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REMAINING LIFE ASSESSMENT OF DAMAGED REINFORCED COMPOSITES UNDER INELASTIC MATERIAL BEHAVIOUR

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ABSTRACT

In this article, an investigation on bi-directional carbon fiber composite INDCARF manufactured in India - to study remaining life assessment-RLA- of the composites to enable one to design suitably. But since composites are made of different materials bonded and reinforced with fibres, they develop distress in the form of cracking and damage while in service and there is a need to assess their performance in terms of strength and stiffness for the remaining portion of their life. The cracking/damage under different conditions is simulated in the form of hair-line cracks, introduced on the surface of the coupons used for testing. Based on coupon test results, analytical studies using non-linear finite element model were carried out to assess the influence of different characteristics of damage on failure and remaining life. The cracking parameters were identified as initiation, spread and inelastic material behavior using elastic-plastic material model. The samples were evaluated by tensile tests according to the ASTM D3039.

Keywords: composites, remaining life assessment, damage, cracking, finite element analysis, tensile test.

1. INTRODUCTION

Carbon fabric reinforced composite structures are increasingly used for manufacturing components as flaps, aileron, landing-gear doors, and other artifacts used in aeronautical industry to meet the demand for lightweight, high strength/stiffness and corrosion-resistant materials in domestic appliances, aircraft industries, etc. Usage of composites in defense and space applications [1] is increasing day by day with new materials and easy methods of manufacturing composites. But the major factor which needs to be looked into is the performance of these composites when distress or damage due variety of reasons [2] occurs in the systems where they are used. All aircraft and aerospace vehicles during their service life are subjected to severe structural and aerodynamic loads, which may result from repeated landings and take-off, maneuvering, ground handling and environmental degradation such as stress corrosion. These loads can cause damage or weakening of the structure especially for an aging aircraft thereby affecting its load carrying capabilities and safe life. Strength and stiffness of composite materials [3] are two favourable properties that are used to their full extent in various structural applications under different kinds of loading. First the ‘long term’ behaviour that involves extended exposure of the component to applied condition that may include mechanical, thermal, chemical environment. Second, since the ‘end life’ is defined by the reduction of strength, the damage tolerance can be discussed in terms of strength, or more precisely in terms of remaining life after having some damage during in service. The composite behaviour generally reflects that of the matrix material, but with enhanced stiffness, strength and wear resistance, these properties improve with increased volume fractions of reinforcement. Here a typical commercially available composite-INDCARF-manufactured in India, is used to study the effects of cracking and damage on remaining life.

2. EXPERIMENTAL PROCDURE

2.1. Materials details

This investigation has been carried out on bi-directional carbon fiber reinforced composite manufactured by IPCL Baroda (India) with trade name INDCARF-30. The fibers are plain weave with 13-15 ends per inch in both wrap and weft direction. The properties of weaved carbon fiber fabric are mentioned in Table-1. The epoxy resin used was Araldite LY-5052, hardened by Hardener HY-5052 (products of Ciba-Geigy India Ltd) with 100:38. The composite plates were fabricated in the vacuum bag technique and cured at room temperature for 24h and post - cured at 100°C for 2h. The laminates made with eight layer of fabric have a nominal thickness of 2 mm corresponding to a fiber volume fraction of 55% (+1). The basic properties of the fabricated carbon /epoxy material are presented in Table-2.

Table-1. The properties of bi-directional weaved carbon fibre fabric.

Property	Magnitude
Weight/sq. meter of the fabric	200 gms
Thickness	0.2 mm
Fibre count	3 K carbon
Yarn denier	-
Wrap	54
Weft	52
Weave	Plain weave

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Table-2. Mechanical properties of Bi-directional carbon/epoxy composite.

