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A Review Paper on Study of Progressive Damage of Composite Structure Under Tri Axial Loading by Referencing Macro-Mechanical Based Failure Theories

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ABSTRACT
Paper reviewed laminate failure occurred under tri axial loadings by using macromechanical based failure theories applied under static loading conditions. The proposed failure model by various authors is an extension of the strain energy failure theory for tri axial loading conditions. The paper summarizes laminate failure which includes initial failure, progressive damage, and final failure different laminate ply and material configurations. The paper also reviewed the structure failure due to stress concentration effects arrive due to edging effects. The aim of paper is to present failure of complex composite laminate by various means due to complex loading conditions much similar to actual operational loadings.

Keywords: *Composite laminate, failure, Strain energy model, progressive damage etc*

1. INTRODUCTION
Composite material is combination of two phases designed for better engineering properties. Composite materials used in design of structures such as mud and straw, now days they are continue to be used in concrete. Fiber is stiff member which is embedded in matrix and exhibits more load sustaining capacity. Load on structure received by matrix and transferred to fiber. Fibers are oriented in different directions to enable to achieve desired property configuration and strength. Fiber can be woven braided or separately placed apart. Fiber may be continuous or discontinuous and decision will be taken based on sort of property configuration needed. Matrix may consist of polymer, ceramics or metal. Fiber and matrix forms the lamina structure which would have definite width, length and thickness, when several such laminas placed one above the other (The lamina fiber either may have same or different orientation) the resultant structure would be called as laminate. The property configuration of lamina and laminate is different from each other, and despite made of same material the ultimate load sustaining capacity and loading behavior is not same. The failure initiates from lamina and reach to laminate which leads ultimate structure failure.

The broad application of fiber-reinforced composite laminates has led to a large amount of research into their progressive damage and failure, and many authors have devoted their work in similar context. There are numerous progressive and failure models that predict mechanical response of structure which includes all loading configurations, boundary conditions, lay-ups, and thicknesses of composite laminates. Categorizing the existing failure theories is expected to highlight with regards to composite laminate progressive damage and failure where existing literature may be sparse. Existing failure criteria are classified as micromechanics or macro mechanics based, the structure failure analysed at lamina constituent level is recognized micromechanical approach where failure analysis at lamina level recognised as macro mechanical approach.

The failure analysis of composite structure is an important aspect to understand to enhance its utility and scope both. While trying in similar context the failure theories (Micromechanical based) are discussed throughout paper which project light on nature of loading, factors responsible in failure, and lamina behaviour before occurrence of ultimate failure, and thus knowledge of such few responsible parameters would enables the technical fellow to design robust structure to serve said application in desired manner.

2. Authors and failure investigation work based on Micromechanical failure theories:

Macro mechanical model, Uniaxial loading		
Sr. No.	**Author & Year**	**Research conclusion**
1	Stowell & Liu (1961)	Extends maximum stress theory to accounts effects of constituents, effect of tensile strength of fiber and effect of transverse strength of matrix.
2	Kelly & Davies (1965)	Extends Stowell and Liu theory accounts the interaction between fiber and matrix
3	Prager (1969)	Extends the Kelly & Davies theory accounting interaction between transverse and shear failure mode of matrix
4	Nahas (1986)	Maximum strain theory does not consider interaction between strain components but of stress components due to poisons effect.
5	Lane & Robinson (1971)	Yield occurs when critical shear stress along longitudinal plane or plane inclined at an angle 45 degrees to material yield stress
6	Hills Theory (Extension to Von Mises Theory or Distortional Energy Theory)	States anisotropic behavior of material, the criterion only predicts failure and not failure mode.
7	Azzi & Tsai (1965)	Lamina is transversely isotropic
8	Norris (1962)	General representation of Von Mises theory
9	Yamada & Sun	Theory predicts the laminate failure
10	Griffith Buldwin (1962)	Defines composite failure based on distortion energy theory, author proved distortional energy stored in structure is difference between total strain energy and volumetric strain energy
11	Hoffman (1967)	Find the failure of transversely isotropic composite lamina
12	Puck & Sehneider (1969)	Predicts failure of constituents. The author proposed possible modes of composite failure as, fiber failure by breaking, matrix yielding, and failure at fiber-matrix interface. The theory is not applicable for multidirectional laminates.
13	Sandhu (1974)	Accounts non-linear behavior of laminate and possible modes of failures.
14	Gol denblat & Kopnov (1966)	Generalized failure criterion for anisotropic materials to predict the failure.
15	Giang & Tensyon (1989)	Developed a model depicts surface failure
16	Ashkenazi (1965)	Author proved normal strength is twice the shear. Further investigations determined interaction coefficient between fiber and matrix for 45 degree fiber
17	Hashim & Rotem (1973)	Proposed several equation describing fiber and matrix failure
18	Hashin (1980)	Distinguished tensile and compressive failure for fiber and matrix
Uniaxial Loading on Angle ply laminates		
19	Blewer & Legace (1988)	Delamination of [+ 15/ -15] laminate under uniaxial tension
20	Hung Chang (1996)	Predict progressive damage as a function of stress, the results are applicable to 45 degrees angle ply laminates.
21	Hwang & Sun	Performed 3D Finite Element Analysis and predicts modes of fiber failure,

