Visual Abstract

Mechanisms for introduction of pseudo ductility in fiber reinforced polymer composites- a review

Vinayak S. Uppin, P. S. Shivakumar Gouda*, I. Sridhar
Research Center, Department of Mechanical Engineering, SDM College of Engineering & Technology, Dharwad, Visvesvaraya Technological University, Karnataka, India.
vinayakuppin@gmail.com, ursshivu@gmail.com, sridhari74@gmail.com

ABSTRACT. Advanced polymer matrix composites are gaining the market in their way due to their exceptional specific stiffness, specific strength, fatigue, and corrosion resistance in the field of Auto-Tech, Aero-Tech, Biotech, etc. However, the lack of ductility and catastrophic failure has limited their application in these areas. Hence there is a need to explore the state of art technological developments in designing toughened composites by minimizing their factor of safety. A new generation of high-performance composites with pseudo-ductile or ductile behavior is essentially required for the fiber-reinforced composite structures to mitigate the catastrophic failures. The present High-Performance Ductile Composite Technology (HiPerDuCT) program is jointly between the University of Bristol U.K and Imperial College London working to address this challenge by developing newer materials. The various fiber architectures made under this project gave a more gradual failure rather than catastrophic failure with improved mechanical properties. This review mainly focuses on summarizing the pseudo ductility evolution in fiber-reinforced composites by eminent researchers with a possible alternative like fiber positions in matrix materials for introducing reasonable ductility in composites.

KEYWORDS. Pseudo- Ductility, Fiber Hybridization, Fiber orientation, Discontinuous inter slip, Gradual Failure.

Citation: Uppin, V. S., Gouda, P.S.S., Sridhar, I, Mechanisms for Introduction of Pseudo Ductility in Fiber Reinforced Polymer Composites- A Review, Frattura ed Integrità Strutturale, 65 (2023) 17-31.

Received: 09.01.2023
Accepted: 11.04.2023
Online first: 13.04.2023
Published: 01.07.2023

INTRODUCTION

In the present scenario development of novel materials is more prominent to change the world towards the modern lane. Advanced composite materials are in excellent development due to their superior properties such as high specific strength, stiffness, lower density, and lower thermal expansion. But, a major drawback of these composites is the lack of ductility [1]. These composite materials will exhibit catastrophic failure within the linear elastic response which is shown in Fig. 1a. This failure begins with delamination or interlaminar failure between the plies in laminates. It may occur due to the consequence of imperfections in the production process or the effects of external factors during the service life of the composite laminates, such as the impact of foreign objects, etc. The unfavorable nature of failure in polymer composites is to restore with a set of design and manufacturing considerations. Hence, there is a growing interest in the area of pseudo-ductile concepts. This is driven by reducing the safety factor in the design of composites without affecting the stiffness and toughness [2]. The ductile failure is most desirable; this can be achieved by introducing various state of art techniques for pseudo-ductile mechanisms within the reinforcements like fiber hybridization, Fiber position, and Interfacial slip in discontinuous fiber composites [1]. The key terms of pseudo ductile stress-strain curves are:

a) Pseudo ductile strain(ε_{Pd}): It is the difference between final strain, and elastic strain at the same level of stress based on the initial modulus which is shown in Fig. 2.

b) Pseudo-yield stress (σ_{PY}): It is the stress level at which the tensile response has a significant deviation from the initial linear elastic behavior.

c) Pseudo-yield strain (ε_{PY}): It is the strain level at which the tensile response deviates significantly from the initial linear elastic behavior.

Detailed discussions on pseudo-ductile mechanisms are thoroughly discussed in the following paragraphs.

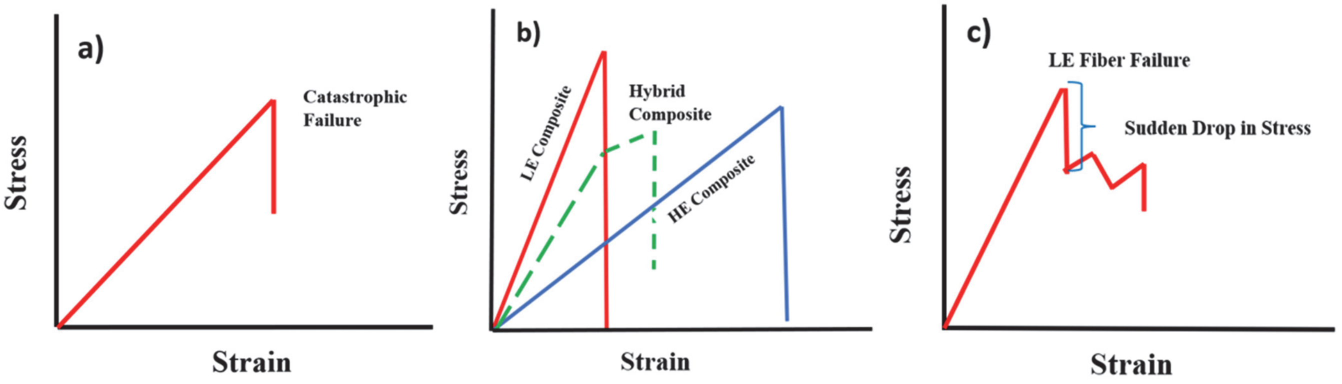

Figure 1: Plot showing stress versus strain and Load versus displacement a) Catastrophic Failure of the composite, b) Effect of Hybridization and, c) Sudden Drop in hybrid Composite

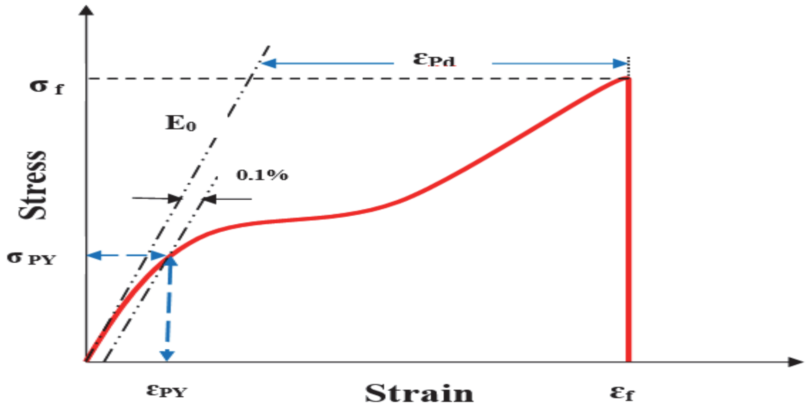

Figure 2: Schematic of a pseudo ductile stress-strain curve.

FIBER HYBRIDIZATION

Fiber hybridization is a promising strategy in which two or more fiber types are tailored to get optimized properties in their behavior of composite laminates as shown in Fig. 1b. The two types of fibers are typically referred to as lower elongation (LE) and higher elongation (HE) fibers. The one which fails first normally is the LE fiber and secondly the HE fiber. The higher elongation fiber does not necessarily have a larger strain but it is always greater than the LE fiber [2]. The most commonly used fibers in FRP composites and their strain to failure are displayed in Fig. 3. The fibers which are having higher modulus have lower strain to failure. For example, it was known that carbon fiber has more brittle behavior with linear elastic region there after a complete failure has been reported. But in the case of glass fibers, a marginal yielding takes place before the complete failure. Fiber Hybridization leads to a change in failure strain and failure mode [2], and functionally graded hybrid composites made of Glass Carbon fibers showed a gradual failure in their behavior [3]. But the hybrid effect is the result of stacking sequence, yarn arrangement, and volume fraction [4-7]. HE and LE fibers can be combined in different configurations while manufacturing the FRP composites. But the interlayer and intra-yarn configurations were most commonly used and are shown in Figs. 4a & 4b and their failure strains are shown in Figs. 5a & 5b. When LE and HE fibers are reinforced in a common matrix the strength of LE fibers is enhanced, hence it is termed a hybrid effect. The load transfer from LE fibers to HE fibers without complete debonding of LE fibers leads to attain higher strain to failure. But in some cases, if LE fiber fails there is a sudden drop in the stress was noticed, this is due to the unpredicted breakage of LE fibers with complete debonding occurring at the failure strain and this can be observed in Fig. 1c. This kind of failure can prevent the superior performance of composites. In most of the hybrid composites, the stacking sequence and the volume fraction of HE fibers showed a positive hybrid effect this can be realized in Fig. 5a.

