

DELAMINATION BEHAVIOUR AND EXPERIMENTAL VALIDATION OF GLASS FABRIC/EPOXY MATRIX AND CARBON FABRIC/EPOXY COMPOSITES IN MODE-1 LOADING

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ABSTRACT

Delamination is a common kind of failure observed in various composites. Delamination due to the opening mode of a double cantilever beam (DCB) is quantified and analyzed in this investigation. A Finite Element Method (FEM) approach using ANSYS software is employed here to evaluate the delamination due to in plane loading in addition to opening mode. A new technique of using a Teflon tape has been used for exact results of delamination results. Various parameters that affect delamination are studied and evaluated in this investigation. Experimental validation has been done using ASTM5528 standard with the help of INSTRON machine.

KEYWORDS

Delamination, DCB, FEM, In-Plane loading, INSTRON, ASTM 5528

1. INTRODUCTION

The most common failure observed in composite materials is delamination. The cause of the failure is a great research topic of its own. This project studies mainly the extent of delamination in different kinds of loading conditions. We have mainly concentrated on two types of loading conditions where in the first case consists of in-plane loads and the other consists of mode 1 loading condition which is also called as the standard Double Cantilever Beam test (DCB)1.

Composite structures according to the fibre architecture can be regarded as: laminated composites which are obtained by stacking a number of unidirectional lamina, 2D fabric composites, and structural composites, such as 3D fabric composites in which the fibrous reinforcements are interlaced in multi-directions. Delamination in layered plates and beams has been analyzed by using both cohesive damage models and fracture mechanics. Cohesive damage model1 implements interfacial constitutive laws defined in terms of damage variables and damage evolution law.

1.1 Principle of Double Cantilever Beam (DCB) Condition and In-Plane Loading:

1.1.1 DCB ^[1] LOADING CONDITION:

In a DCB loading condition to get the required results of displacement and stress values a [0/90] laminate is used. Two areas are taken into account each measuring 100mm length and 3mm width. One side of the rectangular surface is fixed with all the degrees of freedom to be zero and on the other end forces are applied to rip apart the areas. This kind of loading condition is said to be DCB loading

1.1.2 IN-PLANE ^[1] LOADING:

A [0/90] laminate is considered for the analysis. A rectangular plate is modeled using ANSYS and loads are applied in the same plane of the square plate. This kind of loading is said to be in-plane loading.

2. Finite Element Method Description and Input Parameters:

2.1 Material Used For Both the Experiments Are ^[2]:

- Carbon/Epoxy
- Glass/Epoxy

In both cases stresses will be varied accordingly and the results will be studied. The two material properties that are taken into account are as follows.

MATERIAL PROPERTIES	GLASS/EPOXY	CARBON/EPOXY
Youngs Modulous	$E_{xx}=40\text{Gpa}$	$E_{xx}=126\text{Gpa}$
	$E_{yy}=5\text{Gpa}$	$E_{yy}=9.5\text{Gpa}$
	$E_{zz}=5\text{Gpa}$	$E_{zz}=9.5\text{Gpa}$
Poisson's Ratio	$\nu_{xy}=0.27$	$\nu_{xy}=0.263$
	$\nu_{yz}=0.27$	$\nu_{yz}=0.263$
	$\nu_{xz}=0.275$	$\nu_{xz}=0.27$
Rigidity Modulus	$G_{xy}=1.07\text{Gpa}$	$G_{xy}=1.07\text{Gpa}$
	$G_{yz}=0.8063\text{Gpa}$	$G_{yz}=0.8063\text{Gpa}$
	$G_{xz}=1.07\text{Gpa}$	$G_{xz}=1.07\text{Gpa}$

2.2 In-Plane Loading:

Input parameters:

- Area of the plate: 250 X 250 mm²
- Fibre orientation in the plate: [0/90]
- Number of layers in each plate: 3
- Load applied: 1N-5N with a variation of 0.5N
- Direction of load: In the same plane

Finite Element Parameters:

- Element type:
- shell 3-D 4 node 181

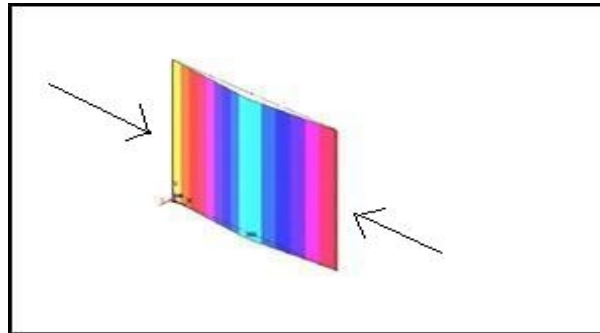


Fig. 1 In plane loading.

