Progressive Failure in Woven Composites: A Literature Review

Kinjal V Ranolia, Bhairav K Thakkar, J D Rathod

Abstract--**In this paper, results of experimental research available in literature on notched and un-notched woven composites under tension and compression are discussed. Under tension, woven composites behave in a linear fashion up to failure, whereas in compression, they often show a non linear response due. Fatigue damage in plain weave fabric composite usually gets initiated by bundle cracking. Woven and knitted fabric composites usually show comparable results in fatigue life and residual strength. Experimental study available in literature, focused on tensile, compressive and bearing strength of woven composites and fracture or crack propagation in woven composites have also been included in the current review. While a large number of publications are available in the literature, the most relevant publications have been included in the current review.**

Keywords: **Woven composites, Progressive failure, Fatigue damage, Literature review**

I. INTRODUCTION

Composites are attractive for industrial applications because of their ability for reducing manufacturing cost and increasing impact resistance and toughness. The use of composite material can also reduce the weight of structure [2]. More advantages of the materials include toughness, resistance to corrosion and fatigue, resilience, translucency and greater efficiency in construction compared with more conventional materials [21].

Composite materials consist of two or more distinct physical phases, one of which fibrous is dispersed in a continuous matrix phase. It is possible to introduce fibers in polymer matrix at highly stressed regions in a certain position to obtain maximum efficiency from reinforcement. Fiber Reinforced Polymers (FRP) composites were first developed during the 1940s, primarily for military and aerospace engineering applications. FRPs have been successfully used in many civil engineering applications as well including load bearing and infill panels, pressure pipes, tank liners, roofs, bridge repair and retrofit, mooring cables, structural strengthening, etc.Compared to steel and concrete,FRP composites are about 1.5to 5 times lighter[15].FRP composites provide only a nominal increase in stiffness so they are generally useful for increased structural strength, rather than deflection control[22].

FRP composites could be composed of either uni-directionally placed fibers or a woven fabric of fiber material embedded in a polymer matrix. Two major types of fabrics are available in composite industry: woven and nonwoven fabrics [1]. Woven fiber fabrics can be made by adopting any of the following techniques.1) Weaving 2) Knitting 3) Non-woven 4) Braided 5) Nets 6) Laces. Weaving is the most commonly used method of fabric construction, where two sets of yarns are interlaced with one another at right angles. Weaving of a fiber fabric is done in a way similar to weaving of cotton fabric, except for the fact that yarns are used for interlacing and a loom is used to hold the thread instead of a frame.

Application of woven composites is increasing because of their suitability for injection moulding and fiber placement. Also, woven polymer matrix composites offer advantages such as symmetric and balanced behavior with superior impact properties. Main advantage of woven materials is that they can be dropped over or in non-flat moulds while retaining most of their orthogonal properties. Further, woven fabrics exhibit a higher value of elasticity modulus in both principal directions along with superior shear strength as compared to a ply of uni-directional composite. This gives an added advantage of having better mechanical qualities in a single ply thickness, thereby reducing the weight of structure as compared to uni-directional plies.

Owing to these properties, woven reinforced composites are becoming a common material of choice in aerospace engineering industry. Polymeric composites are used to manufacture hinge less, bearing less composite rotor hubs for helicopters.

II. RESULTS FROM EXPERIMENTS

YEE and Pellegrino [12] conducted studies on one ply and two ply laminates made from woven T300 carbon fiber and Hexcel 913 and 914 epoxy resins. These laminates are effective for deployable structure applications. One ply laminate denoted by [0, 90] and two ply $[0, 90]_2$. The maximum surface bending strain measured by means of large displacement buckling test was found to be 2.8% for one ply and 1.9% to 2.2% for two ply specimens in directions of fiber. In tension the maximum strains in fiber direction are 0.9% to 1.0% and in compression 0.4% to 1.0%.