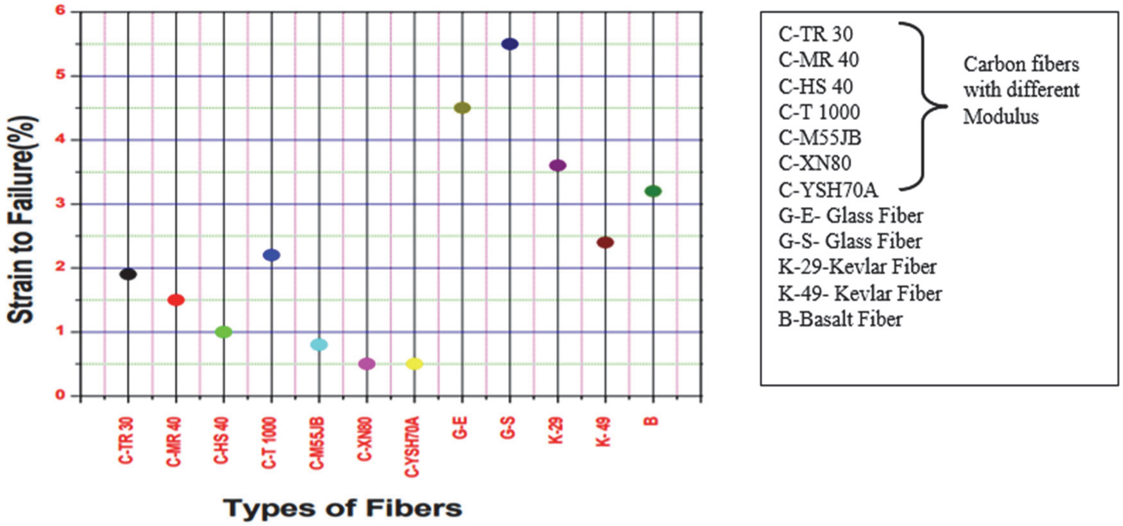

Figure 3: Failure of different fibers by maximum strain [19-38].

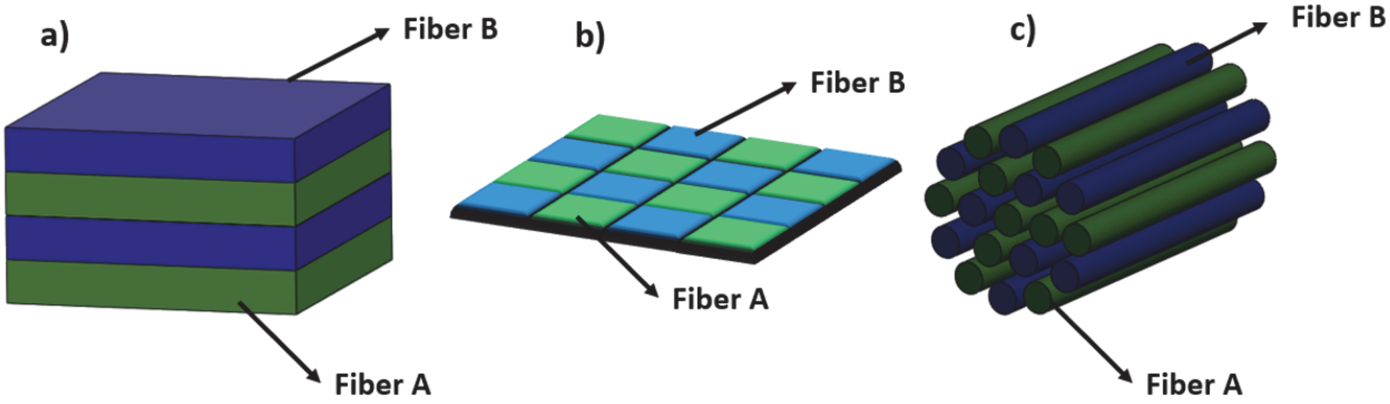

Figure 4: Artistic images showing a) Interlayer or layer-by-layer b) Intralayer or yarn-by-yarn and c) Intrayarn or fibre-by-fiber

The joint HiPerDuCT program between the University of Bristol and Imperial College, London has been working to address the most critical limitation of current FRP composites concerning their brittleness by introducing pseudo-ductility. Through this approach yielding as in the case of metals can be achieved by incorporating fiber hybridization, fiber orientation, and novel architecture techniques. Under this program composites developed using thin plies along with novel architectures showed more gradual failure compare to the traditional FRP composites[15]. Thin Carbon plies composites showed an improvement in various mechanical properties as compared to laminates developed with standard fiber/plies of relatively higher thickness than thin fibers. This is due to good fiber packing with uniform dispersion (reduced resin-rich regions), low void volume fractions, and homogenous microstructures [16]. Gergely Czel. et.al.[17] carried out experimentation to demonstrate the pseudo-ductility by using the concept of thin-ply hybrid laminates. The hybrid composites were developed by sandwiching the Carbon plies between the Glass plies. Progressive failure is one of the key factors to overcome catastrophic failure in FRP composites, to achieve this the strain energy require for stable pull-out of the central layer(LE fibers) should be less than the energy required for delamination. A schematic of the stress-strain response of standard-ply and thin-ply hybrid composite laminates and the typical appearance of the thin-ply hybrid specimens at different damage phases is shown in Fig. 6. In this work, the lower volume fraction of carbon showed prominent pseudo-ductile nature of the failure. The lower volume fraction of LE fiber in the combination of high modulus carbon with E glass and Basalt and high modulus Carbon with standard Carbon fiber results in good pseudo ductile nature of failure [18]. Gergely Czel. et.al. [19] have designed thin-ply unidirectional (UD) interlayer hybrid composites comprising S-glass with different types of thin carbon prepregs to explore the characteristics of pseudo-ductility. The stitching of hybrid laminates was followed [17], to satisfy the constant pseudo-ductility failure for UD glass/ carbon interlayer hybrids. Resulting, the layup sequence of SG/XN802/SG showed a higher initial modulus with 2.64% of pseudo-ductile strain. Stable pull-out of fiber and multiple cracks were formed on the central (carbon) prepregs of laminates which leads to overcoming the sudden drop in stress and exhibits the pseudo-ductile failure which is showed in Fig. 7. The failure mechanisms in thin-ply UD Carbon/Glass hybrid laminates were investigated by using the acoustic emission (AE) technique [21]. The number of Carbon plies to be used for stable crack propagation is considered based on Analytical modeling[20]. It was observed that the amount of high AE signal amplitude during the fragmentation of the carbon layer was shown in Fig. 8 [21]. The pseudo ductile response of all Carbon /epoxy UD hybrid composites was studied by Gergely Czel. et.al.[22]. The stitching of all Carbon/epoxy hybrid laminates was followed based on the damage mechanisms [17]. The tensile test response of the M55 configuration provided a high initial modulus of 160 GPa with a pseudo yield stress of 1400 MPa and 0.83% of pseudo yield strain as shown in Fig. 9a. Similarly, 50 grams per square meter (GSM) XN-80 blocked type material showed 245 GPa in initial modulus with a yield stress of 990 MPa and the highest pseudo strain of 0.94% as compared to all the configurations shown in Fig. 9b. And also, a similar kind of pseudo ductile failure was observed in IM7(12K unsized intermediate modulus Carbon fiber)/T 700(12K sized high strength Carbon fiber)/PA-12 intra-tow hybrid composites concerning non-hybrid composites[23]. Gergely Czel. et.al.[24] showed that proper hybridization can lead to eliminating the stress concentration in tensile and compressive loadings.

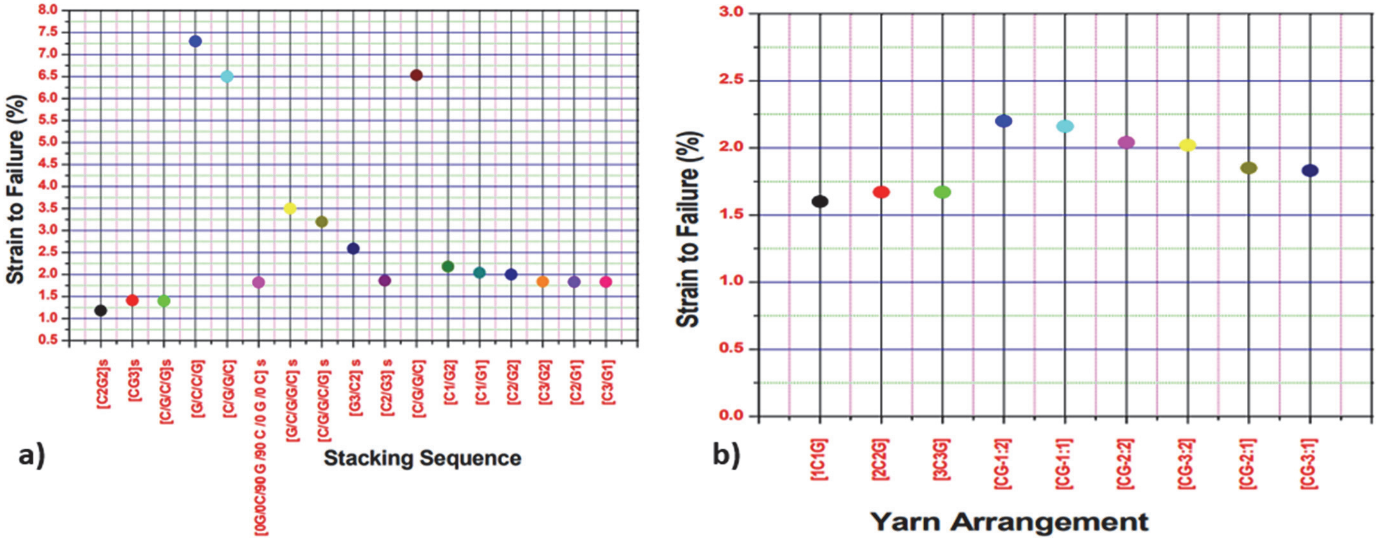

Figure 5: Influence of Stacking sequence on failure strain: a) Inter ply and b) Intra ply [5,6,8–14]

