CURVED BEAM STRENGTH AND TOUGHNESS OF THIN PLY CFRP NON-CRIMP FABRIC LAMINATES

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ABSTRACT

Carbon fiber reinforced plastics are most widely used composite materials in aerospace and wind turbine industries. Their superior in plane properties with light weight structures and also ability to change and design the structure and form make composites preferable to metallic materials. Composites are applied to the primary load carrying members with complex and curved geometries with the new manufacturing techniques. On the other hand, failure mechanisms of composites are different and complicated than the metallic structures. Out of plane properties of composites are not as good as in plane properties, unbalanced properties of reinforcement and matrix and radial geometry of the curved part creates weakness through the thickness direction leading to delamination failure. In this study effect of novel material-thin ply non crimp fabric laminates on delamination resistance of carbon fiber reinforced plastics composites are presented. For this purpose standard test methods are carried out, fracture toughnesses and behavior of laminates under moment loading are obtained experimentally. The dynamic delamination propagation and failure sequences are captured using Photron© Fastcam SA5 ultra high speed system. Changing the material type from unidirectional to thin-ply non-crimp fabric material increased the mode I, mode II fracture toughness and curved beam strength of the laminates. It is observed that the manufacturing defects are the potential failure initiation sides.

INTRODUCTION

Demand for composites especially in aircraft and wind turbine industries emerges from the need of light weight structures without any loss of strength and stiffness. Composite materials have superior properties compared to metallic materials such as improved strength, stiffness, fatigue and impact resistance, thermal conductivity, corrosion resistance, etc. [Kaw 2006]. Light weight structures with improved properties of composite materials satisfy the requirements of advanced technologies, leading to increase in the demand for these materials especially carbon fiber reinforced plastics (CFRP) for both industries. Although, composites are widely used in aerospace and wind turbine structures generally as a plenary parts, with the recent advanced manufacturing technologies, Composite materials are incorporated into complex geometries and curved parts instead of metallic materials. Rib and spar flanges of wing and spar sections of wind turbine blades are the main applications of load carrying metallic structures replaced with curved composite materials [Sørensen et al. 2004, Edwards and Thompson 2005, Vanttinen 2008]. However, use of composites in such complex geometries is not sufficient for load carrying applications due to their weakness at the radius. The weakness is caused by high normal stresses in addition to shear stresses that may cause delamination which is separation of layers with significant loss of mechanical toughness.

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The concept of non-crimp fabric or multiaxial composites was first utilized 90s by basically stitching the conventional unidirectional laminates in different orientations to create fabric type layers with less waviness and more possible orientations in order to reduce required cost and time required for manufacturing the composite laminates with unidirectional prepregs. Albeit the reduced in plane properties of the non-crimp fabric composites compared to equivalent UD configuration, they provide reduced waviness and increased mechanical properties in the out-of-plane and impact performance over fabric type composites and also they are more flexible, easy to store and handle with respect to equivalent UD fiber tapes. Besides, stitching can improve through the thickness strength, delamination and impact resistance [Arteiro, 2012, Roure and Sanial, 2013]. Although starting from late 90s some work done on the reducing of the conventional ply thickness, in early 2000s development of the novel spread tow-thin ply technique eventuated in new class of material called thin ply non-crimp fabric. This method enables producing dry ply thicknesses as low as 0.02 mm. The term thin ply non-crimp fabric is used for fabric type layers with less waviness and reduced ply thickness. Thin ply NCF are formed by stitching the tow spread thin UD layers in the desired configuration instead of wovening the filaments [Shin et al., 2007, Tsai and Nettles, 2011].

In this study, Failure behavior and fracture toughness of thin ply non-crimp fabric laminates are determined by conducting ASTM standard fracture toughness and curved beam strength tests. The results are compared with the equivalent conventional composite laminates with the same orientation. high speed camera system is used in the experiments in order to gain better understanding of the effect of thin ply non-crimp fabric materials on failure process and the dynamic crack growth process..