	(1989)	delamination, matrix cracking, first and last ply failure, and non-linear behavior of laminate. Fiber with low angle of orientation, difference between first and last ply failure is high.
22	Kam & Lai (1999)	Predict first ply failure for out of ply transverse loading by acoustic emission techniques
23	Hwang & Chang (1996)	Develop model for progressive damage prediction.
24	Pal & Ray (2002)	Progressive failure of laminate for out of ply transverse loading. Failure of each lamina evaluated till ultimate laminate failure. Failure of angle ply laminate evaluated using stress theory, strain theory etc.
25	Reddy & Pandey (1987)	Developed first order shear theory to predict first ply failure of laminate.
26	Shahid & Chang (1995)	Laminate progressive damage under tensile loading. Stress strain curve plotted for angle ply laminates with fiber orientation 60 degrees subjected to uniaxial tensile load. Post initial failure is due to ply delamination.
27	Yeh Kim (1994)	Investigate effect of component interaction towards postpone of failure
28	Yeh (2003)	Experimental data from compression, tension and torsion used to determine model parameters, the model used to find axis stresses for angle ply laminate. The criterion suggested by author called as, "Quadratic Surface Criterion"
29	Yamada & Sun (1978)	Predict failure strength of angle ply laminates subjected to uniaxial load.
30	Al-Khalil (1990)	Predict failure of [+55/-55] laminate made of glass/epoxy subjected to uniaxial loading
	Uniaxial Loading on Cross Ply Laminates	
31	Hung chang (1996)	Plotted load vs deflection curve for cross ply laminate subjected to compressive load and same is verified with experimental results. The laminate failure load was predicted 5% more than experimental failure load.
32	Joo, Hong, Kim (2001)	Three dimensional FEA method is used to model stress filed and thus to predict effects such as lamina damage by micro cracks, lamina damage by means the progressive failure etc. The laminate stacking sequence used was, $[90_5/0]_s$ & $[0/90_5]_s$. The model predicts ultimate failure correctly for $[90_5/0]_s$ under uniaxial tensile load, where overestimates the failure load for $[0/90_5]_s$.
33	Hybrechts (2002)	Used Tsai-Wu theory to predict laminate failure which precipitates value for failure load 20% less than actual failure strength of laminate obtained experimentally.
34	Kum & Jam (1995)	Used FEA model to predict first ply failure strength of thick laminate by using Tsai-Wu criterion, the results obtained shown 20% error with respect to experimental findings.
35	Kum & Jam (1996)	Predicted first ply failure strength by using Tsai-Wu, Tsai-Hill criterion for cross ply laminates subjected to out of plane transverse loading.
36	Liu (1993)	Investigates matrix failure by means of crack propagation and delamination growth. The further part of work includes, plotting of stress-strain curve for concentrated out of plane load.
37	Pal & Ray (2002)	Predicted failure of cross ply laminate for out of plane transverse load.
38	Prasty (2001)	Used FEA method conjunction with Tsai-Hill, maximum stress theory to predict first ply failure.
39	Reddy & Pandey (1987)	Had similar experimental investigation as did by Pal & Ray, except extended work for out of ply transverse tensile load.
40	Shahid & Chang (1995)	Plotted stress-strain curve for [0/90] laminate for transverse tensile load, results were compared with 10 degrees off axis test.