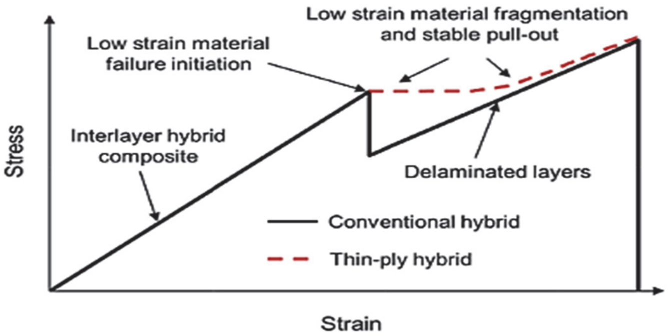

Figure 6: A schematic plot showing the stress versus strain response of standard-ply and thin-ply hybrid composite laminates [22]

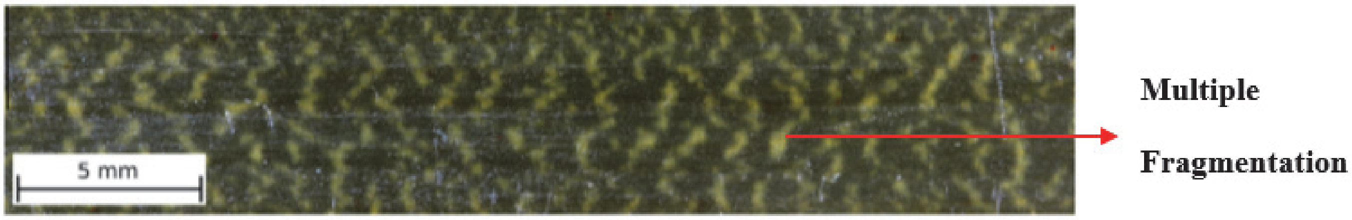

Figure 7: Optical microscope image indicating Carbon-ply fragmentation in a "1 ply carbon" hybrid composite [17]

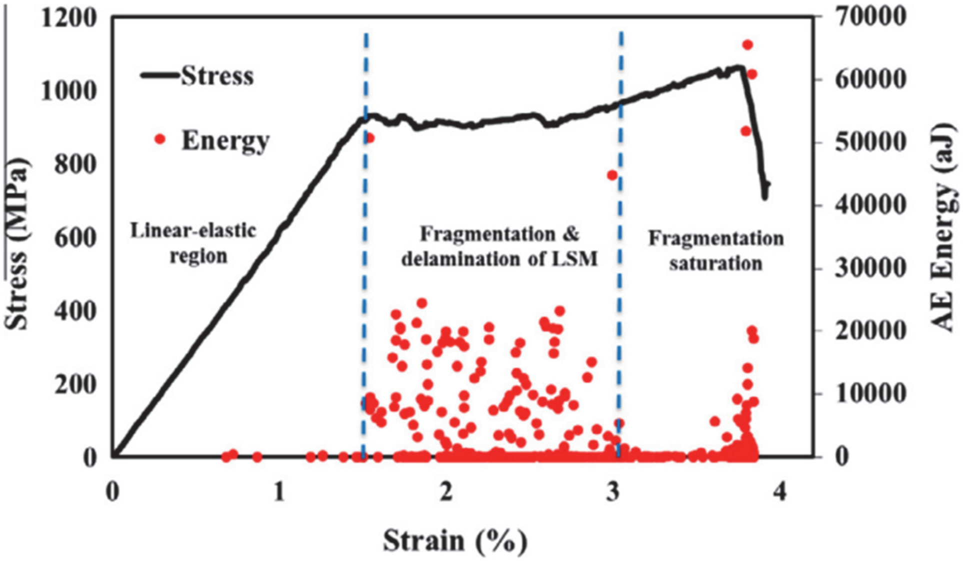

Figure 8: Stress-strain and AE energy distribution for a typical MR40/S-Glass type specimen [21].

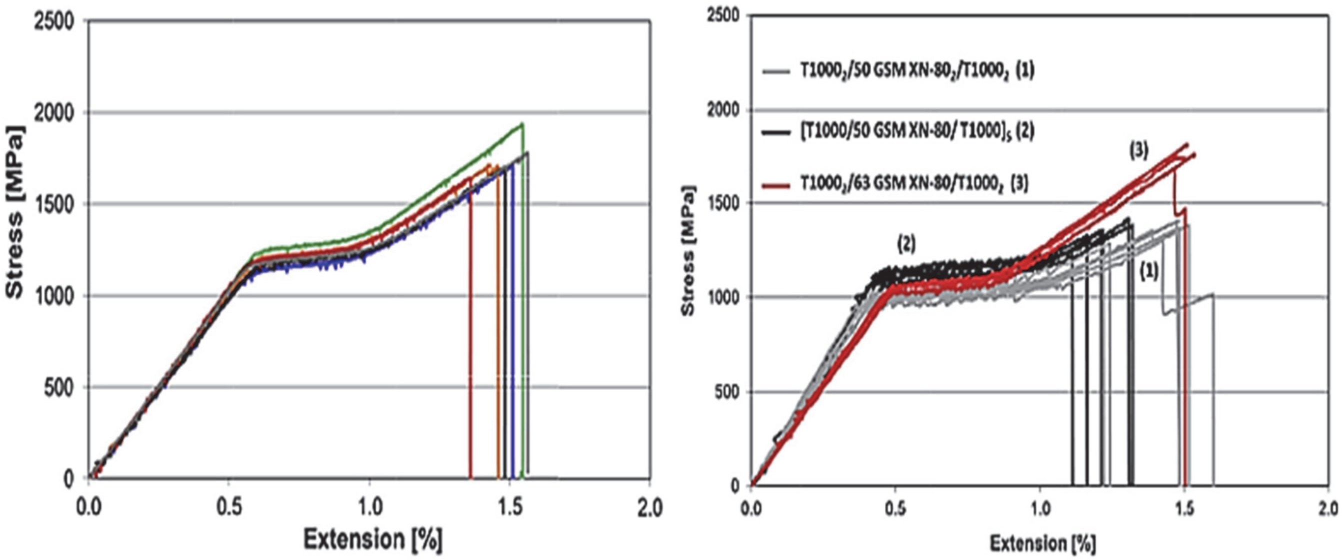

Figure 9: Plot showing a) Stress versus Strain of M55 configuration and b) Stress versus Strain of T1000/XN-80 configuration[22].

It's not possible to conclude that only one parameter i.e thickness of Carbon plies helps to induce the pseudo-ductile nature of the failure. Because the yield strength, modulus, and interlaminar strength of constituent materials may also influence it. The analytical model was developed by Meisam Jalalvand et.al. [25] to explain the influence of different parameters on the gradual failure and pseudo-ductility of thin UD hybrid laminates. Meisam Jalalvand et.al [26] proposed the analytical method by considering the stress level for each damage mode. The proposed damage model is the compilation of three stages i.e (i) fragmentation in low-strain material, (ii) delamination, and (iii) failure of the high-strain material. The failure of both low and high-strain materials can be predicted by comparing the values of stress against the tensile strength of lower and higher elongation fibers. Each damage mode stress was calculated by referring to the equations which are listed in Tab. 1. Eqn. 1 describes the stress developed during the fragmentation of lower elongation fiber, and Eqn. 2 describes stress developed during the delamination process using the critical energy release rate. And the final failure stress in the laminate depends on the failure of higher elongation fiber which was calculated using Eqn. 3. Pseudo-ductile strain and yield stress are considered as two main parameters representing the performance of the UD hybrid composites. Resulting in an increase of both the pseudo-ductile strain and the yield stress values by increasing the stiffness and strength of the lower-strain material. The highest values of pseudo-ductile strain and yield stress are independent of the interface toughness [25]. Damage patterns indicated that the thickness of carbon plies plays a major role in the introduction of pseudo ductility[20-25]. For the Carbon S-Glass epoxy hybrid composite, an increase in hybridization effect up to 20 % for 29 µm carbon layer thickness, but it was observed that no significant effect for thicker plies laminates. The positive influence of the hybrid effect depends on the thickness of carbon plies. This is due to the constraining effect of the critical cluster which leads to the breakage of fiber at the fiber and ply level [27]. Fragmentation was observed in the woven CFRP layer when the thickness was below 14% in UD self-reinforced polypropylene (SRPP) hybrids. This yields the gradual failure of composite laminates [28]. In thin continuous hybrid composites, the pseudo ductile response does not influence by a change in the temperature range -50 °C to 80 °C as compared with discontinuous thick hybrid composites. The change in the response of discontinuous thick hybrid composites was also noticed because the temperature has a strong influence on the interlaminar behavior of the hybrid composites[29].

