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Mechanical behavior of MWCNT reinforced GFRP composites under fatigue constant amplitude loadings with the presence of artificial notches

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***Abstract* — This work studies the effect of artificial surface notches on glass fiber reinforced polymers (GFRPs) under constant amplitude fatigue loadings and for various nano-reinforced matrices. Different concentrations of Multi-Wall Carbon Nanotubes (MWCNTs) were added to the resin before the vacuum assisted resin infusion (VARI) of the composites. Three different MWCNT nanocomposites were manufactured that had concentrations namely 0.5, 0.75 and 3.0 wt% MWCNTs. Before testing, an artificial notch was introduced and two different regions of the composite was continuous monitored during mechanical testing: (a) healthy (without defect) and (b(notched (with the presence of defect). Fatigue tests were performed and with different fatigue maximum stress levels so as to address all fatigue regimes. It was found that a sudden increase takes place on the transition of stage III of the fatigue mechanism. This sudden increase point in the electrical resistance change was applied maximum stress as well as wt% MWCNT concentration (different matrix) dependant.**

***Keywords* — Carbon nanotubes, Glass fibers, Mechanical properties, Electrical resistance change method**

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I. Introduction

Polymer composites have a strong demand in the aerospace sector the last decade. The use of carbon nanotubes (CNT) in polymer composites has attracted great attention nowadays due to their excellent mechanical and electrical properties. Using a modified resin doped with MWCNTs, a non-conductive GFRP composite can now become electrically conductive. Therefore, exploiting the electrical resistance change methodology introduced by Baron and Schulte [1], GFRPs can now be monitored by measuring simultaneously surface electrical resistance change of a coupon during mechanical loading. Therefore, the addition of electrically conductive MWCNTs offers to non-conductive GFRP composites the potential for sensing capabilities through changes in electrical resistance on the onset of damage [2, 3] and enhanced fracture properties e.g. [4, 5].

Research on these newly-developed, multi-functional materials is mainly focused on the enhancement of their mechanical performance as well as measurements of electrical resistance change simultaneously recorded from stress/strain variances of the testing specimens, e.g. [5, 6]. However, critical parameters such as the mechanical/electrical response under cyclic loadings or even fatigue (with the presence or not of surface notches) are scarcely reported on the open literature.

A. *Material manufacturing*

The resin used was a typical resin used in the aeronautics, Araldite LY 564. It was selected primarily to its low viscosity and its high mechanical properties. For each different case, resin of approximate 400 g and different percentages of carbon nanotubes were mixed in the dissolver. Use of Torrus Mill dissolver was preferred since it introduces high shear forces by a high speed rotating disc and the compound is stirred in a vacuum container to avoid air inclusions. Dissolver's mixing time of the resin with the different percentages of MWCNTs, namely 0.5 wt%, 0.75 wt% and 3.0 wt% lasted more than 24 h each. Resin was then mixed with the catalyst (Aradur 2954 by Huntsman) and was placed on open metallic moulds and in the shape of a typical tensile specimen

For the manufacturing of the composite plate the following process was followed: 10 plies of glass fiber fabric (style 6781, S2 glass by Fiber Glast Developments Corporation), oriented at 0/90° had been cut at the required dimensions (300 x 300 mm). The plies were laid and the wrap faces were alternated upwards and downwards during the lay-up, resulting in a cross- ply balanced and symmetric laminate. Resin with different percentages of carbon nanotubes, prepared from the previous section, was used to manufacture the composites with the same lay-up sequence. Vacuum infusion method had been used to manufacture the plates of the material. Appropriate bagging material was placed, vacuum was then applied and the infusion of the resin followed, Figure 1. The manufactured plates was thereafter cured for 2 hours at 60°C followed by a 4 hour at 120°C post cure, as recommended by the resin manufacturer's data sheet.

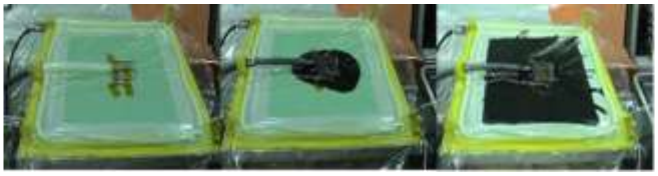

Figure 1: Manufacturing process of the hybrid composites with the vacuum infusion method

The specimens had been cut from the material plates according to the ASTM D3039 specification and edge-polished. The dimensions of the testing specimens were width x length = 25 mm x 250 mm.

