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Remaining Life Assessment of Damaged Reinforced Composites Under Inelastic Material Behaviour

KEYWORDS: Remaining Life Assessment, Damage, Finite Element Analysis, Coupon test

Dalbir Singh

Assistant Professor, Dept. of Aeronautical Engineering, Hindustan University, Chennai-603103

ABSTRACT *Role of composites in different applications ranging from aircrafts to sports equipments is always on the rise and this is due to many favourable properties of composites and also the research going on in material science. In this study, an investigation on remaining life of a typical bi-directional fibre reinforced composite damaged during its design life, is done using a hybrid method. Material testing, carried out on coupons as per ASTM standard with and without damage, is used as the basis for analytical studies done with non-linear finite element method. Different studies were carried out to assess the influence of different parameters of damage on the response in linear and nonlinear material behavior and based on these results, remaining life is assessed assuming that damage can occur at different levels of design load and curves are given to enable the loss due to damage to help in design and rehabilitation possibilities.*

INTRODUCTION

Carbon fabric reinforced composite structures are increasingly used for manufacturing components as flaps, aileron, landing-gear doors, and other artifacts in aeronautical industry [1] to meet the demand for lightweight, high strength/stiffness and corrosion-resistant materials in domestic appliances, aircraft industries, etc. 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 [2, 3] or weakening of the structure especially for an aging aircraft thereby affecting its load carrying capabilities and safe life. Since the 'end life' is defined by the reduction of strength and damage tolerance, remaining life assessment –RLA- after damage developed while in service, becomes important. The composite behaviour generally reflects that of the matrix material, bonding, number of layers used and type of reinforcement so that enhanced stiffness, strength and wear resistance are obtained and 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.

EXPERIMENTAL STUDIES

Material details

This investigation was 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 given in Table 1.

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

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– 2
MECHANICAL PROPERTIES OF BI-DIRECTIONAL CARBON/EPOXY COMPOSITE

Mechanical Properties	CFRC Material
Tensile Strength (MPa)	583.32
Young's Modulus (GPa)	37.069
Flexural Strength (MPa)	483.23
Flexural Modulus (GPa)	30.064

Specimen 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 50x25x1mm) 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 damage/ cracks were introduced on the

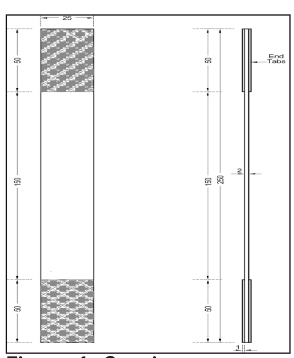

Figure 1: Specimen geometry and dimensions for tensile test

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virgin specimens in three different directions i.e., vertical, horizontal and inclined (45°). A typical coupon is shown in Figure 1.

Testing procedure

The coupons fabricated as above, were removed from the laminates and subjected to uni-axial tension using an Instron 3367 UTM, with constant crosshead speed of 0.15 mm/min as shown in Figure 2, with a set of specimens on the right. Twelve specimens, three in each category for damaged and undamaged types, were tested.. Tensile tests were conducted to form the basis for material characteristics to predict the remaining life assessment of the composites. Based on test results, characteristic properties like young's modulus, stress and strain [5] at different loads were obtained which will be used in analytical model..

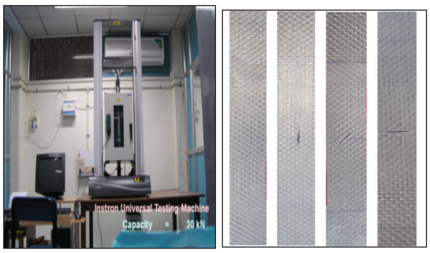


Figure 2: Testing of coupons

Experimentally obtained values of bi-directional composite material properties with and without damage are given in Table 3.The tested specimens after failure are shown in Figure 3.

TABLE– 3
EXPERIMENTAL RESULTS OF MATERIAL PROPERTIES WITH AND WITHOUT DAMAGE

Mechanical Properties	Units	Value for CFRC
Tensile Strength	(MPa)	37.069
Young's Modulus (VC)	(GPa)	35.50
Young's Modulus (IC)	(GPa)	30.50
Young's Modulus (HC)	(GPa)	26.15

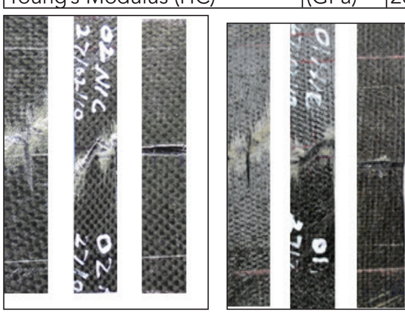
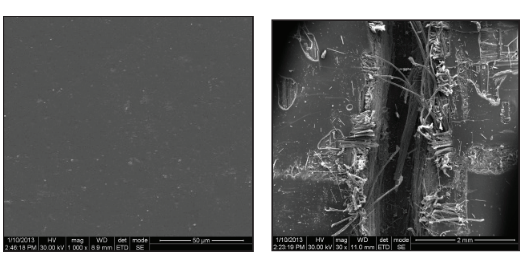
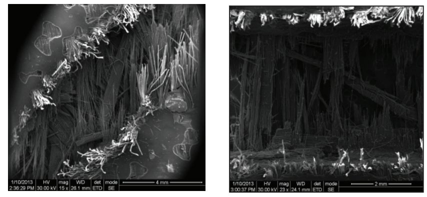


Figure 3: Specimen after tensile test

Typical SEM-scanning electron microscope- images of different types of damage in these coupons are shown in Figure 4 to give an idea of the complexity the damage can set in either in the material or in the fibre or in the composite.