Damage Modes	Equations
Fragmentation in the low-strain material	$\sigma_{@LF} = \dot{\acute{\mathrm{S}}}\mathrm{L}\frac{\alpha\beta + 1}{\alpha(\beta + 1)}$ (1)
Delamination	$\sigma_{@del} = \frac{1}{1 + \beta}\sqrt{\frac{1 + \alpha\beta}{\alpha\beta}\frac{2G_{IIC}\,E_H}{t_H}}$ (2)
Failure in the high-strain material	$\sigma_{@HF} = \frac{S_H}{K_t}\frac{1}{(1 + \beta)\sqrt[m]{V}}$ (3)

Table 1: Summary of the stress in the laminate for each damage mode[26]

Novel properties in materials should not be limited to one kind of loading that leads to constraints to exposure in the commercial market. UD and quasi-isotropic (QI) hybrid composite laminates showed to have excellent pseudo-ductility responses in quasi-static and high strain rates conditions [30] which helps to develop the composite with the reduced factor of safety under tensile loading. To extend the benefits of the pseudo ductility concept, Putu Suwarta et.al. [31] have carried out an experiment to demonstrate the effect of pseudo ductility over fatigue loading. Free fragmentation of carbon layers in heavily loaded hybrid composite leads to a sudden reduction in stiffness as compared to pristine hybrids under fatigue loading. The shear behavior of the pseudo ductile CFRP laminates was studied by Yu-Chien Ho [32] and the study was based on the effects of the UD prepreg size on the punch force, punching resistance (Ks), quality, and sheared surfaces of the through-holes.

FIBER ORIENTATION

To introduce pseudo ductility, the orientation of the fiber will be maintained in the direction of the axis of loading. The purpose of maintaining the least orientation is to overcome the sudden drop in stress after the matrix crack. Introducing this concept yields to induce extra strain before the failure. The theory behind this concept is initial cracking of the matrix leads to delamination between the layers of laminate refer to Fig. 10. b. Due to this the orientated fibers rotates towards the loading direction shown in Fig. 10.c. This mechanism may induce an extra amount of strain for the failure of laminates.

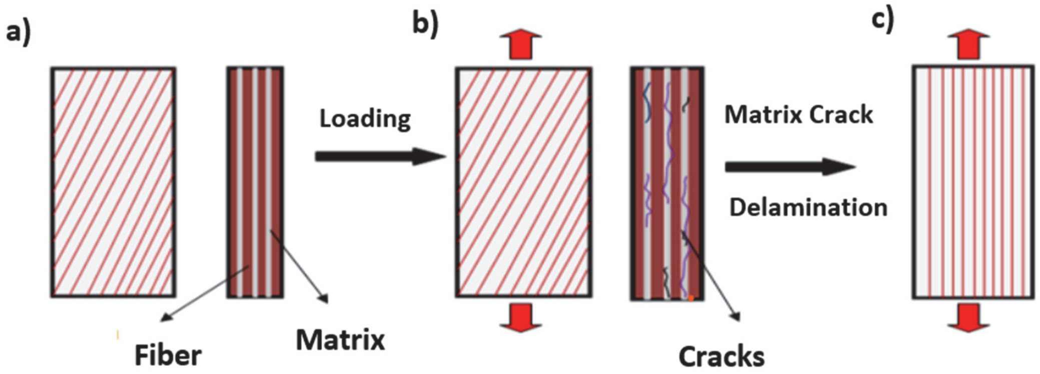

Figure 10: Images showing (a) Front view and side of fiber orientation, (b) Matrix crack and delamination, and (c) Orientation of fiber towards loading direction.

J.D. Fuller et al.[33] have successfully investigated the effect of fiber orientation in Carbon/epoxy prepregs for inducing pseudo ductility in polymer composites. Stacking of laminas made in the sequence of $[\pm Q_5]_s$ for the different angles like $\pm 15^0$, $\pm 20^0$, $\pm 25^0$, $\pm 30^0$ $\pm 45^0$ to make laminates. It was noticed that the fiber orientation of $\pm 45^0$ results in higher non-linear strain-strain behavior due to yielding under tensile loading as shown in Fig. 11 with reduced stiffness. Out of all orientations, the balanced property was achieved for an angle $\pm 25^0$ with maximum stress of 927 MPa and a pseudo ductile strain of 1.23% which is shown in Fig. 12. The concept of fiber orientation and fragmentation of thin carbon plies was used in building the $[\pm Qm/Q_0]_S$ laminates [34]. Demonstration of pseudo ductility was carried out by analytical modeling and experimentation was done for the stacking configuration $[\pm 26^0 n/0]$s (where n=4,5) as shown in Figs. 13. a and 13. b. The layup $[\pm 26^0{}_5/0_1]$s shows a prominent pseudo-ductile strain of 2.2% as compared to $[\pm 26^0{}_4/0_1]$ s. The thin angle ply laminates of $[\pm 26_5]_S$, $[\pm 27_5]$s exhibit ductile behavior rather than pseudo ductile; this behavior was observed due to the effect of orientation with $[\pm \theta_5]$ fibers. Further, it was also found that the material stiffness was increased for repeated cyclic loadings. But for orientation $[\pm 26_5/0]$s author observed a reasonable amount of pseudo-ductility with gradual failure of 0^0 layers in the stacked plies of laminates [35].

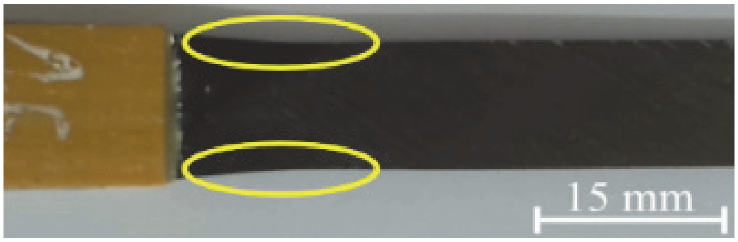

Figure 11: Necking of $\pm 45^0$ angle thin carbon/epoxy prepreg laminate [33].

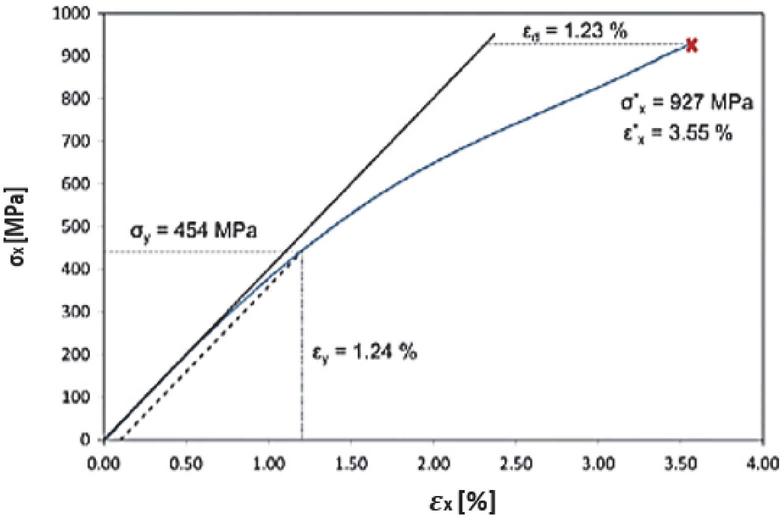

Figure 12: The pseudo-ductile response of thin ply (±25) carbon/epoxy laminate [33].

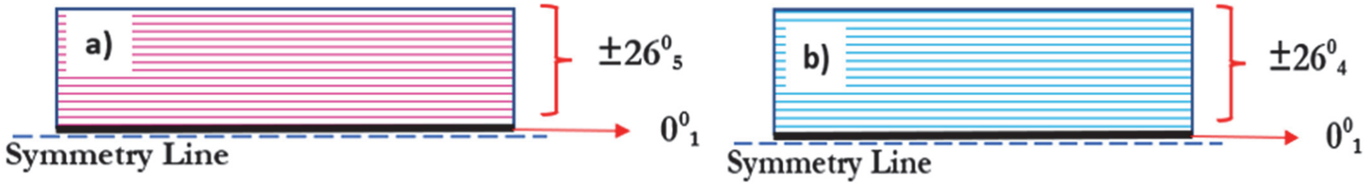

Figure 13: UD CFRP Laminates a) Stacking configuration of [±26$^0{}_5$/0$_1$]s b) Stacking configuration of [±26$^0{}_4$/0$_1$]s

The analytical method for thin-ply CFRP angle-ply laminates was developed by J.D.Fuller et. al.[36] with an associate of matrix plasticity and reorientation of fiber towards the loading direction. This method stands good for [±θ$_5$]s laminates with an orientation ranging from 15^0 to 45^0. For the validation, purpose author correlated the developed model with the experimental results of J.D. Fuller et. al.[33]. The plie orientations of 25^0, 26^0 & 27^0 show promising results with minimal deviation as compared to experimental results as shown in Fig. 14. Also, the modeling has allowed direct identification of a particular fiber angle that exhibits strength of more than 900 MPa, strain to failure is greater than 3.5%, with the pseudo ductile strain of 1.2%.

