Chapter 4

RESULTS AND DISCUSSION

4.0 Introduction

Polymeric composites, reinforced with high performance fibre like Carbon, shows mechanical properties similar or higher than the conventional metallic materials. An advanced polymeric composite presents high strength-to-weight and stiffness-to-weight ratio.

In addition, the polymeric composites present higher fatigue strength and higher corrosion resistance. Hence, uses of fibre reinforced composites are increased in many of engineering applications especially in aerospace, sports, transportation, marine and corrosion resistant equipment. As discussed in previous chapters many researchers have focused on comparative study of effect on mechanical properties due to:

- Variation in resin thickness.
- Variation of reinforcing material and matrix resins.
- The effects of skew angle, aspect ratio and boundary condition.
- Effect of the plies stacking sequence in different loading directions.
- Interply and intimately mixed hybrid composites like Carbon/glass, Carbon/Kevlar, Carbon/nylon and aramid/nylon etc.
- Composite material with different fabric type: woven, knitted and non-woven.
- Hybrid composites with different type of yarn in the warp and weft directions.

On the basis of the various experimental data generated to study the effect of orientation in terms of skew angle, weave, intraply hybridization, and types of fibre on the mechanical properties like tensile, flexural, impact and quasi static indentation were analyzed here.

In this work, specific hybrid fabrics were required. These fabrics consists of Carbon tow (fibre) having multifilament (6000 and 12000) without twist. Unlike other fibres, weaving of Carbon fibre is difficult and technique to weave Carbon is not reported widely. The crux of this research of weaving fabric containing carbon fibre, which are important for any researcher in future was found. Detailed procedure along with difficulties in weaving the fabrics containing Carbon fibre have been discussed in the previous section 3.4. Several hybridized fabrics were prepared. The details of the fabrics are tabulated in Table 3.1. All fabric samples used for the construction of the polymer textile laminated composites are shown in Figure 3.21a. All the polymer textile composite laminates manufactured by layering the fabric layer with different lay-up sequence, weave and type of reinforcement yarn are shown in Figure 4.1 and details of these composites sample are given Table 3.3.

In this work investigation has been focused on mechanical properties such as tensile, flexural, impact and damage resistance properties of textile polymer composite laminates made of different fibers, laying sequence and weave structure. The fracture behavior of typical specimen after these tests were examined through SEM analysis. To understand the effect of laying angle on tensile properties of textile polymer composite laminates, mathematical method of numerical simulation was adopted by using finite element analysis (FEA) and Ansys software. The validation of the numerical model was done by comparison between experimental and simulated data.

4.1 Comparing the properties of differently oriented textile polymer composite laminate (TPCL)

In chapter III, detailed preparation of hybrid composite having fabrics/fibres laid differently in terms of skew angle, layering, weaving and fibres is described. The physical properties of these prepared fabrics are reported in Table 3.3. During course of this work, attention is focused on the study of effect on the physical and mechanical properties of composite, made by hand layering technique, due to layering fibres/fabrics differently. Other factors like matrix system (including resin-epoxy, initiator, air releasing agent, coupling agent, temperature and type of curing), processing technique and compacting pressure were kept constant. Thus, all samples are uniform as far as matrix is concerned which is one of two constituents of composite. The variation is only in another constituent of the composite that is reinforcement, particularly their orientation. The comparison of different properties, physical and mechanical, are real representation of effect of orientation of fabric.

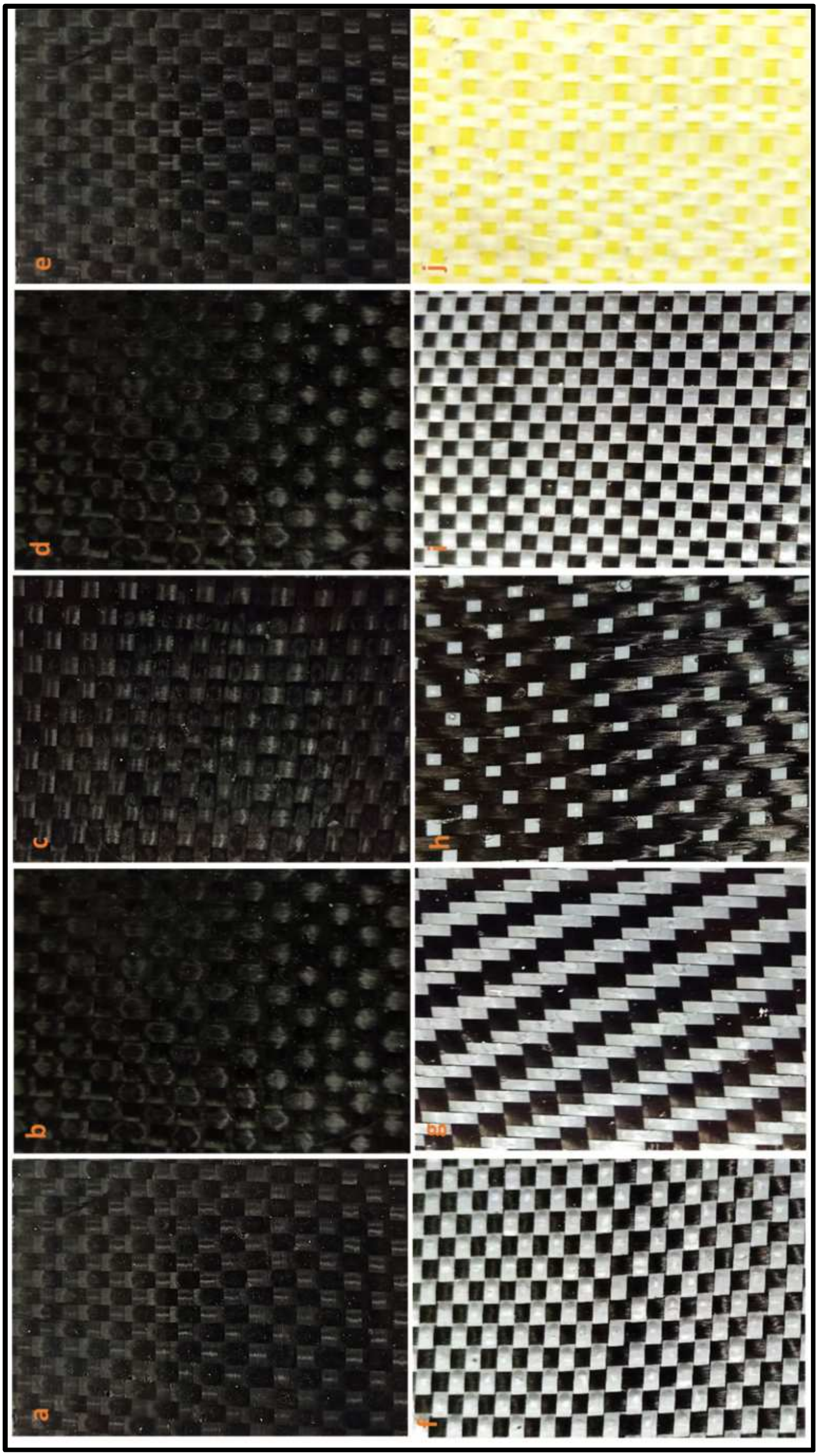


Figure 4.1: Polymer textile composite laminates with different layup sequence (a. CC1; b.CC2; c.CC3; d.CC4; e.CC5; f.CH1; g.CH2; h.CH3 i.CK and j.KH1)

The subsequent part of this section is devoted to discuss the results obtained during this work.

4.2 Physical properties

4.2.1 Density

To determine the density of the TPCL, Archimedes principle was used. There were five test pieces for each type of composite laminate and the results were averaged. The detail calculation is presented in Appendix III. The out-come of results are being tabulated here in Table 4.1

It is clear that the sample CC1, CC2, CC3, CC4 and CC5 doesn't show appreciable variation in the density. As per table 3.3, all the layers of these composites are constructed from same fabric, Carbon-Carbon plain weave (refer Table 3.1, C1C2). The variation among these composites is only their angle of orientation i.e. skew angle. That means the effect of skew angle is negligible on the density.

Table 4.1: Density of textile polymer laminated composites and matrix

Sr. No	Sample code	Density (g/cm^3)
1	CC1	1.3349
2	CC2	1.3285
3	CC3	1.3328
4	CC4	1.3298
5	CC5	1.3402
6	CH1	1.1358
7	CH2	1.2184
8	CH3	1.2571
9	KH1	1.1222
10	CK	1.1248
11	Matrix	1.233

While comparing samples CH1, CH2 and CH3, density variation is observed. CH1 is having minimum density i.e. 1.1358 g/cm^3, CH3 is having maximum density 1.2571 g/ cm^3 and the density is of CH2 i.e. 1.2184 g/ cm^3. CH1, CH2 and CH3 are plain, twill and sateen respectively it implies that type of weave affects the density. These CH1, CH2 and CH3 composites are made of hybrid fabric consisting of Carbon(weft) and HDPE (warp). Plain weave has densely woven structure. Due to dense woven structure, the lighter fibre, HDPE is more per unit area. Hence, the density is less. Similar observations were reported by Sapakul (2002) and Stankard (2015). According to them, the sateen weave has high density. This indicates that weaving pattern have the effect on the density of composite.

While comparing the sample CC1, CH1, KH1 and CK, all are having same weave i.e. plain weave but having different fibres. It can be observed that there is appreciable difference in density of composite, maximum is of 1.3349 g/ cm^3 of CC1 and minimum is of 1.222 g/ cm^3 of KH1. This concludes that type of fibre has effect on density. As matrix is common in all these composites and having same density. The composite density is proportional to both density of fibre and their quantum used per unit area. The higher density CC1 is due the highest density of Carbon fibre compared to HDPE and Kevlar.

4.2.2 Fibre volume fraction

To determine the fibre volume fraction of the TPCL, equation 3.18 was used. There were five test pieces for each type of composite laminate and the results were averaged. The detail calculation is presented in Appendix IV. The out-come of results are being tabulated here in Table 4.2

From table 4.2, it is clear that the sample CC1, CC2, CC3, CC4 and CC5 show minimal variation in the fibre volume fraction (V_f). Referring Table 3.3, all the layers of these composites are constructed from same fabric Carbon-Carbon plain weave [refer Table 3.1, $(C_{12k}C_{6k})_p$]. These composites are produced by varying their angle of orientation i.e. skew angle. The fibre volume fractions values comparison gives around 5 % variation for Carbon composites. Thus, skew angle does not have considerable effect on fibre volume fraction values.

Table 4.2: Fibre volume fraction of textile polymer laminated composites

Sample No.	fibre volume fraction
	V_f (%)
	Equation 3.19
CC1	65.90
CC2	61.13
CC3	68.39
CC4	69.52
CC5	68.77
CH1	61.77
CH2	52.97
CH3	48.00
KH1	62.57
CK	53.45

CH1, CH2 and CH3 composites are prepared with plain, twill and sateen weave respectively (Refer table 3.1). These are hybrid composites consisting of Carbon (1.81 g/cm^3) and HDPE (0.97 g/cm^3). On comparing samples CH1, CH2 and CH3 considerable variation is found in V_f values. CH1 has highest V_f that is 62% than CH2 and CH3 with V_f value 53% and 48% respectively. Plain weave structure having higher interlacement as compare to twill and sateen. Thus, it consists of a denser structure as compared to both others. In these hybrid composites HDPE is highest in plain weave and lowest in sateen. As the lighter fibre is more in CH1 it gives higher V_f value. Similarly, V_f value is lower of twill and lowest of sateen. HDPE is having less density as compared to other hybrid fibre in the composite. that means higher denser structure contribute more volume. This is the reason for higher V_f value in CH1. That indicates that weave structure has considerable effect on the fibre volume fraction of composite.

Composites CC1, CH1, KH1 and CK were prepared with plain weave structure. These composites have different reinforcing fibres in their structure. These reinforcing fibres have different densities. Carbon, Kevlar and HDPE fibres have densities 1.81, 1.44 and 0.97 g/cc respectively. This density difference is reflected in fibre volume fraction. Higher the density of fibre, lower is the fibre volume. That means higher the density, lower the V_f. It can be observed that V_f, is maximum is 62.57% of KH1 whereas 62 % of CH1 is minimum. CK has V_f value as 53.45%. This concludes that type of fibre used for reinforcement has effect on V_f.

4.3 Mechanical properties

To evaluate any engineering materials, it becomes important to know their mechanical properties, such as tensile strength, flexural strength, impact strength and damage resistance. Mechanical properties are the physical properties of the material which describes its behaviour under the action of loads on it. As discussed previously, in-plane mechanical properties of textile composites are usually anisotropic. Anisotropic behavior is due to fibres oriented differently in the fabric. Due to composite being anisotropic, the mechanical strengths are evaluated and compared in both directions, longitudinal (in this work, warp way) and transverse (in this work, weft way).

There are many mechanical properties of materials. Here in this work properties namely tensile strength, flexural strength, impact strength and damage resistance, are evaluated and compared below.

As the detail given in the Table 3.1, carbon-carbon fabric is hybridized by using 12K Carbon in weft and 6K Carbon in warp. Envisaging different behaviour in both direction, study is focused in both longitudinal and transverse directions.

4.3.1 Tensile Strength

Tensile property is the property of a material that allows it to deform under tensile loading without breaking under the action of a load.

The objective of this research was to gain a better understanding of tensile properties of epoxy resin composite laminates reinforced with Carbon, HDPE and Kevlar. The study was focused on the effect of fibre orientation on laminates.

The laminates were cut to suit ASTM D3039 standards. Specimens such prepared were subjected to tensile loads on UTM machine. The experimental data were collected by applying load and measuring the elongation. Detail experimental method is explained and recorded in Chapter 3 (3.4.2.1). The tests were carried out for five samples for each composite and the results were averaged arithmetically. This research indicates that tensile strength is influenced mainly by the fibre orientation of textile polymer laminated composites.

Here data collected as load v/s elongations were utilized to calculate properties related to tensile strength like stress, strain, modulus of elasticity, breaking stress, yield stress etc. These properties are compared for different textile polymer laminated composites made by Stacking fabric at different angle. The final values of both longitudinal and transverse direction are reported in Table 4.3. The average value of ultimate tensile strength and strain along with modulus of elasticity is depicted in Table 4.4.

Table 4.3: Tensile properties stress v/s strain% of textile polymer laminated composites in longitudinal direction and transverse direction

Sr.no	Sample code	Longitudinal		Transverse	
		Strain %	Average Stress	Strain %	Average Stress
1	CC1	0.60	27.09	0.89	116.61
		0.90	42.42	2.59	352.81
		1.80	89.19	4.26	634.88
		2.52	136.12	5.94	894.04
		3.45	191.68	6.27	980.06
		3.58	216.86		
		4.91	268.98		
2	CC2	0.60	38.71	0.06	8.95
		0.90	53.36	1.80	130.15
		1.30	72.66	3.40	254.19
		1.82	103.32	4.80	354.81
		2.53	142.26	5.33	401.01
		3.92	202.43		

Continued.

3	CC3	0.62	45.53	0.03	3.81
		1.20	69.50	1.80	92.98
		1.80	98.70	3.41	193.56
		2.40	130.37	4.21	251.47
		3.00	158.32	5.76	352.68
		3.42	175.70		
4	CC4	0.60	48.85	0.88	67.17
		0.89	64.95	2.55	187.00
		1.27	93.07	4.20	300.62
		1.78	128.35	4.77	335.28
		2.87	184.31	5.10	365.78
		3.12	163.11		
		4.38	239.45		
5	CC5	0.59	47.38	1.82	180.65
		0.84	69.99	2.56	252.27
		1.73	132.11	3.39	339.01
		2.53	196.85	4.20	417.79
		3.27	266.43	4.29	437.00
		3.52	293.72		
		4.40	372.52		
		6.26	456.73		
6	CH1	0.40	5.37	1.83	5.00
		2.43	16.47	3.25	122.90
		3.70	20.04	6.57	242.40
		5.73	23.70	8.33	170.00
		10.05	31.54	10.00	70.00
		15.03	45.60	13.72	29.10
		16.50	45.42		
		17.00	11.28		
7	CH2	0.46	5.03	2.17	45.06
		3.80	20.10	4.94	220.61
		7.58	24.88	7.25	314.34
		13.67	33.70	7.84	324.35
		21.67	38.48	10.00	137.98
		24.50	36.46	14.00	13.84
		26.00	26.89		
		26.00	5.18		

Continued.