METHOD

Material

The manufacturing process distinguishes Thin ply NCF laminates from the conventional composite laminate. At the first stage laminate forming process, filaments in an original thick tow are spread uniformly by passing through very low, stable airflow between the filaments. The tow sags downward and loses tension with the flow of air. As air passes through the filaments in the downward direction from air duct to vacuum, it creates pressure difference around fibers and distributes them as shown in figure 1a. NCF are formed by placing the spread tow UD plies on top of one another in the desired directions on a multiaxial machine. Plies are tied together with a very fine stich [Arteiro, 2012].

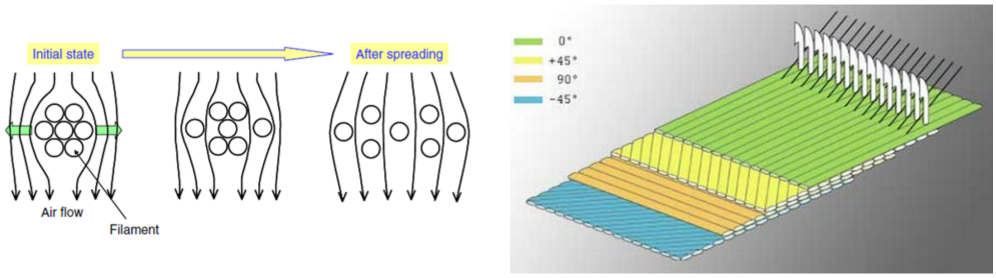
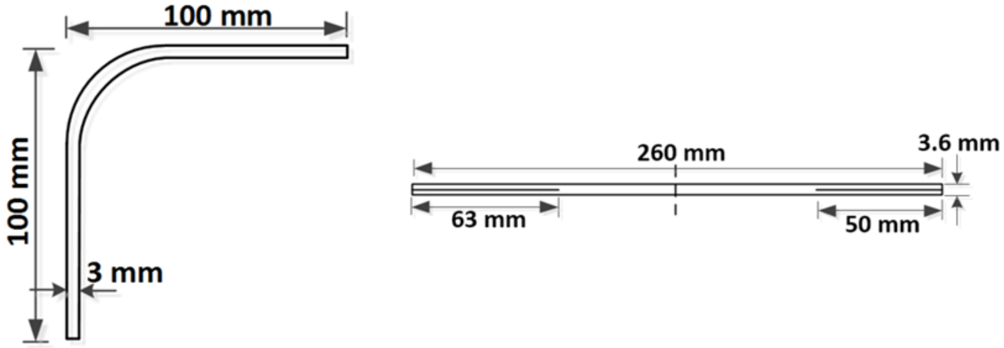


Figure 1: *schematic of (a) tow-spreading process (b) ENF test, (c) Ply combining process during manufacturing*

In this study thin ply NCFs are composed of 24 plies and each having 2 thin plies tied together by stitching in the [0/45] configuration. And this NCF plies are stacked in the order of [0/45/-45/0]12T stacking sequence. Choromat C-Ply (carbon fiber T700) NCF and UD prepregs with AR2527 epoxy resin produced by Aldita composite materials are used. C-Ply NCFs have 0.0625 mm ply thickness which is half of the common UD ply thickness. Toray T800 carbon fiber tows are used for C-Ply NCF material.