(a) Undamaged (b) Vertical Crack



(c) Inclined Crack (d) Horizontal Crack

Figure 4: SEM images of damaged coupons

ANALYTICAL STUDIES

Finite element method of analysis using industry tested software ANSYS-12 was used to do detailed studies 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. Modeling of the region of cracking and loading is done using plane 82 elements initially convergence studies were done to arrive at a base model with nodes and element subdivisions for a standard stress concentration problem. Subsequently using 'no-tension model approach' as done by Zienkiewicz and others [6], the cracking was simulated with reduced values of material parameters from Table 3. Both linear and nonlinear analysis by material characterization using elastic strain-hardening model are done 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. Since the results for various cases have to be processed for proper evaluation and interpretation, the following damage parameters were identified:

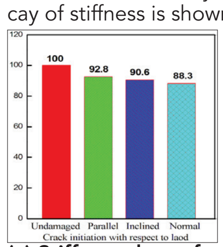
a) Type of initiation and location of damage
- parallel to the load-NVC
- inclined to the load-NIC
- normal to the load-NHC

b) Type of progress or spread
c) Material behavior linear or nonlinear near damage

Different load levels are taken as a fraction of design load at which damage occurs during design life. The studies are presented to give the influence of damage parameters on deformation, stiffness, effects of material nonlinearity and remaining life assessment-RLA in the following sections.

EFFECT OF DAMAGE ON STIFFNESS

Damage in material shifts the distribution of response from decrease in resistance followed by increase in deformation and this aspect needs detailed study as it gives an indication of the performance of the system for further increase in load. From the distribution of deformation it is clear that stiffness varies significantly and overall resistance of the system having damaged components also reduces. Consequently stiffness decay is a good parameter to indicate the influence of the type of damage characterized earlier. The stiffness decay is shown in Figure 5 for different cases of cracking as defined earlier and one can see that damage normal to load brings down the stiffness considerably by more than 30% under normal design considerations. Under static elastic behavior, crack initiation vertically-parallel to the load- reduces the stiffness only marginally whereas inclined and horizontal cracks stiffness decay is pronounced. Histogram on the decay of stiffness is shown in Figure 5(a).



(a) Stiffness decay for initiation

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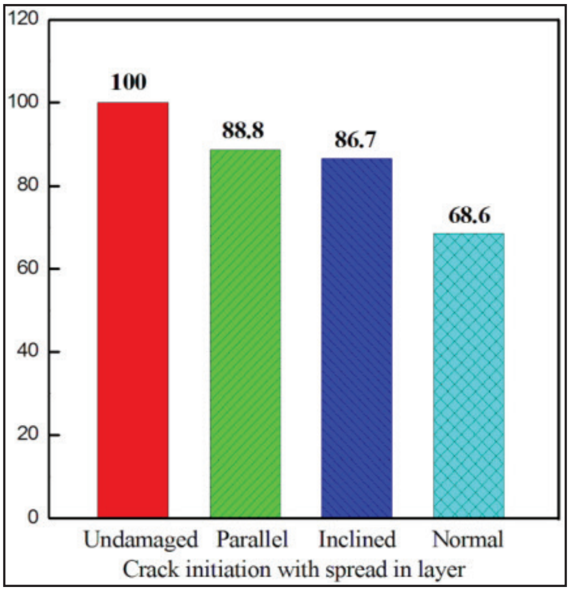


(a) Stiffness decay with initiation and spread
Figure 5: Stiffness decay with damage parameters

But when the damage spreads either in an inclined or horizontal way, stiffness decay gets accentuated as shown in Figure 5(b) for critical ones. While crack initiation normal to loads, brings down maximum effect on stiffness, as high as 11.7%, spread of crack after initiation into horizontal of any type of initiation shows a different behaviour. For example if a vertical crack spreads horizontally, its effect on stiffness reduction is high as compared to vertical or inclined. Spread of horizontal crack in horizontal direction has a significant effect bringing the stiffness down from 11.7% to 31.4%.

EFFECT OF MATERIAL NON-LINEARITY 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 as the load gets increased. Figure 6 (a) gives the load-deformation curve for a typical vertical crack parallel to load- NVC damage for different strain-hardening values ranging from 0.25% to 1%. Here one can observe that as crack progresses the material enters inelastic 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 behavior. All these curves relate to damage occurring at 80% of load.