8	CH3	0.56	5.25	2.70	136.47
		2.05	12.71	3.23	172.12
		4.50	19.56	6.30	313.43
		8.03	23.34	7.68	356.26
		13.35	27.47	8.51	369.75
		19.17	32.08	10.00	235.95
		23.33	26.37	15.44	15.25
		24.33	14.66		
9	CK	0.25	3.46	1.73	4.05
		1.90	6.37	2.97	47.38
		3.05	133.82	4.25	89.59
		6.00	237.25	6.60	146.06
		7.40	250.75	7.67	161.26
		9.10	201.47		
		12.15	55.88		
		16.08	15.44		
10	KK	0.13	0.84	2.57	47.97
		2.00	6.26	4.23	132.74
		3.33	23.71	7.05	182.88
		13.48	52.20	9.65	112.23
		18.75	67.54	17.17	14.69
		22.00	14.28		

Table 4.4: Modulus of Elasticity of TPCL

	Longitudinal			**Transverse**		
Sample code	**Strain**	**Stress**	**Modulus of Elasticity**	**Strain**	**Stress**	**Modulus of Elasticity**
	%	**MPa**	**GPa**	**%**	**MPa**	**GPa**
CC1	4.91	268.98	5.475	6.27	980.06	15.63
CC2	3.92	202.43	5.164	5.33	401.01	7.524
CC3	3.42	175.70	5.134	5.76	352.68	6.124
CC4	4.38	239.45	5.471	5.10	365.78	7.179
CC5	6.26	456.73	7.292	4.29	437.00	10.18
CH1	15.03	45.60	0.303	6.57	242.40	3.691
CH2	21.67	38.48	0.178	7.84	324.35	4.139
CH3	19.17	32.08	0.167	8.51	369.75	4.345
CK	7.40	250.75	3.389	7.67	161.26	2.103
KK	18.75	67.54	0.360	7.05	182.88	2.594

4.3.1.1 Effect of skew angle of fabric orientation on tensile properties of TPCL

To study the effect on tensile property due to differently oriented fabric in respect of their angle, CC1, CC2, CC3, CC4 and CC5 samples were prepared. The detail of stacking sequence and angle of orientation are given in Table 3.3. As the detail given in this table, carbon-carbon fabric is hybridized by using Carbon 12K in weft and Carbon 6K in warp. Envisaging different behavior in both direction, study is focused in both longitudinal and transverses direction.

The stress-strain curves of the woven fabric composites with four layers, differently sequenced at different skew angles are shown in Figure 4.2. Figure 4.2a gives stress v/s strain for longitudinal direction and Figure 4.3b gives stress v/s strain for transverse direction. This graph depicts the effect of orientation with respect to skew angle on tensile property.

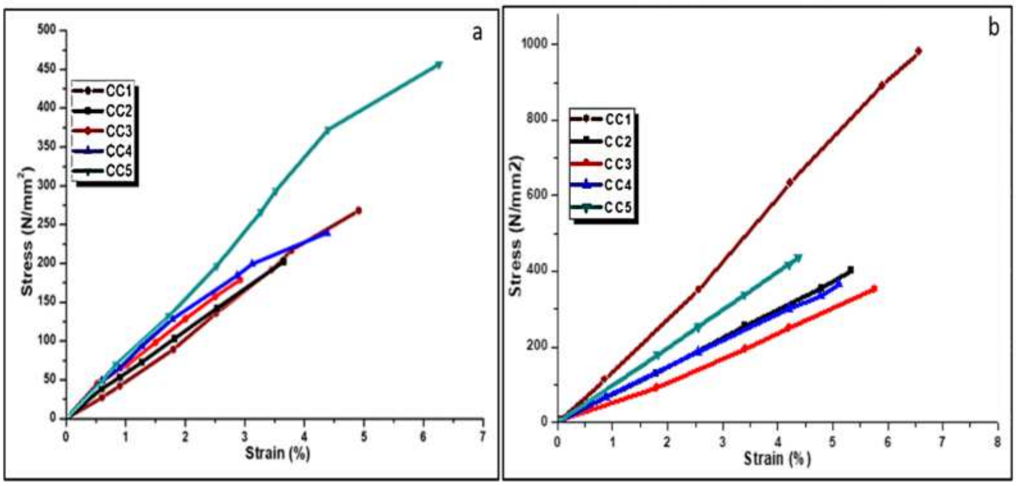


Figure 4.2: Effect of skew angle of fabric orientation on tensile behavior of TPCL (a) longitudinal (b) transverse

In this case, the maximum stress is observed for CC5 for longitudinal direction and CC1 for transverse direction. There is considerable tensile strength variation between Carbon composites CC1 to CC5.

It is observed that for same stress the response in terms of strain is different. Strain is increasing progressively as we move from CC5(0/+90/-90/0) to CC4(0/+60/-60/0) to CC5(0/+45/-45/0) to CC2 (0/+30/-30/0) to CC1 (0/0/0/0) in case of longitudinal direction. While, in the transverse direction for the same stress, trend of the strain is different. For same stress the strain varies CC1<CC5<CC2<CC4<CC3.

Figure 4.3 is the comparison of ultimate tensile strength of all the specimen CC1, CC2, CC3, CC4 and CC5 in both direction longitudinal and transverse. Comparing all the tests, CC1 pattern of composite laminate in transverse direction gives maximum ultimate tensile strength that is about 980MPa. This is about 60% strength the carbon fibre used. The next lower strength achieved is 450Mpa of CC5 in longitudinal direction.

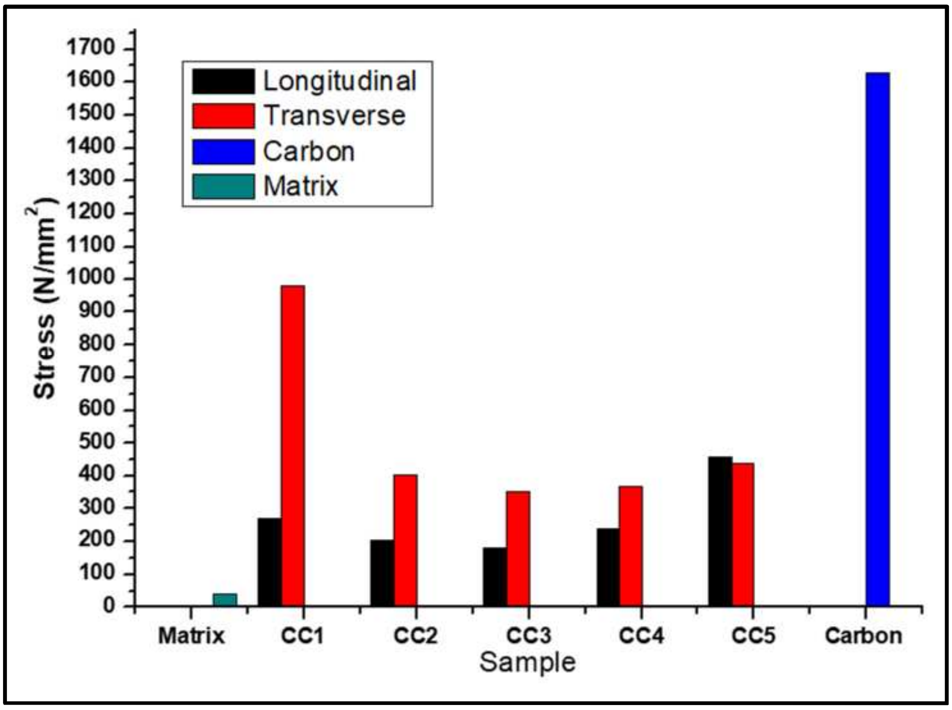


Figure 4.3: Effect of skew angle of fabric orientation on breaking strength of TPCL

Figure 4.5 is the comparison of tensile modulus of elasticity of all the specimen CC1, CC2, CC3, CC4 and CC5 in both direction longitudinal and transverse. Comparing all the tests, maximum modulus of elasticity is obtained in CC1 composite laminate in transverse direction i.e. 15.6 GPa. This is about 2.5% of the carbon fibre used. The next lower elastic modulus is 10.5 GPa of CC5 in transverse direction only. A remarkable observation is noted that the minimum modulus of elasticity (5.13GPa in longitudinal and 6.94 GPa in transverse direction) is attended by the composite laminate CC3.

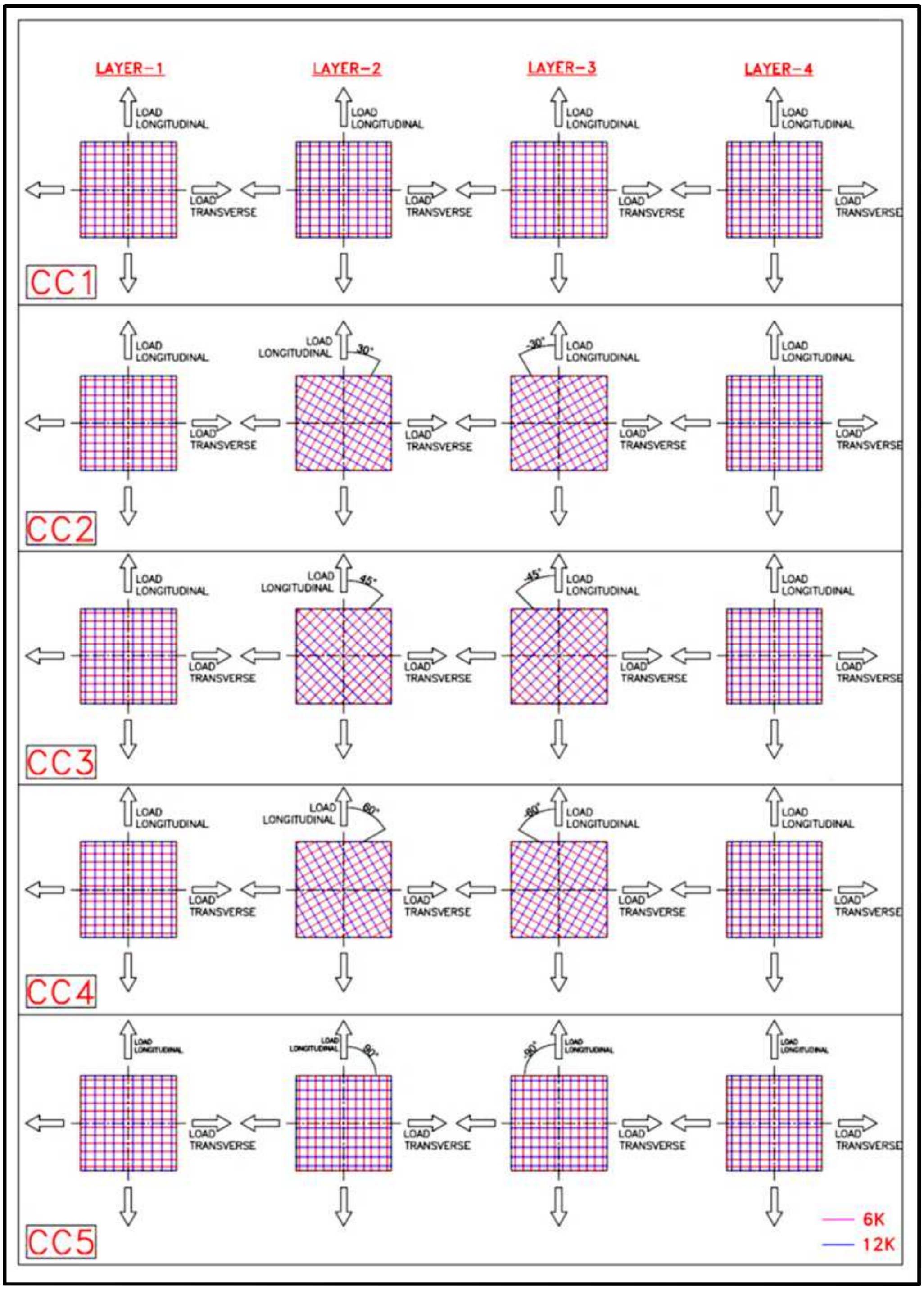


Figure 4.4: Schematic diagram of effect of skew angle on tensile properties of TPCL

As discussed above, the CC3 composite laminate is weakest in tensile ultimate strength. Similarly, tensile strength and stiffness of CC2 and CC4 are less then CC1 and CC5. Referring to the Figure 4.4, CC1 and CC5 are distinguished from CC2, CC3 and CC4 due to the angle of orientation. CC1 and CC5 have no

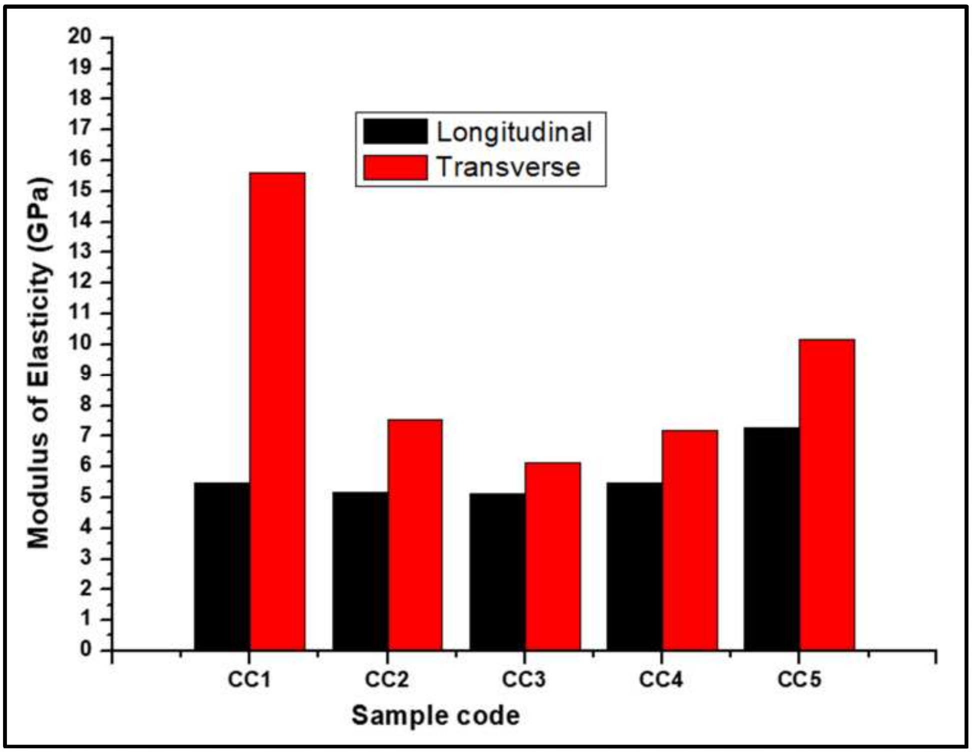


Figure 4.5: Effect of skew angle on tensile modulus of carbon-carbon composite

fibre/fibres at an angle to the direction of load either longitudinal or transverse. Both have same number of fibre layers in the direction of load that is four. Contrary to these CC2, CC3 and CC4 have always only two fibre layer in the direction of load while two fibre layers are at the angle to the direction of load (refer Figure 4.4). At the loading, the limiting condition is the bonding between fibre and matrix. Moreover, there is involvement of shear stress. During the application of tensile load in axial direction, the fibres at angle tried to be aligned with direction of the force. Shear stress resist this alignment of fibres. At certain load, bonding between the fibre and matrix breaks. This is causing an early failure of specimen CC2, CC3 and CC4.

4.3.1.2 Effect of weave structure of fabric on tensile properties of TPCL

Figure 4.6 shows the effect of weave structure on the tensile strength of CH1, CH2 and CH3 in longitudinal direction. The results show that the plain weave structure has the highest tensile strength in longitudinal direction, about 45 MPa (N/mm^2) compared to another weave structure. However, the tensile strength of twill and sateen are 38 and 32 MPa respectively, which are about 15 % and 29%

respectively lower than the plain weave. This is due to less dense weave structure as compared to plain weave.

While in case of transverse direction, the results are different as revealed from Figure 4.6. Contrary to longitudinal direction, in transverse direction, the sateen weave structure had the highest tensile strength, about 260 MPa compared to another weave structure. However, the tensile strength of plain weave and twill weave are 240 and 220 MPa respectively which are about 7.6 % and 15.3% respectively lower than the sateen weave. This is due to the weave structure and least no of interlacement in case of sateen.

In case of transverse direction, the Carbon tow is in the direction of load. The maximum interlacement of yarn is present in Plain as compared to twill; sateen has minimum. If it is analyzed in terms of number, it implies that Carbon fibre will have four times the interlacement in plain as compared to sateen. Whereas, twill will double. Hence, the plain weave in transverse direction will give weaker performance of Carbon as compared to sateen.

Figure 4.7 and 4.8 illustrates nature of these plots depending upon the weave structure in longitudinal and transverse direction respectively. The nature of the graphs in figure 4.8 indicate that the fracture behavior of all weave is similar. Curves starts with a nonlinear increase in stress with rising strain till fracture occurs. Then a dramatic decrease in stress is observed, this is due to the initiation of the crack. For comparison, at same stress there is more strain observed in twill weave as compared to plain weave whereas sateen has maximum. It means that plain weave has maximum resistance to deformation. The resistance to deformation is nothing but modulus of elasticity. The Figure 4.9 is also revealing same behavior.