B. Experimental procedure

Electrical cable connectors were attached to the specimen’s surface, Figure 2. The cables were connected to the Agilent multimeter and the initial electrical resistance of the reference test section was measured. The electrical cable connectors were attached in two regions of the specimen (healthy and notched, respectively) in order to record their electrical resistance change during mechanical testing.

Figure 2: Photograph of a specimen with a formed artificial notch and electrical cable connectors

The artificial surface notches were introduced by a precise saw cut and the notch depth was measured with image analysis. Two regions of the specimen were monitored by the electrical resistance change method; the so-called “healthy” region and the “notched” region that had the presence of the artificial notch, as can be seen in Figure 3.

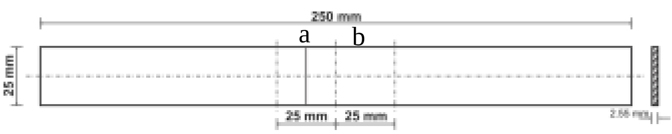

Figure 3: Specimen with two measuring areas: (a) healthy and (b) notched

On the opposite flat surface of the coupon, strain gauges were attached and the readings of strain gauges and electrical resistance were continuously recorded in a PC during the progressive fatigue cycles. The first target of the present work is to assess the composites’ monitoring capabilities for different concentration wt% MWCNTs in the resin matrix. The last target is to seek the monitoring capabilities of the same composites under the presence of an artificial notch and during the constant amplitude fatigue tests.

Fatigue tests were performed in a servohydraulic MTS 100 kN loading frame with a constant stress ratio of $R = 0.1$. Three different fatigue stress levels were investigated to address different fatigue regimes, Table 1. The gross applied force was calculated to be equivalent for axial stress of 275, 185 and 125 MPa for the healthy region, while this force was translated to higher stress level for the notched regions and according to the decrease of the composite’s cross-section.

Table 1: Different fatigue stress levels investigated.

Gauge area	Maximum applied stress (MPa)		
Notched	400	275	185
Healthy	275	185	125

II. Results

Figure 4 shows the results of the electrical resistance change of the two gauge areas under constant amplitude fatigue loading till fracture for the case of 0.75 wt% MWCNTs composite. It can be seen that in the notched area the electrical readings have higher values than the respective healthy area and for the same applied fatigue cycles. For the case of the healthy area, an almost linear increase in electrical resistance change is noticed with increasing fatigue life. For the case of the notched area, this almost linear correlation is evident up to almost 50% fatigue lifetime, while an exponential trend is noticed. The electrical readings of the notched area are well higher than the respective initial values and this is evidence of continuously introduced damage in that region.

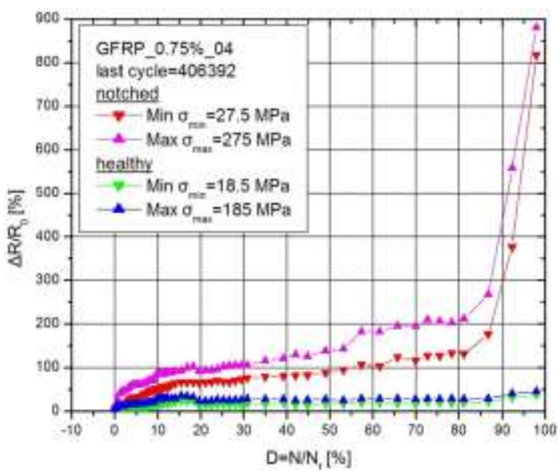

Figure 4: Diagram of fatigue maximum and minimum electrical resistance change values as a function of fatigue cycles for the case of maximum applied stress of 275 MPa for 0.75% wt MWCNTs.

Figure 5 shows that the electrical resistance change in the notched area is greater than in the healthy region after 50% of the specimens’ lifetime. The respective electrical resistance change values of the notched region increased gradually and an essential sharp increase of around 90% was noticed. As can be seen in the figure, the specimen failed at the artificial notch region after 227,283 fatigue cycles.