2.3 Mode -1 Loading:

Input parameters

- Number of areas: 2 in number overlapping each other
- Fibre orientation in the plate: [0/90]
- Number of layers in each plate: 3
- Load applied: 1N-5N with a variation of 0.5N
- Direction of load applied: Perpendicular to the area.

Finite element Parameters

- Element type²: Solid Quad 4 node 182.
- Cohesive zone material between the two areas: 2-D 4 node.
-

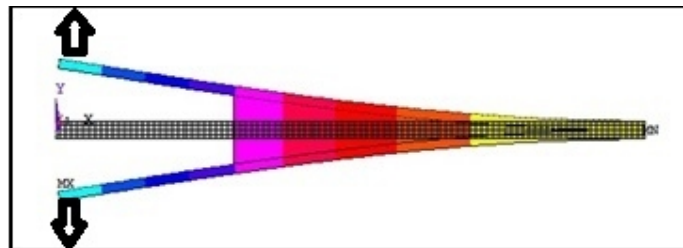


Fig.2 DCB loading

3. Procedure for Modeling and Analysis^[7]:

The process required to make a virtual model involves the following steps:

3.1. Modeling¹:

- a) In plane loading: A square plate of $250 \times 250 \text{mm}^2$ is modelled. Its sectional view will contain a fibre orientation of $[0/90]_T$.
- b) DCB: Two areas will be modelled with 100 mm length and 3mm width. One will be modelled above the x-axis and other one below the x-axis but both have to overlap each other. Its sectional view will contain a fibre orientation of $[0/90]_T$.

3.2. Analysis and Meshing:

It is the heart of the process where all the parameters are assigned to the model. Using these parameters results can be observed.

- a) In plane loading: Area mesh is taken with an optimum element size of 5. The material properties are taken as mentioned above for carbon/epoxy composite and glass/epoxy composite. Shell 3-D 4 node 181 is taken as the element type.
- b) DCB loading: Area mesh is taken with an optimum element size of 5. The material properties are taken as mentioned above for carbon/epoxy and /epoxy composite respectively. Additional cohesive zone region is added between both the overlapped areas up to $3/4^{\text{th}}$ the original area that is modelled.
- c) Solid Quad 4 node 182 is taken as the element type to satisfy the model behaviour in case of loading conditions.

3.3. Applying the Load Parameters:

In both the cases (in plane and DCB specimen) loading conditions are varied from 1Newton to 5Newton with a variation of 0.5 Newton.

3.4. Solving using ANSYS:

In this process check the various element type that have been assigned, various material properties that have been taken into account and various loading conditions applied for both the cases. These will generate a series of solutions; to get the optimum solution for all the values applied will give us the desired result. These optimum solutions are calculated using a series of equations that will meet at a point to give the best output.

The coding and programming in Ansys is taken from the references Finite element and analysis of composite materials¹

4. Results using ANSYS:

Loading conditions in both in-plane and delamination case has been increased with a difference of 0.5 Newton and the following results have been observed. The results are plotted in a graph and the difference between the stresses and displacement are observed in both the experiments.

Loading condition are referred to the sections 2.2 and 2.3 for inplane and Double cantilever beam loading conditions respectively. The initial loading condition would be 1N and corresponding stresses would be identified by processing in ANSYS. Sequential increase in loading conditions would be done accordingly and will be compares to the energy release rates in the experiment

4.1. Results of In-Plane Stresses:

GLASS/EPOXY COMPOSITE:

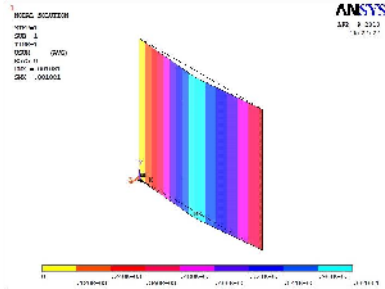


Figure 3: Displacement

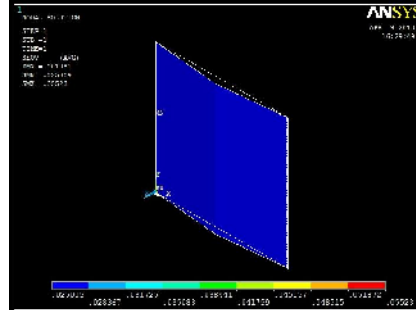


Figure 4: Von Mises Stress

Table I: In Plane Glass/Epoxy Load vs Displacement

LOAD(N)	DISPLACEMENT(mm)
1	0.001081
1.5	0.001621
2	0.002162
2.5	0.002702
3	0.003242
3.5	0.003783
4	0.004323
4.5	0.004863
5	0.005404

Table III In Plane Glass/Epoxy Load vs Stress

LOAD(N)	Stress (N/mm ²)
1	0.05523
1.5	0.082845
2	0.110461
2.5	0.138076
3	0.165691
3.5	0.193306
4	0.220921
4.5	0.248536
5	0.276152

CARBON/EPOXY COMPOSITE:

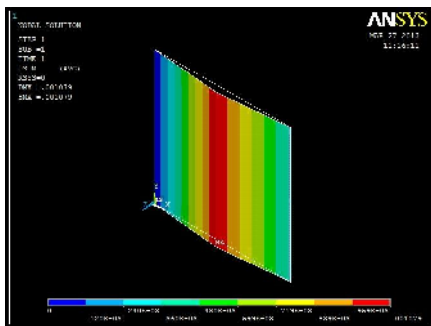


Figure 5: Displacement

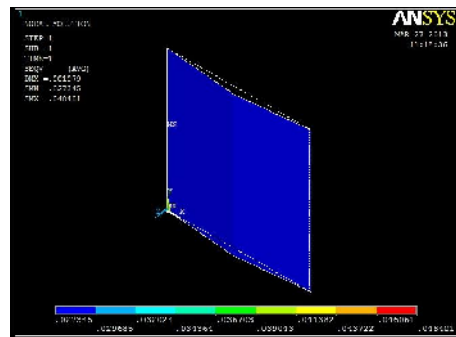


Figure 6: Von mises stress

Table IV: Inplane carbon/epoxy load vs displacement values vs stress values:

LOAD(N)	DISPLACEMENT(mm)
1	0.001079
1.5	0.001618
2	0.002158
2.5	0.002697
3	0.003237
3.5	0.003776
4	0.004316
4.5	0.004855
5	0.005359

Table V. Inplane carbon/epoxy load vs stress values:

LOAD(N)	STRESS(N/mm ²)
1	0.048401
1.5	0.072602
2	0.096802
2.5	0.121003
3	0.145203
3.5	0.169404
4	0.193604
4.5	0.217805
5	0.242005

4.2 Results for delamination (DCB- specimen):

GLASS/EPOXY COMPOSITE:
LOAD VALUE FOR 1.5N:

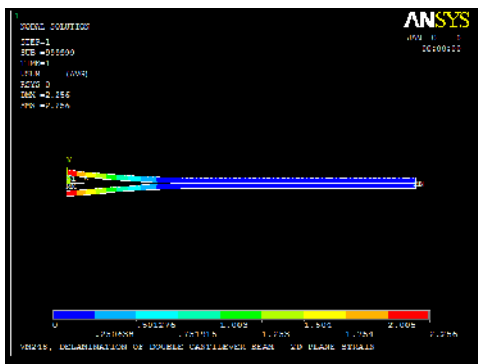


Figure 7: DISPLACEMENT

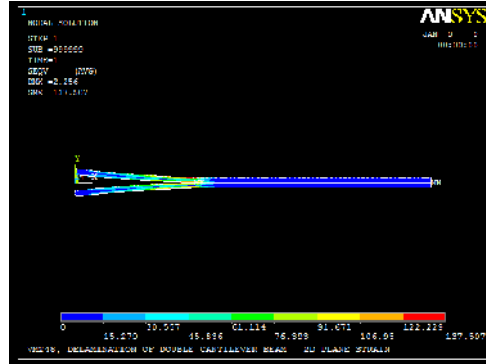


Figure 8 VON-MISES STRESS

Table VI. Load vs displacement values of delamination in in glass/epoxy glass/epoxy composite:

LOAD(N)	DISPLACEMENT(mm ²)
1	2.983
1.5	2.256
2	1.506
2.5	1.002
3	1.253
3.5	1.002
4	0.75221
4.5	0.752311
5	0.752413

Table VII Load vs stress values Composite

LOAD(N)	STRESS(N/mm ²)
1	245.562
1.5	137.507
2	664.988
2.5	108.243
3	170.69
3.5	88.885
4	83.912
4.5	83.786
5	77.846

CARBON/EPOXY COMPOSITE:

LOAD VALUE OF 1.5N

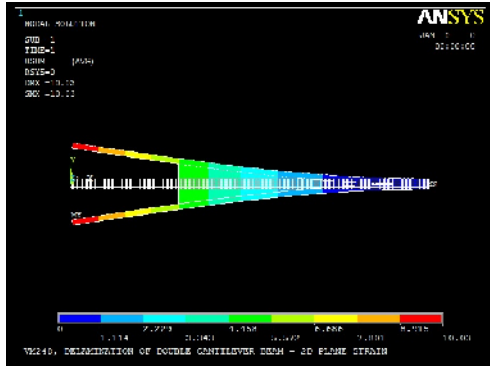


Figure 9: Displacement value

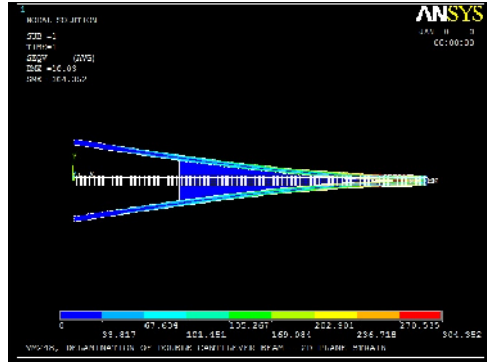


Figure 10: von-mises stress

Table VIII. Load vs displacement values of delamination in values of delamination in Carbon/epoxy composite Carbon/epoxy composite:

LOAD(N)	DISPLACEMENT(mm)
1	10.028
1.5	10.03
2	10.032
2.5	10.035
3	10.038
3.5	10.04
4	10.042
4.5	10.044
5	10.047

Table IX Load vs stress

LOAD(N)	STRESS(N/mm ²)
1	202.152
1.5	304.352
2	404.655
2.5	505.652
3	603.154
3.5	705.288
4	816.361
4.5	928.789
5	1043

5. Experimental Results using INSTRON MACHINE:

5.1. Introduction and preparation of the Composite specimens:

Manufacturing Process

HAND LAYUP TECHNIQUE WITH BUILT IN PRECRACK USING TEFLON TAPE:- Although the method has been replaced by many automated techniques, the layup of pre-impregnated material by hand is the oldest and the most common fabrication method for advanced composite [4]

- Step 1:
Surface of the tool and the material is cleaned and release agent is applied. If the surface is not cleaned then it won't give the required results. The release agent used is in liquid form.

- Step 2:
An optional layer is laid on the tool surface which is usually a fibreglass fabric made with the same resin system as the composite laminate. This sacrificial layer protects the composite from irregularities during the manufacturing process
- Step 3:
The preimpregnated plies are cut according to the design consideration of the specimen. The cutting is usually done using steel or blade knife. However, automated cutting machines can also be used.
- Step 4:
The first prepreg ply is placed upon the tool or mould. A roller or a tool similar to it is used to compact the plies and also helps to remove the entrapped air that could later lead to voids or layer separations. Tackiness is a characteristic of preimpregnated material, quantifies the relative stickiness of the plies at room temperature. As the preimpregnated material ages, its tackiness is reduced so this whole process has to be completed within a period of 30-35 min. This process of placing multiple plies one above the other has to be done at a very brisk pace. Oil and dirt on the surface of the composite might lead to reduced composite strength. Safety precautions like the gloves and face masks must be used during the layup.
- Step 5:
After exactly laying up 4 layers we have to introduce a Teflon tape of length equal to the initial crack length. The process of laying up of the prepregs remains the same with the next four layers that have to be placed above the Teflon tape.
- Step 6:
A flexible resin dam is anchored to the sacrificial layer near the edge of the laminate. This dam prevents from the resin leakage during the vacuum bagging process.
- Step 7:
Breather plies are placed over the entire layup. These will conduct the vacuum path into the laminate.
- Step 8:
Sealant tape is placed around the entire periphery of the layup.
- Step 10:
The vacuum bag is cut to the size and placed over the layup.
- Step 11:
The bag is sealed by pressing the bag over the sealant tape. It is critically important to ensure the bag is properly sealed before proceeding to the processing cycle. This whole process kept rest for a little more than 24 hours upon which the further experimental testing is used.