Figure 4.8 is similar study of loading in transverse direction. Nature in this figure indicate that fracture behavior of all weaves is similar. Curve starts with linear increase in strain with stress till fracture occurs. Unlike, Figure 4.7 for longitudinal direction, here there is no sudden decrease in strain. But there is gradual decrease in stress. This trend continued till the breaking point. For comparison, same stress there is more strain for twill and sateen weave compare to plain weave. But at yield point maximum modulus of elasticity is observed in case of sateen, then twill and plain have minimum. The same is clear from figure 4.9. That means twill have less resistance to applied stress. Sateen

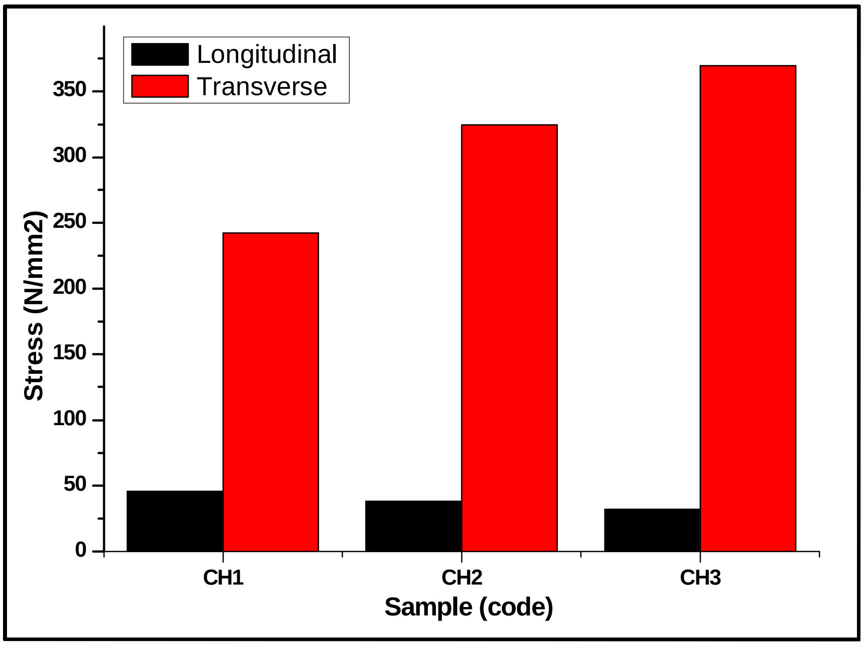


Figure 4.6: Effect of weave effect on breaking strength of composites

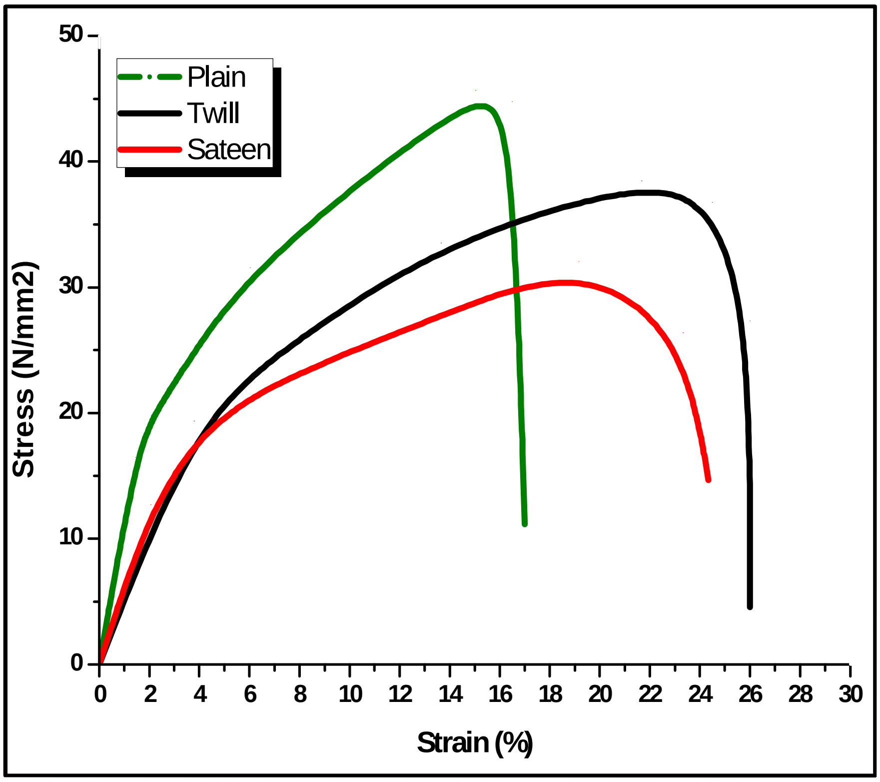


Figure 4.7: Effect of weave structure on longitudinal direction of composites

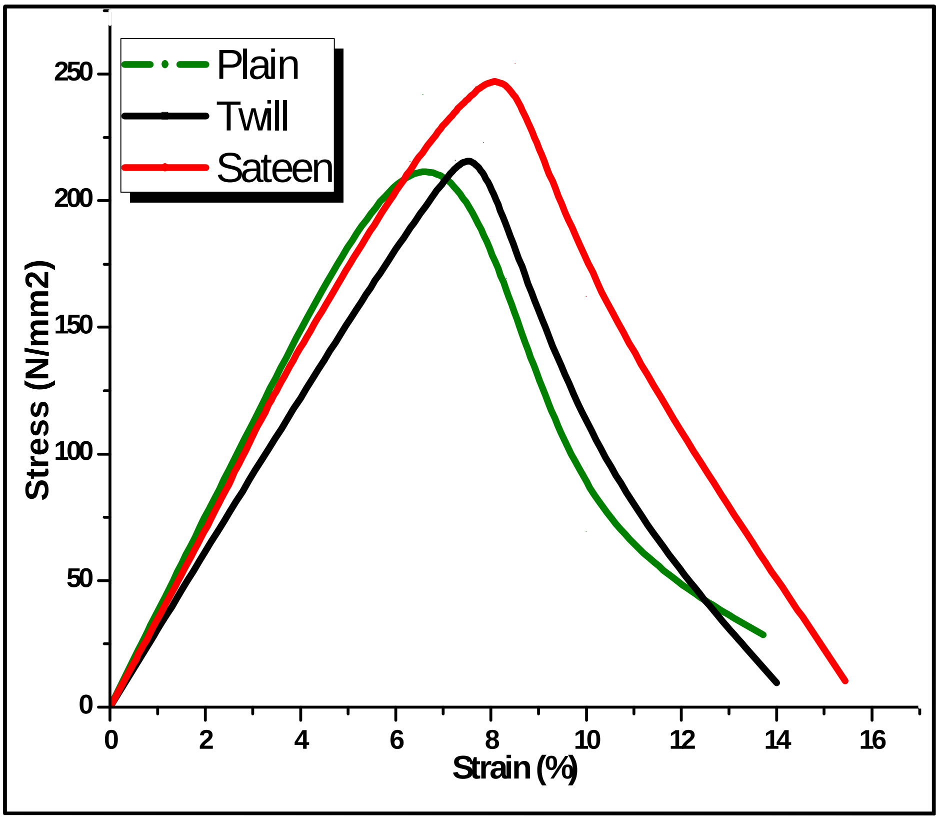


Figure 4.8: Effect of weave structure on transverse direction of composites

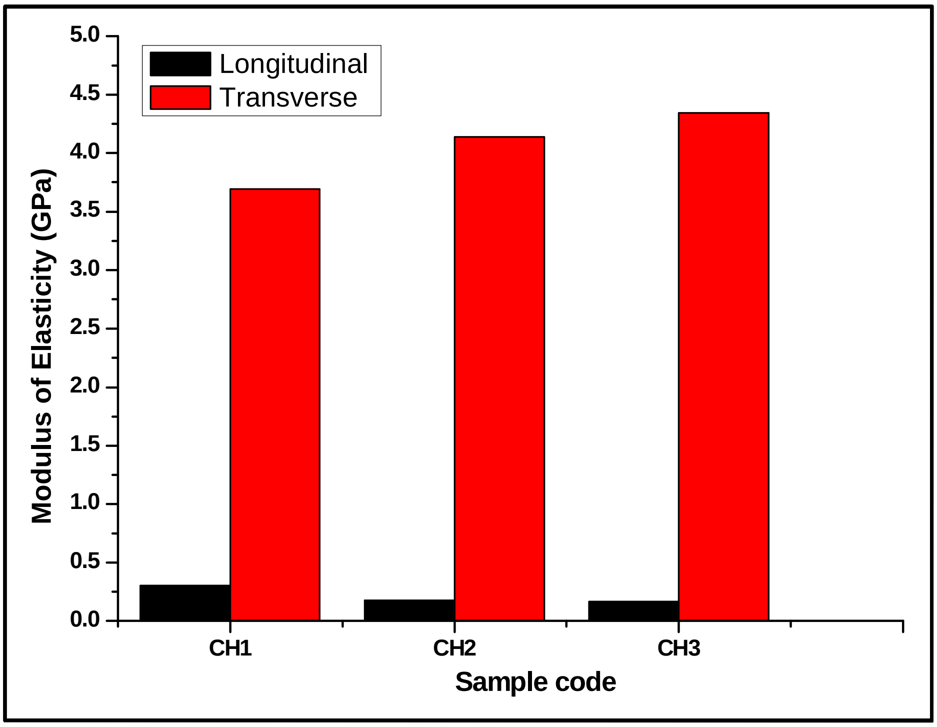


Figure 4.9: Effect of weave effect on Modulus of elasticity of composites

behaves differently, after fracture it is followed with a big crack extension in the specimen. After this, the crack propagation continues with crosshead movement.

The divergent behavior in longitudinal (Figure 4.7) and transverse (Figure 4.8) direction is observed. The curve for transverse direction, stress vs strain curve shows almost elastic behavior while in longitudinal direction it shows plastic behavior till the crack initiates.

4.3.1.3 Effect of type of reinforced yarn fabric on tensile properties of TPCL

Figure 4.10 shows the modulus of elasticity of the composite samples, CC1, CH1, CK1, KH1, having sequence of four layers stacked of different fibre as detailed in Table 3.3. From the graph, it was found that samples CC1 and CH1 showed higher modulus of elasticity than other samples in the range of 15.6 and 3.7 GPa respectively in transverse direction. While sample KH1 and CK shows poor modulus of elasticity i.e. 2.5 and 2 GPa respectively in transverse direction.

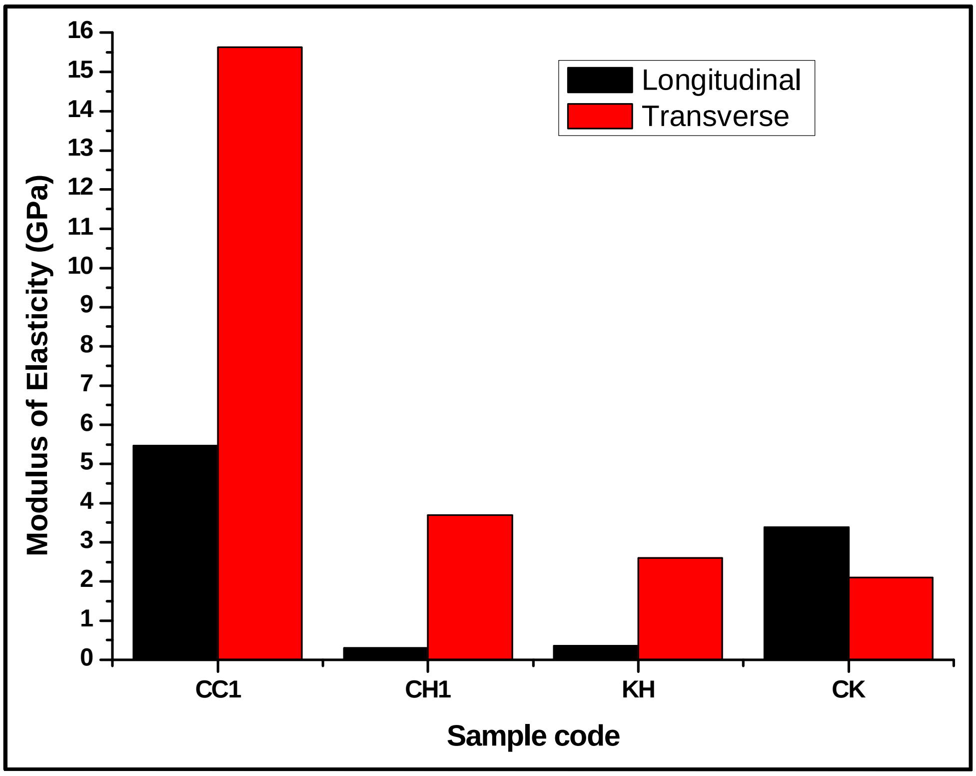


Figure 4.10: Effect of yarn type on Modulus of elasticity of composites

This result is similar to literature cited by Algahtani [46]. In longitudinal direction CC1 and CK have an appreciable modulus i.e. 5.5 GPa. And 3.4 GPa. Other samples show modulus less than 3.5 GPa in longitudinal direction. This phenomenon can be explained by the interface bonding. In case of CC1, which having sequence of layer carbon fibre (0,0,0,0), interface bonding of Carbon fibres with the matrices compared to other fibre is higher. In case of CK, there is carbon fibres along with Kevlar and HDPE yarn. A strong interface bonding permits higher load stress transfer through the composite fibres where as a weak interface bonding will deprive adhesion between the fibres and matrices. As soon the force on the composite supersede a bonding force, it causes the fibres to snap and pull out.

4.3.1.4 SEM Analysis

Scanning electron microscope images were carried out to observe and analyse the condition of post fractured surface of specimen CC1 at different spots. To properly understand fractural behaviour of the composite made from Carbon and epoxy resin, several images were recorded on SEM. While scanning the fractured surface of the specimen, different kinds of fractures were observed at different positions. Hence, eight micrographs having different feature were recorded and analysed. These micrographs were observed from directions shown in Figure 4.11

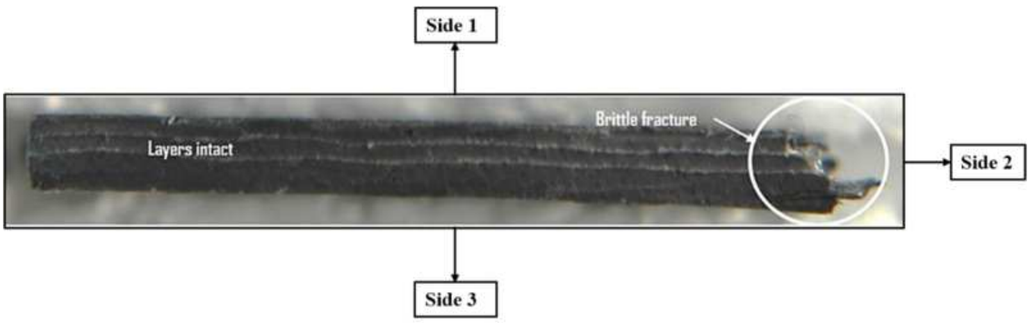
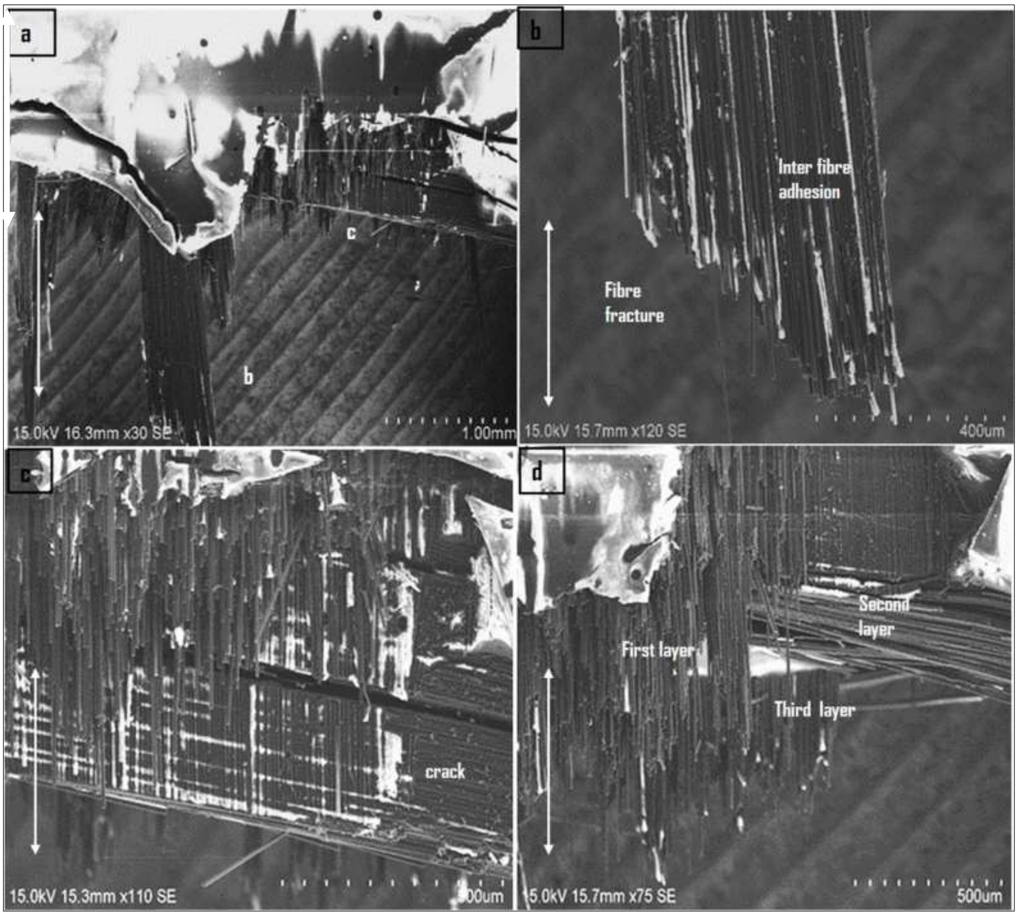


Figure 4.11: Fractured tensile sample CC1 from four different sides

While investigating the images as shown in Figure 4.12,4.13 and 4.20, a distinct observation was perceived that is there is little debonding. That indicate that the matrix has sufficient adhesion with the Carbon fibre.

In Figure 4.12 (a-d), the side 1 of the fractured CC1 sample SEM images are displayed. In Figure 4.12a, it is observed that several fibres are broken without any appreciable stretching and pull out. This deduces brittle failure of the Carbon fibre without debonding. In addition, it is observed that the tow of Carbon filament is intact without any splitting. Figure 4.12a indicates the failure of matrix catastrophically. There is no peeling or cracking of matrix layer. This supports that there is good adhesion between fibre to matrix and layer to layer.