Mechanical properties	**Tensile strength** (MPa)	**Young's modulus** (GPa)	**Flexural strength** (MPa)	**Flexural modulus** (GPa)
CFRC	583.32	37.069	483.23	30.064

2.2. Specimens preparation

The specimens were prepared from the fabricated carbon reinforced composite plate. The standard specimens size of 250 x 25 x 2 mm as per ASTM standard D3039 [4] were cut from the fabricated laminates size 300x300mm using water-jet cutting to avoid machining defects and to maintain a good surface finish. Two aluminum tabs (size 50 x 25 x 1mm) were used on each side of the sample to facilitate breakage as close as possible to the centre of the 150 mm gauge length and to reduce the grip noise. Aluminum loading tabs were then bonded onto both ends of specimens using a high strength Araldite® epoxy adhesive. The virgin specimens and the specimens with induced cracks/damage in different orientation i.e., vertical, inclined and horizontal are as shown in Figure-1. The specimens were prepared for tensile testing: (1) as received (2) vertical crack (3) inclined crack (4) horizontal crack. Tensile test specimen of ASTM D3039 standard is shown in Figure-1.

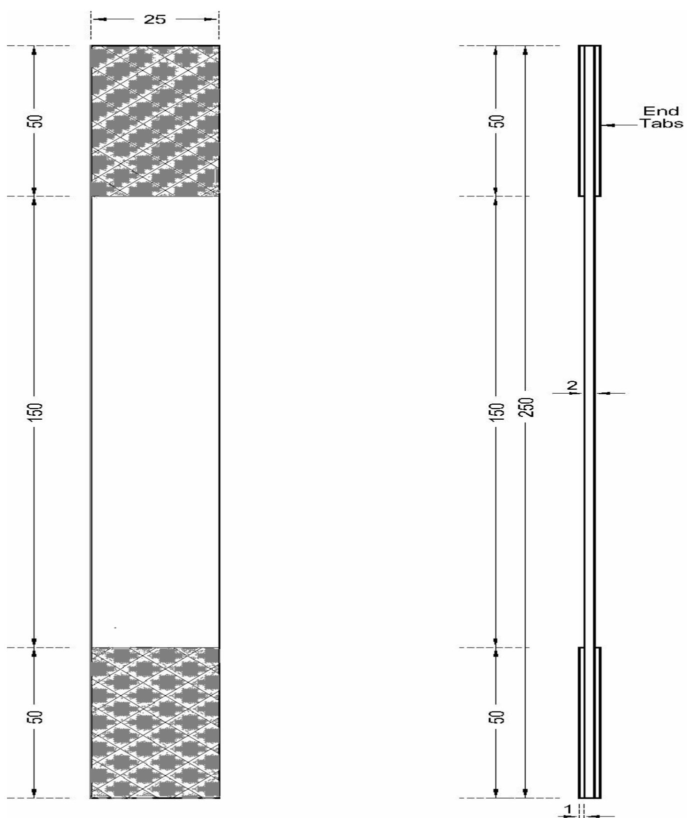


Figure-1. Specimen geometry and dimensions for tensile test.

2.3. Testing procedure

ASTM D3039 tensile test specimens, removed from the laminates are subjected to uni-axial tension using an Instron 3367 universal testing machine. Twelve specimens, three in each category of bi-directional composite were tested. For all the specimens the crosshead speed was maintained at 0.15 mm/min. All tests were performed using universal testing machine at ambient temperature, and the grips were fixed in such a way that neither bending nor torsion influenced the specimens. Tensile test were conducted on universal testing machine to predict the remaining life assessment of the composite with damage and virgin specimens. Based on test results, characteristic properties like young's modulus, stress and strain [5, 6] at different loads were obtained which will be used in analytical model. Experimental obtained values of bi-directional composite material properties with and without damage were given in Table-3. The tested specimens after failure are shown in Figure-3.

Table-3. Experimental obtained values of Bi-directional material properties with and without damage.

Mechanical properties	**Tensile strength** (MPa)	**Young's modulus** (GPa) **virgin specimen (1)**	**Young's modulus** (GPa) **vertical crack specimen (2)**	**Young's modulus** (GPa) **inclined crack specimen (3)**	**Young's modulus** (GPa) **horizontal crack crack specimen (4)**
CFRC	583.32	37.069	35.500	30.500	26.150

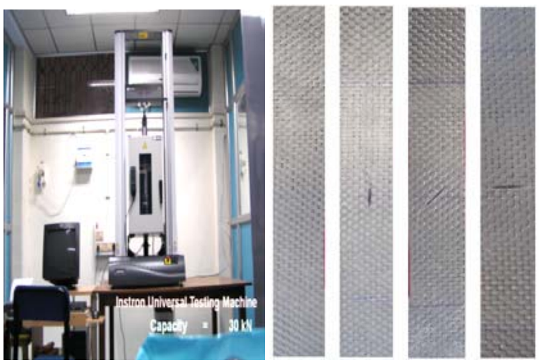


Figure-2. Testing of coupon.