Figure 11: Glass/Epoxy Specimens



Figure 12: Carbon/Epoxy Specimens

5.2 Experimental Procedure:

ASTM5528 STANDARDS ^{[5],[9]}

Delamination growth may proceed in one of the two ways 1) By a slow stable extension ,2) A run arrest extension in which the delamination front jumps ahead abruptly. But only the first type of growth is of interest in this test method. In this DCB test, the delamination grows from the insert, resistance-type fracture behaviour typically develops where the calculated G_{ic} first increases monotonically, and then stabilizes with further delamination growth. In this test method, a resistance curve(R curve) depicting G_{ic} as a function of delamination length will be generated to characterize the initiation and propagation of a delamination in a unidirectional specimen. The principal reason for the observed resistance to delamination is the development of fibre bridging problem with the insert.

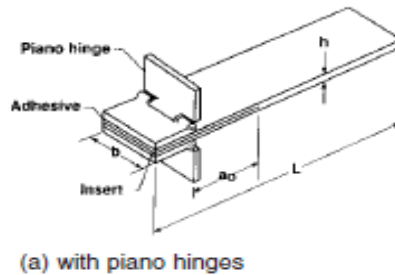


Figure 13: Specimen with piano hinges

The DCB specimen is cut from the composite layup that has been done previously using hand layup technique. The specimens are cut according to the dimensions 275mmx30mmx3mm and then the door hinges are attached to the ends as shown in the figure with the help of resin that has been used previously during the layup technique. They are left to rest for about 24 hours. Each specimen is loaded onto the INSTRON MACHINE individually which are held on to the machine with the door hinges that have been fixed earlier. The system connected to the INSTRON is fed with the values of the load that will be applied and the dimensions of the specimen.



Figure 14: INSTRON Machine setup manufactured specimens.

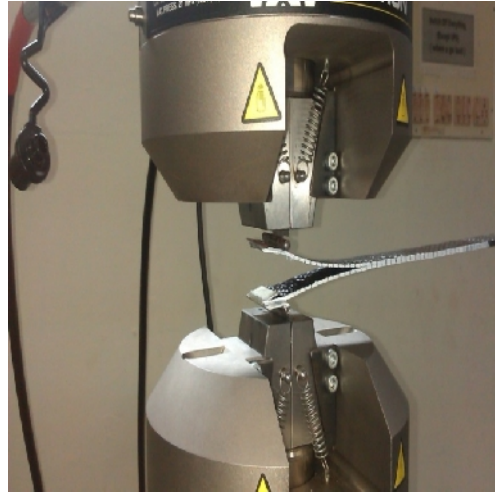


Figure 15: INSTRON MACHINE with the specimens.

5.2. Methodology:

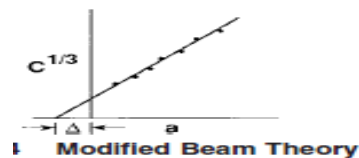
5.3.1. Interlaminar fracture toughness calculations

Three data reduction techniques for calculating the energy release rate (G_{ic}) values have been evaluated. They consist of Modified beam theory (MBT), a compliance calibration method (CC), and modified compliance calibration method (MCC).

- Modified Beam Theory (MBT) Method- The beam theory expression for the strain energy release rate of a double cantilever beam.

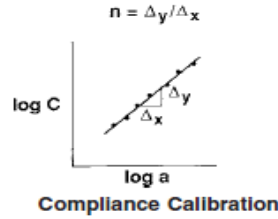
$$G_1 = \frac{3P\delta}{2ba}$$

This expression will overestimate G_1 because the beam is not perfectly built in. One may have to correct this rotation to treat the specimen DCB as if it contained a slightly longer delamination, $a + \Delta$, where Δ may be determined using experimentally by generating a least's squares plot of the cube root of compliance, $C^{1/3}$ as a function of delamination length. The compliance, C , is the ratio of the load point displacement to the applied load, δ/P . The values used to generate this plot should be the load and displacements corresponding to the visually observed delamination onset on the edge and all propagation values.