To have better understanding of this feature, Figure 4.12a was magnified further in Figure 4.12b and 4.12c. These both figures also support the same observation. In Figure 4.12b, a single minor crack is seen in transverse (weft way) direction along the Carbon tow. This indicates the filament in the tow are intact without any fibrilisation or pull out. This observation is strengthened by analysing Figure 4.12c where in, brittle breakage of bundle of fibres is seen.



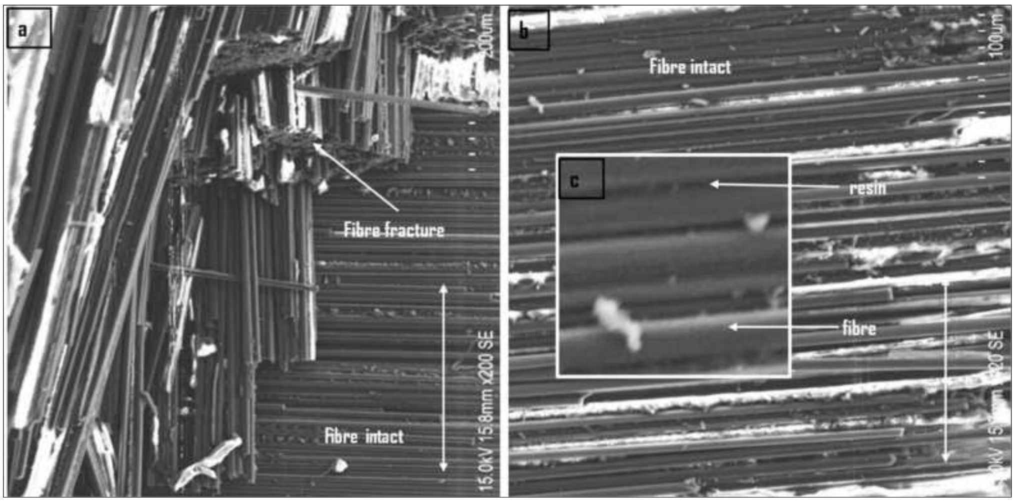
(Double headed arrow indicates tensile load application direction)

Figure 4.12: SEM images of the fracture surface of composites after tensile test: a) CC1 b)CC1 c)CC1 d) CC1 from side 1

Further to have proper analysis, SEM of side 2 (Figure 4.13) of the same sample was obtained, which is shown in Figure 4.13d. This Figure, is also divulging similar information. In this Figure, three layers are distinctively seen. All of these three layers do not show any debonding, pull-out and fibrilisation. This indicates, there is good adhesion between matrix and fibres is observed.

Further to have a detailed nature of fracture a side 1 (Figure 4.12) was focused and exposed in Figure 4.12a. In Figure 4.12b indicates same feature of the fracture. Here, a Carbon tow is observed which is intact, without any splitting. To ensure non splitting a further magnification is shown in Figure 4.12c, which does not show any splitting. A thin layer of matrix between two fibres is seen without any damage.

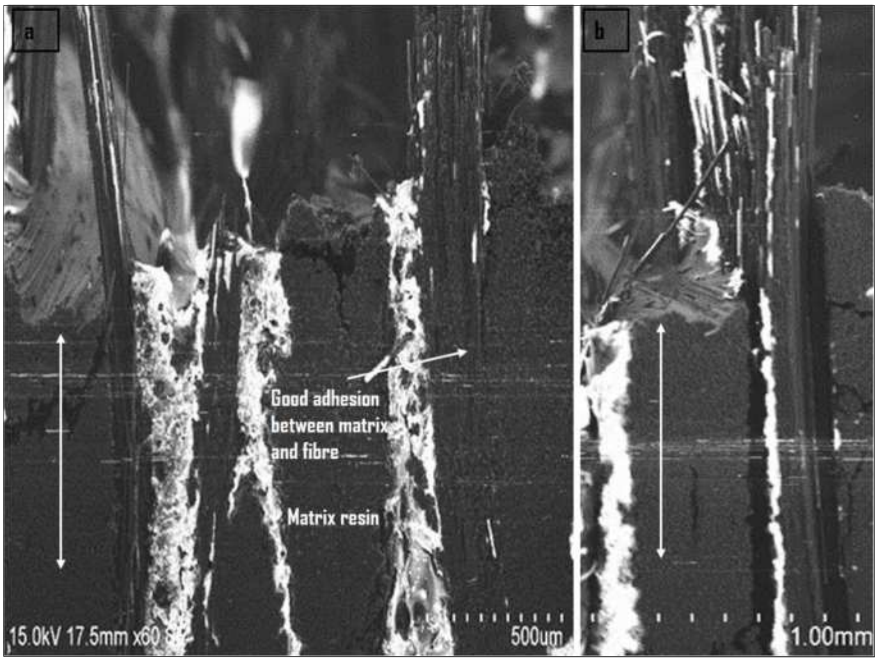
To have comprehensive knowledge of fracture of composite made of Carbon with epoxy, a SEM from side 2 (Figure 4.13) was obtained as shown in Figure 4.13a and 4.13b. It shows a uniform mass of resin between tows, which is intact. It is not showing any distinct seam between the layers. This supports good adhesion between the layers.



(Double headed arrow indicates tensile load application direction)

Figure 4.13: SEM images of the fracture surface of composites after tensile test: a) CC1 b)CC1 from side 2 c) expanded view of b from side 2

There is a good bonding between Carbon fibre and matrix, between layer to layer and inter fibre also (Figure 4.14 a, b). The failure is brittle in nature which supports the observation, analysed in previous section by stress v/s strain Figure 3.23 (a, b).



(Double headed arrow indicates tensile load application direction)

Figure 4.14: SEM images of the fracture surface of composites after tensile test: a) CC1 b)CC1 from side 3

4.3.2 Flexural Strength

In this work, three-point bending test is employed. To determine the flexural

Table: 4.5 Flexural strength and modulus values of polymer textile composite laminates

Sample code	Longitudinal				Transverse			
	Load	CHT	Flexural strength	Flexural Modulus	load	CHT	Flexural strength	Flexural modulus
	F		σf				σf	
	kN	mm	Mpa	GPa	kN	mm	Mpa	GPa
CC1	0.136	4	260.39	0.26	0.22	2.75	280.45	17.78
CC2	0.113	3.75	235.42	0.24	0.123	2.75	187.18	12.78
CC3	0.166	4.529	274.42	0.27	0.23	2.75	359.67	24.88
CC4	0.12	4.5	312.49	0.31	0.228	2.25	567.77	56.83
CC5	0.155	4.176	386.95	0.39	0.105	4.9	235.39	11
CH1	0.028	12.9	52.03	0.05	0.164	3.75	394.08	25.76
CH2	0.0355	13	80.2	0.08	0.253	3	451.48	31.04
CH3	0.026	9.4	51.26	0.05	0.206	3.75	457.86	28.11
KH1	0.043	12.5	71.7	0.07	0.137	6.75	239.8	7.15
CK	0.015	11.75	24.07	0.02	0.105	8.6	157.75	3.54

strength, UTM machine apply increasing amounts of force at the center of two supports. The software attached to UTM precisely records the deformation caused by the applied force, till it breaks. The reading so obtained is analyzed.

4.3.2.1 Effect of skew angle of fabric orientation on flexural properties of TPCL

The flexural test results of the composite samples are presented in Table 4.5. Figure 4.15 and 4.16 shows the flexural load–displacement graphs (F v/s d) for textile polymer laminate composites (TPLC) with four differently oriented layers.

Figure 4.15 is the F v/s d of the PTLC having four layers stacked in view of different skew angle. The F v/s d correlation for both directions, longitudinal and transverse are plotted on same graph to have comparative view. Flexural load on the samples rise almost linearly up to the maximum load in the F v/s d curves. Subsequently, the load value on the samples sharply decreased due to major multiple fibre breakages. Then, minor slip and stick failures were observed. The load–displacement curves for TPCL having same topologic arrangement, curves for transverse directions are steeper than longitudinal direction. That implies that, flexural load required to have same displacement is higher for transverse direction compare to longitudinal direction.

The load–displacement curves for CC1 (0,0,0,0) in both direction (longitudinal and transverse) are steepest. Further effect of skew angle on the slope of F → d curve i.e. stiffness is dominant

The load–displacement curves become steeper in the order from CC5 (0/+90/-90/0); CC2(0/+30/-30/0); CC3 (0/+45/-45/0); CC4 (0/+60/-60/0); CC1(0/0/0/0) in transverse direction. In longitudinal direction there is interchange of order of steepness between CC2 and CC4. This is obviously due rotation of orientation to 90-degree from transverse to longitudinal. This rotation makes CC2(0/+30/-30/0) to pseudo (0/+60/-60/0) that is equivalent to CC4.

The variation in the trend of F v/s d curve constructed for different stacking sequence in view of skew angle confirms, that the skew angle prominently affects the flexural property of TPCL.

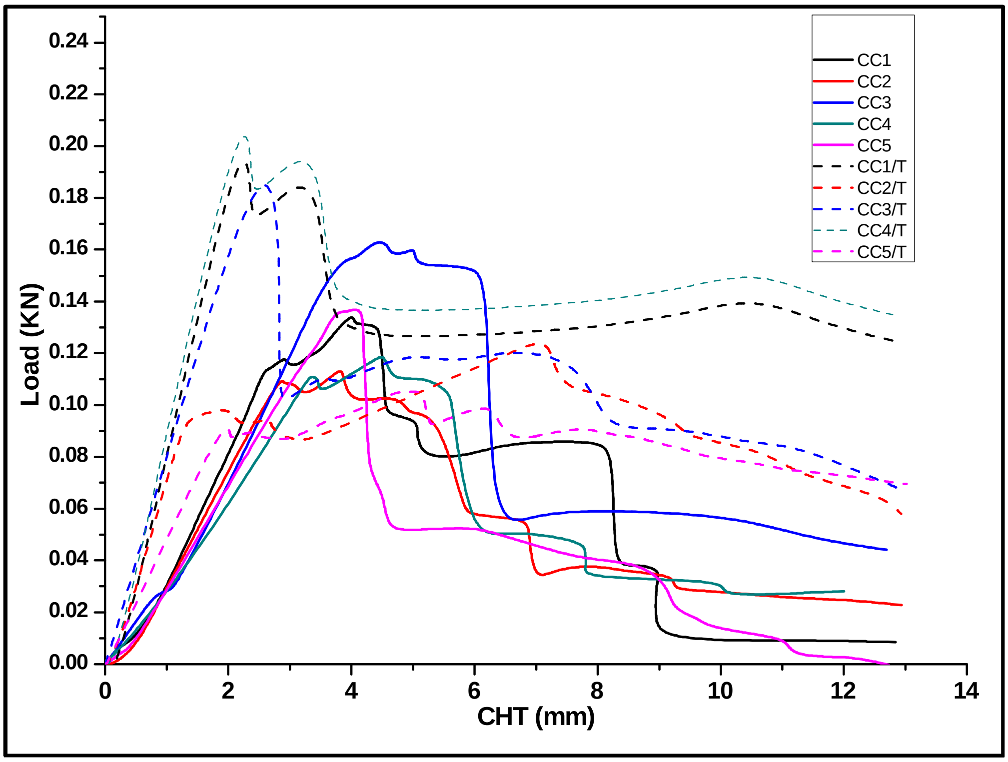
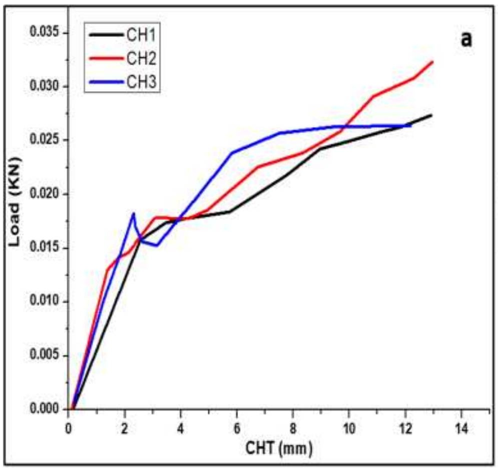


Figure 4.15. Effect of skew angle of fabric orientation on flexural properties of TPCL

4.3.2.2 Effect of weave structure on flexural properties of TPCL

The correlation F v/s d of the TPCL having four layers stacked in view of weave viz. plain, twill and sateen for both directions, longitudinal and transverse respectively are shown in Figure 4.16a and Figure 4.16b.



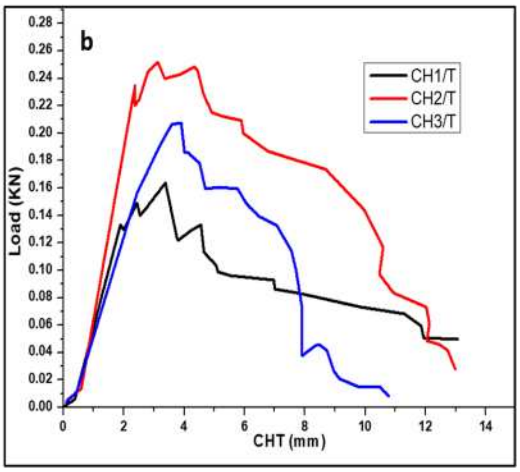


Figure 4.16: Effect of weave structure on flexural properties of composite (a) longitudinal direction (b) transverse direction

The flexural strength of the polymer composites made with twill weave fabric is highest in both direction among TPCL made from plain twill and sateen weaved fabric. This is partly due to huge difference in the strengths of the reinforced yarns of the two fabrics are as shown in Table 3.3, and partly due to the better orientation of the fibre tows of the twill weave fabric. The increase in flexural strength of the CH2 which uses twill weaved fabric is due to better penetration of the matrix into the gap between two consecutive layers resulting in more compactness of the matrix. This compactness lead to better distribution of load among the reinforced fibres. Thereby affecting an improvement in the flexural strength of the composites. The same should also have been true for the composites made with the plain weave fabric. But this is not so. The plain weave is denser show failure with bundle pull-out whereas those made with sateen weave fabric show shear type failure with fibre pull-out. This is evident from the SEM micrographs of the fractured faces of the composites as shown in Figure 4.19 and 4.21.

It is observed that the load–displacement curves become steeper in the order from sateen to plain to twill in both directions. But in this comparison, a distinct trend is observed among longitudinally and transversely direction. In case of transverse direction, flexural load on the specimen increases almost linearly up to the maximum load in the load–displacement curves. Then the load value on the samples sharply decreases due to major multiple fibre breakages. Then, minor slip and stick failures are observed. On the other hand, while analyzing F v/s d for longitudinal direction then it is observed that after the end of linear part of the trend, unlike to transverse direction, the sharp drop in load is not as apparent in these curves, but the curve continues to rise at lower slope and surpasses the previous maximum load. This distinct behavior among longitudinal and transverse direction is due is to the type of fibre in line of axis of loading. In case of Figure 4.16b i.e. load v/s displacement for transverse direction, the Carbon fibre are in line of loading of the axis, that’s why it shows brittle failure. While, in case of Figure 4.16a, HDPE fibre are in line of axis of load, this is the reason it shows ductile behavior.

This discussion lead to a conclusion that the flexural strength (stiffness) is affected by different weave structure along the longitudinal and transverse direction.

4.3.2.3 Effect of type of reinforced yarn on flexural properties of TPCL

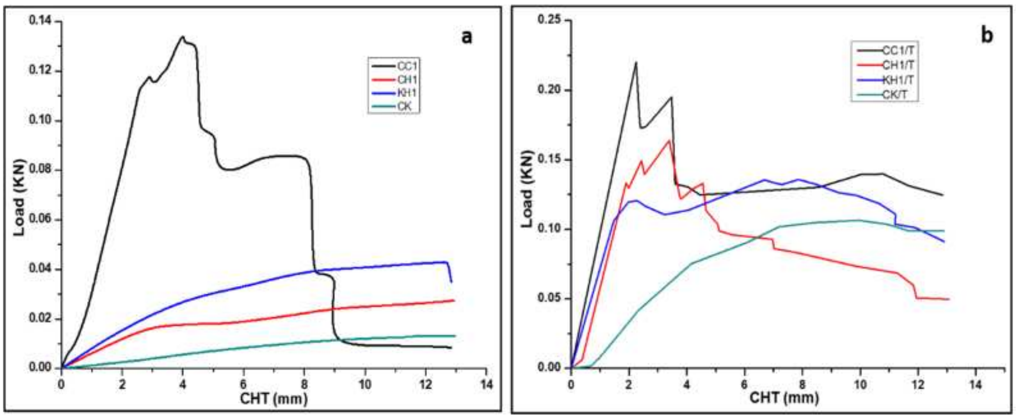


Figure 4.17: Effect of type of reinforced yarn on flexural properties of TPCL longitudinal direction (b) transverse direction

The correlation F v/s d of the TPCL having four layers stacked in view of type of reinforced yarn for both directions, longitudinal and transverse respectively are shown in Figure 4.17a and Figure 4.17b.

Figure 4.17a shows distinct behaviour of CC1 compared to other composite CH1, KH1 and CK. CC1 behaviour is a brittle material while CH1, KH1 and CK are showing ductile behaviour. In case of loading in longitudinal direction HDPE filament is along the direction of loading while as CC1 contains in Carbon tow both directions. Hence, Carbon fibre is in the axis of loading. Due to Carbon as main resisting fibre in CC1, its behaviour is like brittle material. Contrary to this other composites CH1, KH1 and CK have HDPE (Figure 3.22d) as a main resisting fibre. Hence, the outcome of load v/s displacement is resembling to ductile material.