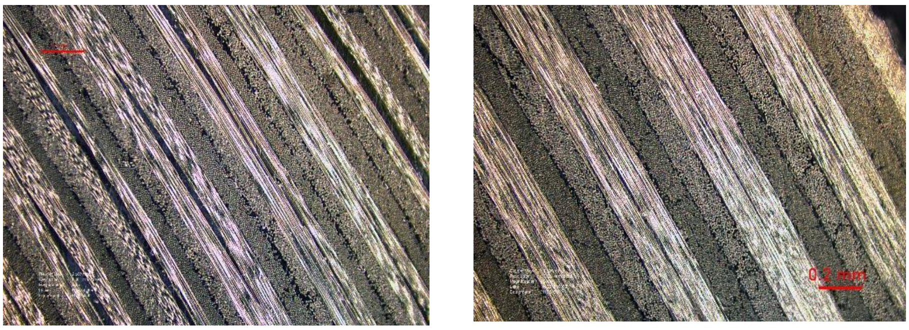
Both unidirectional and thin ply NCF fracture toughness test specimens were manufactured together and 4-point bending test specimens were manufactured separately. Specimen geometries of 4-point bending test and fracture toughness tests are shown in Figure 2a and b, respectively. Thin fiber non-crimp fabric specimens are in the (0/-45/45/0)12T stacking sequence which corresponds 48 plies of thin fiber plies and 24 plies of [0/45] thin NCF plies with 3.5 mm thickness. Unidirectional specimens has 0.17 mm thick plies manufactured with (0/-45/45/0)6T layup corresponding 24 plies with 3.5 mm thickness. L-shaped specimen's leg lengths were 100 mm and inner radius was 10 mm. Flat plates are 260 mm in length and approximately 150 mm wide having 63 mm and 50 mm pre-cracks for DCB and ENF test, respectively.



(a) (b)

Figure 2: *Specimen geometry of thin fiber NCF used for (a) 4-point bending tests and (b) fracture toughness tests.*

Flat plates used for toughness tests and L-shaped specimens were manufactured by hand lay-up technique with vacuum bagging. For all three types of tests two specimens were manufactured. Figure 3 a and b represents the microscopic view of thin-ply NCF and UD material after manufacturing showing the stacking stitched thin UD plies in the direction of [0/45/-45/0] from thickness directions, respectively.



(a) (b)

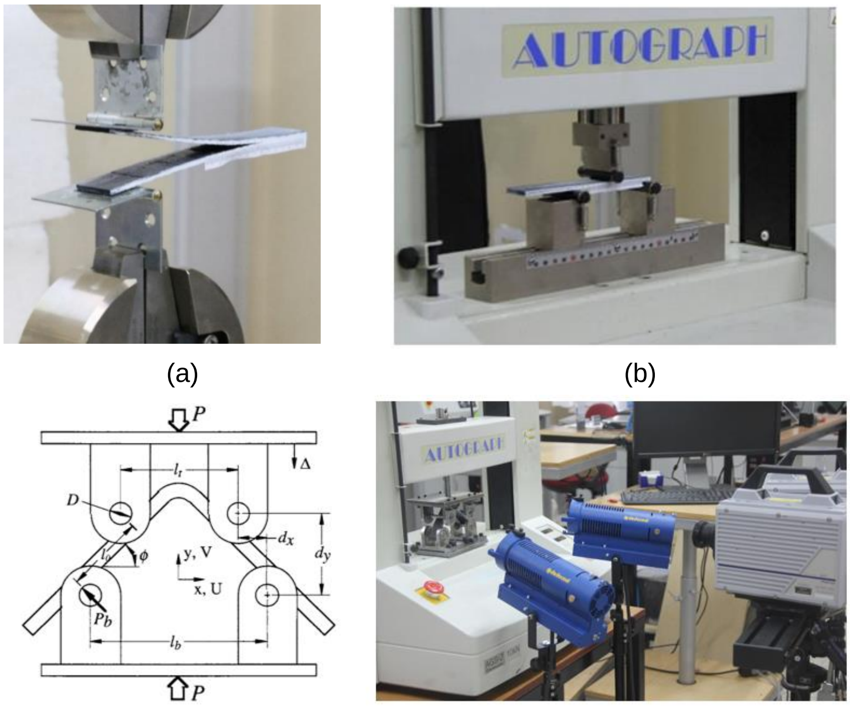
Figure 3: *Microscopic side view [0/45/-45/0] (a) thin ply NCF laminate, (b) conventional thicker ply laminate.*