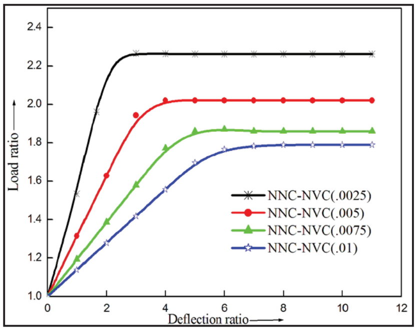
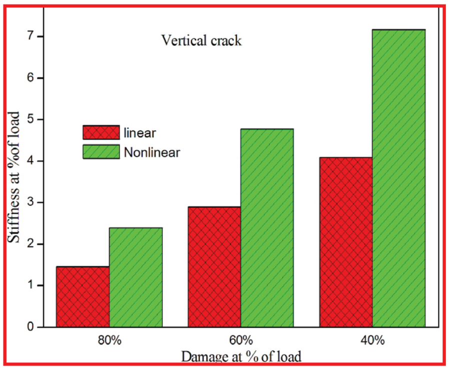
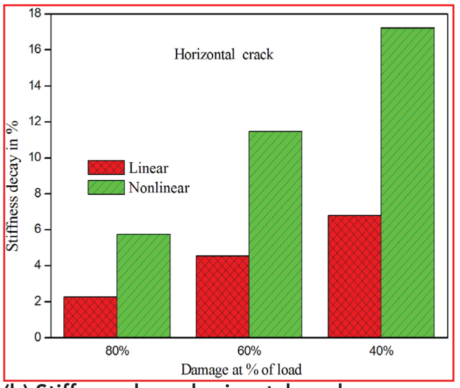


Figure 6 (a): Load-deformation for NVC-damage parallel to the load

The variation in stiffness decay for damage occurring at 80%, 60%and 40% design load for different two type of damage are Figure 7.



(a) Stiffness decay-vertical crack



(b) Stiffness decay-horizontal crack
Figure 7: Stiffness decay for 0.75% strain-hardening.

The different types of damage vertical and horizontal cracking for the same value of strain-hardening 0.75%. 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.

REMAINING LIFE ASSESSMENT- RLA

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 8 for linear material behavior. From this curve one can assess the remaining life 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 a crack parallel to load, the loss in remaining life is only 4%. Similarly the curve gives values depending on when the damage occurs in terms of design load ratio.

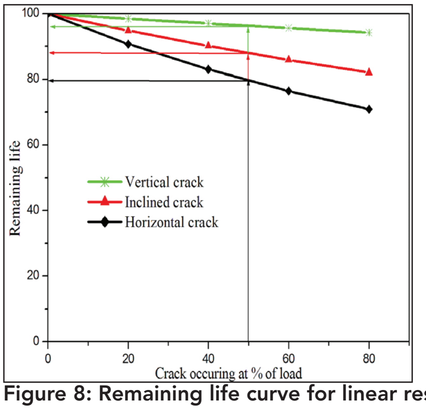


Figure 8: Remaining life curve for linear response

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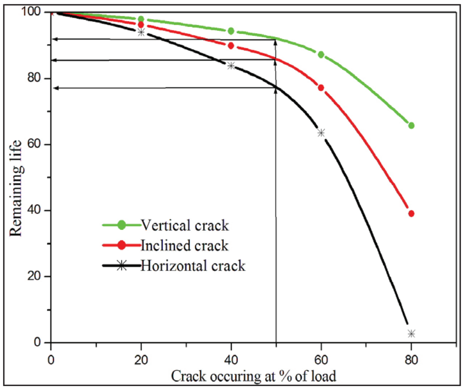
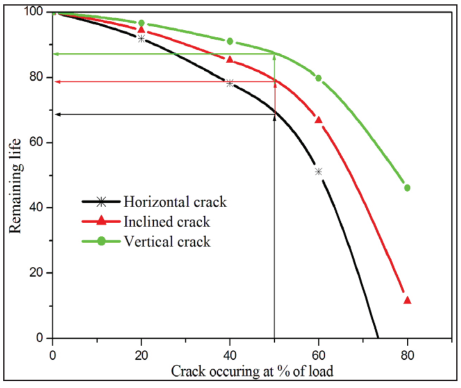
Effect of Material Nonlinearity on Remaining Life

But of one takes into account the material yielding near the crack with nonlinearity, the remaining life curve also changes. Figure 9 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%.



(a) Material nonlinearity 1% hardening



(b)Material nonlinearity 0.5% hardening

Figure 9. Response of material yielding on remaining life

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.

CONCLUSIONS

In this study, a hybrid experimntal-analytical approach is presented to study the response of damage in the form of cracking in a typical bi-directional carbon fiber composite. The experimental studies were doen on coupons with damage and using the material characteristics as the basis, detailed analytical studies using linear and nonlinear finite element method were carried out using different damage parameters like initiation, spread and material nonlinearity. Using the results, effects of damage are given for stiffness decay and remaining life assessment –RLA- and curves are given for different load levels at which damage can occur. It is observed that initiation and type of damage along with nonlinear material behaviour can bring down the remaining life considerably.

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