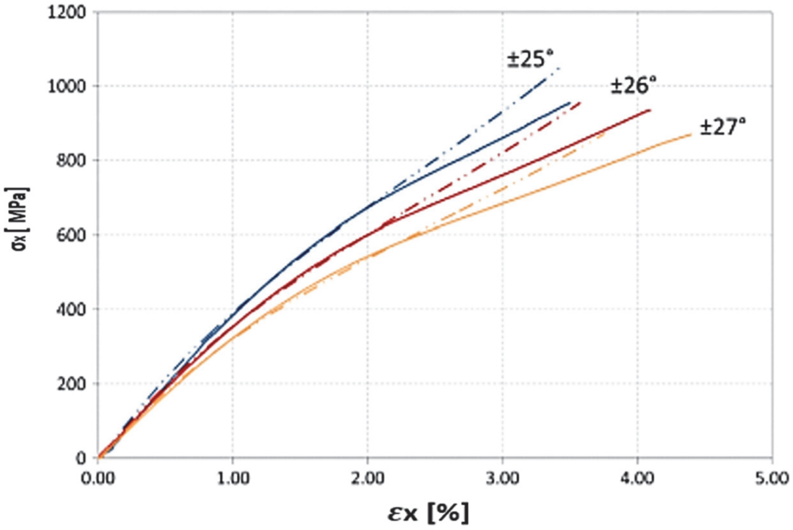

Figure 14: Stress versus Strain response comparison in analytic method(dotted lines) and experimental method (solid Lines) [36].

Two different types of hybridization were considered [T1000/XN80/T1000] and [MR-60/XN80/MR60] to know the tensile response for notched and un-notched Carbon/epoxy hybrid laminates. Each UD sub-laminates were stitched by comprising the lower strain and higher strain fibers; the further building of blocks forms a quasi-isotropic composite as shown in Fig. 15. The non-linear, pseudo ductile stress-strain response was observed for both grades of quasi-isotropic unnotched (QI-UN) laminates. Reducing notch sensitivity can be achieved by increasing the ratio of pseudo-ductile strain to yield strain[37]. The tensile test was conducted on standard modulus- standard modulus (SM-SM) [±26$_5$/0]$_S$ and intermediate modulus- high modulus (IM-HM) [±252/0]S laminates [38] under unnotched and open hole conditions. The author concluded that both grade laminates are notch insensitive; due to the redistribution of stress around the notch in laminated composites[37-38]. Bearing failure of pseudo-ductile composites was examined by double shear–lap bolted joint in tensile mode[39]. Progressive failure was observed for both SM-SM [±26^0/0]$_{S4}$ and IM-HM [±25^0/0]$_{S2}$ laminates. SM-SM [±26^0/0]$_{S4}$ laminate grade showed higher ultimate failure stress as compared to IM-HM [±25^0/0]$_{S2}$ regarding Figs. 16. a & 16. b. The pseudo ductile behaviour of [±27$_7$/0]$_S$ fiber orientation composites after the pre-indentation and pre-impact studied by Alessia Prato et.al.[40]. Pre-indention samples showed nonlinear stress-strain behavior with the pseudo ductile strain of 2.95% and 0.7% for indented fully damaged (Ind_FD), Indented interrupted (Ind_Int), respectively. Finally, it was observed that pre-damaged samples also exhibit pseudo ductility behavior. The concept of orientation dispersion [41-42] in quasi-isotropic laminates were used to overcome the free edge delamination and to reduce the notch sensitivity. The stitching of quasi-isotropic hybrid laminates as per the new layup concept is shown in Fig. 17. This idea is showing a non-linear response of the tensile test for [45G/90G/-45G/0G/0C/45C/90C/-45C]$_S$ and [60G/-60G/0G/0C/60C/-60C]$_S$ was observed with 1% of pseudo–ductile strain before the final failure and also laminates were almost free from free edge delamination as observed from Fig. 18 [41].

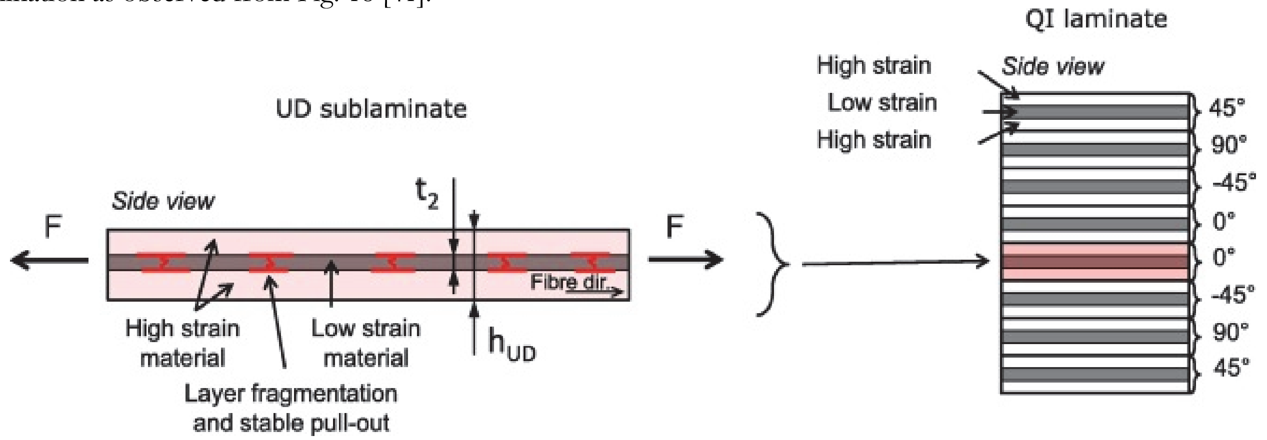

Figure 15: Schematic of hybridization of laminates [37]

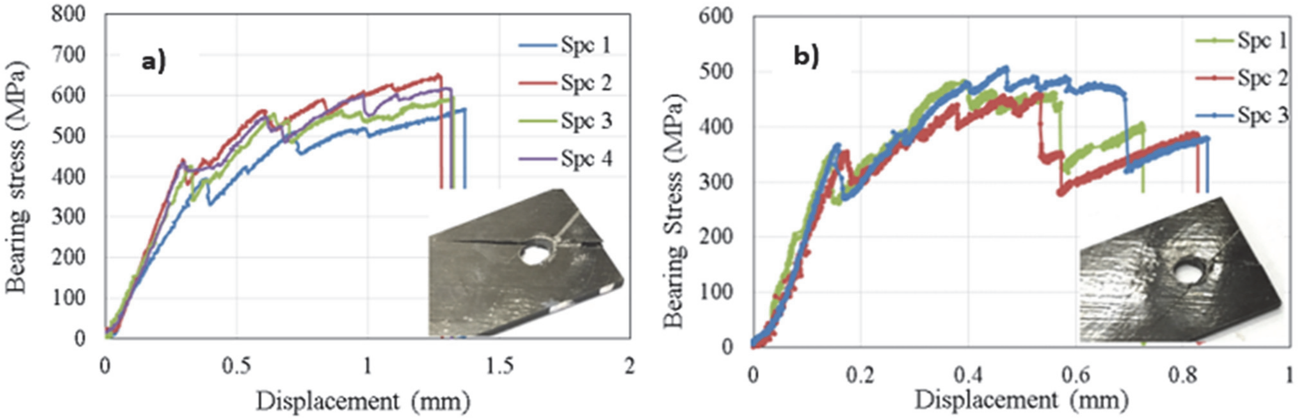

Figure 16: a) Bearing stress-displacement curves of the SM-SM b) Bearing stress-displacement curves of the IM-HM [39]

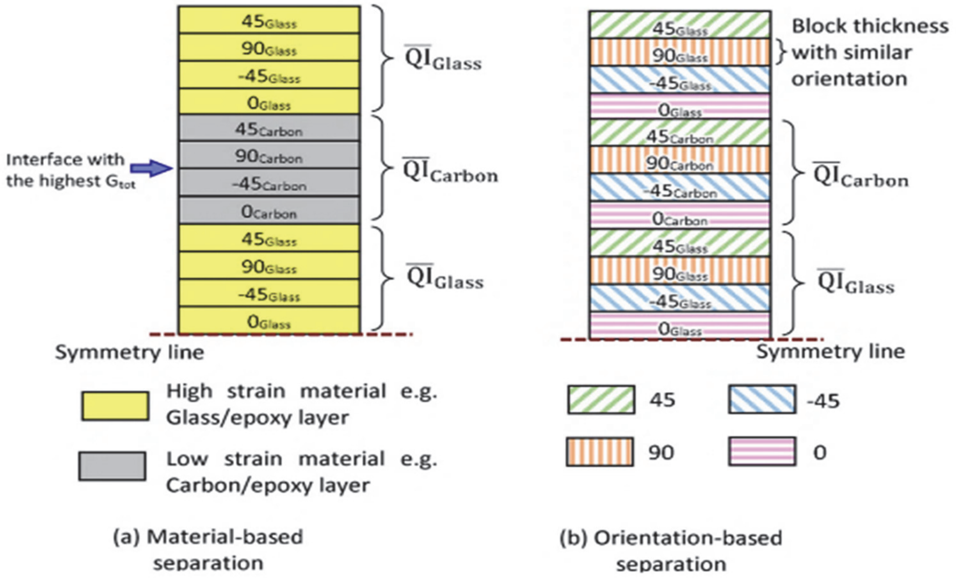

Figure 17: The dispersed orientation stacking method[41]