Figure 4.17b representing load v/s displacement in transverse direction. In this figure, CC1, CH1 and KH1 shows similar behaviour like brittle material. While, composite CK shows ductile behaviour. Referring table 3.3, CC1, CH1, CK have Carbon in transverse direction in all the four layers. Whereas, KH1 have Carbon in only two layers and Kevlar in other two layers in transverse direction.

Carbon fibre always give brittle behaviour (Figure 3.22b), this is the reason responsible for brittle behaviour of CC1, CH1 and KH1.

Comparing flexural modulus of differently oriented TPCL Figure 4.18 and Table 4.4 shows the flexural modulus values of all polymer textile composite laminate for differently stacked four layers as described in Table 3.3 in both longitudinal and transverse direction. The study of effect of orientation of fibre differently on flexural modulus are discussed below.

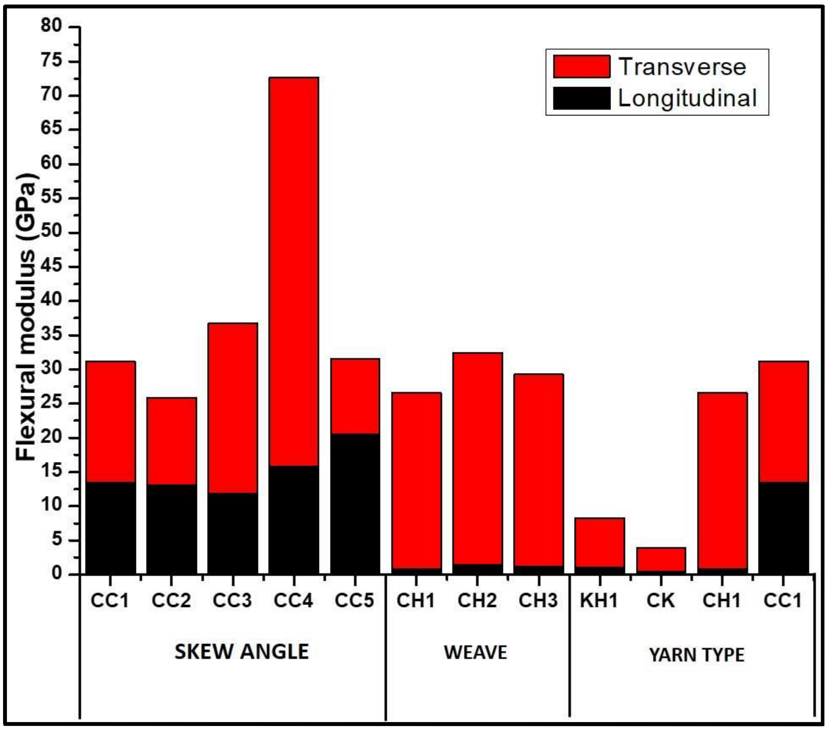


Figure 4.18 Comparison of flexural modulus of differently oriented TPCL

As exhibited in Figure 4.18 and Table 3.3, while studying the effect of skew angle (specimen CC1, CC2, CC3, CC4, CC5) on flexural modulus, it was observed that CC4 with orientation (0/+60/-60/0) demonstrate highest flexural modulus, 56.8 GPa, in transverse direction. Whereas, the flexural modulus of CC5 with orientation (0/+90/-90/0) reveal highest flexural modulus, 0.39 GPa, in longitudinal direction.

Further, Figure 4.18 also reveal comparison of weave structure on flexural modulus. The figure indicates that there is hardly an effect of weave on flexural modulus in longitudinal direction. The values 0.05, 0.08 and 0.05 GPa of CH1, CH2 and CH3 respectively. It shows that values are almost same. But there is moderate effect of weave on flexural modulus in transverse direction, minimum 25.76 GPa to maximum 31.04 GPa.

Figure 4.18 also shows the flexural modulus of the composite samples, CC1, CH1, CK1, KH1, having sequence of four layer stacked of different type of fibre as detailed in Table 3.3. From the graph, it can be derived that samples CC1 and CH1 shows higher flexural modulus than other samples in the range of 17.78 and 25.76 GPa respectively in transverse direction. While sample KH1 and CK shows poor flexural modulus i.e. 7.15 and 3.54 GPa respectively in transverse direction. In longitudinal direction only CC5 have an appreciable modulus i.e. 0.39 GPa. Other samples show modulus less than 0.4 GPa in longitudinal direction. This phenomenon can be explained by the interface bonding. In case of CC5, which is having sequence of layer carbon fibre (0/90/90/0) interface bonding between carbon fibres with the matrices compared to other fibre is stronger. A strong interface bonding permits higher load stress transfer through the composite fibres. Whereas, a weak interface bonding will deprive adhesion between the fibres and matrices. As soon as, the force acting on the composite supersede a bonding force, it causes the fibres to snap and pull out. The composite samples, KH1 and CK contains Kevlar fabric, shows poor modulus flexural as compared to samples having carbon in the upper layer (CC1 and CH2). The Kevlar fibre reinforced composites show

poor interfacial adhesion between fibre and the matrix resin due to low surface energy and chemically inert surface of the fibre. The similar explanation is being given by Herbert (2010).

4.3.2.4 SEM Analysis

Scanning Electron Microscopy (SEM) studies were carried out for the fractured surfaces of some selected specimens. Figure 4.19, illustrates the fracture surfaces of Carbon–Carbon samples having layers differently oriented in view of skew angle. It can be seen from these figures that samples exhibit failure due to fibre pullout. The common failure in these composites were observed that of the fibres situated in the major direction, parallel to the axis of stress. In minor direction, a distinguished crack is observed which run throughout the width,

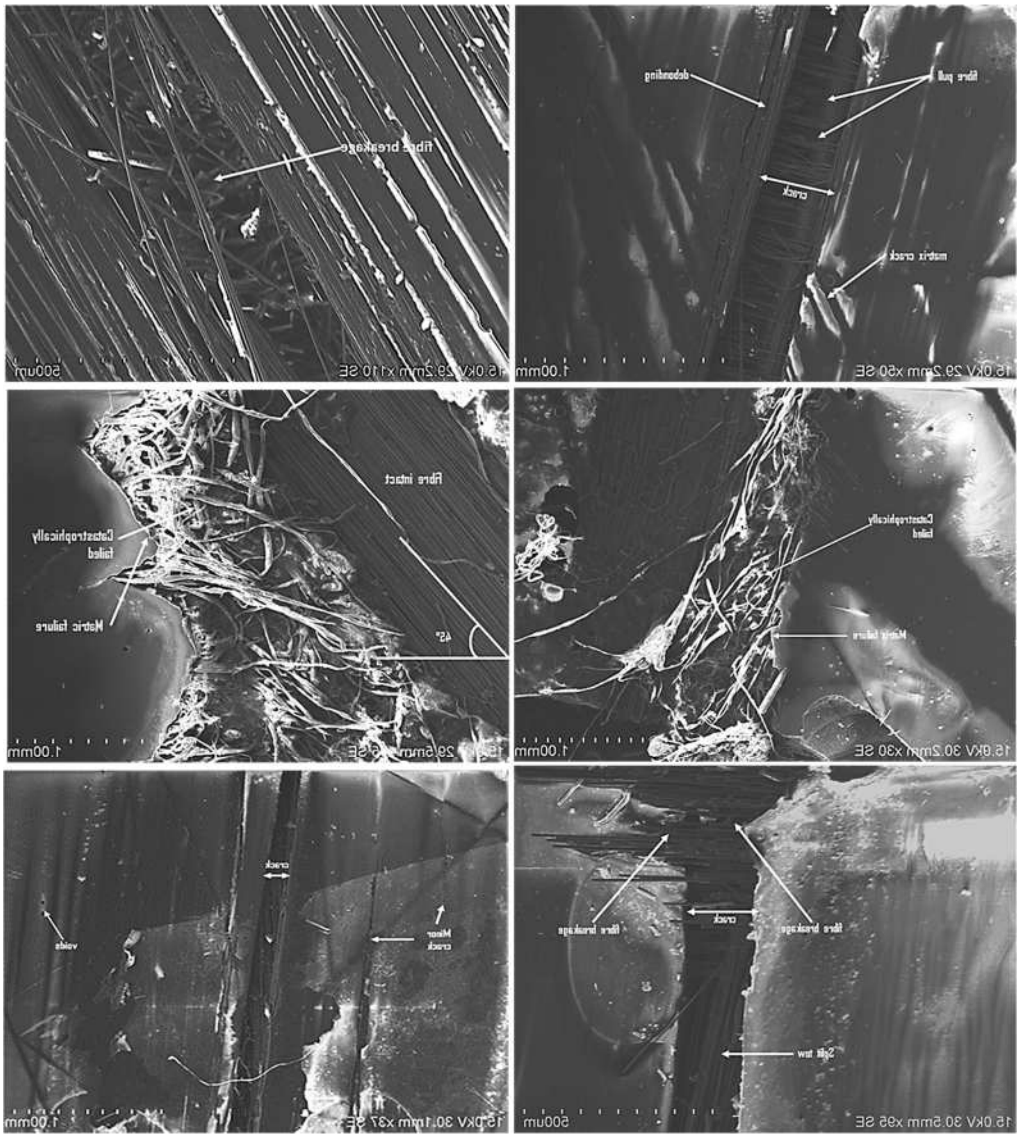


Figure 4.19: SEM images of the fracture surface of composites after flexural test: (a) CC1 (b) CC2 (c) CC2/T (d)CC3/T (e) CC4/T (f) CC4/T

sometime it appeared in zigzag manner or along with supporting minor crack (Figure 4.19e, f). The failures of a composite in tension side is either due to brittle failure of matrix or fibre pullout (Figure 4.19 a-d). It is also evident that the samples show splits of carbon tow laying in the direction parallel to minor axis (Figure 4.19 e, f). In these specimen fibres are almost completely covered with a thick layer of resin (Figure 4.19 d, e, f). It was not possible to identify whether the fracture had peeled off the outer skin of the composite.

Figure 4.19 (c, d), are micrographs of CC2 and CC3 in transverse direction. In these composite specimens' significant parts of the fibre surface was observed intact. This shows that, the interface remains the weakest part of the composite, resulting in adhesive failure for all specimens. These also shows that carbon tow in the direction of major axis are catastrophically failed. While, comparing sample CC2 in longitudinal direction, it indicates that the composites are brittle in the both directions of 12K and 6K Carbon. In the micrographs of CC1, CC2, CC3 and CC4, failure is due to pull out of the fibres.

While studying compressive side, the failed specimens were observed under optical micrographs to provide an insight of damage mechanisms and to explain any anomalies into the mechanical performance. Kinking is the most predominant form of compressive failure. However, Dong et al.,[97] had shown no failure in kink modes in plain carbon composites. Similar observation was obtained here in this work.

The optical images indicate composites failure on compression side is due to either micro-buckling, shear or splitting of fibre as shown in Figure 4.20. On compressive side, shear cracks, compression crack as well as evidence of micro-buckling are the predominant features found in shear failure. There is also delamination observed across the cross section. In case of CK and KH (Figure 4.20f, h) Kevlar fibres are used. They have very high shear stress. Due to high shear stress, there is no clear-cut conclusion

about its mode of failure. The optical image indicates that there is no fibre failure, only matrix failure is observed.

Crack propagation along the warp and weft yarns was considered for plain, twill and 4H-sateen Carbon/HDPE/epoxy composites.

Figure 4.21(a-d) shows SEM micrograph of the fracture surfaces for the plain weave specimens in the longitudinal and transverse direction. The fracture occurred primarily at the fibre-matrix interface as reflected by the bare fibres and cavities left by fibres on the fracture surfaces (Figure 4.21c, d) which indicates poor fibre/matrix adhesion. HDPE is subjected to fibrilization while carbon fibre is fractured and fragmented. This fracture behaviour is apparent due to the inherent nature of carbon (being brittle) and HDPE (being ductile).

Figure 4.21(c, d) the fracture occurs at the joint of carbon and HDPE fibre. The layer over carbon tow is catastrophically fractured and tow is exposed. The

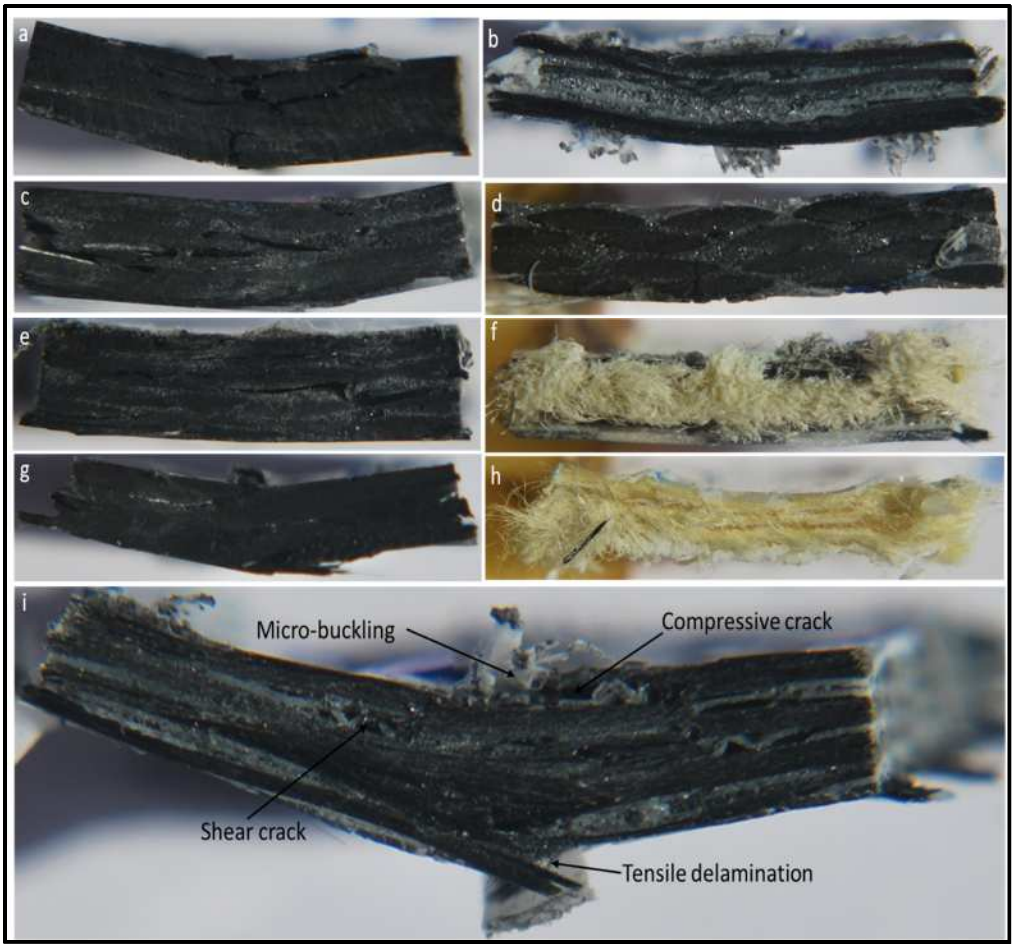


Figure 4.20: Optical images of the fracture surface of composites after flexural test: (a) CC1(b) CH1/T (c) CC2/T (d)CH1(e) CC3/T (f)CK (g)CC4 (h)KH1(i)CH2

bundle of carbon fibre has experience brittle fracture. Some fibres are broken in small pieces and scattered randomly.

Comparing the fracture of CH1 due to loading in longitudinal and transverse direction, the former show ductile failure while later shows brittle behaviour. The reason can be stated as presence of HDPE in major axis i.e. parallel to the direction of loading in case of longitudinal direction while in transverse direction the carbon tow is in major axis i.e. parallel to direction of loading.

