A REVIEW OF FATIGUE AND LIFE PREDICTION OF UNIDIRECTIONAL FIBER-REINFORCED COMPOSITES

RUSHIKESH ASHTEKAR
(MTechMechaniacalEngg. Dept. Student, Vinshwakarma Institute of Technology, Pune,India)
rushikesh.ashtekar16@vit.edu

AKSHY GITE
(MTechMechaniacalEngg. Dept. Student, Vinshwakarma Institute of TechnologyPune,India)
akshay.gite16@vit.edu

VIKRAM NIKAM
(MTechMechaniacalEngg. Dept. Student, Vinshwakarma Institute of TechnologyPune,India)
vikram.nikam16@vit.edu

PROF. N. S. KULKARNI
(Ass. Prof. MTechMechaniacalEngg. Dept., Vinshwakarma Institute of Technology Pune,India)
nishant.kulkarni@vit.edu

ABSTRACT
A detailed review on fatigue damage of unidirectional fiber composites and life prediction is covered in this paper. In order to summarize and present current work, the detailed work is divided in four parts in order to complete the overall review; fatigue of unidirectional composites, damage mechanism, failure criteria and composite Fatigue life prediction. The review starts with study on factors affecting the fatigue of composites. This is trailed by a fairly broad depiction of the composite and an outline of normally utilized fatigue criteria for expectation. Also, towards the end, models and techniques for weariness and life forecast of composites are condensed and discussed.

INTRODUCTION
Because of their high strength and stiffness composites are becoming more popular in different applications. Some examples of application area are sports, aircraft and aerospace, automobile and marine where composites are widely used nowadays. For fatigue of structures cyclic and fluctuating loads are responsible which are in these applications very easily. Composite materials are efficiently crafted to meet design requirements of strength, stiffness and other parameters all in various directions. These advantages should lead to new aerospace vehicle designs that are radical departures from the past efforts based on conventional material. The advantages of composite materials are so compelling that the research and development is being conducted across broad fronts instead of down the most obvious paths whole organizations have sprung up to analyse, design and manufacture parts made of composite materials. There is mutual connection between fatigue damage and life prediction of composite materials. The current study on fatigue damage and the life prediction of composite structures is in beginning stage. [12].
Composite materials deliver a mix properties of at least two materials that can't be accomplished by either fiber or matrix when they are acting alone.[1] The properties of a fiber-strengthened composite essentially relies upon the fiber modulus and strength, chemical composition, matrix strength and the interface holding between the fiber/matrix to empower stress transfer.[2] Some of the outstanding writing distributed in the region of exhaustion reaction of fiber-fortified composites were by Boller[3] in the mid-1970s, trailed by Owen and his collaborators.[4] At that point Baker and partners [5,6] were additionally setting out the establishments that depict the exhaustion conduct of metal grid composites (MMCs). While some of these early studies on fatigue are centeredon phenomenological thinks about, it rapidly ended up evident that a comprehension of the micro structural damage mechanics is the main factor for cyclic loading failure and is essential for the improvement of life prediction and fatigue resistance. Analysts, for example, Reifsnider and

Talreja[7,8] are related with the key improvements in the rising field of damage mechanics. The development of fatigue damage is basically a stochastic procedure and fundamental measurable translations of exhaustion conduct in conjunction with life prediction of composites were distributed by Hahn,[9] Al-Assaf and El Kadi[10,11] are among a portion of the most punctual scientists in the zone of ANN connected to weakness of composites. It is presently valued that the conduct of composite under exhaustion stacking is totally not quite the same as that of metal. Fatigue in metal happens by the start of single crack, which engenders until the point that calamitous failures happens. As opposed to metal, damage development in composite is global phenomenon rather than localized.

Composites have a various damage accumulation mechanisms, fiber– matrix debonding, fiber fracture, delamination and matrix cracking. These damage mechanisms can happen freely relying upon material properties and testing conditions [12].The purpose of this literature review is to guide the right path for the future development in this area of research.

UNIDIRECTIONAL COMPOSITE MATERIALS

The composite material with all fibres in the loading direction is more simple form. The properties of resin influence the fatigue strength of glass fiber composite is seen in study of several researchers.[1,2] the start of crack in matrix region leads to fatigue damage of material. Thermoplastic resin has more advantage over thermoset resin in terms of ductility and toughness. As shown in Figure1 thermoplastics resin have longer fatigue life.[13-15]. The interface between matrix and fiber affects the fracture toughness. Crack propogation in matrix is resisted by weaker interface which tends to improve fracture toughness, and also reduces the effectiveness of the stress transfer [16].