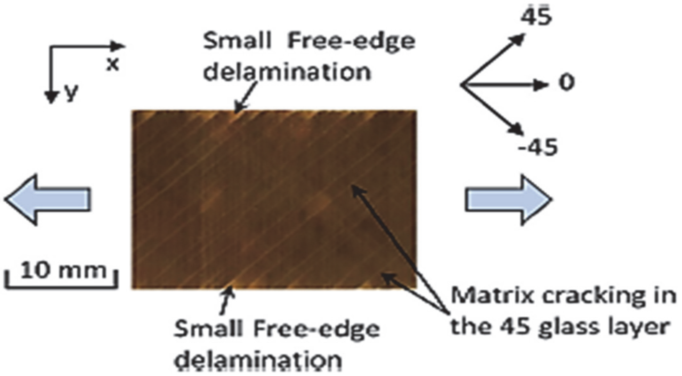

Figure 18: Free edge delamination in the configuration of $[45G/90G/-45G/0G/0C/45C/90C/-45C]_s$ [41]

The details of fiber orientation and fragmentation effect on yield stress and pseudo ductile strain are displayed in Fig. 19. The $\pm 20^0$ fiber position showed a higher stress value but a less pseudo ductile response and the reverse case was noticed for $\pm 45^0$ orientation. Balanced properties were noticed for $[\pm 27_7/0]_S$ due to the stable fragmentation of 0^0 plie and complete reorientation towards the loading direction.

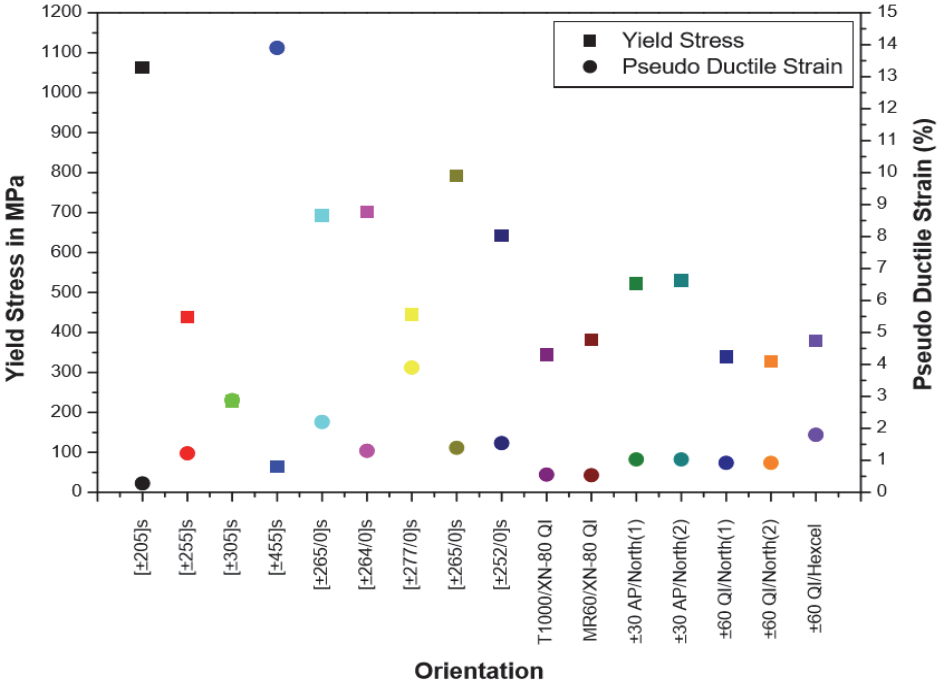

Figure 19: Orientation influence on yield stress and Pseudo ductile strain (Figure is plotted without considering LE fiber volume fraction) [33,34,37,38,40,42]

INTERFACIAL SLIP IN DISCONTINUOUS FIBER COMPOSITES

Interfacial slip in discontinuous fiber composites is another mechanism to induce pseudo ductility in polymer composites. In this technique, hybrid laminates were developed based on the concept of damage mechanisms for example fragmentation of the lower strain materials, stable delamination in between interlayers, and failure of higher strain materials[17] the schematic of this technique is shown in Fig. 20. The behavior of pseudo ductility was successfully demonstrated for newer grade hybrid composites, in which partial and periodic discontinuous platelets of Carbon/epoxy prepregs were embedded between UD Glass/epoxy prepregs. Configuration of [1SG/1HS40/1SG]-12mm showed 60% higher modulus as compared to the pure Glass/epoxy laminates with plateau stress of 860 MPa and 2% pseudo-ductile strain [43]. The pseudo ductile strain of 0.25% was observed in samples developed using UD discontinuous aerospace-grade

IM7/8552 Carbon fiber/epoxy prepregs with ply block thickness of 0.25mm and overlap length of 8mm[44]. In introducing the pseudo ductility in interfacial slip laminated composites[43-44], platelet length and its thickness play a key role.

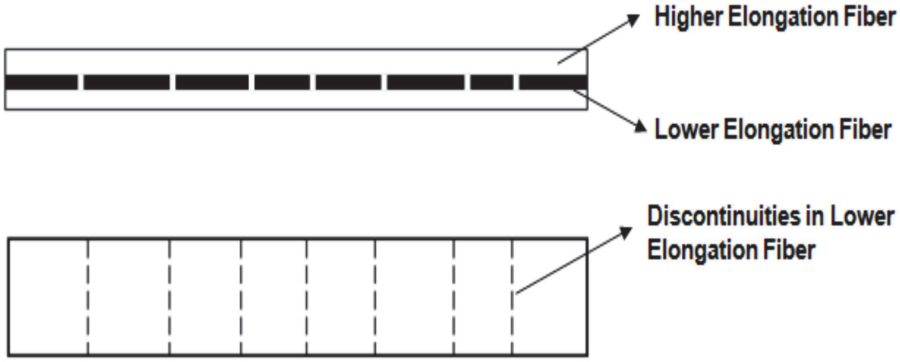

Figure 20: The schematic of the interlayer discontinuous composite [43].

The pseudo ductile failure was successfully demonstrated using intermingled and hierarchical hybrid composites [45-46]. The maximum pseudo ductile strain of 1.1% with a tensile modulus of 110 MPa was observed in high modulus Carbon/E-glass intermingled hybrid composite [45]. The pseudo ductile response of hierarchical hybrid composites is depending on the stress-strain response of intermingled hybrid composite and the volume fraction of LE fiber [46]. Improved specific strength and stiffness were noticed in micro and nano-cellulose-filled polymer composites [47]. The pseudo ductile strain of 0.04% was noticed in Glass Cellulose epoxy composite for a surface coating density of 319.08 g/m2 [48]. The uniform surface coating of micro-sized Cellulose fibers on Glass UD plies leads to gradual failure. High Performance-Discontinuous Fiber (HiPerDiF) method is a new high-speed process to produce discontinuous fiber architectures with high volume fraction. It allows the manufacture of tow or tape-type prepregs with highly aligned reinforcements directly from short fibers rather than from pre-existing tows. [45,46,49-50] The HiPerDiF method provides 67% of fibers were aligned with a deviation of ±30 and performed better in terms of mechanical properties concerning continuous fiber composites [49]. The volume fraction of the recycled carbon fiber (rCF) in intermingled rCF/vCF composites and in interlaminated (sandwiching the intermingled rCF/vCF composite in between UD Glass fiber layers) hybrid composites play a major role in inducing the pseudo ductility [50]. The hybrid Carbon fiber/Self-Reinforcement Polypropylene composite has a gradual failure in tension mode and it depends on cut length, cut friction, and step length of Carbon prepreg [51]. Gradual failure associated with the pseudo ductile strain of greater than 10% was claimed in hybrid composites of Aligned Discontinuous Carbon Fiber (ADCF) and SRPP[52]. Brittle to ductile phase transition was observed for the range of 6.9% to 8.6% of total volume fraction (Vf) in randomly orientated discontinuous Carbon fiber/self-reinforced Polypropylene composites. But pseudo ductility associated with a failure strain of 10 % was achieved for the Vf of Carbon fiber lower than 7%[53]. The concept of interleaving helps to delay the catastrophic failure in UD composites as compared to interlayer composites [54].