Figure 4.22(a, b) shows SEM micrographs of fracture surfaces for the twill weave composite specimen CH2 in transverse direction. Loose (debonded)and fractured fibres are observed on the fracture surface of the specimen (Figure 4.22 a, b). Also, delamination of composites may involve fracture of debonded

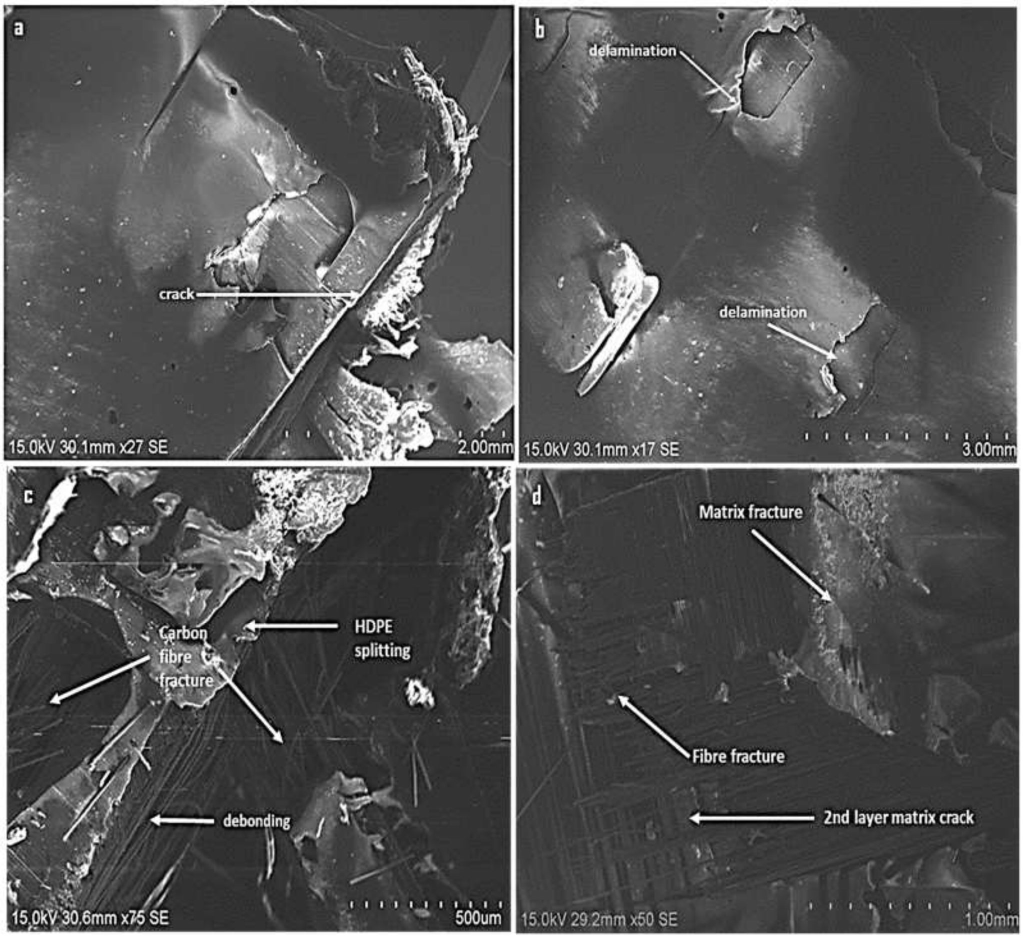


Figure 4.21: SEM images of the fracture surface of composites after flexural test: (a) CH1 (b) (b) CH1 (c) CH1/T (d) CH1/T

fibres. Debonded longitudinally oriented fractured fibres were observed in a large quantity on the fracture surfaces. At higher magnification (Figure 4.22a) there is evidence for substantial matrix deformation associated with the fracture process. The highly deformed roughness on the fracture surface, called 'shear hackles', are signs of intense shear deformation which may occur locally in such structures. It is observed that crack occur at 30° to the along the loading axis.

SEM micrographs of fracture surfaces for the sateen weave composite (Figure 4.22 c, d) reveal a fracture process, and display loose and broken fibres in the specimen. The crack is straight along transversely laid carbon fibre. The magnified micrograph shows fragmented carbon fibres. Here, composite failure is due to cracking of matrix. The matrix remains stuck over carbon fibre. The fracture occurred at the fibre/matrix interface without much matrix deformation.

(Double headed arrow shows direction of loading)

Figure 4.22: SEM images of the fracture surface of composites: (a) CH2/T (b) CH2/T (c) CH3(d) CH3

4.3.3 Impact strength

Toughness is one of the critical mechanical property of engineering material as it influences the service life of the part. In this work, Impact strength reflects toughness of the textile polymer composite laminates (TPCL). This test is used for quality check and comparison of materials for general toughness.

In this work, Impact test was performed to assess the toughness on TPCL. XJUD-5.5 IZOD Impact Tester is used to estimate the impact strength of the samples. The required notch for the Izod impact test was cut by using JJANM-21 notching machine. The depth was kept constant as 2 mm.

4.3.3.1 Effect of skew angle of fabric orientation on impact properties of TPCL

Specimens CC1, CC2, CC3, CC4 and CC5, with differently oriented fabric, as detailed in Table 3.3. are impact tested and compared.

The impact test results of the composite samples are presented in Table 4.6. Figure 4.23 shows the comparison of impact strength (kJ/m^2) of TPCL with four differently oriented layers in view of different skew angle.

In Figure 4.23, the bar graph depicts the effect of orientation with respect to skew angle on impact property. As revealed from this figure, the impact strength is higher in transverse direction compared to the longitudinal direction in all specimens. Further, the specimen CC3 shows highest impact strength among all differently oriented skew angle carbon composite. The impact strength of CC3 for transverse and longitudinal directions are 99.9 kJ/m^2 and 76.41 kJ/m^2 respectively. It can also be concluded that CC2 and CC4 are having poorest impact strength in both the directions. While CC1 and CC5 are having impact strength less than CC3 but more than CC2 and CC4.

The sample CC3 is having orientation (0/+45/-45/0) while CC2 and CC4 is having orientation (0/+30/-30/0) and (0/+60/-60/0) respectively whereas CC1 and CC5 are having (0/0/0/0) and (0/+90/-90/0) respectively. When comparing fibre orientation influence, the orientation of fabric has considerable effect on impact strength. The order of impact strength is $E_{iCC3}>E_{iCC5}>E_{iCC1}>E_{iCC4}>E_{iCC2}$ as revealed from the Figure 4.23.

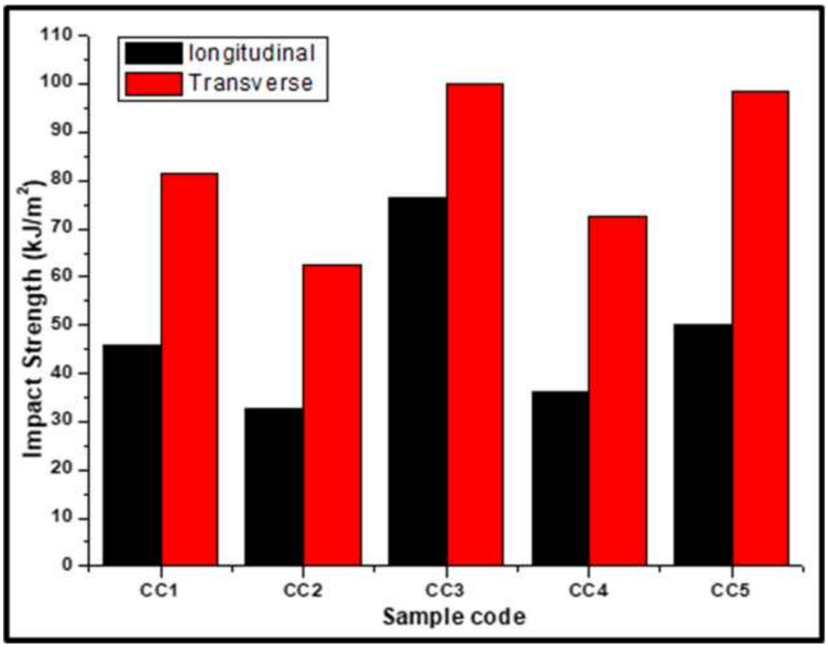


Figure 4.23: Effect of skew angle on Impact properties of carbon composite

Table 4.6: Impact strength and energy absorbed values of TPCL

		Longitudinal		Transverse	
Sr. No	Sample code	Energy absorbed	Impact strength	Energy absorbed	Impact strength
		Joules	kJ/m²	Joules	kJ/m²
1	CC1	0.636	45.854	0.953	81.336
2	CC2	0.505	32.771	0.972	62.548
3	CC3	1.077	76.413	1.506	99.906
4	CC4	0.456	36.233	1.309	72.448
5	CC5	0.644	50.056	1.481	98.287
6	CH1	1.347	100.208	0.726	58.784
7	CH2	1.151	73.688	0.773	46.541
8	CH3	0.836	51.407	0.649	48.520
9	CK	1.054	79.449	0.958	71.016
10	KH1	0.828	52.543	0.743	49.353

As expected, CC3 made from fabric having orientation of (0/+45/-45/0) possess highest impact strength. This is obvious, as CC3 is having fibres distributed equally in all directions. That is 0°, 90°, 135°, 180°, 225°, 270°, 315°, 360°. That means the CC3 is pseudo isotropic and behaved like a metal. Contrarily, to this specimens CC2 and CC4, having orientation (0/+30/-30/0) and (0/+60/-60/0)

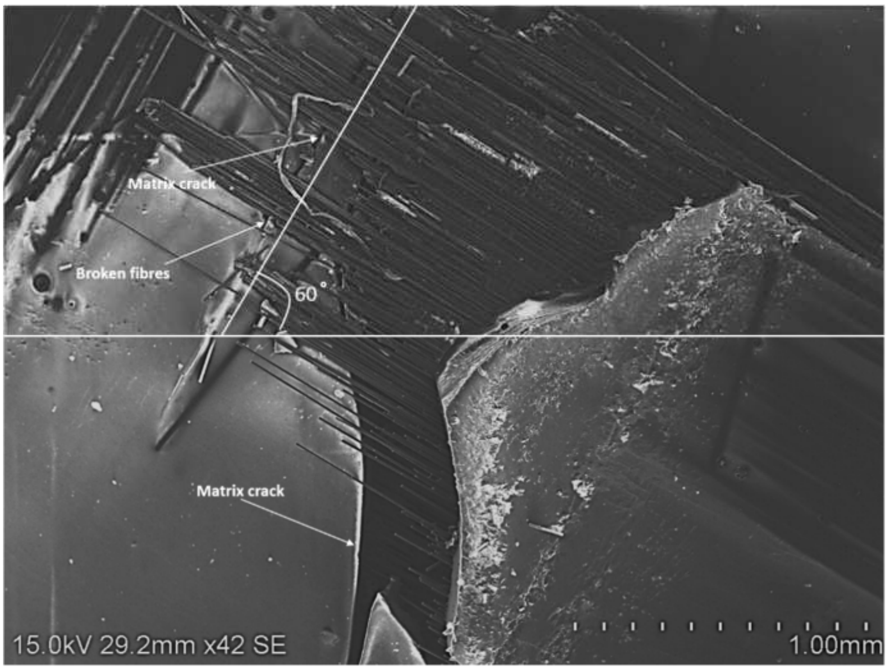


Figure 4.24: SEM image of fracture of sample CC2

respectively, this orientation leads to concentration of fibre in acentric direction. Due to concentration of fibre in acentric direction the impact finds a way to create fracture between 30° to 90°**.** This is also supported by analyzing the SEM image of sample CC2 (Figure 4.24). The SEM image indicate that crack is developed at an angle of 60°.

4.3.3.2 Effect of weave structure of fabric on impact properties of TPCL

In this section, effect of weave structure on impact strength of TPCL is discussed. The samples CH1, CH2 and CH3 were tested for impact strength and reported in Table 4.6 and Figure 4.25. The details of stacking sequence of this composites are given in Table 3.3 As depicted in Table 3.3, here samples are prepared with fabrics having same weave structure in four layers consisting same orientation.

It demonstrates that weave structure largely effects the impact strength. The impact strength for all weaves is higher for longitudinal direction compared to transverse direction. The results show that plain composite (CH1) is having highest impact strength as 100.21 kJ/m^2 as compared to twill composite (CH2) and sateen composite (CH3), having impact strength as 73.69 KJ/m^2 and 51.41 KJ/m^2 respectively in longitudinal directions. Similarly, in transverse direction also plain composite (CH1) is having highest impact strength of 58.78 kJ/m^2 whereas twill (CH2) and sateen composite (CH3), having impact strength as 46.54 kJ/m^2 and 48.52 kJ/m^2 respectively in longitudinal directions.

The reason for higher impact strength in longitudinal direction is the existence of HDPE yarn in longitudinal direction in TPCL. HDPE is ductile in nature hence; the impact strength of HDPE is high compared to Carbon fibres.

While comparing impact strength for different weaves, the highest strength shown by plain weaved composite. Plain weave is having square symmetric structure. Moreover, plain weave has maximum interlacement points. This supports the higher impact strength in plain weaved composite.

Contrarily, to plain weave, in sateen weave no of floats is higher and interlacement points are less. Due to this binding of yarn to each other is less as compared to plain. Due to this, during impact the fibre give an easy way for propagation of fracture.

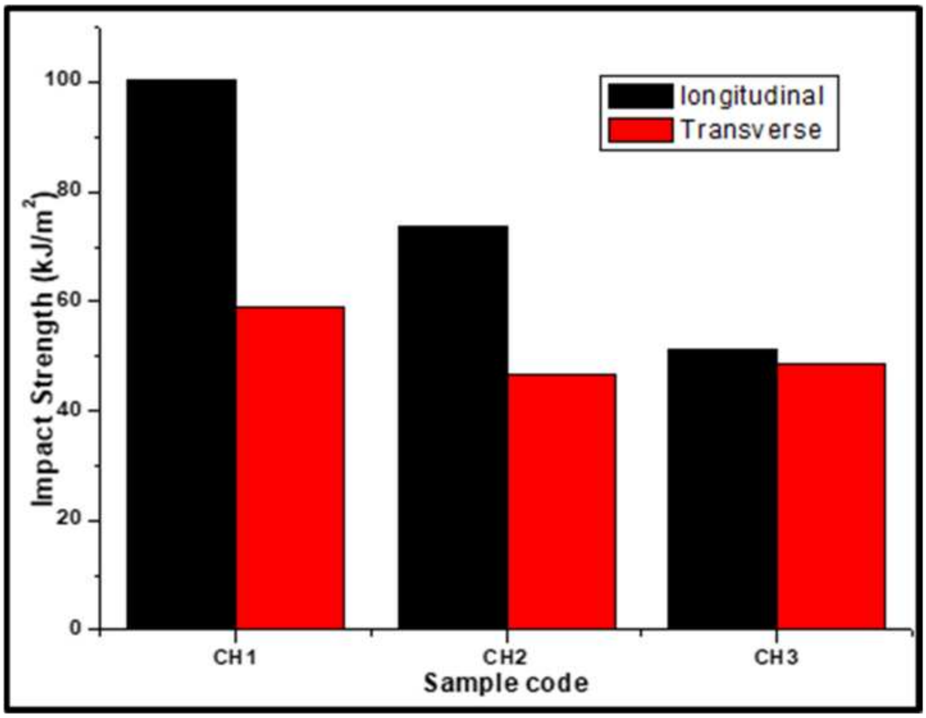


Figure 4.25: Effect of weave structure on Impact properties of TPCL

4.3.3.3 Effect of type of reinforced yarn on impact properties of TPCL

In this work, effect of type of reinforced yarn on impact strength of TPCL have also been carried out. The samples CC1, CH1, CK1 and KH1 are tested for impact strength and reported in Table 4.6 and Figure 4.26. This figure shows the impact strength comparison of the TPCL, having sequence of four layer stacked of different fibre as detailed in Table 3.3.

Referring Figure 4.26, the impact strength of all specimen except CC1 have higher strength in longitudinal direction compared to transverse direction. The strength of CH1 is about 100 kJ/m^2 in longitudinal direction is maximum among this comparison. In longitudinal direction, the strength varies $E_{iCH1}>E_{iCK}>E_{iKH1}>E_{iCC1}$. While in transverse direction, the impact strength of composites, CK and CC1 are almost same i.e. 72 kJ/m^2, other two samples CH1 and KH1 has lower impact strength 58.78 and 49.35 kJ/m^2 respectively.

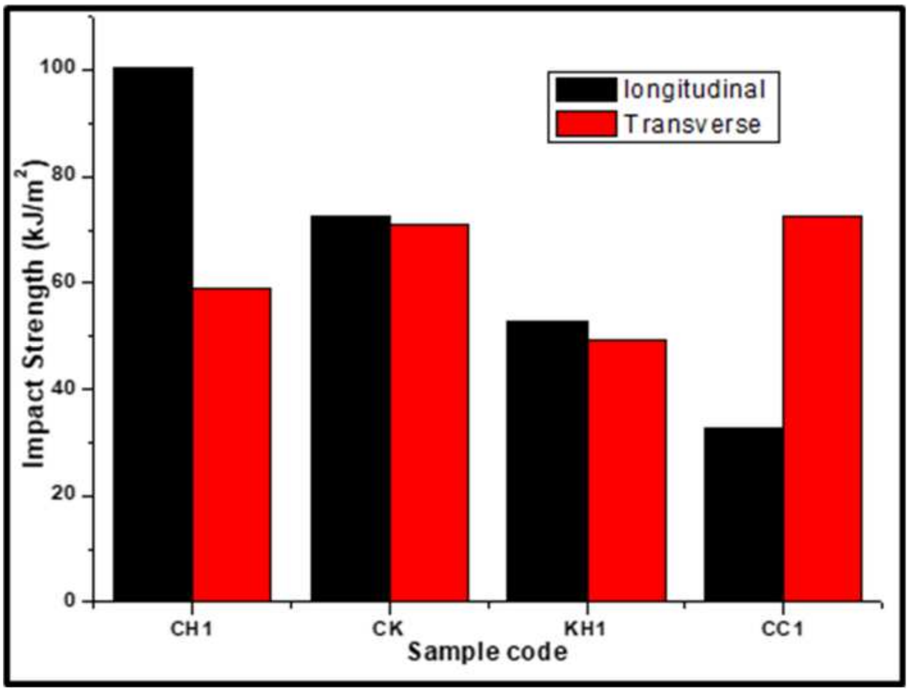


Figure 4.26: Effect of type of reinforced yarn on Impact properties of TPCL

The composites in which, HDPE is along the direction of loading have higher impact strength because of high ductility of HDPE. This fact is confirmed by having high impact strength of CH1 in longitudinal direction. CH1 has HDPE filament along the direction of loading. CK and CC1 have almost same strength in transverse direction because in both cases 12K carbon fibre is in direction of loading.