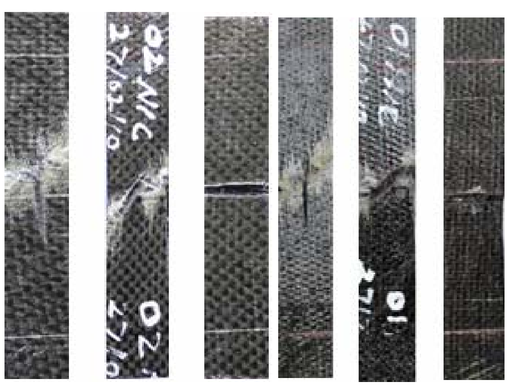


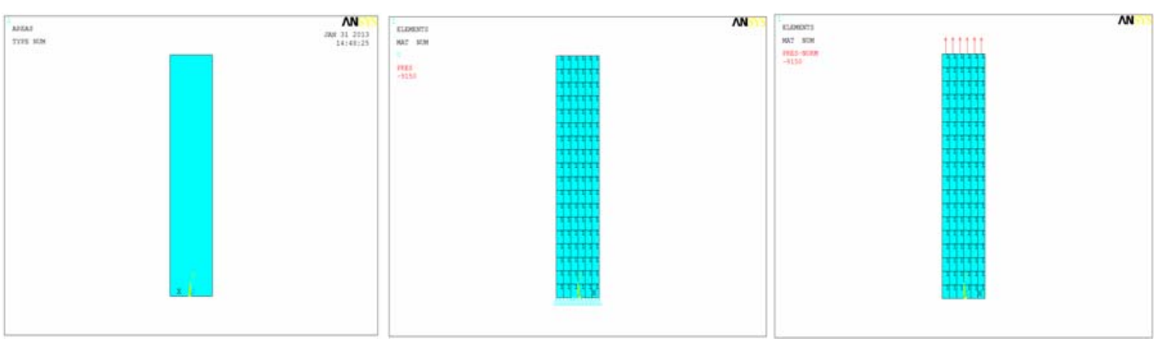
Figure-3. Specimen after tensile test.

3. ANALYTICAL STUDIES

3.1. Analytical modeling for response assessment

Static analysis [7] is used to determine displacements, stresses, etc. under static loading conditions, both linear and nonlinear static analyses. Nonlinearities can include plasticity, stress stiffening, and large deflection, large strain, hyper elasticity, contact surfaces, and creep.

Finite element method of analysis using industry tested software ANSYS-12 was used to do detailed analytical study and here both linear and nonlinear analysis accounting material changes are done to get an idea of the influence of type and spread of damage. By considering the above analysis element plane 82 is the best suited to this problem. Finite element method of modeling the region and use of reduced values of material parameters from Table-3 to simulating crack are done to analyses the different types of damaged specimens and static linear analysis followed by material nonlinear characterization using elastic strain-hardening model are used to get the responses in terms of deformation and stresses. Processing the different analytical results to assess the performance in terms of stiffness and later load carrying capacity is done after characterizing the damage suitably. The specimen region is model of half of the physical model assuming symmetry. Finite element model with actual domain and the mesh used with boundary conditions are shown in Figure-4.



a) Specimen region b) Boundary condition c) FE model

Figure-4. FE model-Virgin specimen material (1).