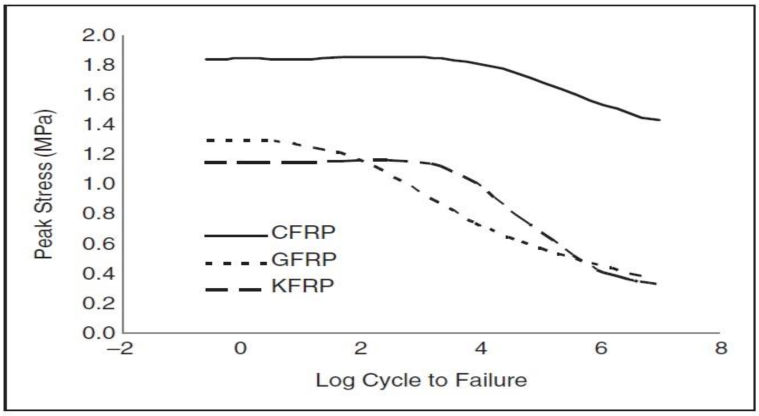

Figure1. S-N curve for unidirectional Composite materials [14].

Since, in tensile loading of unidirectional composites maximum load is carried by the fibers, hence the fatigue behaviour is expected to be depend on fibers, and since the fibers are not usually sensitive to fatigue loading, good fatigue behaviour should result. Because of the interfacial damage between fiber and resin high parallel splitting to fibers is shown by resin at failure which leads to the brush-like failure in several unidirectional composites.[19].

In the beginning of the fatigue damage of composites with fibers are in same direction as the loading direction, matrix cracks will start to propagate along the direction offibers. As the cyclic load continues the cracks increases and forms several stress concentration spots. When the applied cyclic load touches the level of the residual strength, fiber matrix breakage will cause total failure. The damage mechanism will be similar for composite material with smaller ply angle(less than 20^0)as the damage mechanism of unidirectional composites adjusted at 0^0. Be that as it may, the last failure of unidirectional composites adjusted at bigger ply angle (greater than 20^0) will well on the way to be commanded by matrix failure [20].

A. COMPOSITE DAMAGE MECHANISM

Fatigue damage mechanisms rely upon the loading condition in unidirectional composite, for example tensile or compressive, and on whether the loading is parallel or in angle to the fiber direction. Here we discuss only tensile loads and damage mechanisms under in-axis loading and off-axis loading separately.

There are three types of damage mechanisms in tensile loading as shown in fig. (see figure2). Fiber breakage (figure a) occurs when stresses crosses the limit of strength of the weakest fiber in the composite. Under cyclic loading of a composite the obliged matrix is subjected to strain-controlled fatigue and if the associated cyclic strain exceeds its strength the matrix breaks (figure b). At low strains the matrix crack would stop at interface whereas at high strains, the stress at the crack tip may exceeds the fracture strength of fibers, following fiber failure. The matrix crack may grow as micro crack under fatigue in an opening till it bumps into an interface, whereas the shear stresses may responsible for progressive damage of the interface with imitiation in the sliding mode (figure c).[18]

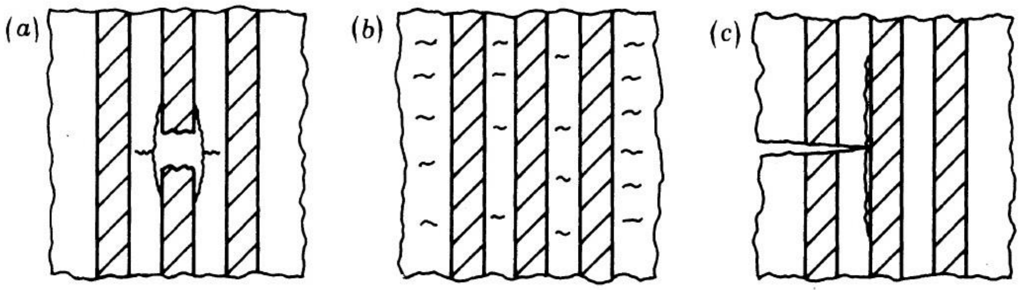

Figure 2. Fatigue damage mechanism in unidirectional composites under parallel loading tofibers: (a)fiber breakage, interfacial debonding; (b) matrix cracking; (c) interfacial shear failure [18]