Experimental Method

Experimental Procedure:

Double cantilever beam tests according to ASTM D5528-01 standard and End Notch Flexure or 3 point bending tests are conducted in order to obtain Mode-I fracture toughness (G_{IC}) and Mode-II fracture toughness of laminates. Both fracture toughness test specimens have flat rectangular shape. In order to demonstrate the initial delamination, Teflon film is inserted at the mid layer of the laminates during manufacturing For both test types film insert creates resin rich region and acts like obstacle against delamination yielding higher energy absorption initiation value obtained from the precrack propagation gives higher values. For this reason tests are conducted in two parts. At the first part initial crack is propagated about 2 mm by DCB test to obtain real sharp crack. Mode-I fracture toughness obtained by putting Specimen into loading machine to be aligned perpendicular to the loading line and applying opening forces. The first crack propagation and first load drop gives the initiation value. This procedure is continued up to 45 mm crack growth to obtain fracture toughness resistance curves (R-curves).Mode-II fracture toughness is obtained by applying concentrated load at the mid plane of the laminate creating shear force at the precracked end of the laminates and propagating the initial delamination. Since delamination propagation in ENF test is unstable, test is stopped after first load drop. Only one fracture toughness (G_{IIC}) value is obtained.

4-point bending test aims to determine curved beam strength of 90^0 curved composite specimens. The moment per unit width generating delamination is the curved beam strength of a composite. Tests are conducted according to ASTM D6415/D6415M – 06a standard named 'Standard Test Method for Measuring the Curved Beam Strength of a Fiber-Reinforced Polymer-Matrix Composite'. In the test constant bending moment is applied to the specimen. Test setup configuration used in the 4-pt bending tests and specimen positioning are shown in Figure 4c.



(a) (b)

(c)

Figure 4: *Experimental Setup for (a) double cantilever beam test (b) ENF test, (c) curved beam strength test of L-shaped laminate*

In the experiments Shimadzu Autograph AGS-J 10 kN displacement controlled, screw driven tensile testing machine were used as the load indicator and load displacement data was recorded by Trapezedium software. During the experiments, Photron AS4 1.000.000 fps high speed cameras (1 MP full frame) were used for capturing the crack length and delamination sequences.

Calculations:

Mode-I fracture toughness is obtained by modified compliance calibration method according to ASTM D5528 given by,

$G_{IC} = (3P^2\, C^{\frac{2}{3}}))/(2A_1\, bh)$,

where a is the initial crack length, P is the load, C is the compliance obtained by dividing the displacement by the load, b and h are width and thickness of the specimen, respectively, and A1 is the slope of a/h versus C1/3 curve.

Mode II Fracture toughness is found based on direct beam theory given

$G_{IIC} = (9a^2\, P\delta)/2b(2L^3 + 3a^3\,)$

where δ is the load point deflection, L is the span length of the specimen, (a) is the initial crack length, (P) corresponds to load, (δ) is the deformation, b and L are width and span length of the specimen.

RESULTS

Fracture Toughness

Load displacement curves of Mode I and Mode II fracture toughness tests are represented in figure 5 a and b, respectively. DCB load displacement curves have different trend for TPNCF and UD material. The main difference is that TPNCF laminate can resist higher loads compared to UD laminate. TPNCF laminate is stiffer than the UD material. Moreover, load decreases slightly as crack propagates for the [0/45] material, while for the TPNCF laminate Load drops at the initiation is more stable, load increases up to 65 N, after 15 mm crack propagation sudden load drops are observed. Similar to the DCB test results, TPNCF laminates can resist higher loads for the ENF tests. For the thin ply NCF laminates stiffness of the curves, maximum load prior to failure are exactly same in two of the tests. Although failure loads are similar, high deviation in the stiffness of the ENF load displacement curves are observed for the [0/45] UD laminates.