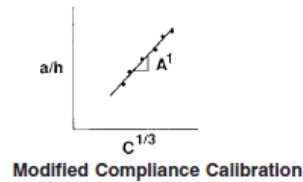
$$G_1 = \frac{3P\delta}{2b(a+\Delta)}$$

- **Compliance Calibration (CC) Method-**
Generate a least squares plot of $\log(\delta/P_i)$ versus $\log(a_i)$ using the visually observed delamination onset values and all the propagation values. Calculate the exponent n from the slope of this line according to $n = \Delta y / \Delta x$, where Δy and Δx are defined.



$$G1 = \frac{n P \delta}{2 b a}$$

- **Modified Compliance Calibration (MCC) method-**
Generate a least squares plot of the delamination length normalized by specimen thickness, a/h , as a function of cube root of compliance, $C^{1/3}$.



$$G1 = \frac{3 P^2 C^{\frac{2}{3}}}{2 A_1 b h}$$

5.4. Tabular Results of Glass epoxy composite

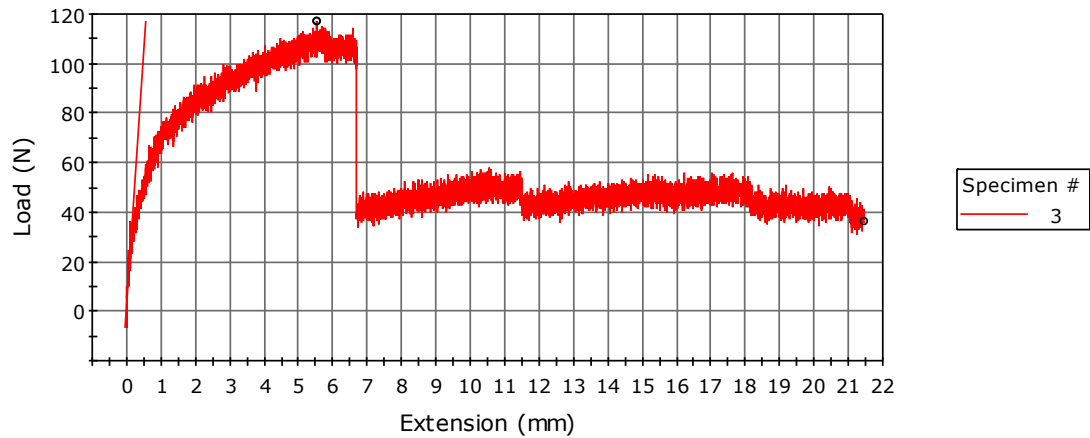
S.NO	a(mm)	δ (mm)	P(N)	MBT	CC	MCC
Specimen-II						
1	11.5	0.2	106	0.382	0.62	2.073
2	11.7	2.5	86	0.484	0.719	8.59
3	12	5.3	67	0.789	1.159	10.16
4	12.5	7	66	1.026	1.447	12
5	13	9	64	1.225	1.735	11.08
6	13.3	15.3	62	1.992	2.79	18.583
7	13.5	18	60	2.249	3.13	19.84
8	13.6	20	57	2.36	3.28	19.86

S.NO	a(mm)	δ (mm)	P(N)	MBT	CC	MCC
Specimen-III						
1	8.9	2	166	1.109	5.191	7.028
2	9.3	5.5	165	2.954	13.57	13.75
3	9.7	7	158	3.508	15.867	15.3
4	10	9	155	4.343	19.413	17.55
5	10.3	11.3	153	5.528	23.35	20.21
6	10.7	13	151	5.85	25.531	21.698
7	11.4	16.2	146	6.773	28.873	24.04
8	11.6	20	142	8.04	34.07	26.7

S.NO	a(mm)	δ (mm)	P(N)	MBT	CC	MCC
Specimen-IV						
1	10.3	2.7	87	0.68	2.88	3.62
2	10.5	5.5	79	1.257	5.227	5.158
3	12.7	7.2	69	1.275	4.94	5.145
4	13	7.5	46	0.872	3.352	3.083
5	13.5	9	41	0.909	3.453	2.98
6	14.3	13	39	1.202	4.479	3.57
7	14.5	15.3	38	1.366	5.065	3.48
8	15.1	17.7	37	1.496	5.479	4.09
9	15.3	20	37	1.675	6.11	4.43