Based on coupon test results typical values of young's modulus and failure patterns are obtained. Using FEM for domain model [8] and elastic-plastic stress-strain curve with initial value of Young's modulus obtained from tests and different strain-hardening parameters ranging from 0.25% to 1%, different analyses were carried out with following damage parameters.

a) Undamaged-NNC
b) Damaged with cracking parallel to the load-NVC

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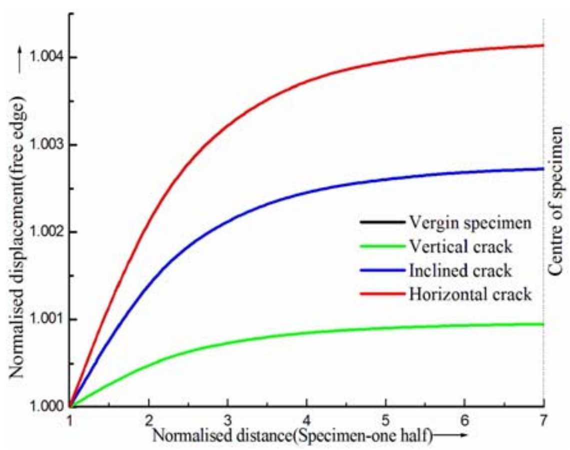
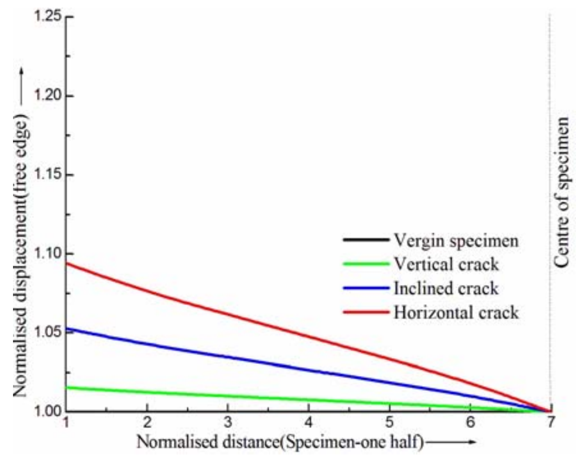
c) Damaged with cracking inclined to the load-NIC
d) Damaged with cracking normal to the load-NHC
e) Response evaluation with type of spread [9]
f) Response evaluation with nonlinear material behavior near damage

3.2. Location of type crack/damage initiation and spread

Displacement variations with different crack initiation are shown in Figure-5 and 6 to show the effects of initiation and subsequent spread. In Figure-5 Displacement variations indicate for two locations of origin, with 5(a) indicating for cracking at the centre of specimen and 5(b) showing for crack originating at free edge [10]. Typically Figures 5 and 6 shows the distribution of deformation along the width of the specimen for one half assuming symmetry. It may be seen that displacements near the crack at initiation increase considerably and the variation changes depending on how the crack progresses. The deformation variation for a horizontally initiated crack spreading in different ways is given in Figure-6.



a) Crack at centre of specimen



b) Crack at free edge of specimen

Figure-5. Displacement variation with different crack initiation.

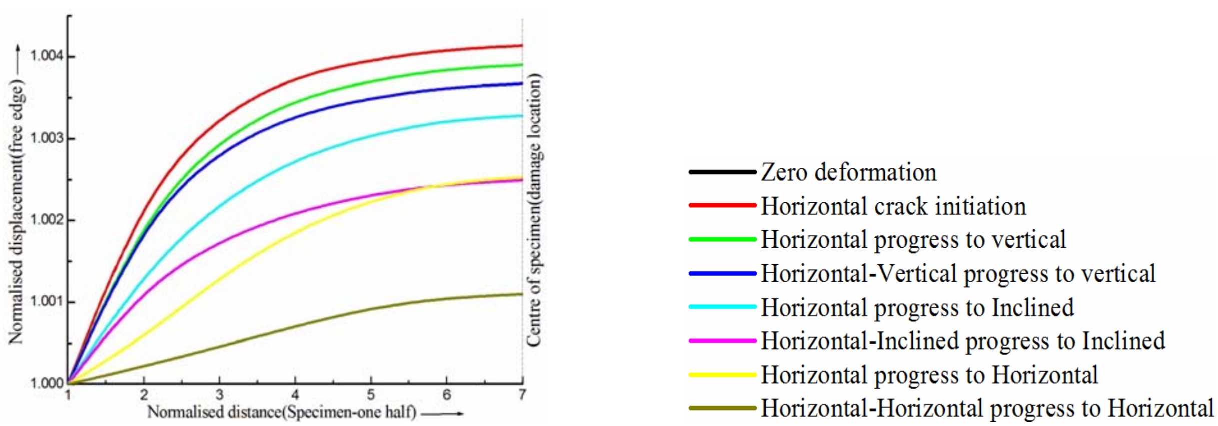


Figure-6. Displacement variation with spread of horizontal crack.

