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Modelling and Analysis of Mode-I and Mode-II Delamination Onset in Composite Laminates

[1] Supreeth S, [2] Manjunath S. B.

[1] Post Graduate Student, Department of Mechanical Engineering, Dayananda Sagar College of Engineering, Bangalore.

[2] Assistant Professor, Department of Mechanical Engineering, Dayananda Sagar College of Engineering, Bangalore

Abstract: **A composite is a structural material that consists of two or more constituents combined at a macroscopic level and not soluble in each other. The advantages of composites over conventional materials are its Lightweight, High Strength, Design flexibility, Dimensional Stability etc. Although composite materials are advantageous than conventional materials, there are some defects in composite materials too, which are Fibre-matrix debonding, fiber misalignment, Delamination, Matrix cracking, Impact damage etc. Among these defects, Delamination is one of the major modes of failure for composite materials wherein separation of two adjacent plies in a composite laminate takes place. Delamination can be studied using two approaches, viz., Virtual Crack Closure Technique (VCCT), Cohesive Zone Modelling (CZM). VCCT is the study of damage based on the Energy Release rate of the material undergoing Delamination. In the present study, Finite Element Modelling and Engineering analysis of DCB and ENF standard specimens have been carried out by using the VCCT approach. Various parametric studies on the behavior of delamination with different material properties, ply orientations and a case study on different crack lengths are also studied and their effect on Delamination is presented.**

Keywords: Composite Materials, Delamination, Fracture Mechanics, VCCT.

I. INTRODUCTION

Composite materials are a group of two or more structural constituents which are combined at a macroscopic level and are insoluble in each other. The study of composite materials is of increased importance due to the ever growing applicability of composite materials and the wide range of advantages it has on offer. Some of these advantages are its Light weight, High strength, Design flexibility and many more, with these advantages on offer it also comes with some disadvantages too, Fibre-matrix debonding, Delamination, Matrix cracking, impact damage are some of them. From the previously mentioned disadvantages delamination is one of the serious threats to the durability and reliability of the Composite materials. Delamination is the Separation of two adjacent plies in composite laminates; it is one of the most critical failure modes in laminates. Basically there are three modes in which the failure can occur; these are called the Modes of Failure in fracture mechanics. These modes are Mode-I called as Opening, Mode-II called as Shearing and Mode-III called as Tearing. The Figure below represents the three modes of Delamination.

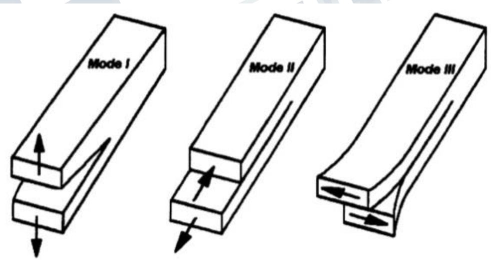

Fig. 1 Modes of Delamination

The Delamination can be studied using two approaches, which are the Virtual Crack Closure Technique (VCCT) and the Cohesive Zone Modelling (CZM). In the VCCT method Energy Release Rate (ERR) is the criteria used to study the crack behaviour, the Load vs applied displacement curve represents the energy release rate which is used to study the delamination behaviour. In the CZM method interface elements such called as cohesive zone elements are introduced in the interface area and traction parameter is the main criteria. The Traction vs Displacement curve gives the delamination behaviour of the component. For our study we are following the VCCT approach. With this background, some of the literature survey carried out can be discussed. Lyle R. Deobald et. al.,[4] proposed advanced enhancements and capabilities that would improve the usefulness of VCCT based inter-laminar Delamination study. M. Uslu Uysal [5] examined

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the critical strain energy release rate (G_IC) values for cantilever beam specimens made of recently development polymer composite. K. Senthil et. al., [6] presented a comprehensive review on the defects and its growth onset and prediction methods. Mikhail A. Tashkinov [7] established the effect of defect size on the parameters of deformation and failure of the sample. Ronald Kreuger [3] presented the approach used in the virtual crack closure technique and an insight into the application to engineering problems was provided.

II. BENCHMARKING AND VALIDATION

For the current numerical Investigation, the Double Cantilever Beam (DCB), as shown in Figure 1, was chosen. The DCB specimen is used to determine the Mode-I inter-laminar fracture toughness, GIc.