Winsom [48] carried out bending test on 26 ply unidirectional XAS/913,3.35 mm thick specimens and observed that the strains were up to 2.5% on compressive surfaces. In pure compression strain was typically around 1%. The maximum compressive strain at failure decreases when the dimensions of specimen are increased. Maximum strains were characterized and compared before failure in tension, compression and bending by means of simple coupon tests. The procedure adopted was based on sandwich column layout. Specimen considered for the tests were smooth, uniform and 0.22 mm (one ply) and 0.43 mm (two plies) in thickness. All the tests were conducted using an Instron 4483 materials testing machine with a load cell of 150 kilo-Newton's. The tensile test specimens were cut with the woven fibers aligned with and perpendicular to direction of applied loads. Multidirectional CFRP 20 mm wide,200 mm long parallel edge, unnotched specimen were sandwiched between 50 mm long aluminum tabs with epoxy resin. For more uniform distribution of stress in fiber weave, the specimens were subjected to four load cycle upto about 80% of ultimate stress. Compressive tests were carried out on short sandwiched column. The specimens were designed so that they want fail by micro buckling. Steel end plates were bonded to both ends of each specimen to minimize any stress concentration. The aim of bending test is to determine the smallest radius of curvature that a particular specimen will survive without failing. Results indicated that the response was clearly linear elastic until failure exhibiting maximum longitudinal strain = 1.14%, average elastic modulus parallel to fiber direction was found to be 60GPa (T300/913) and 50GPa (T900/914) for one and two ply laminates. Finally they concluded that in tension (along one set of fibers) composites are linear up to failure which occurs at an average strain of 1% and in compression they often show a non linear response due to bedding in deformation, endbrooming and delamination at an average strain of 0.7%.

Tsuda and Takahashi [10] worked on bearing failure in plain woven c/c composites. Bonded joining is prone to be weakened by environmental effects, although it has the advantage of low stress concentrations and low weight, so mechanically fastened joining are applied to structures which are used in severe environments. Mechanical fasteners fail in bearing, shear and tension modes; from structural design point of view bearing failure is desirable because of its stable fracture propagation. The bearing strength can be estimated under condition of fully developed bearing failure which occurs only when the width to pin diameter ratio w/D and edge distance to pin diameter ratio e/D are above certain minimum values. According to Japanese Industrial Standard (JIS) K 7080 the use of specimen with w/D = 6 and e/D = 5 is recommended to fully develop bearing failure. C/C composite are promising structural materials for high temperature applications owed to their high specific strength, rigidity and excellent thermal and chemical stability. The bearing strength tests were performed using plain woven c/c composite with different w/D and e/D values. Ratios w/D and e/D were varied from 1.5 to 5 and from 1 to 3.The test specimens were cut to give rectangular solids and then a 6 mm diameter hole was drilled. The thickness of specimen"t" was 3 mm.

Bearing strength was estimated from

$$B_f = P_{max} / Dt$$

Where, P_{max} is during bearing strength test. The bearing failure was observed in specimens with w/d = 2 and e/D =2.The bearing stress was saturated at 125MPa when w/D was 2.5. Thus the bearing strength estimated under the condition of fully developed bearing failure was estimated to be 125MPa. Finally they concluded that the bearing failure of plain woven c/c composites was fully developed in the specimens with w/D = 2.5 and e/D = 2.5.