4. STIFFNESS DEGRADATION

4.1. Effect of material nonlinearity on stiffness decay

Cracking and damage can reduce the resistance of the component in a system and can eventually lead to failure of the system. So it is essential that an assessment of the damaged component in its load carrying capacity is made and this should account for spread of damage and material nonlinearity near the damage. Finite element method allows one to model the damage with progressively reduced material properties using elastic-strain-hardening material model. With this approach the deformation patterns were obtained [11] as the load gets increased. Figure-7 gives the load-deformation curve for a typical vertical NVC-parallel to load- damage for different strain-hardening values ranging from 0.25% to 1%. Here one can observe that as crack progresses the material enters inelastic [12] behavior near the crack and brings in yielding with sudden increase in deformation. This is quite significant for hardening parameter 0.25% which is closer to elastic-perfectly plastic [13] behavior. All these curves relate to damage occurring at 80% of load.

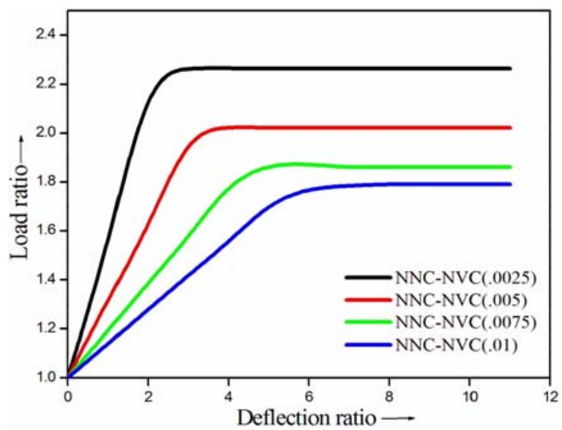


Figure-7. Load-deformation for NVC- damage parallel to load.

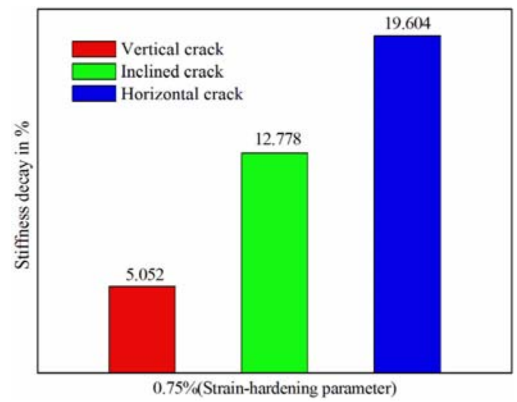
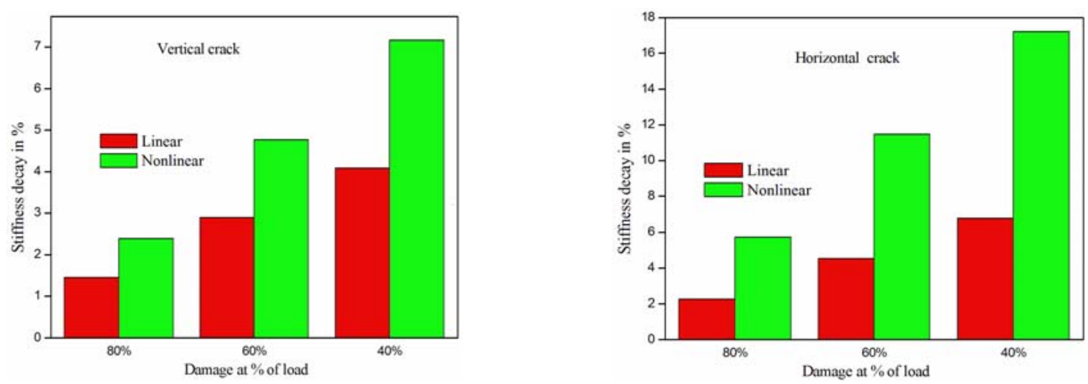


Figure-8. Stiffness decay for damage parallel to load-NVC.