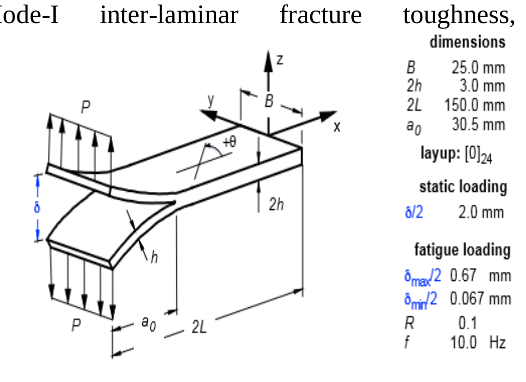

Figure 1: Double Cantilever Beam (DCB) Specimen.

Fig. 2 DCB Specimen

The above figure 2 shows the typical DCB specimen that is used as the benchmark for the analysis. [1]. The material used for the analysis is T300/1076 Unidirectional Graphite/Epoxy, the material properties of which are as specified below in Table 1.

Table 1 Material Properties of T300/1076 Unidirectional Graphite/Epoxy

E_{11} = 139.4 GPa	E_{22} = 10.16 GPa	E_{33} = 10.16 GPa
ν_{12} = 0.30	ν_{13} = 0.30	ν_{23} = 0.436
G_{12} = 4.6 GPa	G_{13} = 4.6 GPa	G_{23} = 3.54 GPa

The specimen was modelled using Design Modeller of Ansys Composite Pre-Post (ACP) program embedded within the Ansys Workbench software. The meshing has been done in the modelling section of the Ansys Workbench, the element used is Quadrilateral. The composite laminate layers, Fiber directions and orientations, Solid model of the embedded layers were created using the ACP program.

The Specimen is analysed for a crack length of 30mm. The benchmark is as represented in the given figure 2.

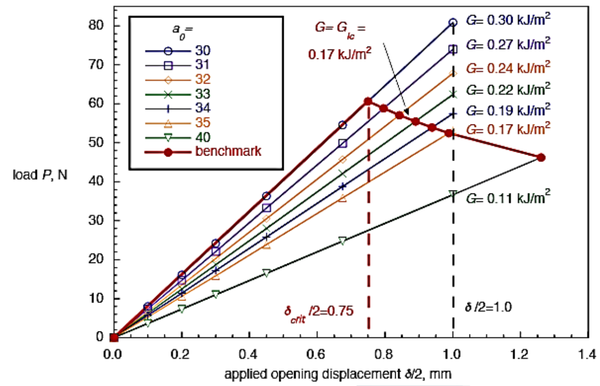

Fig. 3 Benchmark Load v/s Applied Opening Displacement

The Mode-I critical ERR is considered to be 0.17KJ/m2. The above figure depicts the Load v/s applied opening displacement for various crack lengths. Using this figure the benchmark can be recognized and the results can be validated. The mode-1 crack opening is shown in Fig.4.

The Energy Release Rate of Mode-I delamination due to applied opening displacement of 1mm can be seen in the figure.

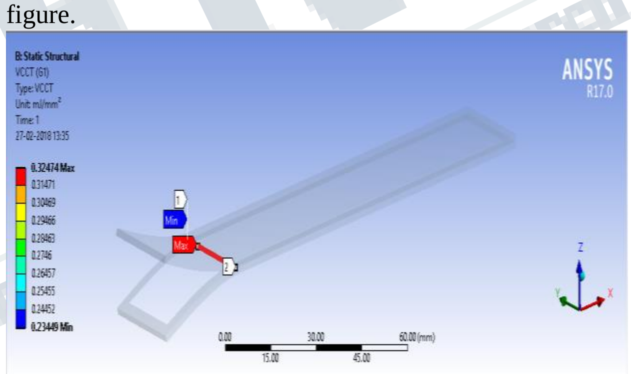

Fig. 4 ERR due to Mode-I crack opening

The variation of ERR along the width of the specimen can be seen in the figure 5. The Graph plotted with Force along the X-direction and applied opening displacement along Y-direction obtained from the results of varying load and displacements for 30mm crack length are as shown in figure 6.