The two fundamental microstructural damage mechanisms generally saw in composites under cyclic loading are fiber failure and matrix failure [8]. The failure procedure because of these damages relies upon the kind of reinforcement in the composites; unidirectional, multi-directional, woven and three-dimensional (3D) reinforcement. Fiber failure in composites paying little mind to static or fatigue failure is ordered into two methods of failure: tensile and compressive fiber failure. Fiber pull-out, fiber fracture and debonding are the typical tensile fiber failure modes. When both fiber and matrix are brittle then Fiber pull-out failure occurs. For tension loading in composite, nearby fiber crack and stress distribution happens respectively. After which, debonding of fiber from matrix happens and this is trailed by fiber breakage that prompt the final failure. Compressive fiber failure is, however, less reliant on fiber quality and depends more on fiber dependability, for example, fiber buckling and wrinkling. Free edge and zone in the region of void are where fiber buckling more often starts [21]. The figure shows damage mechanism pattern for fatigue life(Figure 3).

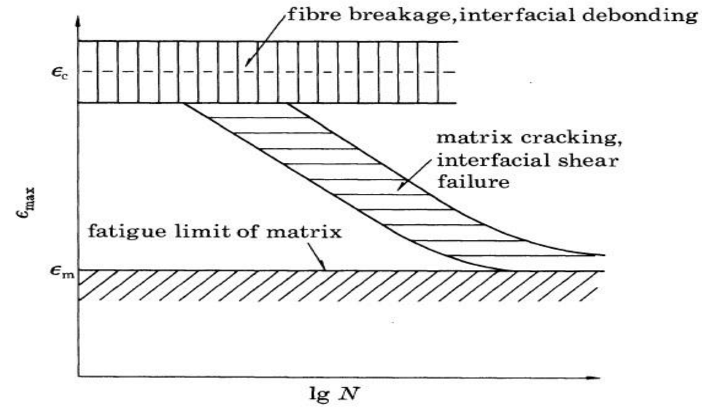

Figure 3.Fatigue-life diagram for unidirectional composites under loadingParallel to fibers [18].

The initial segment of the shows the non-progressive damage in nature since; zone of damage developing from a beginning time of the fatigue life to the final failure can't be followed. The progressive damage happens at strains beneath the scatter band of the break strain (i.e. elastic strength for linear composites).The progressive damage for the most part rely upon the matrix i.e. start of crack matrix area [18].

FATIGUE MODELLING AND LIFE PREDICTION

For the life prediction of metallic components the most used technique is linear elastic fracture mechanics. This technique is based on the growth of single flaws to failure, something notvseen in composites thus the applicability of such a technique to composite materials must be considered at the very least to be very restricted.Three main groups of composite fatigue models are fatigue life model, phenomenological model and progressive damage model. Figure shows the relation between the three main groups and composite fatigue models [12].

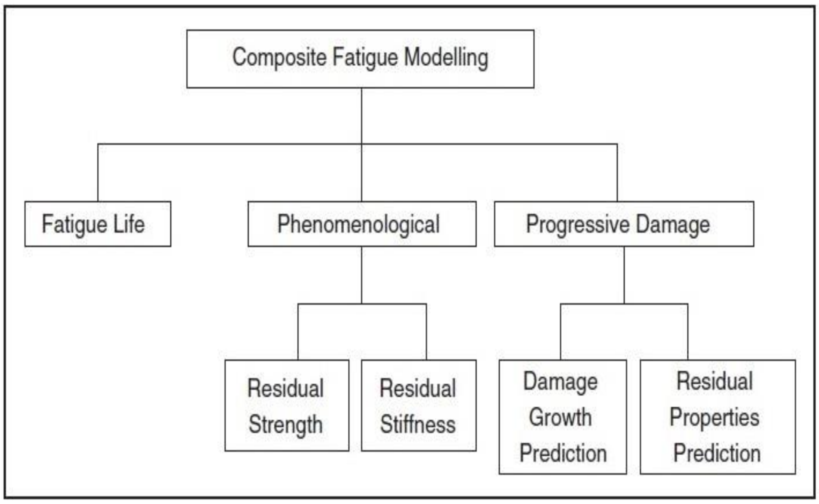

Figure.Composite fatigue modelling classification. [12]