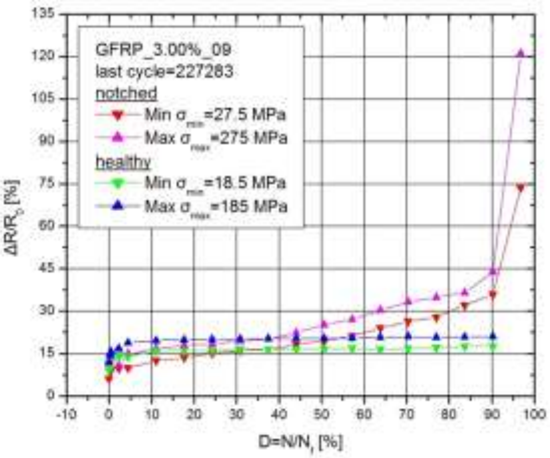

Figure 5: Diagram of fatigue maximum and minimum electrical resistance change values as a function of fatigue cycles for the case of maximum applied stress of 275 MPa for 3.00% wt MWCNTs

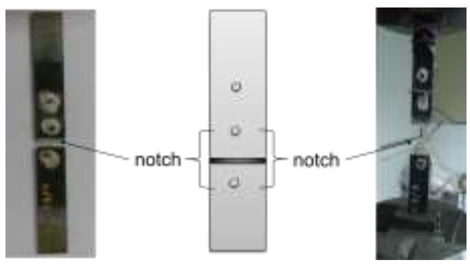

Figure 6: Specimens (left: 0.75 wt% MWCNTs and right: 3.00 wt% MWCNTs) of the previous figures after failure in the notched gauge area.

Figure 7 shows the electrical resistance change curves of three specimens of the same material (0.75 wt% MWCNTs) tested under different maximum tensile stress, namely 185, 275 and 400 MPa at the notched area. It can be noticed that the electrical resistance change increases significantly for all cases; increased electrical resistance values are recorded after 80% of fatigue lifetime for the case of the low-applied stress regime; for the higher stress regime, this sudden increase is noticed only after 65% of fatigue lifetime. Finally, for the heavily stressed specimen, ERC values show an essential increase only after 45% that is evident of irreversible, permanent matrix cracking damage.

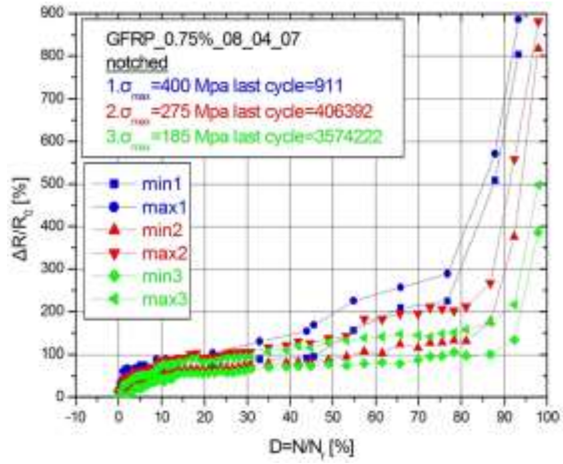

Figure 7: Diagrams of maximum and minimum electrical resistance change values over fatigue life different applied maximum stresses, namely 400, 275 and 185 MPa for specimens reinforced with 0.75 wt% MWCNTs.

Figure 8 shows the respective curves for the case of specimens reinforced with 3.00 wt% MWCNTs. Almost the same qualitative results can be noticed for this case with the exception of the poorest screeening of the electrical resistance values.

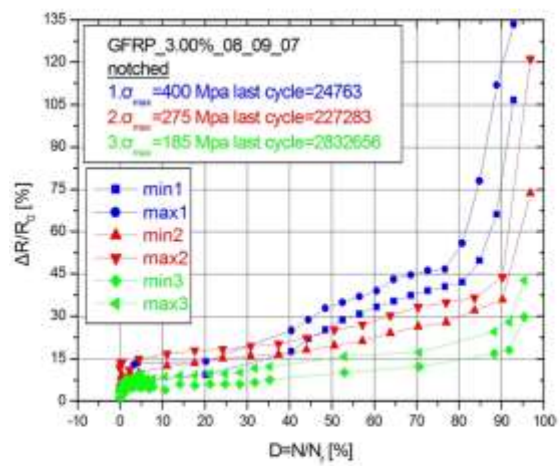

Figure 8: Diagrams of maximum and minimum electrical resistance change values over fatigue life different applied maximum stresses, namely 400, 275 and 185 MPa for specimens reinforced with 3.00 wt% MWCNTs.

III. Conclusions

- Notched regions exhibit higher electrical resistance change values that respective healthy for all materials and applied maximum stress regions.
- Composite reinforced with 0.75 wt% MWCNTs showed higher screening of electrical resistance change values.
- Matrix cracking damage can be identified with progressive fatigue damage and can be assessed for the different applied maximum stresses.

Acknowledgments

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