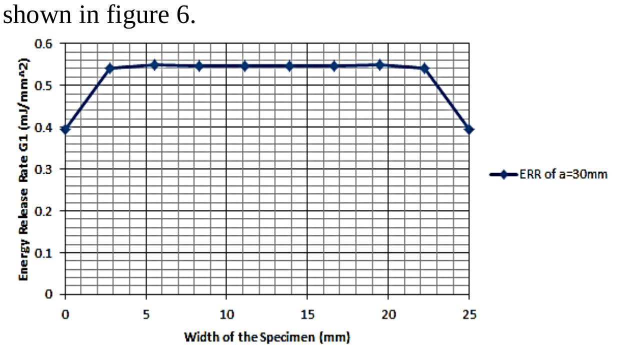

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Fig. 5 Variation of ERR along the width of the specimen

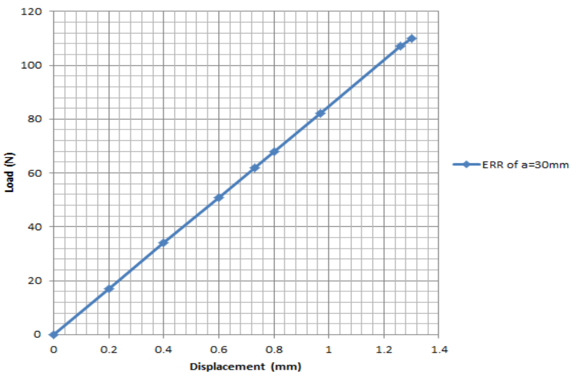

Fig. 6 Load vs Displacement curve

The curve represents the Energy Release Rate (ERR) at that particular Loading condition. For varying load and displacements according to the curve depicted in the benchmark, the energy release rates are obtained and are tabulated as shown in the Table 2.

From the Tabulation and the Benchmark results two values can be compared which are at 60N load, 0.75mm displacement and another is at 80N load and 1mm displacement. These values are compared with the benchmark results and the error is calculated. This can be seen in Table 3.

Table 2 Energy Release Rates for varying Loads and Displacements conditions

Crack Length (mm)	Load (N)	Displacement (mm)	ERR (KJ/m^2)
30	10	0.12	0.0046763
30	20	0.25	0.020296
30	30	0.37	0.044457
30	40	0.48	0.074821
30	50	0.62	0.12483
30	60	0.75	0.17306
30	70	0.87	0.2458
30	80	1.00	0.32474

Table 3 Comparison of Results obtained with Benchmark

Crack Length (mm)	Load (N)	δ (mm)	Benchmark [1] (KJ/m^2)	Numerical Solution (KJ/m^2)	Error (%)
30	60	0.75	0.17	0.17306	1.76
30	80	1.00	0.30	0.32474	7.61

Hence from the above tabular column we can say that the values of Energy Release Rate of benchmark and the calculated numerical solution values are in agreement with each other. Hence the Results are validated and the validation is complete.

III. PARAMETRIC STUDY

Having studied the Mode-I Delamination for a crack length of 30mm in the DCB specimen with Uni-Directional fibre orientation, there is a requirement to study the delamination under various parametric conditions such as varying material property and varying fiber orientations. Also since only Mode-I Delamination is studied there is also a need to study Mode-II along with the same parametric conditions to compare the differences. Hence a parametric study has been carried out in order to present the behaviour of components under varying conditions.

Case-1 –Effect of change in Fibre orientation in DCB-T300/1076 Graphite Epoxy Material with 30mm crack length. The dimensions remain same.

Fiber orientations considered are as follows –

1. [UD]24
2. Quasi-Isotropic [-45/90/45/0]3s
3. Anti-Symmetric [30/0/-30/0/30/0/30/0/-30/0/-30/30]AS

The modeling approach and the procedure is exactly the same as explained in the previous section.

The analysis has been carried out and the variation of Energy Release Rate along with the change in opening displacement can be seen in figure 7.

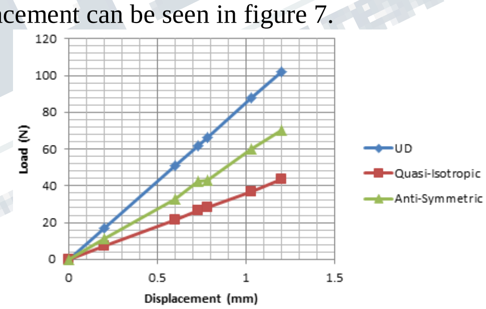

Fig. 7 Load vs Displacement curve for varying Fiber direction

From the above figure it can be observed that from the ERR values obtained, the onset of delamination or the critical opening displacement occurs at i.e., the critical ERR reaches 0.17KJ/m2 at 0.73mm for UD, 1.03 for Quasi-Isotropic and 0.78mm for Anti-Symmetric. These are the critical displacements (δcrit). The corresponding forces (Pcrit) are 62N, 37N and 43N respectively. The Load required for crack opening and propagation is more in Uni-directional Fibers which is followed by Anti-Symmetric and Quasi-isotropic respectively. Hence this concludes that Uni-Directional fibres offer the best resistance to crack propagation, this is followed by Anti-Symmetric and at last Quasi-Isotropic orientation.