Khashaba [46] conducted research on behavior of $[0]_8$woven composite under monotonic and combined loading, the objective was to investigate the mechanical properties of woven glass fiber reinforced polyester (GFRP) composite under monotonic and combined loading. Woven carbon fibers are being extensively used in aerospace, automotive and civil engineering applications owing to their high specific strength, high fracture toughness and low production costs. Tests were performed under monotonic loading conditions in tension, three point bending, four point bending and combined tension/bending. The bending moments were applied through offset shims of various thicknesses placed between the plane of the specimen and loading axis to give various eccentricities. In this discussion comparison between quasi isotropic woven GFRP laminate $[0/\pm45/90]_s$ and $[0]_8$woven composite have been discussed.$[0]_8$ composites have higher tensile strength and stiffness than $[0/\pm45/90]_s$ composites. Eccentricity "e" has more prominent effect on decreasing the ultimate tensile load for $[0]_8$ specimens than quasi isotropic woven GFRP laminate $[0/\pm45/90]_s$. Failure of the $[0]_8$ specimen started at the tension side for 3 point & 4 point bending tests and was due to combined tensile and bending stress at the ends of the gage length. Structural members such as shaft, beams and plates are subjected not only to uniaxial loading but also to multiaxial loading. Twenty specimens were reported, twelve of which were tested in tension and bending tests whereas eight were tested under combined bending and tension loads. In tension tests the strain gauge was bonded longitudinally at the centre of test specimen to determine actual value of tensile modulus. Khashaba concluded that the failure of angle ply woven specimen in tension test was at the end of the gripping length. The aluminum end tabs not only reduce the stress concentration from ragged grips but also prevented the slipping of the test specimen from the grip. Experiments were also conducted on woven SIC/SIC composites in two direction under tensile loads. The composite was made by chemical vapour infiltration of a SIC matrix into a fabric of SiC Nicalon fibers [13]. Two batches of 12 specimens were tested under quasi static tensile conditions at room temperature. Two types of specimens used in the size effect observations are 8×30 and 16×120.The strain-stress curves were identical for all specimens showing significant scatter of ultimate failure loads. The $[0]_8$ woven composites have higher tensile strength and stiffness than $[0/\pm45/90]_s$ composites. The value of flexural strength determined from 4 point bending test was reported to be higher than that from the 3 point bending test.

The compressive strength of composites is frequently a design limiting parameter for long fiber, polymer matrix composite. Compressive strength is usually less than the tensile strength. Compressive tests are usually performed on both notched and unnotched specimen. An infinite band kinking model may be employed to estimate the unnotched strength and a large scale bridging analysis may be conducted to predict the notched strength [25]. Fleck et al. [24] conducted research on these tests for both un-notched specimens and specimens containing a single central hole made from carbon fiber epoxy laminate 2D and 3D woven composite under compressive loads. The predominant failure mechanisms in both un-notched and notched specimens were found to be plastic micro buckling of fibers.

Soykasap [29] examined the mechanical properties of plain weave composites. In a plain weave composite the warp and weft yarns pass over and under each other alternately. The macro mechanical behavior of woven composite depends on fiber bundles and matrix and their interaction, geometry of yarns, the spacing between them, the crimp angle and fiber volume fraction. A woven materials made of a few plies is not like unidirectional composites, for which classical lamination theory is established and works well [8]. Karkkainen and Sankar [36] noticed a factor of 2.9 in the bending stiffness appeared when the classical lamination theory (CLT) was directly adopted. The classical lamination theory (CLT) assumes the mid-plane as a reference plane and that the fibers are distributed homogenously across the thickness of lamina. The homogenized properties of such a laminate under are obtained by integrating the stiffness across the thickness. Hence, the estimates based on CLT can result in large errors in computed stresses, strain and bending stiffness. Several approaches based on micromechanics of woven composites have been adopted to obtain mechanical properties of plain weave composites. Such approaches usually utilize relatively simple analytical methods having high accuracy, rule of mixtures and composite beam and mosaic model. The macro-structure of the composite can be obtained by considering a repeating cell, which is the smallest unit of the composite and composite assumed to be balanced, hence its material properties are same in warp and weft directions.

N.Srinivasababu et al. [26] presented that okra (natural fiber) woven FRP composites showed the highest tensile strength and modulus of 64.41 MPa and 946.44 MPa respectively than all other composites. Yang and Cox [34] deducted that damage mechanics that can be employed successfully to predict delamination, splitting cracks within plies, multiple matrix cracking within plies, fiber rupture or micro buckling, friction acting between delaminated plies, process zone at crack tips and oblique crack bridging fibers. Gao et al. [9] described about residual property changes and damage accumulation of different laminates under monotonic loading. P.Shrotriya[31] concluded that total deformation of the composite increased with increase in temperature. Linear elastic fracture mechanics (LEFM) concepts normally applied to homogeneous isotropic materials are valid for composite materials in which strain energy release rate may be used to characterize toughness of composites [43].