CONCLUSIONS

- The favorable pseudo ductile stress-strain response has been successfully demonstrated with different mechanisms by various research investigators. But, the scaling effect on pseudo ductile response is yet to explore. Hence, in the present study, a gradual failure similar to that of metals was achieved by developing hybrid laminates using thin plies.
- The reorientation of fibers towards the loading direction and fiber fragmentation was successfully demonstrated by existing analytical and experimentation methods. Dispersion of orientation showed that the developed composites were free from edge delamination. But, a Bidirectional stress-strain response is yet to explore.
- The HiPerDiF method helps to develop laminates by aligning the short fibers in a specific direction with a higher fiber volume fraction.
- The HiPerDuCT program also showed newer techniques to develop high-performance composite laminates to overcome catastrophic failures.

ACKNOWLEDGMENTS

The authors would like to acknowledge the appraise their appreciation to the organization for providing the required facilities at the Research Center, Mechanical engineering department of SDM College of Engineering and Technology, Dharwad for their motivation and backing throughout the investigations.

NOMENCLATURE

LE- Lower Elongation Fiber
HE- Higher Elongation Fiber
εf - Final failure strain of the high material
σf- Final failure stress of the high strain material
α- Young's modulus ratio of the low to high strain material
β- Thickness ratio of the low to high strain material
$\sigma_{@LF}$- Laminate stress at low strain material failure
$\sigma_{@HF}$- Laminate stress at high strain material failure
$\sigma_{@del}$- Stress in the laminate at which delamination propagates
m -Weibull modulus of high strain material strength distribution
UD-Uni directional
QI- Quasi Isotropic
SH-Strength of the high strain material
SL-Strength of the low strain material
ŚL-Strength distribution average of the low strain material
EH -Modulus of the high strain material
t_H-Half thickness of the high strain material
V-Volume of the specimen
G_{IIC} -Mode II critical strain energy release rate
Kt - Stress concentration factor

REFERENCES

[1] Wisnom, M.R., (2016), July. Mechanisms to create high-performance pseudo-ductile composites. In IOP Conference Series: Materials Science and Engineering, 139(1), p. 012010). DOI: 10.1088/1757-899X/139/1/012010.
[2] Swolfs, Y., Gorbatikh, L. and Verpoest, I., (2014). Fibre hybridisation in polymer composites: A review. Composites Part A: Applied Science and Manufacturing, 67, pp.181-200. DOI: 10.1016/j.compositesa.2014.08.027.
[3] Singh, S.B. and Chawla, H., (2019). Hybrid effect of functionally graded hybrid composites of glass–carbon fibers. Mechanics of Advanced Materials and Structures, 26(14), pp.1195-1208. DOI: 10.1080/15376494.2018.1432792.
[4] Taketa, I., (2011). Analysis of Failure Mechanisms and Hybrid Effects in Carbon Fibre Reinforced Thermoplastic Composites.
[5] Pandya, K.S., Veerraju, C. and Naik, N.K., (2011). Hybrid composites made of carbon and glass woven fabrics under quasi-static loading. Materials & Design, 32(7), pp.4094-4099. DOI: 10.1016/j.matdes.2011.03.003.
[6] Zhang, J., Chaisombat, K., He, S. and Wang, C.H., (2012). Hybrid composite laminates reinforced with glass/carbon woven fabrics for lightweight load bearing structures. Materials & Design (1980-2015), 36, pp.75-80. DOI: 10.1016/j.matdes.2011.11.006.
[7] You, Y.J., Park, Y.H., Kim, H.Y. and Park, J.S., (2007). Hybrid effect on tensile properties of FRP rods with various material compositions. Composite structures, 80(1), pp.117-122. DOI: 10.1016/j.compstruct.2006.04.065.
[8] Aklilu, G., Adali, S. and Bright, G., (2020). Tensile behaviour of hybrid and non-hybrid polymer composite specimens at elevated temperatures. Engineering Science and Technology, an International Journal, 23(4), pp.732-743. DOI: 10.1016/j.jestch.2019.10.003

[9] Murugan, R., Ramesh, R. and Padmanabhan, K., (2014). Investigation on static and dynamic mechanical properties of epoxy based woven fabric glass/carbon hybrid composite laminates. Procedia Engineering, 97, pp.459-468. DOI: 10.1016/j.proeng.2014.12.270

[10] Rajpurohit, A., Joannès, S., Singery, V., Sanial, P. and Laiarinandrasana, L., (2020). Hybrid effect in in-plane loading of carbon/glass fibre based inter-and intraply hybrid composites. Journal of Composites Science, 4(1), p.6. DOI: 10.3390/jcs4010006.

[11] Zhang, J., Chaisombat, K., He, S. and Wang, C.H., (2012). Hybrid composite laminates reinforced with glass/carbon woven fabrics for lightweight load bearing structures. Materials & Design (1980-2015), 36, pp.75-80. DOI: 10.1088/1757-899X/377/1/012157.

[12] Boztepe, M.H., Uzay, C. and Bayramoglu, M., (2016). Investigation of Tensile Behavior of Woven Carbon, Glass and Hybrid Fiber Composites. In Conference of the International Journal of Arts & Sciences (pp. 1943-6114).

[13] Ambigai, R. and Prabhu, S., (2018), August. Analysis on mechanical and thermal properties of glass-carbon/epoxy-based hybrid composites. In IOP conference series: materials science and engineering, 402(1), p. 012136. DOI: 10.1088/1757-899X/402/1/012136.

[14] Ikbal, H., Wang, Q., Azzam, A. and Li, W., (2016). GF/CF hybrid laminates made through intra-tow hybridization for automobile applications. Fibers and Polymers, 17(9), pp.1505-1521. DOI: 10.1007/s12221-016-5953-6.

[15] Wisnom MR, Czel G, Jalalvand M, Potter KD., (2016). Pseudo-ductile hybrid composites with overload sensing capability. ASC 31st Technical Conference, Williamsburg, Virginia.

[16] Galos, J., (2020). Thin-ply composite laminates: a review. Composite Structures, 236, p.111920. DOI: 10.1016/j.compstruct.2020.111920

[17] Czél, G. and Wisnom, M.R., (2013). Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridization with thin-ply carbon prepreg. Composites Part A: Applied Science and Manufacturing, 52, pp.23-30. DOI: 10.1016/j.compositesa.2013.04.006

[18] Ribeiro, F., Sena-Cruz, J., Branco, F.G. and Júlio, E., (2018). Hybrid effect and pseudo-ductile behaviour of unidirectional interlayer hybrid FRP composites for civil engineering applications. Construction and Building Materials, 171, pp. 871-890. DOI: 10.1016/j.conbuildmat.2018.03.144

[19] Czél, G., Jalalvand, M. and Wisnom, M.R., (2016). Design and characterization of advanced pseudo-ductile unidirectional thin-ply carbon/epoxy–glass/epoxy hybrid composites. Composite Structures, 143, pp. 362-370. DOI: 10.1016/j.compstruct.2016.02.010.

[20] Jalalvand, M., Czél, G. and Wisnom, M.R., (2014). Numerical modelling of the damage modes in UD thin carbon/glass hybrid laminates. Composites Science and Technology, 94, pp. 39-47. DOI: 10.1016/j.compscitech.2014.01.013.

[21] Fotouhi, M., Suwarta, P., Jalalvand, M., Czel, G. and Wisnom, M.R., (2016). Detection of fibre fracture and ply fragmentation in thin-ply UD carbon/glass hybrid laminates using acoustic emission. Composites Part A: Applied Science and Manufacturing, 86, pp.66-76. DOI: 10.1016/j.compositesa.2016.04.003.

[22] Czél, G., Jalalvand, M., Wisnom, M.R. and Czigány, T., (2017). Design and characterization of high performance, pseudo-ductile all-carbon/epoxy unidirectional hybrid composites. Composites Part B: Engineering, 111, pp. 348-356. DOI: 10.1016/j.compositesb.2016.11.049.

[23] Diao, H., Bismarck, A., Robinson, P. and Wisnom, M.R., (2012), June. Pseudo-ductile behaviour of unidirectional fibre reinforced polyamide-12 composite by intra-tow hybridization. In Proceedings of ECCM, 15.

[24] Czél, G., Jalalvand, M. and Wisnom, M.R., (2016). Hybrid specimens eliminating stress concentrations in tensile and compressive testing of unidirectional composites. Composites Part A: Applied Science and Manufacturing, 91, pp.436-447. DOI: 10.1016/j.compositesa.2016.07.021.

[25] Jalalvand, M., Czél, G. and Wisnom, M.R., (2015). Parametric study of failure mechanisms and optimal configurations of pseudo-ductile thin-ply UD hybrid composites. Composites Part A: Applied Science and Manufacturing, 74, pp.123-131. DOI: 10.1016/j.compositesa.2015.04.001.

[26] Jalalvand, M., Czél, G. and Wisnom, M.R., (2015). Damage analysis of pseudo-ductile thin-ply UD hybrid composites–A new analytical method. Composites Part A: Applied Science and Manufacturing, 69, pp. 83-93. DOI: 10.1016/j.compositesa.2014.11.006.