Case-2 – Effect of change in Fibre orientation in DCB-C12K/R6376 Graphite Epoxy Material with 30mm crack length. The dimensions remain the same and Mode-I critical ERR=0.341KJ/m2.

The material properties of DCB-C12K/R6376 Graphite Epoxy is as given in the following Table 4

Table 4 Material Properties of DCB-C12K/R6376 Graphite Epoxy

E_{11} = 146.9 GPa	E_{22} = 10.6 GPa	E_{33} = 10.6 GPa
ν_{12} = 0.33	ν_{13} = 0.33	ν_{23} = 0.33
G_{12} = 5.45 GPa	G_{13} = 5.45 GPa	G_{23} = 3.99 GPa

The variation of Energy Release Rate along with change in opening displacement for can be seen in figure 8.

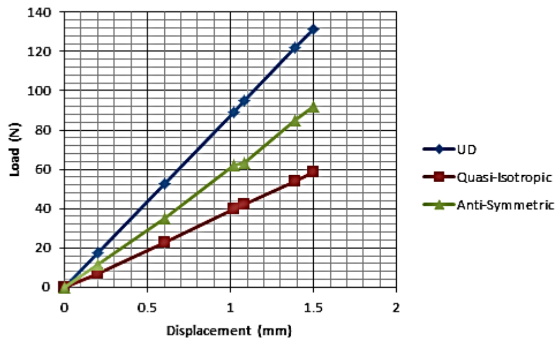

Fig. 8 Load vs Displacement curve for varying Fiber direction

From the above figure it can be observed that from the ERR values obtained, the onset of delamination or the critical opening displacement occurs at i.e., the critical ERR reaches 0.341KJ/m2 at 1.02mm for UD, 1.39mm for Quasi-Isotropic and 1.08mm for Anti-Symmetric. These are the critical displacements (δcrit). The corresponding forces (Pcrit) are 89N, 54N and 63N respectively. The Load required for crack opening and propagation is more in Uni-directional Fibers which is followed by Anti-Symmetric and Quasi-isotropic respectively. Hence the same can be concluded as in the previous case.

Case-3 – Comparing the results of DCB-T300/1076 Graphite Epoxy and DCB-C12K/R6376 Graphite Epoxy Material for a crack length of 30mm with Uni-Directional, Quasi-Isotropic and Anti-Symmetric fibre orientation, we can observe that the opening displacement at which the crack opening takes place is 0.73mm in case of DCB-T300/1076 Graphite Epoxy material and 1.02mm in case of DCB-C12K/R6376 Graphite Epoxy material and the Load required to achieve crack opening is 62N and 89N respectively in Uni-directional fibre orientation. Also from the figure it can be seen that the amount of force required for crack propagation is more in DCB-C12K/R6376 Graphite Epoxy material, hence it offers more resistance to crack propagation when compared to DCB-T300/1076 Graphite Epoxy material. Hence arguably it can be concluded that while choosing from these two materials, choosing DCB-C12K/R6376 Graphite Epoxy is the better choice.

Case-4 – Effect of change in Fibre orientation in ENF-IM7/8852 Graphite Epoxy Material with 25.4mm crack length and Mode-II critical ERR=0.774.

The ENF specimen is a standard specimen used to simulate Mode-II Delamination. The dimensions of the ENF specimen are as shown in Fig. 4.

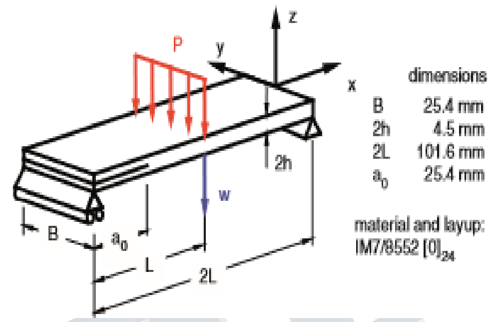

Fig. 9 ENF Specimen

The Material Properties of the IM7/8852 Graphite Epoxy is as mentioned in the Table 5.