III. PROGRESSIVE FAILURE IN WOVEN COMPOSITE

The idea behind progressive damage is quite simple. Both, matrix controlled and fiber controlled types of failure can separately and sequentially occur during the loading of various lamina within laminate. Thus the term progressive damage essentially means predicting damage progression at lamina level and then laminate failure from lamina level damage, ultimately leading to failure of the laminate [47].

Zahariand Azmee [35] worked on damage coupled progressive failure analysis of woven glass/epoxy laminated plates. They performed non-linear finite element analysis to simulate the progressive failure of the laminate. Tsai-Hill failure criterion has been embedded in the progressive failure model to detect damage coupled failure of woven fiber composite laminates. The use of numerical simulations tools such as finite element method allow us to replace structural component testing with virtual testing to predict the damage behavior and the mode of failure [19,20].Under normal operating conditions laminated composite structures can exhibit local damage mechanisms such as matrix cracks, fiber breakage, fiber matrix debonding and delamination, either alone or in combination, which lead to final rupture of the laminate [37, 39]. For composite structures the use of failure criteria is not sufficient to predict ultimate failure of structure because the laminate can accumulate damage before structural collapse [17]. To bridge this gap, the past recent years have seen rigorous development of numerical methodologies for the progressive failure of composite materials. Studies on damage behavior of woven fabric or bi-directional composite laminates are limited. Zahari and Azmee conducted studies on woven fabric glass/epoxy composites used as case study to demonstrate the capability of the progressive damage analysis for composite laminates using non-linear finite element analysis to predict failure of brittle fiber reinforced composites for static stress analysis. Woven glass/epoxy panels were fabricated and tested experimentally. Experiments were conducted to evaluate the performance of woven panels made of C-glass epoxy subjected to compressive load. Panels with and without centrally located circular cut-out consists of eight layers with different fiber orientations were fabricated and tested. Geometry of fiber glass laminated panels contained a central circular hole with length l of 320 mm, width w of 60 mm, average thickness *t* of 2.5 mm and cut-out diameter D of 38 mm. The panels without cut-outs had the same dimensions. Effective length of the specimen was 210mm.The elastic material properties were to depend on the field variables which could be a function of any Gauss point quantity such as stress and strains, etc.

When local failure or damage occurs, a change in the stiffness is calculated based on material degradation model. Structural analysis is the process by which the relevant data for the structure are obtained. These data can be the stresses, deformations, displacements, oscillations, etc. Finite Element Method (FEM) is a numerical method of structural analysis. For finite element simulations, the four woven composite panels were modeled in ABAQUS. The geometry, boundary conditions and loading of the plate were similar to that of specimen. Analysis was performed using a four noded shell element with six degrees of freedom per node. The load versus end-shortening curves for tested and simulated panels have been presented and were found to correlate well with the experimental results. The panels behave almost linear before reaching the peak loads. Beyond peak loads, laminates experienced large deformations before failure. They observed that cross ply laminates possess the greatest strength since they were subjected to only a uni-axial compressive force. Three areas were identified as being the cause of reduction in strength; criming of fibers,resin rich areas and damage during the weaving process[4]. Since Tsai-Hill theory is an interactive type of failure criteria it does not provide the information on mode of failure of failed lamina. Non interactive failure theories in conjunction with progressive failure analysis should be used, if modes of failures are required. Experimental elastic characteristics were obtained from stress-strain curves.