41	Sleight (1997)	Develop progressive failure analysis methodology to predict laminate failure and nonlinear response. $[0/90]_s$ specimen under test consideration, made up of glass/epoxy subjected to uniaxial load. The free edge effect also considered in laminate failure
	Uniaxial Loading on Quasi Isotropic Laminates	
42	Hung & Chang (1996)	$[45/90/-45/90_2]_s$ laminate subjected to uniaxial compression and stress-strain curve was plotted same was also compared with experimental results obtained under similar loadings.
43	Kim & Soni (1984)	Predicted delamination for $[0/45/-45/90]_s$ laminate subjected to uniaxial compression and tension one by one. The work of author based on self-developed "Inter laminar normal stress failure criterion". The results obtained were compared with experimental test which shows 5 to 10% marginal difference.
44	Shahid & Chang (1995)	Predict progressive damage model based on Hashin criterion for laminate $[45/90/-45/90/45/90/-45/90]_s$ subjected to uniaxial tensile loading
45	Sleight (1997)	Predicted failure for laminate $[+45/-45/0_2/+45/-45/0_2/+45/-45/0/90]_s$ subjected to uniaxial compression.
46	Reddy & Pandey (1987)	Predicted first ply failure strength $[45/-45/90/0/45/90/-45/90]_s$ & $[45/0/90/45/0/-45/90]_s$ for in plane transverse tensile loading by using FEA method conjunction with maximum stress and strain criterion
47	Reddy & Pandey (1987), Prusty (2001)	Predicted failure of quasi isotropic laminates, $[90/45/-45/0]_s$ made of AS_4/3501-6 carbon epoxy, for uniaxial tension in y direction and out of plane transverse loading by using maximum stress, strain, Tsai-Wu and Hill criterion.
48	Christoforoa (1984)	Tested specimen for internal pressure
	Uniaxial Loading on Anisotropic Laminates	
49	Brewer & Legace (1988)	Predict delamination of laminates $[\pm 15_n/0_n]_s$ & $[0_n/\pm 15_n]_s$ for uniaxial tension
50	Hung & Chang (1996)	Predict experimental failure strength for laminate, $[(60/90/-60/90)_2]_s$ & $[(30/90/-30/90)_2]$ subjected to uniaxial compression.
51	Kim & Soni (1984)	Studied delamination of $[\pm 30_n/90_n]_s$ subjected to uniaxial tensile load
52	Shahid & Chang (1995)	Studied progressive damage in laminates, $[\pm 30/90_n]_s$, $[\pm 60/90_n]_s$, $[\pm 60_2/90_n]_s$, $[60/90/-60/90]_{2s}$ subjected to uniaxial tensile loading by means of Hashan failure criterion
53	Huybrecht's (2002)	Studied first ply failure of anisotropic laminate by using maximum stress, strain and Tsai-Wu criterion.
	Bi axial loadings	
54	Eckold (1998)	Design the laminate which would not undergo micro cracking failure and creep rupture, the maximum allowable strain maintained below design strain, the strain was observed to be a function of modulus which was further function of fiber orientation.
55	Edge (1998)	Develop method consider interaction between shear-tension during matrix failure, shear-compression in fiber failure. The initial failure was function of transverse tension and ultimate failure as longitudinal failure.
56	Mecartney (1998)	Predicts stress at which transverse crack induced in laminate under bi-axial loading, ply has one way orientation, parameters associated to crack were elongation and macroscopic properties of lamina.
57	Hart-Smith (1998)	Studied limitations of maximum strain theory
58	Hart-Smith (1998)	Generalize shear stress criterion and compare the result with experimental findings.
59	Hinton (2004)	Measured longitudinal modulus, longitudinal tensile failure strength, and longitudinal compressive failure strength for 45 degrees lamina.

60	Sun & Tao (1998)	Obtained failure envelopes for unidirectional and multidirectional laminate using linear laminate theory. The fiber break leads longitudinal modulus equals to zero, the matrix failure leads to shear and transverse modulus equals to zero. The degradation modulus is the function of crack density.
61	Zinoviev (1998)	Studied deformation and failure when load increment was given until ply attains maximum stress.
62	Boyelti (2004)	Progressive failure is function of maximum strain load carried by ply by the time of failure. The moment first ply fails load transferred to remaining ply and process continues until occurrence of laminate failure.
63	Cuntze & Freund (2004)	Considers interaction of stresses during failure of fiber and matrix and thus also studied nonlinear 3D failure model.
Bi-Axial loading on Unidirectional Laminate		
64	Theocaris (1983)	Use biaxial hydrostatic loading to evaluate tonsorial polynomial criterion
65	Theocaris (1983)	Predicted Tsai-Wu criterion of failure for anisotropic material under hydrostatics load
66	Choo & Hull (1983)	Predicted failure of unidirectional composite laminate made of glass fiber and polymer resign, subjected to bi-axial tensile compressive load, added, internal pressure superimposed with applied loadings, the Mohr's Circle method was used in the stress analysis and associated failure prediction.
67	Swanson (1988)	Obtained the experimental data for AS4/55A Carbon epoxy laminate subjected to torsional shear and tension, the Tsai-Wu failure theory was used in failure prediction, the conclusion of work was, value of shear stress increased with increase in compressive stress and value of stress, strain decreases at laminate ultimate failure.
68	Daniel (2009)	Considered unidirectional laminate subjected to multi axial state of stress. By using Tsai Wu theory author studied interlaminate failure of laminate by means of Inter laminar stresses combined with normal stresses. Author also studied first ply and last ply failure of laminate. The laminate material was AS4/3501-6 carbon/epoxy.
69	Hutter (1974)	Studied the failure of filament tubes, made of E glass/AY 556, subjected to combined loading effect of torsion, tension and compression.
70	Schelling & Aoki (1992)	Studied the failure of axially wound tubes made of material T300914C carbon/epoxy subjected to combine loading effect of torsion, tension and compression.
71	Al Khalil (1996)	Studied the failure laminate made from material E glass/AY 750 subjected to internal pressure and circumferential wind.
Bi-Axial loading on Angle Ply Laminates		
72	Soden (1978)	Analyze the failure of tubular specimen with laminate configuration [+35/-35] & [+55 & -55], made of glass polymer, subjected to biaxial loading. Authors leaded to conclusion; laminate is series of orthotropic ply, and laminate is homogeneous structure.
73	Francis (1979)	Studied the first ply failure of tubular angle ply specimen made of material T300/1034 by suing maximum strain theory
74	Soden (1989)	Predicted fracture strength of thin walled tubes subjected to biaxial loads, which is combination of axial compression/tension and internal pressure. The laminate under consideration was [+55/-55] and made of material E glass fiber/epoxy. Author also predicted first and ultimate ply failure strength of laminate.
75	Gargiulo (1996)	Predicted strength of filament wound carbon-fiber epoxy thin walled tubes under biaxial loadings. The laminate fiber orientations were 35, 55 and 75 degrees, CLT (Classical Lamination Theory) & Tsai-Hill criterion used to predict state of stress in each ply and their ultimate impact on laminate failure.