Table 5 Material Properties of IM7/8852 Graphite Epoxy

E_{11} = 161 GPa	E_{22} = 11.38 GPa	E_{33} = 11.38 GPa
ν_{12} = 0.32	ν_{13} = 0.32	ν_{23} = 0.48
G_{12} = 5.2 GPa	G_{13} = 5.2 GPa	G_{23} = 3.9 GPa

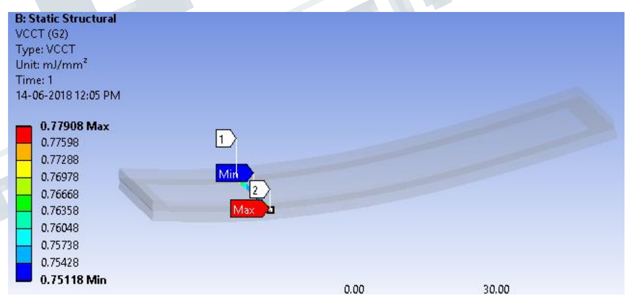

Fig. 10 ERR due to Mode-II crack opening

The analysis for change in Fibre orientations in ENF-IM7/8852 Graphite Epoxy Material with 25.4mm crack length has been carried out and the variation of ERR along with the change in opening displacement for can be seen in figure 11. The Fibre orientations are the same as considered for previous cases. From the graph 6 it can be observed that from the ERR values obtained, the onset of delamination or the critical opening displacement occurs at i.e., the critical ERR reaches 0.774KJ/m2 at 1.31mm for UD, 1.72 for Quasi-Isotropic and 1.37mm for Anti-Symmetric. These are the critical displacements (δcrit).The corresponding forces (Pcrit) are 1372N, 738N and 900N respectively. The Load required for crack opening and propagation is more Uni-directional Fibers which is followed by Anti-Symmetric and Quasi-isotropic respectively. Hence this concludes that Uni-Directional fibres offer the best resistance to crack propagation, this is

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followed by Anti-Symmetric and at last Quasi-Isotropic orientation.

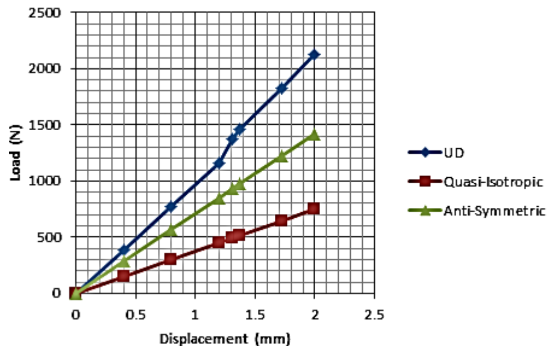

Fig. 11 Load vs Displacement curve

Case-5 – Effect of change in Fibre orientation in ENF-T300/1076 Graphite Epoxy Material with 25.4mm crack length and GIIc=0.494KJ/m2.

The Material Property and the dimension of the ENF specimen remains the same. The variation of Energy Release Rate along with change in opening displacement for can be seen in figure 12. From the figure 12 it can be observed that from the ERR values obtained, the onset of delamination or the critical opening displacement occurs at i.e., the critical ERR reaches 0.494KJ/m2 at 01.12mm for UD, 1.47mm for Quasi-Isotropic and 1.17mm for Anti-Symmetric. These are the critical displacements (δcrit).The corresponding forces (Pcrit) are 1022N, 550N and 672N respectively. The Load required for crack opening and propagation is more Uni-directional Fibers followed by Anti-Symmetric and Quasi-isotropic.

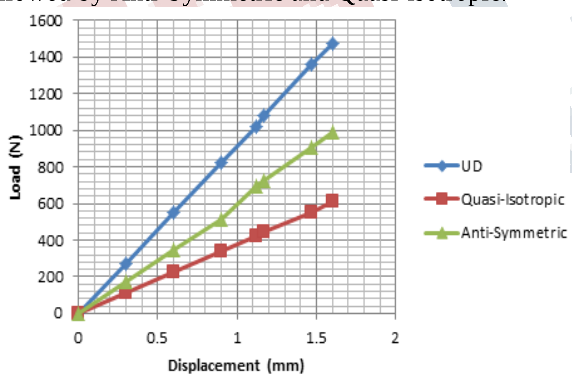

Fig. 12 Load vs Displacement curve for varying Fiber direction

Case-6 - Comparing the results of ENF-IM7/8852 Graphite Epoxy and ENF-T300/1076 Graphite Epoxy Material for a crack length of 25.4mm with Uni-Directional, Quasi-Isotropic and Anti-Symmetric fibre orientation, we can observe that the critical opening displacement at which the crack opening takes place is 1.31mm in case of ENF- IM7/8852 Graphite Epoxy material and 1.12mm in case of ENF-T300/1076 Graphite Epoxy material and the Load required to achieve crack opening is 1372N and 1022N respectively. Also from the figure it can be seen that the amount of force required for crack propagation is more in ENF- IM7/8852 Graphite Epoxy material, hence it offers more resistance to crack propagation when compared to ENF-T300/1076 Graphite Epoxy material. Hence arguably it can be concluded that while choosing from these two materials, choosing ENF-IM7/8852 Graphite Epoxy is the better choice.

