decrease of the fatigue strength was observed, which is more significant under 3 point bending loading.
- The fatigue ratio in bending loading increases slightly with the addition of nanoclays and significantly with 0.5% MWCNTs, but decreases for 1% of MWCNTs as a consequence of the formation of agglomerates.
- The fatigue ratio in tension–tension loading increases with the addition of nanoclays and multi-walled carbon nanotubes, suggesting that both nanoparticles can act as barriers to fatigue crack propagation.

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