Hinton, Kaddour and Soden [11] compiled a very useful collection and assessment of many different approaches. Puck and Schurmann [33] give an approach originally based upon Coulomb-Mohr type behavior. Mayes and Hansen [23] descriptively designate their method as MCT (Multi-Continuum Theory).Daniel [3] treats many aspects of failure. Robbins and Reddy [38] give an approach using internal variables. Tsai et al. [44] give and use MMF (Micromechanics of failure).A finite element approach to damage and failure is given by Tay et al [45], EFM (Element Failure Method). Naik et al [28] analyzed 2-D elastic models using the unit cell approach in which structure is divided into repeated cells representing properties and behavior of lamina. This approach is employed in analysis of most material models of woven composite structures. Paul [30] discussed application of MLT-based approach to model damage in woven carbon composite materials. Stepan V. [42] discussed on comparison of numerical analysis results for effective elastic properties of four representative 3D woven E-glass/epoxy composites, surface strain field under tensile loading and the respective experimental validations. Palmer et al.[30] simulated and tested for the progressive tearing failure of pultruded composite box beams. Y.A.Bahei-El-Din et al. [49] concluded that the transformation field analysis (TFA) based computational approach offer a robust method for evaluating the overall response of woven composites.

IV. FATIGUE DAMAGE IN WOVEN COMPOSITES

The problem of fatigue failure in aircraft structures arose in the 1940's with the jet propelled aircraft and remains a significant problem today. Fatigue failure often occurs at load levels that are well below the static strength of the material. Unidirectional, woven and 0/90 laminated carbon/epoxy composites were found to possess superior tensile fatigue properties to metals such as aluminum. Fatigue damage does not progress as a single crack but may take form of many micro cracks dispersed throughout the laminate. The damage in composite does not necessarily lead to immediate catastrophic failure but the stiffness and residual strength of composite gradually reduce during the fatigue life until the material is sufficiently weakened to precipitate catastrophic failure. Damage progression during fatigue process is observed by plotting changes to the elastic modulus of the composites over the fatigue life.

Pandita [41] observed that fatigue damage in plain-weave fabric composite was initiated by transverse bundle cracking. Woven fabric composites show better fatigue resistance then knitted fabric composite. Composite structures are often subjected not only to impact but also to fatigue loads. The failure mechanism in woven fabric composites is initiated by fiber-matrix debonds in fiber bundles oriented transversely to the loading directions. The fatigue properties of woven fabric composites are also influenced by the stress concentrations around notches and by ductility of matrix. The publication focuses on the fatigue damage development and the nature of the fatigue failure in correlation with residual strength, the relative residual stiffness and the fatigue life. Scanning electron microscopy (SEM), optical microscopy and acoustic emission were used to evaluate the fatigue damage. In tests, woven and knitted fabrics were impregnated using epoxy film F533 from Hexcel. Fatigue tests were carried out at different maximum stress fatigue ratios ($S_{max}=\sigma_{max}/\sigma_{ult}$), S_{max}= 0.4, 0.5, 0.7 and 0.9 were used. The fatigue specimens had a width of 25 mm and a length of 230mm.For the microscopic analysis, the fatigued specimens were cut and polished using silicon graphite paper and the polished specimens were then coated with gold before being inspected by scanning electron microscopy. The acoustic emission (AE) technique is the only in situ non-destructive test, which can be applied to detect damage when it develops while the experiments are being loaded. Microscopic technique scanning electron microscopy (SEM) has been used to complement AE in the damage investigation [5]. The main disadvantage of SEM is that the technique is destructive means that an investigated specimen can only be subjected until a certain damage level or number of fatigue cycles. Stiffness and strength decreased slightly when the fatigue cycles increases, because transverse fiber bundles give only a small contribution to the total mechanical properties.