IV. CASE STUDY

In the previous section we studied about the variation in behaviour of the Delamination due to change in Material Properties and Fibre orientations, along with these it also becomes important to study about the behaviour of Delamination with varying crack length. Hence for the DCB specimen varying crack lengths of 30mm, 35mm and 40mm are considered and for ENF specimen varying crack lengths of 25.4mm, 27mm and 30mm are considered. The following figure shows the Load vs Displacement graphs for varying crack lengths in DCB specimen.

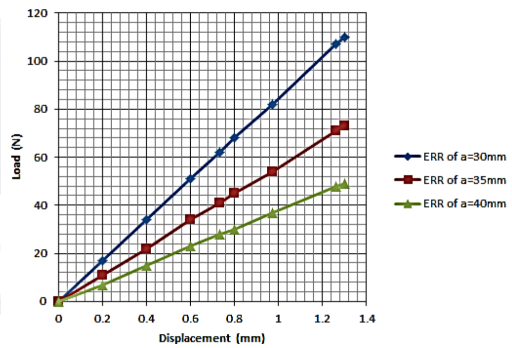

Fig. 13 L vs δ for DCB T300/1076 Graphite Epoxy -UD

The Above figure indicates the ERR for crack lengths 30mm, 35mm and 40mm for DCB-T300/1076 Graphite Epoxy material. Similarly the graphs have been plotted for varying fiber orientation (Fig. 14 and 15). Figures 16 to 18 shows the ERR for crack lengths 30mm, 35mm and 40mm for DCB-C12K/R6376 Graphite Epoxy material. All explanations have been discussed in the Conclusion.

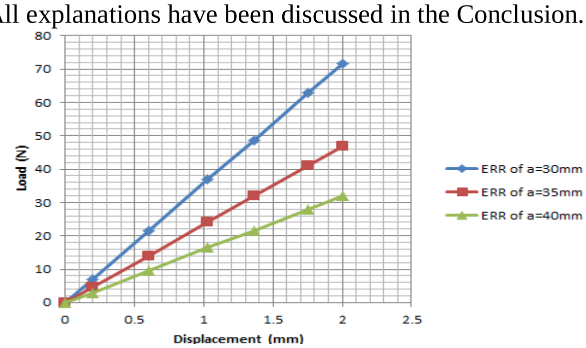

Fig. 14 L vs δ for DCB T300/1076 Graphite Epoxy - Quasi isotropic

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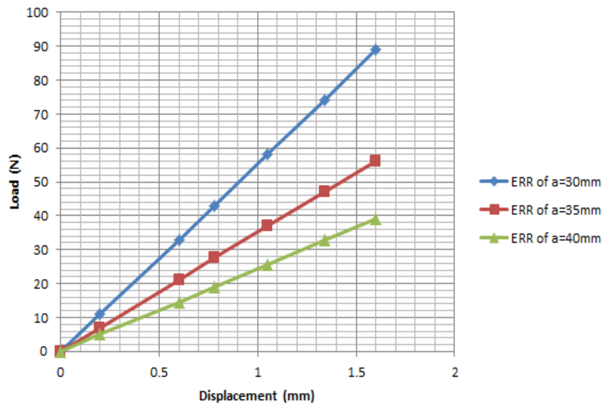