The stiffness decay accounting nonlinear material behavior near the crack. This trend varies with type and progress of crack [14] and the stiffness degradation is used as a measure to reflect this and the histograms in Figure-8 give an idea of the decay for NVC-damage parallel to load.

4.2. Role of damage type on stiffness with material nonlinearity

The figure-9 shows the variation of stiffness decay when damage occurring at 80%, 60% and 40% of design load. It is observed for vertical and horizontal cracking/damage for the same value of 0.75% strain-hardening parameter. One can clearly see how damage/cracking normal to load can cause significant material yielding and consequent increase in deflection causing considerable loss in stiffness.



a) Stiffness decay-vertical crack b) Stiffness decay-horizontal

Figure-9. Stiffness decay for different types of damage for 0.75% strain-hardening.

5. REMAINING LIFE CURVE AND ESTIMATION

5.1. Remaining life studies of material for linear response

Since the type of damage and at what level of load it occurs, are significant parameters affecting the response, the FEM study was used to evaluate the remaining load carrying capacity for different types of damage? This is shown in Figure-10 for linear material behavior. From this curve one can assess the remaining life [15] as for example if damage or cracking occurs normal to load at 50% design load, the further load carrying capacity is not 50% but only 29% -a reduction of 21%-due to damage. Whereas for crack parallel to load the loss in remaining life is only 4%.

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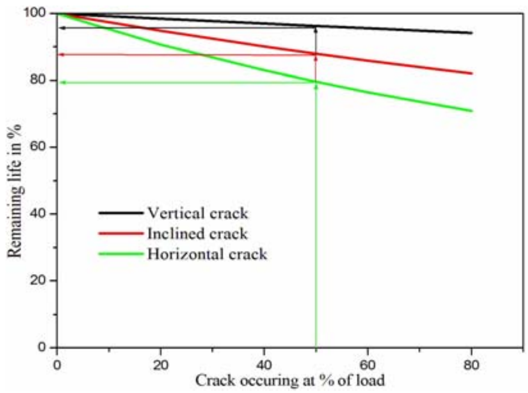
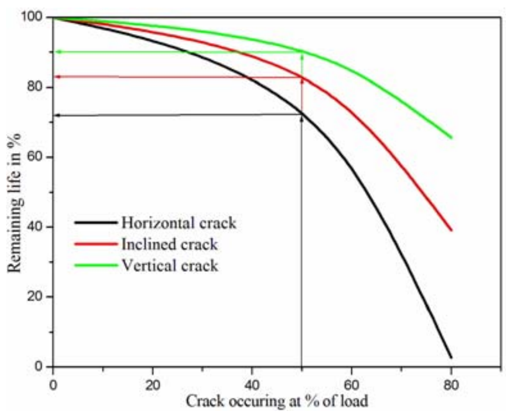


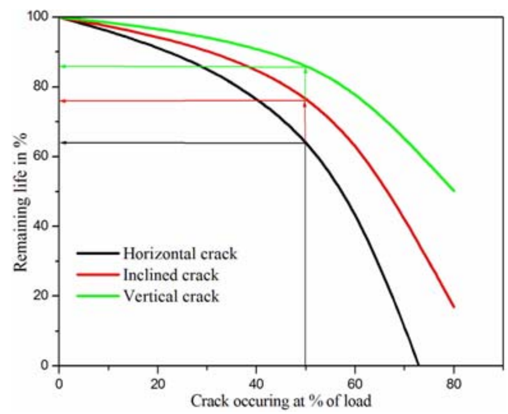
Figure-10. Remaining life curve for linear response.

5.2. Effect of material nonlinearity on remaining life

But of one takes into account the material yielding near the crack with nonlinearity, the remaining life curve also changes. Figure-11 gives the curve for different types of crack with material non-linearity values of 1% and 0.5% hardening. The specimen which had damage at 50% of design load, starts yielding and if one uses 1% strain-hardening, the remaining life values are 10% for NVC and 29% for NHC showing a further loss of 6% and 8%. But when the material yields at 0.5% strain-hardening, the values are 13% for NVC and 36% for NHC bringing in a loss of 3% and 7% more. If one assumes that cracking occurs at 70% or more the remaining life is zero meaning that the material has failed.