Fatigue life model

Several fatigue life models available to study in the literature; Jen and Lee[22,23]and Philippidis and Vassilopoulos[24] developed amodel that is basically a modification of Tsai–Hill criterion and considered as more deterministic, as shown below,

$$\left(\frac{\sigma_{11}}{\sigma_{11f}}\right)^2+\left(\frac{\sigma_{22}}{\sigma_{22f}}\right)^2+\left(\frac{\tau_{12}}{\tau_{12f}}\right)^2-\left(\frac{\sigma_{11}}{\sigma_{11f}}\right)\left(\frac{\sigma_{22}}{\sigma_{22f}}\right)<1 \quad [25]$$

Whereσ_{11}, $\sigma_{22f}$and τ_{12f} are the fatigue failure stresses in the S-N curves. S-N curve available for some value of stress-ration and frequency, this criterion is used to model the fatigue life any stress ratio and frequency [24]. A model developed by Fawaz and Ellyin has ability to predict the S-N curve for arbitrary ply orientation based on modelled S-N curve for laminate for one direction [26].

PHENOMENOLOGICAL MODEL

The two common phenomenological models available: residual stiffness and residual strength. It shows how damage occurs in composites during fatigue loading by showing the degradation of one particular property of composites.

Residual Strength Model: Experimental observations are used by this model to describe the strength loss of composites: sudden death and wear-out are the two sub-models of this model. This model used for glass fiber-reinforced composites [28,29] and Diao and Mai [30]has developed a model of residual strength for predicting the fatigue life of composite laminates.

Residual stiffness model:This types of models have been presented in the literatures [28, 31, 32]One such model is by Whitworth [32],

$$E_{(n)}=E_{(n)}\left(\frac{S}{c_1 S_u}\right)^{\frac{1}{c_2}}\left[-h\ln(n+1)+\left(c_1\frac{S_u}{S}\right)^{\frac{m}{c_2}}\right]^{\frac{1}{m}} \quad [33]$$

whereE_0,E_n Su and S respectively are initial stiffness, stiffness at n cycle, ultimate strength and applied stress. The parameters c1, c2, h and m are obtained from experiments. Major advantage of stiffness models over the strength models is that only the stiffness of composites is needed for material characterization.

PROGRESSIVE DAMAGE MODEL

This model uses fracture criteria for predicting the cycles to failure and degradation of properties of composite. This model has two sub-models that are model predicting damage growth and model predicting residual mechanical properties [34].

Model predicting damage growth:Bergmann presented a model which combines all the modes (mode I tension, mode II shear and mode III shear) in one equation also knows as empirical delamination propagation model.[35] The governing equation of Bergmann model is,

$$\frac{dA}{dN} = c_1[f(G_t)]^k = c_2\varepsilon^k A^l \text{ [36]}$$

Where Gt is the total of mode I, II and III , A is area of delamination and N is the respective number of cycle. The parameters c1, c2, kand l are determined from experiments. Bergmann model can be modified as,(Assuming constant width)

$$N=\frac{a^{(1-m)}-a_0^{(1-m)}}{(1-m)c\sigma^n} \quad [37]$$

Where, a_0 considered as initial crack length.

Model predicting residual mechanical properties: Shokrieh developed a model,which predict the fatigue damage progression of complicated composite structures provided the properties of the composite materials are fully characterize using modified Hashin failure criterion [38-41].For characterization of composite material,following set of tests are needed, for each combination of load and fiber or matrix testing.

- Residual stiffness and strength are determined by carrying out fatigue test of specimen up to certain cycle then followed by a static test till failure.
- S-N curve can be formed by carrying out fatigue test till failure [38].

CONCLUSION

The current study on fatigue damage and life prediction of fiber-reinforced composites is still not up to mark and there is lot more scope in this area. The following points need to be considered for predicting the fatigue life.

- Development of failure criterion for all types of fiber- reinforced composite structure and all type of loading condition,
- Study has to be done on the simpler model of progressive damage and also it should be less expensive computationally.
- Study has to be done on different stacking sequences.
- There is lot of scope for study of unidirectional fibers as they have more fatigue resistance when applied by load along in the direction of fiber.
- Fatigue life model is much easier as it can predict the first point of failure without the details of stiffness degradation before failure.
- The fatigue resistance performance of composite is set by matrix properties, unless the composite fracture strain is lower than the matrix fatigue limit. Hence fatigue performance can be improved by making the matrix material more fatigue resistant.

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