76	Dong Mistry (1998)	Predicted strength of filament used in marine and offshore industries which was then subjected to loading combination such as pressure and axial compression, author used Tsai-Wu failure theory to predict first and last ply failure strength of laminate. The fiber orientation of laminate was [+55/-55].
77	Hu (1998)	Study the tube macroscopic properties by using CLT and 3D FEA model, the laminate configuration used was [+55/-55] made of glass epoxy, maximum stress theory was used to predict ply failure strength.
78	Lin Hu (2002)	Studied non-linear behavior of laminate for in plane shear loading and stresses induced. Author used Tsai-Wu theory which implemented in ABQUS and FORTAN code. The laminate material was e-Glass/epoxy.
79	Liu Tsui (1998) & Edge (1998)	Studied post initial failure laminates described by means degraded or brittle mode until ultimate failure.
80	Li (1993) & Reid (1995)	Plotted stress strain curve for [+45/-45] laminate made of e-glass/MY 750 epoxy. The laminate was subjected to loading combination of axial stress and hoop stress.
Bi Axial Loading on Cross Ply Laminates		
81	Francis (1979)	Predicted failure of cross-ply laminate made of material, T300/1034 graphite epoxy by using maximum stress and strain theory; results obtained were compared with experimental results.
Bi Axial Loading on Quasi-Isotropic Laminates		
82	Guess (1980)	Predicted failure stresses for [30/-30/90] laminate subjected to bi-axial loadings. Authors used maximum stress theory and Nooris criterion in his investigation.
83	Soni (1983)	Author plotted failure envelope for [0/90/+45/-45] laminate made of T300/5208 graphite/epoxy, and subjected to longitudinal and transverse loading effects, the results obtained were also compared with experimental results.
84	Ganesh & Naik (1993)	Predicted first ply failure strength of laminate $[0/90/+45/-45]_s$, made of materials T300/5208 graphite epoxy, AS/3501 graphite epoxy, B (4)/5505 boron epoxy, Kevlar 4a/epoxy. CLT was used to find stress filed, Tsai-Wu theory was used to predict failure of each ply. The failure plots were showing variation with respect to change in fiber orientation. Author observed all ply fails simultaneously for biaxial tensile or compressive loadings.
85	Shahid & Chang (1995)	Studied progressive damage of laminate under tension, compression and shear individually and combined. The laminate configuration under consideration was $[90/+45/-45/0]_s$. The failure of laminate under biaxial loading remains questionable.
86	Swanson (1988)	Studied failure of quasi isotropic carbon epoxy tubular specimen subjected to internal pressure and axial force. The laminate under considerations were $[90/+45/-45/0]_s$. Author found considerable difference between first and last ply failure strength of laminate.
87	Colvin & Swanson (1990)	Laminate of material IM7/8551-7 analyzed for transverse tension, compression and in plane shear loading. Laminate compressive strength was found high than tensions, author also predicted laminate stiffness from ply properties.
88	Daniel (2007)	Author studied behavior and failure of laminate [0/+45/-45/90] & [+30/-30/90], made of AS4/3501-6-carbon epoxy laminate subjected to biaxial shear and normal loading, author used maximum stress and maximum strain theories approach to investigate his work.
89	Swanson (1988)	Plotted stress-strain curve for laminate [90/+45/-45/0], made of AS4/3501-6, which was subjected to pressure and axial loading effects.
Bi Axial Loading on Anisotropic Laminate		
90	Kruss & Schelling (1969), Hutter (1974), & Forster	Studied the laminate failure for configuration $[90/+30/-30/90]_s$, made of material E-glass/L Y556 epoxy, the tubular structure during investigation was subjected to loading combination such as, pressure and axial load, torsion and axial load