Fig. 15 L vs δ for DCB T300/1076 Graphite Epoxy-Anti-Symmetric

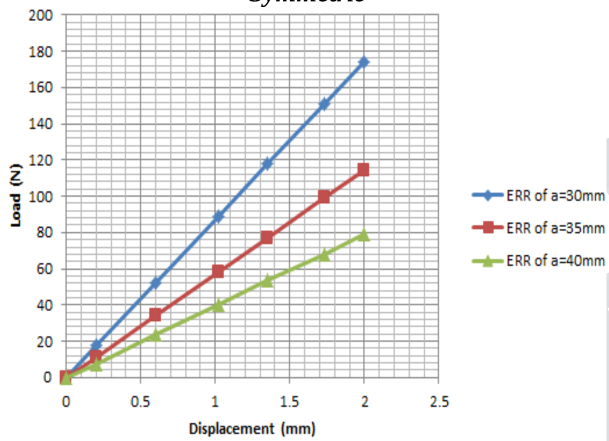

Fig. 16 L vs δ for DCB C12K/R6376 Graphite Epoxy-UD

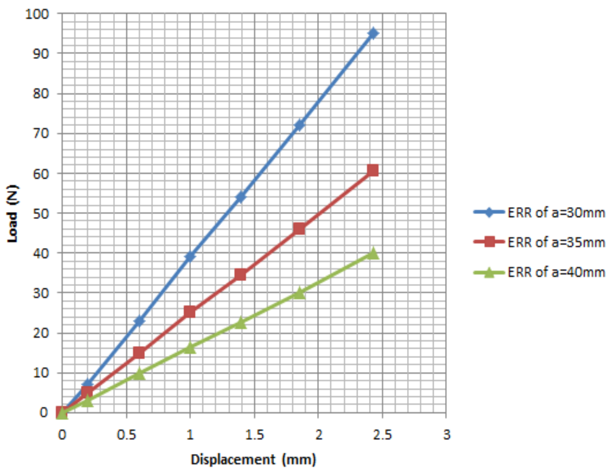

Fig. 17 L vs δ for DCB C12K/R6376 Graphite Epoxy-Quasi-Isotropic

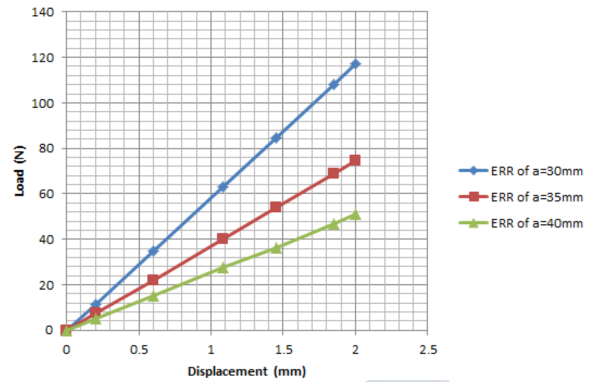

Fig. 18 L vs δ for DCB C12K/R6376 Graphite Epoxy-Anti-Symmetric

The figure 19 indicates the ERR for crack lengths 25.4mm, 27mm and 30mm for ENF-IM7/8852 Graphite Epoxy material. Similarly the graphs have been plotted for varying fiber orientation (Fig. 20and 21). Figures 22 to 24 shows the ERR for crack lengths 25.4mm, 27mm and 30mm for DCB-T300/1076 Graphite Epoxy material. All explanations have been discussed in the Conclusion.