[27] Wisnom, M.R., Czél, G., Swolfs, Y., Jalalvand, M., Gorbatikh, L. and Verpoest, I., (2016). Hybrid effects in thin ply carbon/glass unidirectional laminates: accurate experimental determination and prediction. Composites Part A: Applied Science and Manufacturing, 88, pp. 131-139. DOI: 10.1016/j.compositesa.2016.04.014.

[28] Swolfs, Y., Meerten, Y., Hine, P., Ward, I., Verpoest, I. and Gorbatikh, L., (2015). Introducing ductility in hybrid carbon fibre/self-reinforced composites through control of the damage mechanisms. Composite Structures, 131, pp. 259-265. DOI: 10.1016/j.compstruct.2015.04.069

[29] Czél, G., Bugár-Mészáros, M. and Wisnom, M.R., (2018). The effect of test temperature on the pseudo ductility of thin-ply hybrid composites. ECCM18 – 18th European Conference on Composite Materials, Athene, Greece.

[30] Fotouhi, M., Fuller, J., Longana, M., Jalalvand, M. and Wisnom, M.R., (2019). The high strain rate tension behaviour of pseudo-ductile high performance thin ply composites. Composite Structures, 215, pp. 365-376. DOI: 10.1016/j.compstruct.2019.02.068.

[31] Suwarta, P., Fotouhi, M., Czél, G., Longana, M. and Wisnom, M.R., (2019). Fatigue behaviour of pseudo-ductile unidirectional thin-ply carbon/epoxy-glass/epoxy hybrid composites. Composite Structures, 224, p.110996. DOI: 10.1016/j.compstruct.2019.110996.

[32] Ho, Y.C. and Yanagimoto, J., (2018). Effect of unidirectional prepreg size on punching of pseudo-ductile CFRP laminates and CFRP/metal hybrid composites. Composite Structures, 186, pp. 246-255. DOI: 10.1016/j.compstruct.2017.11.042.

[33] Fuller, J.D. and Wisnom, M.R., (2015). Pseudo-ductility and damage suppression in thin ply CFRP angle-ply laminates. Composites Part A: Applied Science and Manufacturing, 69, pp. 64-71. DOI: 10.1016/j.compositesa.2014.11.004.

[34] Fuller, J.D., Jalalvand, M. and Wisnom, M.R., (2016). Combining fibre rotation and fragmentation to achieve pseudo-ductile CFRP laminates. Composite Structures, 142, pp. 155-166. DOI: 10.1016/j.compstruct.2016.01.073.

[35] Fuller, J.D. and Wisnom, M.R., (2018). Ductility and pseudo-ductility of thin ply angle-ply CFRP laminates under quasi-static cyclic loading. Composites Part A: Applied Science and Manufacturing, 107, pp. 31-38. DOI: 10.1016/j.compositesa.2017.12.020.

[36] Fuller, J.D. and Wisnom, M.R., (2015). Exploration of the potential for pseudo-ductility in thin ply CFRP angle-ply laminates via an analytical method. Composites Science and Technology, 112, pp. 8-15. DOI: 10.1016/j.compscitech.2015.02.019.

[37] Czél, G., Jalalvand, M., Fotouhi, M., Longana, M.L., Nixon-Pearson, O.J. and Wisnom, M.R., (2018). Pseudo-ductility and reduced notch sensitivity in multi-directional all-carbon/epoxy thin-ply hybrid composites. Composites Part A: Applied Science and Manufacturing, 104, pp. 151-164. DOI: 10.1016/j.compositesa.2017.10.028.

[38] Wu, X., Fuller, J.D., Longana, M.L. and Wisnom, M.R., (2018). Reduced notch sensitivity in pseudo-ductile CFRP thin ply angle-ply laminates with central 0 plies. Composites Part A: Applied Science and Manufacturing, 111, pp. 62-72. DOI: 10.1016/j.compositesa.2018.05.011.

[39] Wu, X., Fuller, J., Fotouhi, M. and Wisnom, M., (2018). Bearing failure of pseudo-ductile thin ply angle-ply laminates.In: Procedding of the 18th European Conference on Composites Materials., Athens, Greece, 24-28th June.

[40] Prato, A., Longana, M.L., Hussain, A. and Wisnom, M.R., (2019). Post-impact behaviour of pseudo-ductile thin-ply angle-ply hybrid composites. Materials, 12(4), p.579. DOI: 10.3390/ma12040579.

[41] Jalalvand, M., Fotouhi, M. and Wisnom, M.R., (2017). Orientation-dispersed pseudo-ductile hybrid composite laminates–A new lay-up concept to avoid free-edge delamination. Composites Science and Technology, 153, pp.232-240. DOI: 10.1016/j.compscitech.2017.10.011.

[42] Fotouhi, M., Jalalvand, M. and Wisnom, M.R., (2018). Notch insensitive orientation-dispersed pseudo-ductile thin-ply carbon/glass hybrid laminates. Composites Part A: Applied Science and Manufacturing, 110, pp. 29-44. DOI: 10.1016/j.compositesa.2018.04.012.

[43] Czél, G., Jalalvand, M. and Wisnom, M.R., (2015). Demonstration of pseudo-ductility in unidirectional hybrid composites made of discontinuous carbon/epoxy and continuous glass/epoxy plies. Composites Part A: Applied Science and Manufacturing, 72, pp. 75-84. DOI: 10.1016/j.compositesa.2015.01.019.

[44] Czél, G., Pimenta, S., Wisnom, M.R. and Robinson, P., (2015). Demonstration of pseudo-ductility in unidirectional discontinuous carbon fibre/epoxy prepreg composites. Composites Science and Technology, 106, pp.110-119. DOI: 10.1016/j.compscitech.2014.10.022.

[45] Yu, H., Longana, M.L., Jalalvand, M., Wisnom, M.R. and Potter, K.D., (2015). Pseudo-ductility in intermingled carbon/glass hybrid composites with highly aligned discontinuous fibres. Composites Part A: Applied Science and Manufacturing, 73, pp. 35-44. DOI: 10.1016/j.compositesa.2015.02.014.

[46] Yu, H., Longana, M.L., Jalalvand, M., Wisnom, M.R. and Potter, K.D., (2018). Hierarchical pseudo-ductile hybrid composites combining continuous and highly aligned discontinuous fibres. Composites Part A: Applied Science and Manufacturing, 105, pp. 40-56. DOI: 10.1016/j.compositesa.2017.11.005.

[47] Kalia, S., Dufresne, A., Cherian, B.M., Kaith, B.S., Avérous, L., Njuguna, J. and Nassiopoulos, E., (2011). Cellulose-based bio-and nanocomposites: a review. International journal of polymer science, 2011. DOI: 10.1155/2011/837875.

[48] Uppin, V.S., Huddar, D.S., Kodancha, K.G., Sridhar, I. and Gouda, P.S., (2016), September. Investigation on pseudo-ductility to improve mechanical behavior in glass-cellulose epoxy composites. In IOP Conference Series: Materials Science and Engineering, 149(1), p. 012112. DOI: 10.1088/1757-899X/149/1/012112.

[49] Yu, H., Potter, K.D. and Wisnom, M.R., (2014). A novel manufacturing method for aligned discontinuous fibre composites (High Performance-Discontinuous Fibre method). Composites Part A: Applied Science and Manufacturing, 65, pp. 175-185. DOI: 10.1016/j.compositesa.2014.06.005.

[50] Longana, M.L., Yu, H., Jalavand, M., Wisnom, M.R. and Potter, K.D., (2017). Aligned discontinuous intermingled reclaimed/virgin carbon fibre composites for high performance and pseudo-ductile behaviour in interlaminated carbon-glass hybrids. Composites Science and Technology, 143, pp. 13-21. DOI: 10.1016/j.compscitech.2017.02.028.

[51] Tang, J., Aslani, A., Swolfs, Y., Bullegas, G., Pinho, S., Lomov, S. and Gorbatikh, L., (2017). Exploring discontinuities and hybridization to design gradual failure in unidirectional carbon fiber/self-reinforced polypropylene composites. Proceedings ICCM21.

[52] Tang, J., Swolfs, Y., Longana, M.L., Yu, H., Wisnom, M.R., Lomov, S.V. and Gorbatikh, L., (2019). Hybrid composites of aligned discontinuous carbon fibers and self-reinforced polypropylene under tensile loading. Composites Part A: Applied Science and Manufacturing, 123, pp. 97-107. DOI: 10.1016/j.compositesa.2019.05.003.

[53] Selezneva, M., Swolfs, Y., Katalagarianakis, A., Ichikawa, T., Hirano, N., Taketa, I., Karaki, T., Verpoest, I. and Gorbatikh, L., (2018). The brittle-to-ductile transition in tensile and impact behavior of hybrid carbon fibre/self-reinforced polypropylene composites. Composites Part A: Applied Science and Manufacturing, 109, pp. 20-30. DOI: 10.1016/j.compositesa.2018.02.034.

[54] Grail, G., Pimenta, S., Pinho, S.T. and Robinson, P., (2015). Exploring the potential of interleaving to delay catastrophic failure in unidirectional composites under tensile loading. Composites Science and Technology, 106, pp. 100-109. DOI: 10.1016/j.compscitech.2014.11.006.