	(1970)	etc.
91	Swanson (1988)	Non quasi isotropic and anisotropic behavior of laminate is due to varying thickness of plies
Tri-axial loading		
92	Hinton (2007)	Analyzed tri-axial loading effect which was combination of hydrostatic load, tensile load and compressive load on unidirectional and multidirectional laminates. Author also analyzed loading effect which was combination of hydrostatic load, tensile load, compressive load and torsional load on unidirectional and multidirectional laminate.
Hydrostatic loading and laminate compressive behavior		
93	Weaver & Williams (1975)	Failure strength of laminate increases with increase in hydrostatic pressure, and strength of material doesn't vary according to material modulus. The fiber epoxy composites subjected to compression under hydrostatic pressure leads fiber longitudinal splitting due to tensile fracturing, the fiber kinking occurs at high pressure leading further fiber fracture along with adjacent fiber.
94	Parrg & Wronksi (1982)	Failure initiation in uniaxial CFRP under hydrostatic pressure and longitudinal compression leads further longitudinal fiber splitting prior to kinking. For high pressure failure of structure more because of kinking. The pressure exhibits proportioned relationship with in plane shear which also bring structure failure by means shear crack induced when load exceeds the yield limit. The kinking occurs at pressure 150 MPa.
95	Wronski & Parry (1982)	Performed test on S-glass epoxy resin matrix subjected to compressive load and hydrostatic pressure, it has observed that, compressive strength increases with pressure, kinking occurred at high pressure, kink band width is affected by pressure, shear strength also increases with pressure, compressive failure is taken place by means of matrix yielding. It was further observed that, result obtained in the case of glass reinforced polymer do not matches with carbon fiber reinforced composite polymer
96	Sigley (1992)	Axial compressive failure occurred in glass fiber reinforced polymer under superimposed pressure further yields conclusion such as, hydrostatic pressure is directly proportional to compressive stress occurred by the time of failure.
97	Sigley (1992)	Failure of glass fiber was by kinking throughout range of hydrostatic pressure. Failure by compression involve matrix shear. A group of fibers together as bundle in glass/polyester and glass/epoxide, the mode of failure observed was longitudinal splitting and bundle buckling.
98	Rhee & Pae (1995)	Compression test on unidirectional carbon fiber epoxy 0 degree laminate superimposed with hydrostatic pressure and results are plotted in the form of stress-strain curve, it was further found from curve, compressive modulus, modulus ratio of compressive strength to fracture strength, fracture strain etc. Stiffness found increases with increase in pressure, high pressure impart curve non linearity and leading ply delamination and crack opening. Longitudinal compressive modulus exhibits proportioned relationship with pressure.
99	Wronski & Parry (1982)	S-glass & epoxy resin matrix subjected to compressive load and hydrostatic pressure yields observations such as, compressive strength is directly

		proportional to hydrostatic pressure, kink band formation occurred at high pressure, shear strength also exhibits proportioned relationship with pressure, failure by compression is mean by matrix yielding.
100	Sigley (1982)	Axial compressive stress superimposed with hydrostatic pressure, kink band formation analyzed and evaluated in fiber bundle rather in single fiber of glass/polyester, glass/epoxide. The kink band formation results ultimately in longitudinal fiber splitting and fiber buckling.
101	Rhee & Pae (1995)	Unidirectional carbon fiber/epoxy matrix laminated composites subjected to pure hydro pressure yields observation such as, stiffness enhances with increase in pressure. Highest pressure causes delamination crack opening. Longitudinal compressive modulus is directly proportional to pressure. Fracture stress & strain is directly proportional to hydro pressure.
102	Rhee & Pae (1995)	Failure of composite is combination of fiber buckling, delamination crack opening split, crack opening by ply separation, and kinking etc. Hydro pressure decreases with occurrence of micro buckling, kinking and resulted in high laminate strength.
103	Lankford (1997)	Test on fiber-reinforced polymer matrix composite when subjected to hydro load and uniaxial compression, the stress-strain curve plotted for 0 degree unidirectional composite.
104	Rhee & Pae (1995)	90 Degree unidirectional E-glass/epoxy laminates subjected to combination of hydro pressure and compression, the observations found can be noted as, strength, elastic modulus and ductility are proportioned with applied pressure.
15	Parry & Wronksi (1989)	Hydrostatic pressure on 0/45/90 degree laminate leading axial splitting but damage was found suppress for high pressure. Shear failure occurred in all laminas at a time which are oriented at 45 degrees. Failure in lamina oriented at 0 degree takes place virtue of kinking. Failure in lamina oriented 90 degree takes place due to shear occurred at 45 degree plane.
106	Rhee (2003)	The behavior of $[0/90]_{16s}$ & $[0/45/-45/90]_{8s}$ cross ply and quasi isotropic laminates leads to following conclusion, Delamination at multiple sites propagated along length of specimen at low pressure. Hydrostatic pressure has an impact on compressive failure of laminates, shear buckling & splitting etc.
Tensile behavior of laminates under hydrostatic pressure		
107	Parry & Wronksi (1989)	Carbon fiber reinforced composites subjected to tension and hydrostatic pressure leading failure is due to shear crack and broken fiber. Tensile failure strength inversely proportional to hydro pressure. Transverse cracking decreases with increase in hydro pressure. Failure strength no more exhibits proportioned relationship with applied pressure. For applied pressure 150 MPa laminate shows nonlinear behavior & more transverse cracking observed.
108	Sigely (1991)	Glass polymer composite subjected to 300 MPa induces maximum principal stress, and magnitude of stress decreases with increase in pressure. Hydro pressure and tension leading fiber pull out crack becomes shorter, no transition in mechanical behavior. Failure strength increases with decrease in pressure.
109	Zinoviev (2001)	Longitudinal moduli is pressure independent, where, longitudinal tensile strength depends on hydro pressure and exhibits inverse relationship. Failure