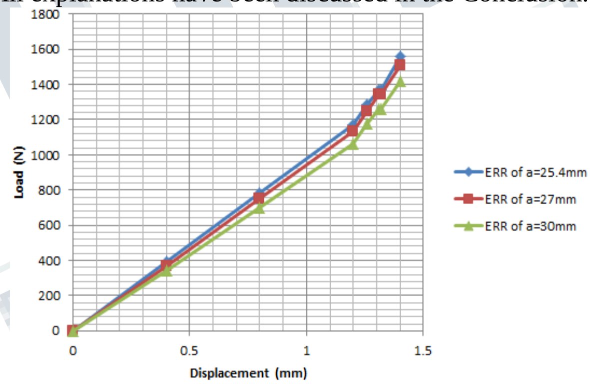

Fig. 19 L vs δ for ENF IM7/8852 Graphite Epoxy-UD

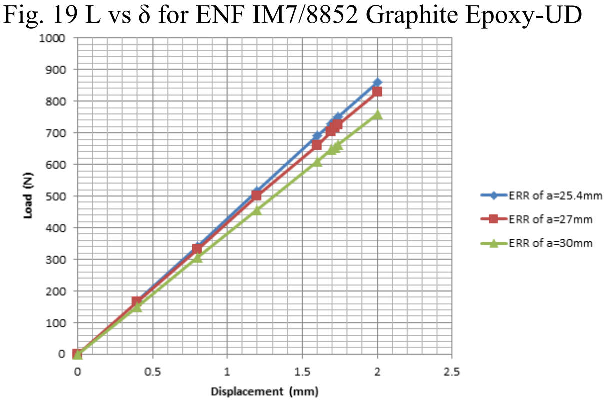

Fig. 20 L vs δ for ENF IM7/8852 Graphite Epoxy-Quasi-Isotropic

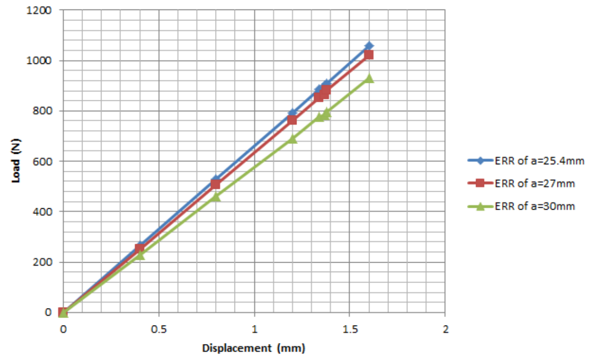

Fig. 21 L vs δ for ENF IM7/8852 Graphite Epoxy-Anti-Symmetric

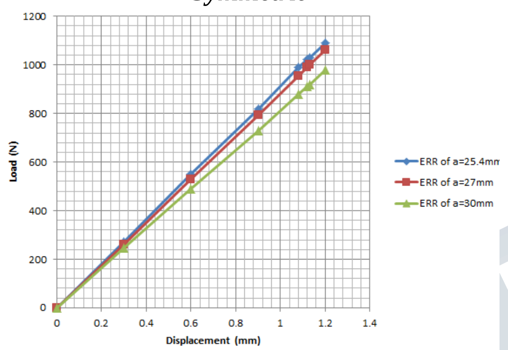

Fig. 22 L vs δ for ENF T300/1076 Graphite Epoxy-UD

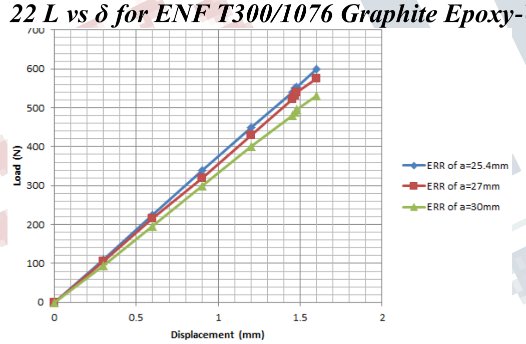

Fig. 23 L vs δ for ENF T300/1076 Graphite Epoxy-Quasi-Isotropic

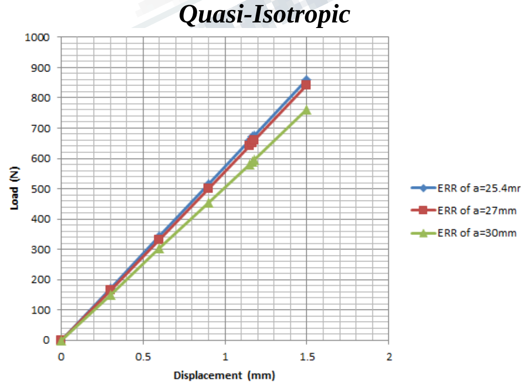

Fig. 24 L vs δ for ENF T300/1076 Graphite Epoxy-Anti-Symmetric

The discussions on the results obtained from above figures have been discussed in the Conclusion below.

V. CONCLUSION

Concluding all the study that has been carried out, the Benchmarking and Validation has been carried out for a DCB standard specimen with 30mm crack length and using T300/1076 Graphite Epoxy material. The results obtained are satisfactory and they have been validated.

In the parametric study we discussed about the effect of variation in material properties, fiber orientations on the delamination onset. Here we may say that among the three materials used C12K/R6376 Graphite Epoxy turns out to be more reliable than T300/1076 Graphite Epoxy in Mode-I and IM7/8852 Graphite Epoxy material turns out to be more reliable than T300/1076 Graphite Epoxy in Mode-II. Hence it turns out that T300/1076 Graphite Epoxy material is the inferior material when compared with the other two materials. Regarding the fibre orientation, from all the studies made, it is evident that Uni-Directional fibres are the most reliable orientation and are more resistant to applied displacement and force. This is followed by the Anti-Symmetric orientation and at the least among the three is the Quasi-Isotropic orientation.

In the case study we took up the effects of varied crack lengths on the delamination behavior. From all the studies, it can be said that as the crack length increases, less displacement, in other words less amount of force is required for crack opening and crack propagation. Also as the crack length increases, the critical ERR value is reached quicker and the crack opening and propagation happens earlier in the larger cracks than in the smaller cracks. For example, in the figure 13 of DCB specimen with uni-directional fibre orientation the critical ERR (GIC) is achieved at a Load of 62N in specimen with crack length 30mm, 54N in the specimen with crack length 35mm and 48N in the specimen with crack length 40mm. The Delamination onset is occurring at a much lesser load as the crack length is increasing. Hence this is about the study on Mode-I and Mode-II Delamination onset in Composite Laminates.

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