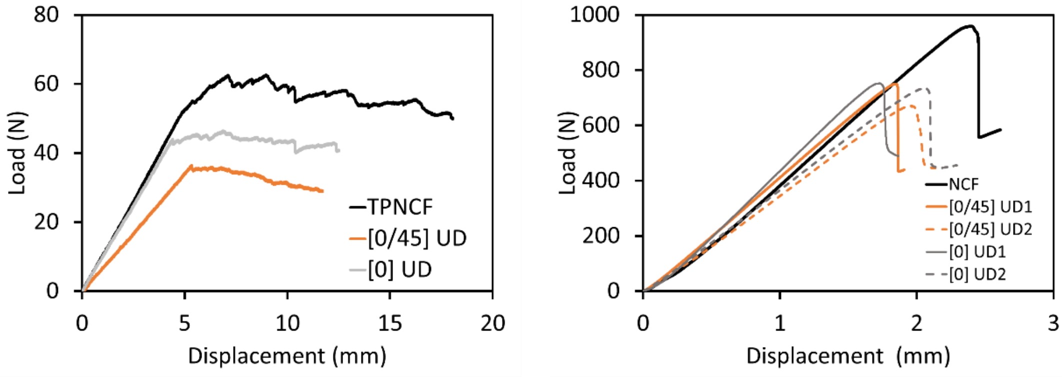


Figure 5: *Load displacement curves of NCF, [0/45] UD and [0] UD laminates obtained (a) DCB tests and (b) ENF tests.*

In figure 6 a and b Mode I and Mode II fracture toughness values of TPNCF and UD laminates are presented respectively. Both initiation and propagation Mode I fracture toughness and Mode II fracture toughness values of TPNCF laminate are higher than the UD laminate.

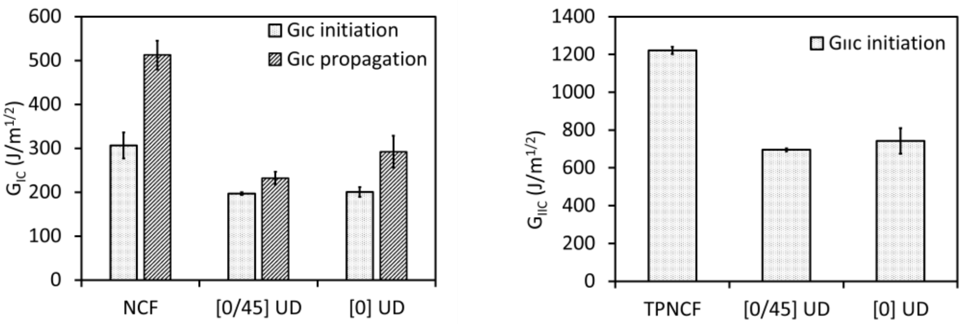


Figure 6: *(a) Bar graph of Mode-I fracture toughness (GIC) initiation and propagation values obtained by MBT and (b) bar graph of Mode-II fracture toughness values calculated by direct beam theory for TPNCF, [0] UD and [0/45] UD laminates.*

Load displacement curves obtained from 4-point bending tests are presented in Figure 7 for all two type of material. [0/45] UD laminates can resist up to 700N and two load drops occur. After the first load drop specimen can still carry load without changing the slope, which indicates that cracks do not extend all through the width of the specimen and specimen does not loss its load carrying capacity completely. Thin ply non-crimp fabric laminate load displacement behavior is different from UD laminates. Specimens can carry load up to 1800N and one load drop occurs. After the load drop load carry in capacity decreases to 500N, indicating that the failure occurs throughout the width direction and specimen loses its stiffness Small voids are observed, however their presence is not fatal for the specimen, and neither load displacement curve nor failure pattern is affected.