		mode less dispersed through composite specimen for high hydrostatic pressure.
Shear behavior of laminates under low hydrostatic pressure		
110	Shin & Pae (1992)	Author studied Torsional shear stress-strain behavior of graphite epoxy composite. The stress strain curve nature found change with increase in hydrostatic pressure, curve shows nonlinear behavior with increase in pressure, fracture strength and strain exhibits proportioned relationship with pressure. Torsional shear modulus which is combination of in plane and out of plane shear plane modulus found increases with increase in pressure. Surface flaws tend to propagate for atmospheric pressure, at high pressure flaws leads to close partially and reduce stress concentration. Premature fracture occurred at 2 bar pressure.
111	Shin & Pae (1992)	Author studied mechanical response of shear load considering fiber orientation. Author also leaded to conclusion, shear strength, shear modulus, yield strength and fracture strength are pressure dependent. Author further observed that, shear properties found enhanced with increase in pressure which become further function of fiber orientation and also exhibits the proportioned relationship with fiber orientation. Rate of change of shear properties observed for 45 degree laminates, it found less in 0 degree laminates and least for 90 degree laminates. The mode of laminate failure also noted unique in the case of every laminate having unique fiber orientation, for example, the laminate with fiber oriented in 90 degrees failed due to fiber-matrix debonding.
112	Pae (1996)	Author studied behavior of lamina with fiber orientations, 0, 45, -45 and 90 degrees for loading combination of shear, compression and hydrostatic pressure. The lamina behavior noted same for 45 and -45 degree lamina.
113	Hine (2005)	Author studied effect of tension and transverse compression on unidirectional composite laminates, the pressure marinated at 850 MPa. It was observed that longitudinal tensile modulus and tensile strength found increase with increase in applied pressure, simultaneously tensile strength drops down due to local damage which further tends to decrease fiber strength too. Failure mode changes from longitudinal splitting to transverse break. Transverse compressive strength and modulus increases with increase in applied pressure. In plane tension behavior found exactly same as transverse compressive behavior.
Tri-axial loading		
114	Theocaris (1983)	Author developed failure model for elliptical paraboloid failure surface, the effect of out of plane stress vs hydro pressure added further in study. Author observed that, tensile strength in out of plane transverse direction of polycarbonate decreases with increase in pressure. The tensile strength found proportioned with applied pressure.
115	Boehler & Raclin (1985)	Author studied behavior of unidirectional composite laminate made of glass fiber and fibers oriented from 0 to 90 degrees, subjected to pressure 0 to 75 MPa. Author took help of Tsai-Wu criterion to predict laminate behavior as mentioned above, which further subjected to effect of compression and hydrostatic pressure. Tsai-Wu criterions underestimate compressive strength of laminates.
116	Zand (2004 & 2007)	Develop model for compliance matrix in strain energy based model for plane stress condition, compliance matrix formulate strain energy in three dimensional

		stresses.
117	Sandhu (1974)	Author drawn piecewise spline interpolation stress-strain curve for uniaxial loading which used further to determine tangent moduli. Tangent moduli also can find out from stress-strain curve drawn for tension-compression loading, loading also can be in plane shear, out of plane shear etc.
118	Zand (2004 & 2007)	Author states after his experimental investigation, strain energy induced due to interaction between transverse and longitudinal direction is separate energy term.
119	Zinovlev (2001)	Author states after his investigation, hydrostatic pressure influence resistance of material to fiber failure. Fiber fails in tension when longitudinal strain energy exceeds strain energy at failure of lamina under uniaxial tension. Area under tensile fiber failure, longitudinal strain energy and stress-strain curve becomes equal.
120	Hine (2005)	Author investigates longitudinal tension and compression loading effect on unidirectional composites which further superimposed with hydrostatic pressure of intensity 850 MPa.
121	Hine (2005)	Author conclude, longitudinal tensile modulus increases slightly and longitudinal strength decreases slightly with increase in hydrostatic pressure. Longitudinal compressive strength increases with increase in hydro pressure. Hydrostatic pressure enhances fiber potential by enhancing effect of individual flaws or decreasing tensile strength of fiber material itself. If matrix are significantly weak than fiber, matrix cracking occurs at hydrostatic tensile stress for below the value having significant effect on fiber failure. Tensile hydrostatic loading debonding fiber-matrix interface at stress even lower than matrix cracking. Load transfer from matrix to fiber would have negligible effect on fiber other than longitudinal direction and so the effect already taken in to account in longitudinal stress.
122	Sandhu (1974) & Butalia (1998)	Suggested extension to strain energy model to predict orthotropic laminate failure. Author validates proposed model by performing tests on multidirectional laminates subjected to uniaxial loading, as well, unidirectional and multidirectional laminate subjected to bi-axial loadings. The author could not extend his work for tri-axial loading as availability of experimental results for validation are not enough and accurate.
123	Pipes & Pagano (1972)	Author concludes, stress concentration at free edge of plies leading ply delamination. Load transfer from damaged lamina to undamaged lamina is important to avoid catastrophic failure of entire structure but effect leads to change mechanical behavior of structure meanwhile.
124	Zinoviev (2001)	Author studied, effect of shear and hydrostatic pressure on unidirectional laminate longitudinal tensile strength, laminate was made of T 300/PR 319 carbon epoxy, whose fibers are oriented in 90 degrees.
125	Shin & Pae (2001)	Cylinder subjected to 600 MPa pressure, also applied with torsion at constant rate, author concluded that primary failure mode is observed as matrix shear failure and fiber-matrix debonding
126	Zinoviev (2001)	Cylinder made of material S-glass/epoxy subjected to hydrostatic pressure and longitudinal tension, compression lead to fail at low pressure and mode of failure observed circumferential splitting and separation. At high pressure fiber ruptures perpendicular to fiber length.
127	Wronski & Parry	A dog bone specimen subjected to longitudinal compression and hydrostatic