4.3.3.4 SEM Analysis

After Izod Impact test, some of the broken specimen were selected and analyzed on the SEM. Post failure examination of fractured specimen is done. The damage mechanism like matrix cracking, matrix delamination, matrix splitting and debonding are present. Figure 4.27 (a-f) are representing these damages. Out of three samples tested one of them was KH1 in transverse direction and other two CK and CC1 were in longitudinal direction.

Specimen CC1, having Carbon fibre in both directions, the broken sample shows clear main crack throughout the width direction. There are some scattered minor cracks which are also in width direction. The matrix shattered in small pieces. Another distinguish observation is that beyond crack there is no sign of any damage. The surface is observed to be intact. This implies that matrix and Carbon fibre have sufficiently strong bonding.

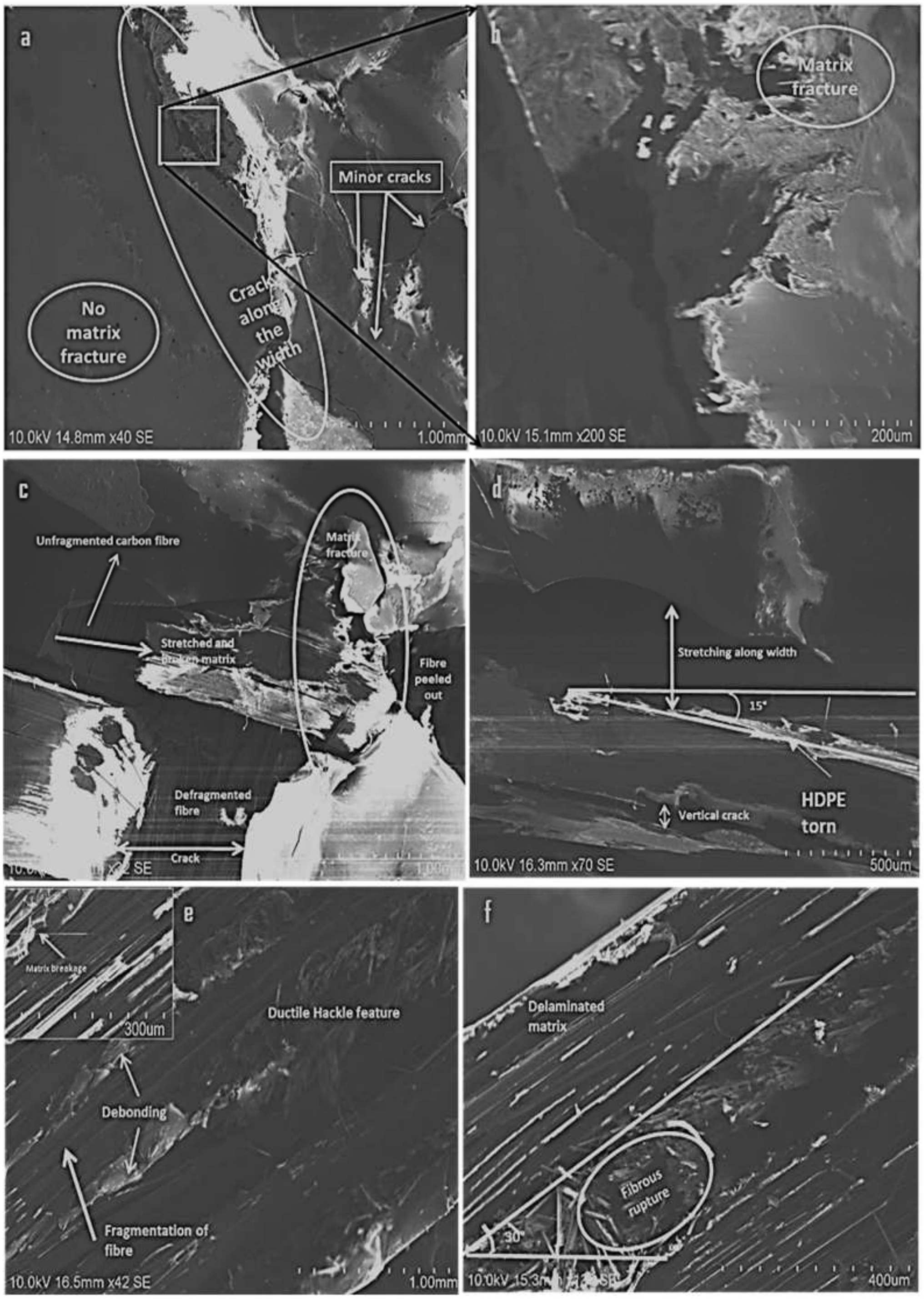


Figure 4.27: SEM images of the fracture surface of composites: a) CC1 b) CC1 c) CK d)CK e) KH1 f) KH1

While examining CK laminate, it is observed that fibres are bending to 15º. The carbon fibres are totally exposed. It indicates that matrix layer over Carbon fibre is catastrophically broken. It is totally peeled off over Carbon fibre and shattered. In this composite the HDPE fibres are torn off, due to stretching resulted by impact. Here, a crack in the transverse direction is also observed. This implies that there is some stretching in width direction. In the micrograph defragmentation of fibres in cracks is observed. This is due to less adhesion of matrix to fibres, Kevlar.

In KH1, the sample was totally failed but not splitted in two pieces due to high ductility of the fibres. The micrograph of this sample shows prominent fragmentation of fibre and de-bonding. In this case, a distinguished observation was witnessed. Fibres are broken in pieces and fracture is inclined at angle of 30º to the horizontal axis. The kink bends starts at the notch and propagates across the specimen width.

4.3.4 Damage resistance (Quasi static indentation test)

In this work, UTM was utilized to perform quasi-static indentation test to study the damage resistance of the TPCL. The results of the test were analyzed in term of force-displacement curves.

4.3.4.1 Effect of skew angle of fabric orientation on damage resistance properties of TPCL

In this section, specimens CC1, CC2, CC3, CC4 and CC5 are tested for quasi indentation test and results were compared. A comprehensive description of differently oriented composites as given in Table 3.3.

After completing the tests, a series of load (F) v/s displacement (m) data were collected and reported in Figure 4.28 and Table 4.7. Figure 4.28 represents the force-displacement correlation of the quasi-static indentation tests for the composites differently oriented in view of skew angle. The interpretation of force-displacement curves of differently oriented Carbon composite laminates (Figure 4.28) follow a similar trend. The force v/s displacement curves of specimens demonstrate that displacement increases with force, reaches to the maximum and then drops.

The correlation plotted in the Figure 4.28 shows that load v/s displacement is initially straight line which indicates their elastic behavior. The initial stiffness (slope of the load v/s displacement curve) is comparatively analogous for all the samples. That indicates, there is minimal effect of orientation on stiffness at lower loading. As observed from Figure 4.28 increase in deformation linearly with force indicates that the laminate responds cohesively without any delamination of matrix.

Table 4.7: Damage resistance properties of composite

Sr. No	Sample code	Force (F)	Displacement (m)	Thickness (b)	Strength (σ′)
		N	mm	mm	(N/mm)
1	CC1	1402.24	2.68	1.92	730.33
2	CC2	1547.72	2.13	2.07	747.69
3	CC3	1471.21	3.02	1.85	795.25
4	CC4	1348.88	2.69	1.82	741.14
5	CC5	1332.00	3.62	1.84	723.91
6	CH1	1198.78	2.20	1.86	644.51
7	CH2	1244.30	4.2	2.26	550.58
8	CH3	1216.24	3.66	2.35	517.55
9	CK	885.94	5.04	1.95	454.33
10	KH1	1024.85	4.18	2.2	465.84

All four layers together resist the deformation at knee point. The knee point was observed to occur when displacement was at approximately 1mm. The matrix layer farthest from the indenter cracks initially. Due to this the resistance of the laminate is reduced and graph starts leaning towards X-axis. Similar behavior was observed by Ahmed et al., 2015[183]. Consequently, one by one layers gets damaged till the peak point. At this peak point, all matrix layers are broken the resistance is only due to fibres. And rest of the trend is the ductile behavior which continue till indenter make space either by breaking fibres, pulling fibres or displacement of the fibres. The fluctuations in the curves are indicating matrix and fibre failure. This is also clear by observing the optical images of the samples taken at front, rear and side view as shown in the Figure 4.30.

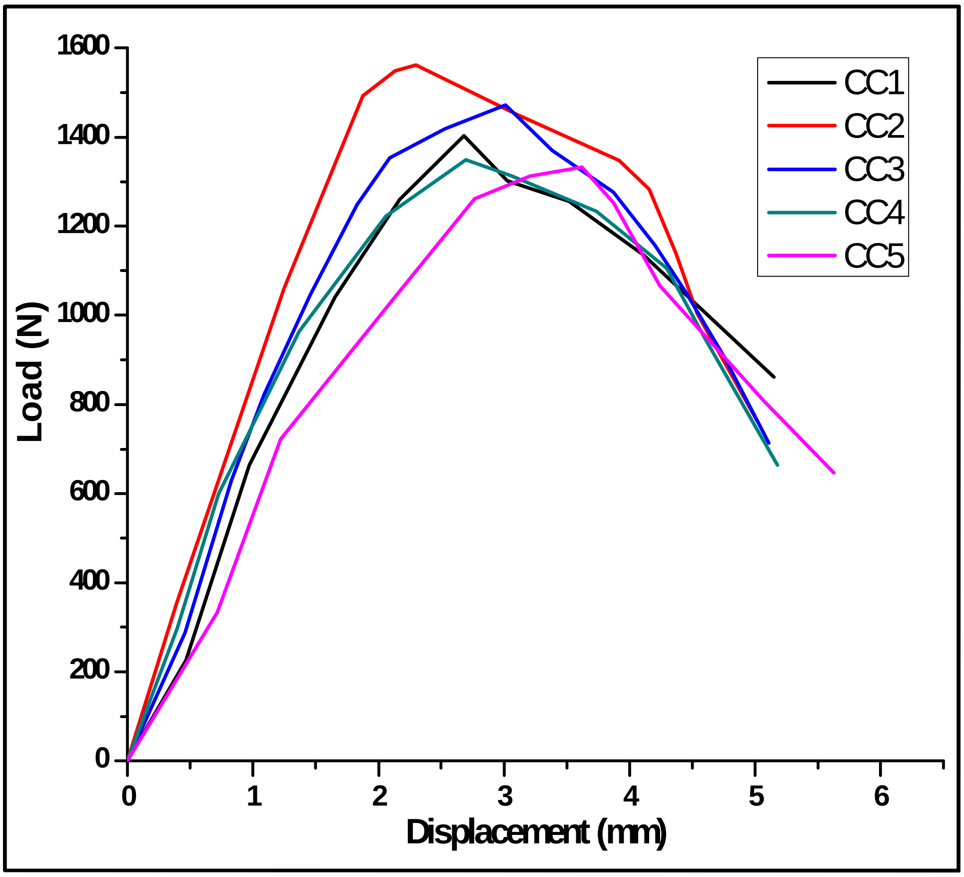


Figure 4.28: Force-displacement curves of Carbon-Carbon composites for damage resistance properties

For comparing damage resistance strength, the values are calculated by using Equation 4.14 and tabulated in Table 4.7. For comparing bar chart are plotted in Figure 4.29. The analysis of this figure indicates that laminate CC3 has highest strength (795.25 N/mm). The order for damage resistance strength is CC3>CC2>CC4>CC1>CC5 as depicted from Figure 4.29

Another important observation is that the specimen CC2 (0/+30/-30/0) and CC4 (0/+60/-60/0) are comparable i.e. 747.69 and 741.14 N/mm respectively. Similarly, specimens CC1 (0/0/0/0/0) and CC5 (0/+90/-90/0) have comparable values i.e. 730.33 and 723.91N/mm respectively. This similarity is because, similar orientation of fibre in radial direction. In CC2 the fibres oriented as ± 30 degree at one axis are having angle ±60 degree with another axis. It is true vice versa for fibre orientation at ± 60 degree in case of CC4. Same is the case for the laminates CC1 and CC5 in which orientations are 0 and 90 degrees. In case of CC3, the reason for having highest damage resistance strength is its equal distribution of fibres in radial direction. In this laminate the fibres are laid in 0,45,90,135, 180,225,270,315 i.e. the fibres are uniformly laid in radial directions, contrary to other specimens.

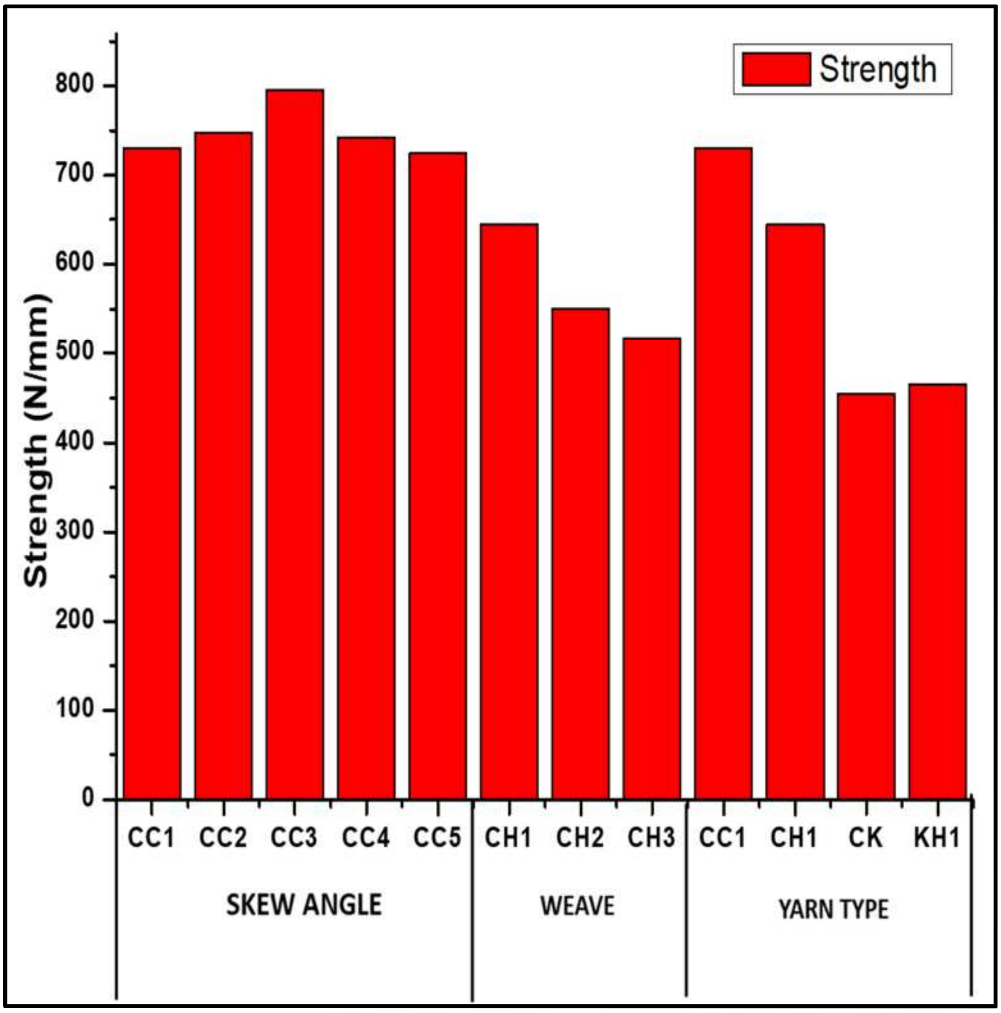


Figure 4.29: Comparison of damage resistance strength of TPCL

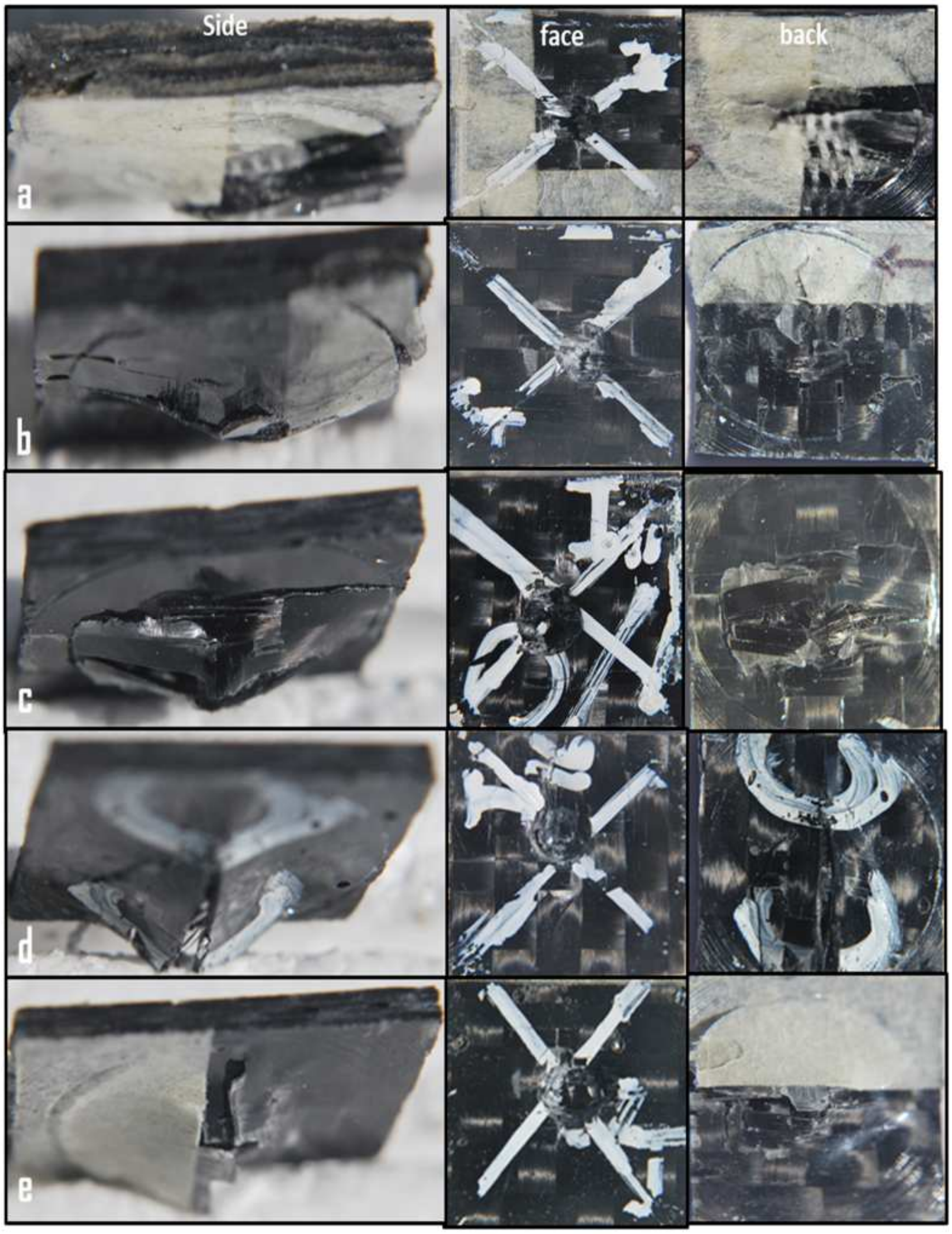


Figure 4.30: Optical image of specimen after damage resistance test for TPCL having differently oriented composites (skew angle)

4.3.4.2 Effect of weave structure on damage resistance properties of TPCL

In current work, the specimen CH1, CH2 and CH3 are tested for damage resistance strength by quasi indentation test to study the effect of weave structure on laminates. The results are tabulated in Table 4.7 and plotted in Figure 4.31.