Tensile fatigue damage can be classified in four stages on woven fabric composites. a) Initial stage: no fatigue failure b) first damage stage: transverse crack in the bundle yarn, c) second damage stage: meta-delamination, typically represents fatigue cycles occurring between 20% and 80% of the composite fatigue life, during this stage, the rate of elastic modulus reduction decreases significantly. During this stage other types of fatigue damage occur such as longitudinal crack coupling and at near the end of fatigue life the elastic modulus of composites drops sharply. d) Third damage stage: final failure. This sudden drop is attributed to the fracture of load bearing fibers that quickly leads to complete tensile fatigue failure of composite. These stages of fatigue damage progression depend on material properties and the maximum stress or strain that is applied to the material. Fatigue life can be studied from S-N curve. The slope of the S-N curve in each region represents the sensitivity of material to the dominant fatigue mechanism. Gam stedt et al. [6] examined the fatigue damage mechanisms in cross-ply laminates and found that even at very low tensile load, a small proportion of weaker fibers will break, and these serve as sites for transverse crack initiation. Xiao and Bathias[14] examined the fatigue damage and strength of three woven laminates (two orthotropic and one quasi-isotropic).The fatigue strengths of the unnotched and notched specimens were determined.

Lee et al [18] analyzed the fracture in woven composites by modeling and comparing with the unidirectional composite. They had proposed anon-linear model with an inelastic fracture. Hashin[50] proposed analytical model for unidirectional composite under fatigue. Kim et al[16] had examined the pressure strength of the woven composites. They concluded that the critical stress which leads to delamination was lower than the stress leading to micro buckling of fibers.

Pandita et al [32] studied the influence of loading direction, stress concentration at the crack tip and the ductility of the matrix on fatigue behavior of woven composites and observed that for a loading in the weft or warp direction the fracture of fibers was predominant and for a loading out of those directions the fracture of matrix occurred in first. The influence of the kind of woven layers on the critical strain energy release rate using the compliance method has been studied by Kim et al, which corresponds to the shape of created crack in woven composites.

V. APPLICATION OF TEXTILE COMPOSITE MATERIALS

The use of textile fabrics has offered a lower cost to composite manufacturing and higher damage tolerance [27]. Woven, knitted, braided fabrics are textile fabrics that are widely used in many applications. Knitted fabric composites have the highest deformability and impact resistance compared to braided and woven fabric composites.

Two example of the application of 3D woven carbon fiber textile composite materials investigated at Engineering Composite Research Centre are a composite component of lower leg prosthesis and a beam with T-shaped cross section [7]. Prosthesis for a below knee amputee was developed within the Northern Ireland Bioengineering Centre (NIBEC).Lower limb prostheses easily provide static structural supports but not provide dynamic functions that correspond to muscle activities that have been lost. Therefore new approach in design was used by taking composite material instead of conventional engineering materials such as steel, aluminum or titanium. The purpose is to achieve improvements in convenience for the patient. The use of composite material has two main advantages. First is light weight, total weight of prosthesis is most important for convenience of amputee. The remaining muscle mass defines an upper limit for total weight of prosthesis and light weight leads to greater mobility and less fatigue for amputee. Second is multifunctinality. The increase in impact strength is very important because people using prostheses often lead an active life style, activities like running, jumping or kicking.

A more recent successful application of 3D woven composites to aerospace structures is the Joint Strike Fighter [40]. During 1990s the CRC-ACS and other research institutions investigated the weaving technology required to reduce aerospace quality. They produced a number of demonstrator 3D woven composites parts such as I-beams and T-sections.T-sections are often used as stiffeners in post buckling panels where the predominant failure mode is separation of the stiffener from the flanges.

VI. CONCLUSION AND SCOPE OF STUDY

Compared to unwoven unidirectional composites, the woven fabric composites provide good reinforcement in the warp and weft directions and lead to reduction in the manufacturing costs. Thus far, there have been numerous studies on the woven composite laminated structures which find widespread applications in many engineering fields namely aerospace, biomedical, civil, marine and mechanical engineering because of their ease of handling, good mechanical properties and low fabrication cost. The catastrophic failure occurs in composite structures due to matrix cracks, fiber breakage, fiber matrix debonding and delaminations under various loadings. From the literature review, it is evident that most of the studies are based on the numerical approach. Less attention has been paid on the buckling of composite plates. Due to the practical requirements, cutouts are often required in structural components due to functional requirements, to produce lighter and more efficient structures. The interaction among stacking sequence, cutout shape and length/thickness ratio on the buckling behavior of woven fiber laminated composites warrant investigations in greater detail.

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