	(1982)	pressure lead to fail due to kinking which occurred slightly in the fiber direction.
128	Wronski & Parry (1982 & 1985)	Author performed compression and tensile test on paltered bars superimposed with hydrostatic stress, the failure in specimen is observed due to kinking.
129	Wronski & Parry (1982)	Compressive mode of failure observed where kinking and buckling of fibers are ahead the kink surface. The effect of excess tensile loading can view in terms of matrix transverse cracking and deboning of fibers from matrix. The hydrostatic loading closes crack in matrix and limiting debonding. Hydrostatic failure shows greater failure impact on S_2 glass fiber than carbon fiber specimen. Hydrostatic pressure exhibits inverse relationship with tensile strength.
	Failure Theories	
130	Zocher (1995)	Author studied first ply failure for three dimensional loading on tubular specimen made of Toray 1000/DER 332-T 403, loading combination considered was axial tension, compression, torsion and internal pressure etc. author used Tsai-Wu and Tsai-Hill criterion to study and evaluate behavior and failure of laminas. The failure curves were plotted for 2D and 3D loading, it was observed that experimental results lie outside the failure envelope. Ultimate failure cannot be predicted neither for 2D or 3D loading.
131	Zinoviev & Tsvetkov (1998)	Author studied effect of hydro pressure on unidirectional laminate made of Kevlar fiber epoxy. The tubular specimen subjected to loading combination such as uniaxial tension, compression and hydrostatic pressure. It was observed that, transverse tensile and compressive strength increases with hydro pressure where longitudinal tensile strength decreases with increase in pressure.
132	De Teresa (1999)	Author studied effect of hydro pressure on compressive strength of IM7/8551-7 carbon epoxy unidirectional composite. Author further investigates effect pressure on longitudinal compressive strength. For investigation purpose author used rectangular specimen which respectively subjected to hydro pressure 345 & 172 MPa, the Tsai-Wu criterion was used to study behavior of material. It was observed that transverse strength and longitudinal strength decreases with increase in pressure.
133	De Teresa (1999)	Author investigates failure mechanics for laminate such as, $[30/-30]_{12s}$, $[45/-45]_{12s}$ made of graphite epoxy (AS_4/3502) when subjected to hydrostatic failure. Author used Mohr-Coulomb criterion to investigate matrix-fiber failure. It was observed that shear strength increases with increase in pressure.
134	Vgas & Pinho (2012)	Author studied mechanical behavior of composites under hydro pressure & three dimensional complex loading.
	Lamina strain energy failure criterion	
135	Sandhu (1976)	Author investigates and developed strain energy criterion to account non-linear response of lamina. Author noted different failure mode of lamina under longitudinal, shear and transverse loading. Theory investigates failure which initiates from lamina and reached to laminate ultimately.
136	Sandhu (1974)	Author developed analytical relationship between material properties of lamina and laminate ultimate strength. Lamina properties obtained from stress-strain curve which obtained by loading lamina in longitudinal, shear and transverse direction. Author applied strain energy criterion to all plies until ultimate laminate failure occurs.
137	Sandhu (1974)	Author finds tangent moduli from stress-strain curve drawn for uniaxial loading.