S.NO	a(mm)	δ (mm)	P(N)	MBT	CC	MCC
Specimen-V						
1	8.5	3.5	67	0.9	4.496	2.9
2	9	4.2	62	0.96	4.716	2.971
3	9.7	5.5	66	1.276	6.099	3.854
4	10	8	70	1.929	9.128	5.362
5	10.3	10.5	65	2.3	10.8	5.823
6	11.3	12.3	62	2.41	11	6.086
7	11.5	15.4	65	3.125	14.18	7.516
8	11.7	18.2	64	3.592	16.22	8.24
9	11.7	20	66	4.07	18.38	9.148

Specimen 3 to 3



5.5. Tabular Results of Carbon- epoxy composite

S.NO	a(mm)	δ (mm)	P(N)	MBT	CC	MCC
Specimen-I						
1	17	1.9	81	0.29	0.686	0.336
2	18	2.2	87	0.34	0.806	0.407
3	26	3.1	97	0.205	0.877	0.593
4	30	6.5	105	0.012	1.725	1.077
5	32	6.7	41	0.33	0.65	0.313
6	35	7	46	0.362	0.697	0.377
7	40	9	47	0.42	0.801	0.459
8	49	11.5	41	0.403	0.729	0.45
9	54	12	46	0.43	0.775	0.62

S.NO	a(mm)	δ (mm)	P(N)	MBT	CC	MCC
Specimen-II						
1	18	1.5	130	0.368	1.585	0.705
2	27	2	140	0.394	1.517	0.931
3	37	2.3	146	0.369	1.328	1.082
4	38	6.5	158	1.105	3.954	2.637
5	45	9	49	0.412	1.434	0.635
6	48	11	56	0.545	1.877	0.865
7	55	15	59	0.697	2.354	1.143
8	56	20	54	0.837	2.822	1.23

S.NO	a(mm)	δ (mm)	P(N)	MBT	CC	MCC
Specimen-III						
1	25	2.5	184	0.751	2.42	0.875
2	29	3.5	190	0.961	3.026	1.15
3	65	4	171	0.484	1.389	1.103
4	67	5.5	182	0.689	1.972	1.483
5	69	6.5	53	0.23	0.659	0.319
6	74	8	62	0.311	0.884	0.372
7	78	12.5	64	0.47	1.353	0.635
8	81	15	64	0.554	1.564	0.718
9	85	20	66	0.728	2.049	0.907

6. Conclusion:

The development of interlaminar fracture tests of polymer-matrix composites has been rather slow. Even for Mode I loading standardization of test methods took about a decade. Multidirectional lay-ups frequently pose problems with Mode I loading because of crack branching and/or deviations of the delamination from the central plane.

The Teflon tape has worked perfectly for a precrack region in the testing facility and perfect crack growth of the delamination has been observed. Both effects invalidate the analysis according to the ASTM standard. Due to stick and slip phenomena the crack propagation of the composite experimental values have been achieved. Observation of all G_{ic} values in Modified beam theory (MBT), Compliance calibration (CC) and Modified compliance calibration (MCC) have been done accordingly and the stick and slip phenomenon is observed in an apt way all through the experiments. The stick and slip phenomenon is such that the G_{ic} value increases initially and there is a sudden slip in G_{ic} when the crack propagates and again increases for the next process, this is a continuous process due to the resin that has been used.

The results of the ANSYS have been run in a DELL LATITUDE INTEL CORE I5 PROCESSOR with a 4GB RAM and the INSTRON Machine is a state of the art machine that uses MERLIN software for results of the energy release rates.

Comparison of glass fabric/epoxy matrix and carbon fabric/epoxy matrix composites been made and the various parameters have been displayed in the form of graphs. This data is useful to choose the right material for the right applications for industries extensively using composites.

7. Nomenclature

- P= load
- δ =load point deflection
- b=specimen width
- G_I = Energy Release Rate
- a= initial crack length
- E_{xx} =Youngs modulus in X direction
- E_{yy} =Youngs modulus in Y direction
- E_{zz} =Youngs modulus in Z direction

- ν_{xy} =Poissons ratio in xy direction
- ν_{yz} =Poissons ratio in yz direction
- ν_{xz} =Poissons ratio in xz direction
- G_{xy} = Rigidity Modulous in xy direction
- G_{yz} = Rigidity Modulous in yz direction
- G_{xz} = Rigidity Modulous in xz direction

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