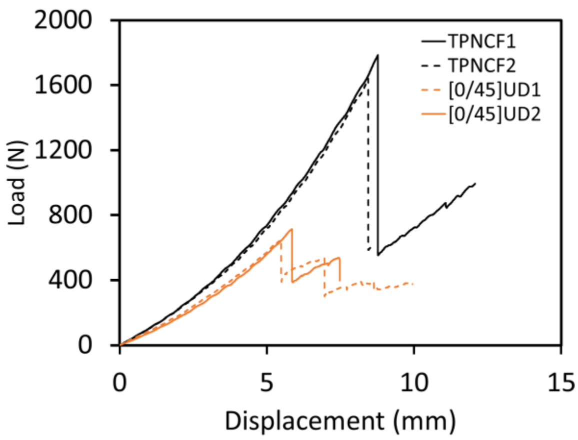
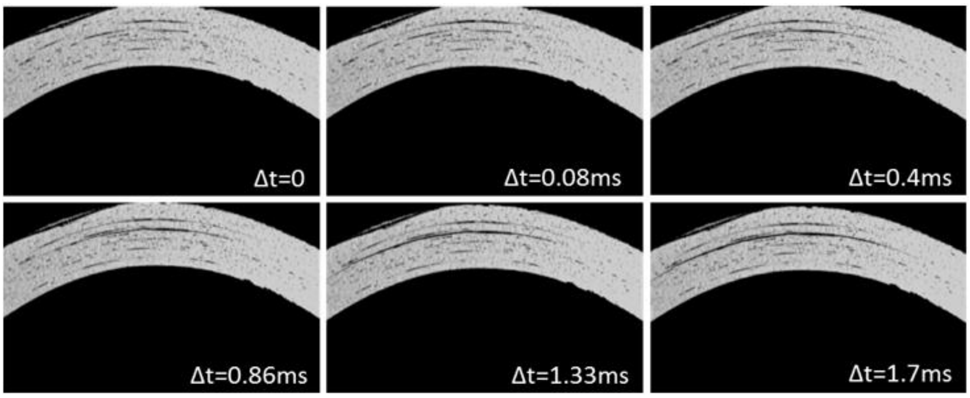
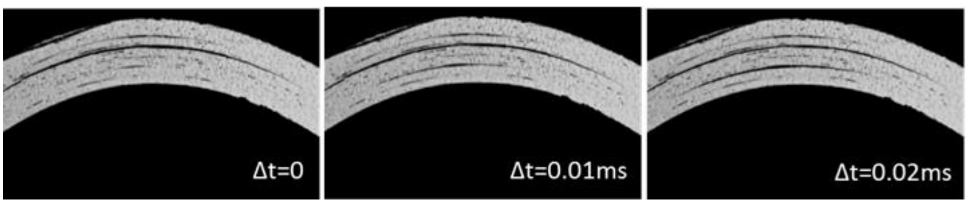


Figure 7: *Four point bending load displacement curves of [0] UD, [0/45] UD and [0/45] thin fiber NCF laminates all together.*

High speed camera photos of UD2 laminate taken at 100,000 fps are given in Figure 8. First load drop occurs at 370 N and first picture in Figure 8 denotes the specimen prior to failure. Two delamination nucleates from the initial defects close to the upper radius and middle part. At the second load drop third delamination nucleates from the initial defect below middle part close to inner radius. Whole process ends in 1.7ms and 0.02ms which are very stable.



(a)



(b)

Figure 8: *HSC photos taken at 100,000 fps for UD2 laminate corresponding at (a) first and (b) second load drop, respectively.*

Figure 9 shows the failure sequence of thin fiber NCF laminates in one load drop captured by high speed cameras at 100,000fps. In Figure 9 whole process takes 70 µs which is highly unstable. First picture shows initial state. Three delaminations propagates simultaneously at the curved region two of them is at the same ply and third is one ply below them, fourth small delamination occurs between middle and inner radius at the right half of the curved region in first 10 µs. in next 10 µs first wo delamination merges and new delamination growth is seen from the left side above the mid part and For the next 50 µs it propagates to the curved part. For all of the tests two major delamination observed at the mid part.