		Compliance lamina properties are determined from tangent moduli's.
138	Sandhu (1976)	Author studied edge effect and non-uniform stress distribution on 15 degree off axis laminate for uniaxial longitudinal tension by using FEA and strain energy theory.
139	Sandhu (1976)	Author studied strain energy based failure model for angle ply laminates under uniaxial loading. Author also plotted stress strain curve for [45/-45] laminates for bi-axial loading.
140	Wolfe & Butalia (1998)	Author determined shape factor for unidirectional laminates under biaxial load and multidirectional laminates for uniaxial or biaxial load.
141	Sandhu (1974)	Author finds strain energy ratio in longitudinal, transverse and shear direction.
142	Sandhu (1979)	Author proposed model technique for sudden unloading, gradual unloading and perfectly plastic behavior In sudden unloading, in the case of matrix failure, transverse and shear moduli reduced to small number and poisons ratio to 0. In the case of fiber failure, lamina unloaded in all the directions. In gradual unloading failed lamina unloaded in small increments and laminate load increased beyond first ply failure. In perfectly plastic behavior mode, failed lamina didn't unload as it didn't carry any additional load.
143	Wolfe & Butalia (1998)	Author observed that none of the strain component exceeds strain at ultimate failure of the laminate under uniaxial loading.
144	Wolfe & Butalia (2002)	Author predicted shear strength of T300/BSL 914C laminate for the loading combination of uniaxial tension and shear, author could yield 100 MPa shear strength of laminate where organizer had given 50 MPa.
145	Wolfe & Butalia (2002)	Author investigates failure of E-glass/LY556 laminate which was subjected to transverse and shear loading. The laminate configurations used were [90/30/-30] and subjected to longitudinal and transverse loading. The failure model suggested by author over predicts the compressive strength in biaxial compression because ply failed due to buckling at lower strength than matrix. Author also investigates failure of unidirectional E-glass/LY 556 laminate of configuration $[90/30/-30]_s$ subjected to biaxial longitudinal loading and shear, the failure of structure analyzed by using strain energy based model, the model states longitudinal strength of laminate more than experimental results, model is also not precisely capable to calculate ultimate longitudinal tensile strength. Author further investigates laminate, [55/-55] subjected to longitudinal and transverse loading but ultimate failure for said angle ply combination cannot be predicted accurately. Further investigation leads author to conclude, unidirectional E-glass/LY 750 laminates lead to higher stress shows less agreement with predicted stress experimentally. Experimental result predicts failure at 600 MPa and theory stresses are much lower in value. In the investigation of E-glass/MY 750 laminate of configuration $[45/-45]_s$ subjected to equal magnitude of longitudinal and transverse tensile loading (Transverse tension and axial compression), it was observed theory stress are less in value than experimental stress. Axial and transverse strains remain

		unpredicted. Author further investigates, Cross ply laminates subjected to uniaxial tension (Tubular coupon specimen) plots the stress-strain curve till failure, author leaded to conclusion, 90 degree laminas fail at low stress, where failure in 0 degree laminas at ultimate stress.
146	Chapra & Canale (2006)	Author draws piecewise cubic spline interpolation to formulate stress-strain curve between two data points. Author also states, uniaxial stress-strain response is different from multi axial stress-strain response. Hydrostatic load impacts on shear stress of lamina, and shear strength exhibits proportioned relationship with hydro pressure
147	Zand (2004, 2007)	Author predicts exact contribution of strain energy component in to matrix cracking and shear failure.
148	Pae (1996)	Author investigates impact of hydrostatic pressure on matrix; the tubular specimen made of material T 300/PR 314 subjected to uniaxial shear and hydro pressure used for test purpose.
149	Hine (2005)	Author studied impact of hydrostatic pressure on fiber; exponential degradation is function of strain accumulation from beginning. Exponential degradation decreases load carrying capacity of lamina and increases rate of load transferred to undamaged lamina. Nonlinearity in material behavior is greater in multidirectional laminate than unidirectional laminate; nonlinearity is function of matrix crack propagation in different direction.
		Multidirectional Laminates
150	Hine (2005)	Author investigates Tubular specimen [35/-35] lamina orientation, subjected to transverse compression and hydrostatic pressure, stress filed is not uniform through laminate thickness longitudinal, transvers and out of plane stresses are constant. Elastic moduli are changed according to fiber orientation. Failure strength found increasing with hydro pressure. The modulus and compressive strength also found increase with pressure. The laminate material used was E-glass/MY.
151	Hinton & Kaddour (2005)	Filament wound tubes with ply orientation [35/-35], longitudinal shear failure occurs through thickness.
152	Connor (1999)	Cross ply laminate, $[0/90]_s$, made of material E-glass/epoxy, subjected to uniaxial tension and behavior was studied in terms of stress-strain curve. Stress filed is not uniform over all laminas.
153	Pipes & Pagano (1970)	Author concludes, stress concentration exists near free edge of angle ply laminates so the maximum stress also is.
154	Pipes & Pagano (1970)	Stress concentration at lower load prevalent through laminate thickness before occurrence of initial failure. High stress near free edge due to stress concentration causes potential delamination leading specimen failure with complex geometry or laminates with hole.

Conclusion

- Yield occurs at 45 degrees
- Lamina is transversely isotropic
- Distortion energy is difference between strain energy and volumetric strain energy which leading material failure.
- Composite failure recognized as, fiber failure, matrix yielding, failure at fiber-matrix interface
- Progressive failure of composite is function of maximum strain load carried by ply.
- Hydrostatic pressure exhibits proportioned relationship with longitudinal compressive strength, transverse tensile strength, and, held inverse relationship with longitudinal tensile strength.
- Increase in hydrostatic pressure leading composite lamina failure by kinking.
- Highest hydrostatic pressure also results in delamination, crack opening and axial splitting.

- Composite structure failure is combination of fiber buckling, delamination crack opening split and crack opening by ply separation.
- Longitudinal modulus is pressure independent, where, longitudinal tensile strength is dependent.
- Shear modulus, shear strength and yield strength are pressure independent.
- Strain energy induced in transvers and longitudinal directions are separate term.
- Longitudinal tensile modulus increases with increase in hydro pressure.
- Stress concentration at free edge plies results in high pressure and further leads to ply delamination.
- Theoretical strength of lamina found more than one predicted experimentally.
- Exponential degradation of fiber is function of strain accumulation from beginning.
- Stress filed through laminate thickness is not uniform.

References

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