Force v/s displacement (F v/s d) curves of the quasi indentation test are shown in Figure 4.31 for the laminates made from differently weaved fabrics. As the force increases the displacements also increase till it reaches to the peak point. After the peak point the force is found to decrease with increase in the displacement. The nature of the graph is similar for all weaves. Here, it can be observed that the knee point is analogous (around 0.5 mm) for all specimens. This indicates that the initial stiffness has no appreciable effect of weave. The graph is having slope highest for CH1 follows CH2 (twill) and last CH3 (4 end sateen). By comparing the peak force these curves indicate that CH1 is the stiffest and CH3 is least stiff.

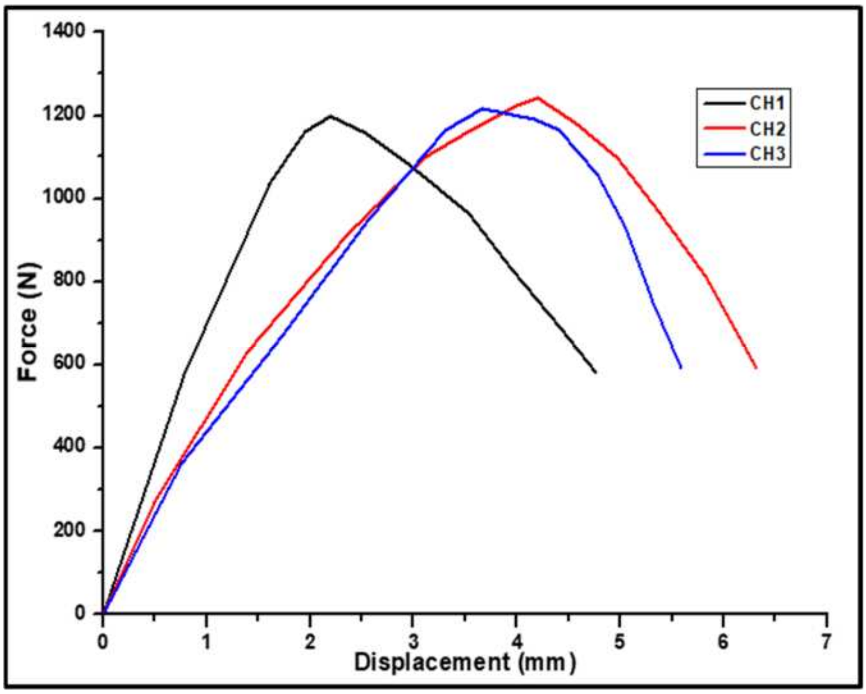


Figure 4.31: Force-displacement curves of Carbon-HDPE composites

To study the mechanism of breakage optical images of all three samples were studied in front, rear and side view. It is observed that there is a fracture of matrix in all the samples. HDPE yarn have not shown any breakage but their failure is either by pull-out or shifting from the place. But Carbon fibres have shown brittle breakage which clearly seen from the (Figure 4.32 a-c). The highest strength of plain weave is also supported by optical images. The optical images of specimen CC1 shows that it is not damaged catastrophically as it is observed in case of CC2 and CC3. From Figure 4.32, it can be deducted that specimen CH1 images that the damage was limited to the impact point and the energy did not propagate to a wider surface. Specimen CH1 was not perforated completely, although it had been damaged.

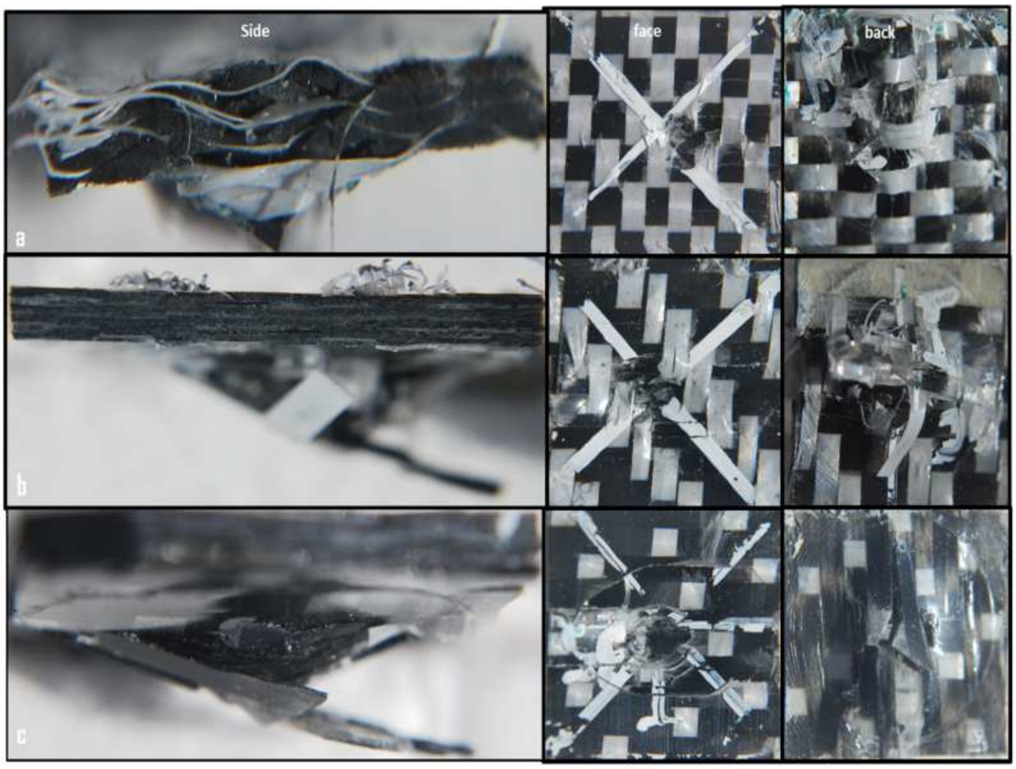


Figure 4.32: Optical image of specimen after damage resistance test of TPCL with different weave structure: a) CH1 b) CH2 c) CH3

Wang et al. (2016) stated that the propagation of damage depends on the extent of hindrance within the fabric cells developed by warp and weft yarns. Similar thing is observed while comparing the damage behavior during quasi static indentation test of laminates made from differently weaved fabrics. In CH1 there are more interlacing points as compared to CH2 and CH3, thus provide more hindrance. Moreover, plain weaves have least floats (most binding of yarn) compared to twill and sateen weaves. Further, the slippage of yarn in the CH1 is less than CH2 and CH3, so the damage resistance strength of CH1 is better than CH2 and CH3. Same is revealed from Figure 4.32.

It establishes that weave structure has significant effect on damage resistance force.

4.3.4.3 Effect of type of reinforced yarn on damage resistance properties of TPCL

In this work, samples CC1, CH1, CK1 and KH1 are tested for damage resistance property to compare the effect of type of reinforced yarn used in composites. The results are tabulated in Table 4.7 and plotted in Figure 4.33. To study the effect of reinforced yarn type F v/s d plots of quasi indentation test are in Figure 4.33. Figure 4.29 shows the damage resistance strength of the composites.

Analysing the F v/s d curves of laminates made from fabrics having different type of fibres. i.e. Carbon, HDPE and Kevlar in different combinations. Unlike, Figure 4.28 and Figure 4.31 all curves show different behaviour and are scattered. CC1 and CH1 show higher stiffness with almost similar numerical values of stiffness. Composite CK is most leaned towards X-axis that means it has least stiffness. As excepted all specimen have high variation in knee point on the curve. To study the variation in stiffness, comparing displacement at arbitrary force 600N,

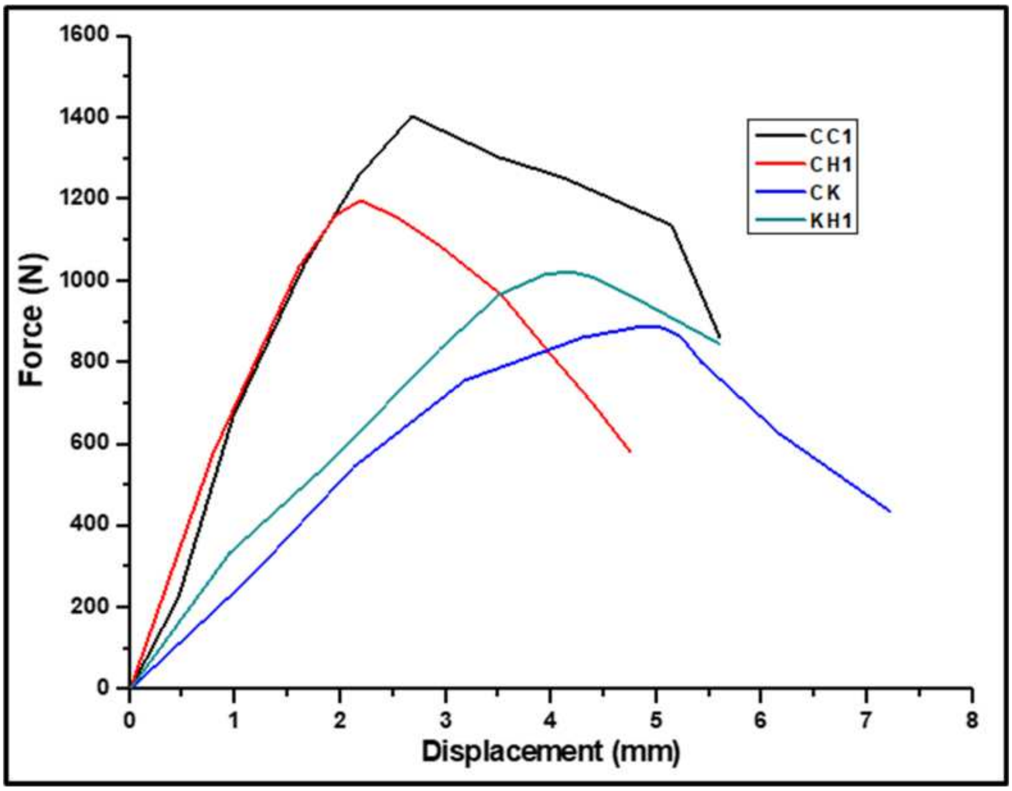


Figure 4.33: Force-displacement curves of composites with different type of reinforced yarn

displacement along CC1, CH1, KH1 and CK are 0.9, 0.8, 2 and 2.5 mm respectively. The displacement of CK is 3 times the displacement CH1. This indicates that there is a significant effect of type of fibre on the stiffness of laminate.

Referring Figure 4.29 the damage resistance strength of CC1(Carbon-Carbon) is highest 730.33N/mm as compared to other samples CH1(Carbon-HDPE), KH1(Kevlar-HDPE) and CK (Carbon-Kevlar-HDPE). The damage resistance strength varies in the order of CC1>CH1>KH1>CK.

Referring to Table 3.3, specimen CK is hybridized by three types of fibre reinforcement namely Carbon, Kevlar and HDPE.

Though specimen CK shows lower strength, individually Carbon and Kevlar are high strength materials. While going in detail of its sequence by referring Table 3.3 Outer two layers (upper and lower) are of Carbon-HDPE while sandwiched middle two layer are of Kevlar-HDPE. This reveal that every second fibre is HDPE that means thread density is 50 % of HDPE, 25 % of Carbon and 25% of Kevlar. As HDPE is having least strength, it reflects in the strength of laminate CK. Moreover, epoxy matrix used in this work has poor adhesion with Kevlar and HDPE. These facts lead to drastic reduction in the damage resistance strength of laminate, CK. Similar type of composite were studied by Salman et al (2017) and reported observation. They identified the reason for lowest strength of CK composite samples is due to low interfacial adhesion of fibres with the matrix. The similar observation was reported by Naik et al., [105]. They used Carbon along with Kevlar and observed reduction in strength.

The Optical images of these sample are shown in (Figure 4.34). By comparing side view of the laminates, it is observed that CK (Figure 4.34d) the layers totally separated at layers 3rd and 4th. This indicates that the matrix has very little adhesion with Kevlar. This is the reason for showing poor strength in CK. The failure of KH1 (Figure 4.34c) is deferred from others, it is observed that there is only matrix failure but fibres remain intact.

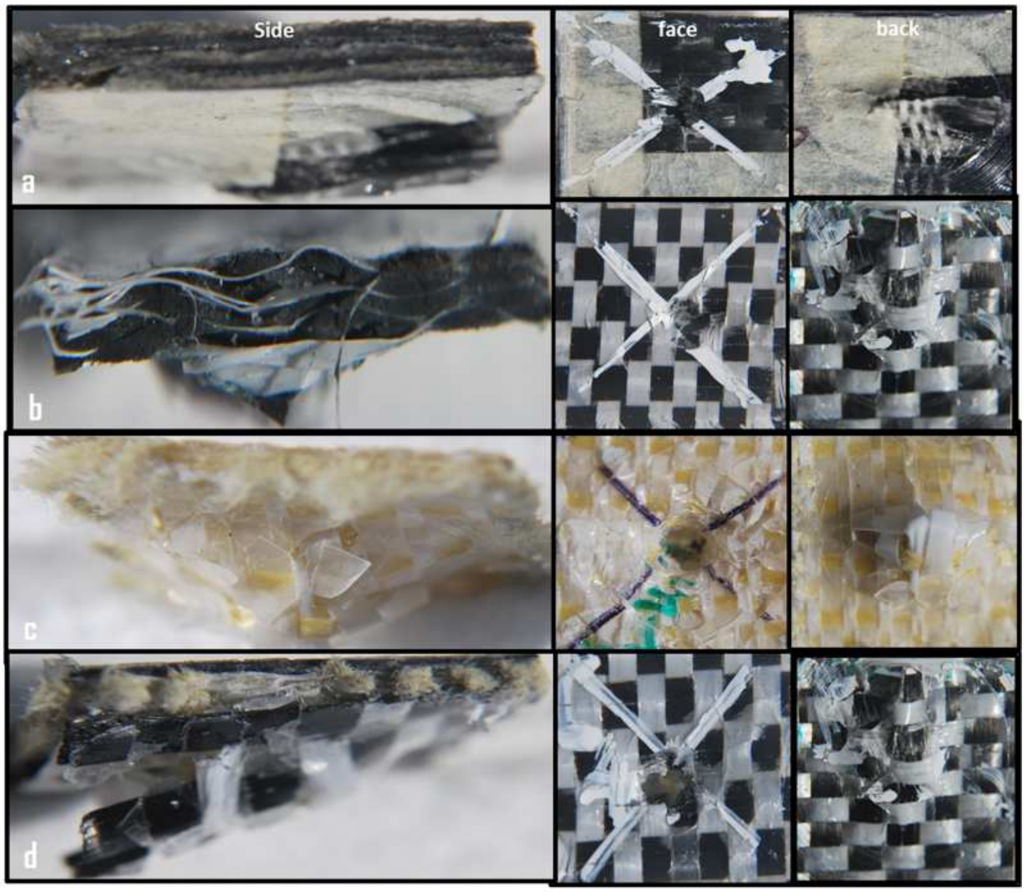


Figure 4.34: Optical image of specimen after damage resistance test of TPCL having different type of reinforced yarn: a) CC1 b) CH1 c) KH1 d) CK