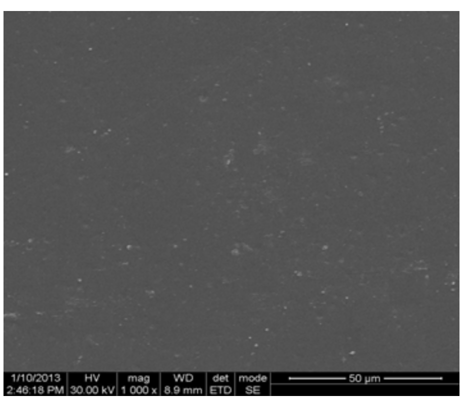
(a) Material nonlinearity 1%



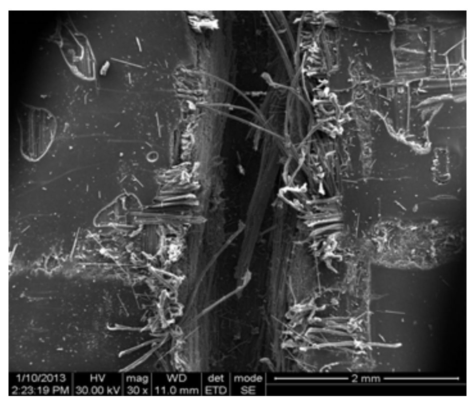
(b) Material nonlinearity 0.5%

Figure-11. Response of material yielding on remaining life.

6. SEM (Scanning Electron Microscope) SCAN



(a) SEM scan of virgin specimen



(b) SEM scan of vertical crack

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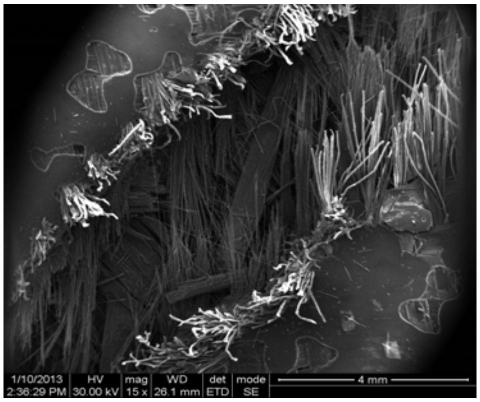
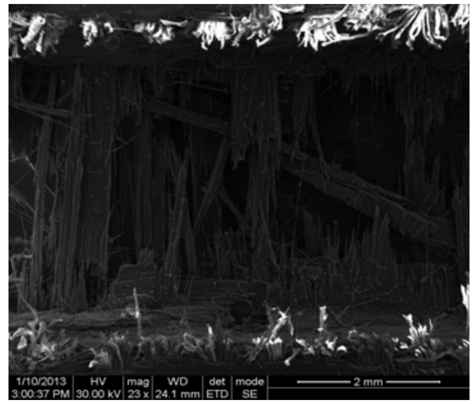


(c) SEM scan of inclined crack



(d) SEM scan of horizontal crack

Figure-12. SEM scans of virgin and different types of crack/damage specimens.

Figure-12 shows SEM scans of the virgin and specimens with different types of cracks/damage fractured in tensile tests shows the typical failure modes predominantly such as fiber tear, deboning with fiber fracture, matrix cracking, delaminations, mixed failure, fractured laminates and multi-stepped fracture obtained for bi-directional coupons. It is observed that horizontal crack/damage initiation and propagation resulting in a more rapid total failure of the composite coupon under test and hence reducing remaining life the most.

7. CONCLUSIONS

In this study, copuon of bi-directional carbon fiber with different type of crack/damage are subjected to tensile test. Analytical studies using FEM with nonlinear material model obtained from coupon tests form the basis of studies carried out to assess the behaviour of a typical fibre-reinforced plastic composite. The parameters chosen are the damage/cracking initiation type, its spread and the role of yielding causing nonlinear material behaviour. Stuffness decay and remaining life are given in the form of bars and curves so that one can get an idea of the influence of type of damage and nonlinear model. It is found that depending on the load level at which damage occurs. Remaining life can get affected significantly depending on the type of damage.

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