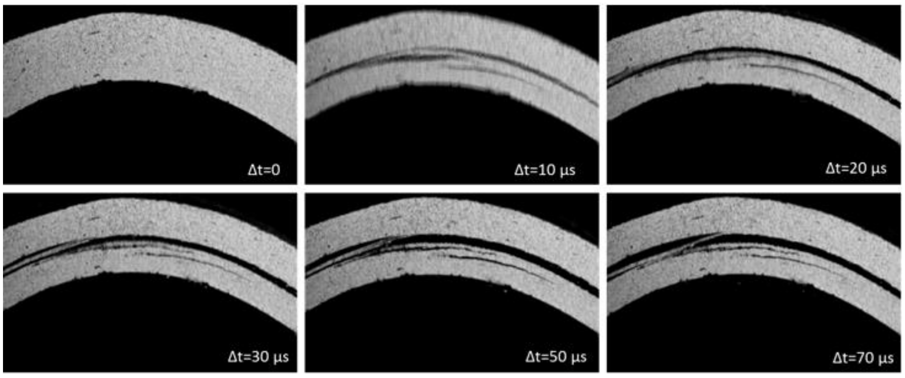


Figure 9: *High speed photos of TPNCF2 specimen 2nd test (2nd batch), taken at 100,000 fps showing the failure sequence.*

CONCLUSIONS

In this study, thin ply non-crimp fabric configuration is found to increase the stiffness, maximum load and Mode-I, Mode-II fracture toughness of the material. Results of all of the three tests are very consistent for thin ply NCF laminates. Effect of manufacturing quality on the strength of curved composite laminates is observed for [0/45] UD laminates. Initial defects are the potential crack nucleation points. For [0/45] UD laminates can resist up to 700N and two load drops occurred, however cracks were nucleated where initial defects are seen. The argument that cracks do not extend all through the width of the specimen and specimen does not loss its load carrying capacity completely after the load drop is attributed to the different failure surfaces at the front and back sides. For the thin ply non-crimp fabric laminates one load drop occurs and after the load drop specimen lose their stiffness load carrying capacity. Delamination occurs between 0/45 and 45/-45 plies inside the stich meandering in 450 plies during propagation. In the witdh direction crack meandering is also seen clearly which results in slight difference at the front and back sides of the specimens.

References

Arteiro A.J.C., (2012) *Technology development and structural mechanics of composites built of spread tow thin-ply technology*, Ms thesis, University of Porto (UP).

Kaw K.A., *Mechanics of Composite Materials*, CRC Press Taylor & Francis Group, Boca Raton/London/New York, 2006

Edwards T., Thompson J. (2005), *Spar Corner Radius Integrity for the A400M Wing*, Applied Mechanics and Materials, Vols. 3-4, pp. 197-204.

Shin S., Kim R.Y., Kawabe K., Tsai S.W. (2007), *Experimental studies of thin-ply laminated composites*. Composites Science and Technology; 67: 996-1008.

Sørensen BF, Jørgensen E, Debel CP, Jensen FM, Jensen HM, Jacobsen TK, Halling KM. (2004), *Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report*, Risø National Laboratory Denmark, Risø-R-1390(EN).

Thomas Roure and Philippe Sanial. (2011), *C-PLY™, a new structural approach to multiaxials in composites*, JEC Composites Magazine, No68:53–54, October 2011. Special JEC Asia.

Tsai SW, Nettles AT. (2011),Representative test data on bi-angle thin-ply NCF. JEC Compos Mag;68:62–3.

Vanttinen, A., (2008), *Strength prediction of composite rib foot corner*, Ms thesis,Helsinki University of Technology.