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Finite element analysis of 4ENF testing of stitched carbon/epoxy laminate

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Abstract. Stitching technique improves both mode I and mode II delamination toughness significantly by reducing the opening and sliding displacement, respectively. However, measuring mode II delamination behaviour of stitched composites using three point end notched flexure test (ENF) is facing a serious problem where the premature failure of specimen occurs prior to delamination propagation. This work is addressed to conduct numerical study of four points end notched flexure (4ENF) test of stitched composites. Four models were simulated including unstitched unidirectional, unstitched multidirectional laminate, stitched multidirectional laminate with and without tabs on top and bottom of specimen. Furthermore, stitch threads were modelled using spring connectors with user define force-displacement relationship. Load-displacement and crack propagation length vs. displacement curves were plotted. Stress distributions across the thickness were also presented to recognize the possibility of specimen damage during the test. The results showed that simple 4ENF test seems to be quite enough for evaluating mode II critical energy release rate (G_{IIC}) at the initial crack length of 35mm. However to evaluate R-curves (G_{II} vs. crack propagation length) of stitched multidirectional laminate, tabbed 4ENF test specimen is recommended.

1. Introduction

Despite of excellent strength and stiffness to weight ratio of carbon fibre reinforced plastics (CFRP), the delamination between plies become a serious issue of conventional laminates. Stitching is one of potential 3-Dimensional reinforcement by inserting threads in the thickness direction during preform fabrications.

The improvement of mode I delamination toughness of stitched laminates have been evaluated successfully using double cantilever beam (DCB) test [1, 2]. However, evaluation of mode II delamination properties using three points end notched flexure (ENF) is facing a difficult problem. The laminate is failed prior to delamination propagation. To overcome this problem, tabbed end notched flexure (TENF) test has been conducted [3, 4]. Embedded plates (tabs) at top and bottom side of the specimen require a modification of data reduction method [3]. In case of stable crack propagation, compliance calibration method could be directly applied for TENF test.

Four points end notched flexure (4ENF) test is a simple test with stable crack propagation[5]. Many data points could be recorded with stable crack propagation, so that R-curve (energy release rate vs. crack propagation) could be obtain using one specimen. This work is addressed to conduct feasibility study of using 4ENF test for mode II delamination properties of stitched composites. Both normal 4ENF and tabbed 4ENF specimen of stitched multidirectional laminate are investigated numerically using commercial finite element software (ABAQUS). The maximum normal stresses are used to predict whether the specimens failed before the delamination reach mid of the span. Furthermore, R-curve of stitched composite was also predicted based on compliance calibration method.

2. Modelling techniques

2.1. Modelling of 4ENF test

The schematic set-up for Tabbed 4ENF testing is shown in figure 1 and related finite element model is described in figure 2. The fixture dimensions refer to the work reported by Davies et.al [6]. It is important to be noted that center loading pin has capability to be rotated so that the load is kept balanced during the test. Similar set-up for normal 4ENF test is modelled by omitting the tabs. In this study, the fixture is also considered in the finite element analysis because the relatively high load used during the test for stitched laminate. Therefore the fixture is also modelled as 3-dimensional geometry instead of a simple rigid shell. The laminate consist of 20 layers of carbon fibers with lay-up order of [+45/90/-45/0/0/+45/90/90/-45/0]s. The mechanical property of laminae is calculated based on homogenization method using in house codes [7] and summarize in table 1. The thickness of each layer is 0.205 mm, and total thickness of specimen is 6.35 mm including aluminum tabs and adhesive bonding. Four types of finite element models are developed, called unstitched unidirectional, unstitched multidirectional laminate, stitched multidirectional laminate with and without tabs. Both of unidirectional and multidirectional laminate consist of 20 layers as described above. The delamination propagates at 0°/0° interface for all models.

The crack tip is positioned exactly after the first stitch row with the distance of 35 mm from the lower-right support pin as shown in figure 1. This crack tip position (in between first and second stitch rows) is important in the experiment to capture effect of stitching on fibers volume fraction [4].

Table 1. Mechanical property of laminae

E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	G_1 (GPa)	G_2 (GPa)	G_3 (GPa)	υ_{12}	υ_{13}	υ_{23}
158.6	4.7	4.7	3.8	3.8	2.7	0.33	0.33	0.47

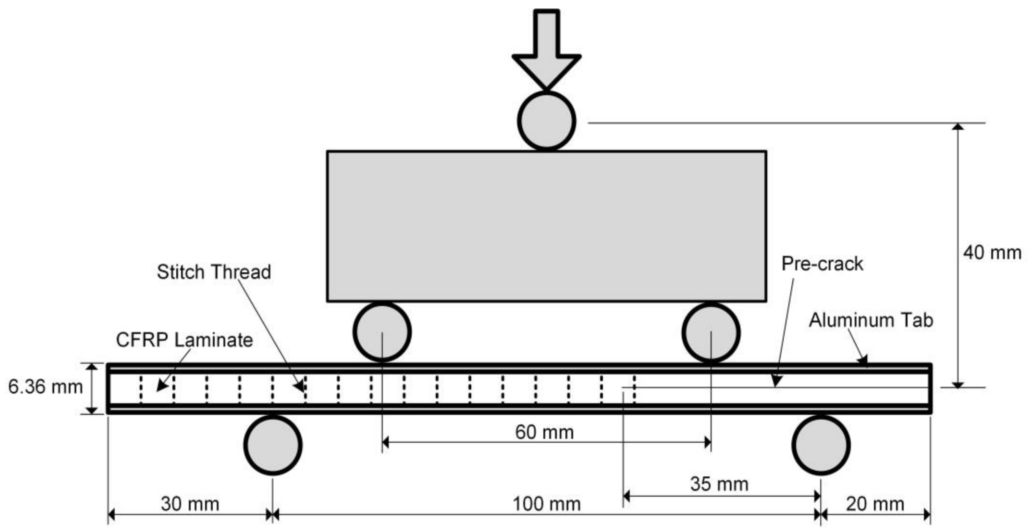


Figure 1. Set-up of tabbed 4ENF test.

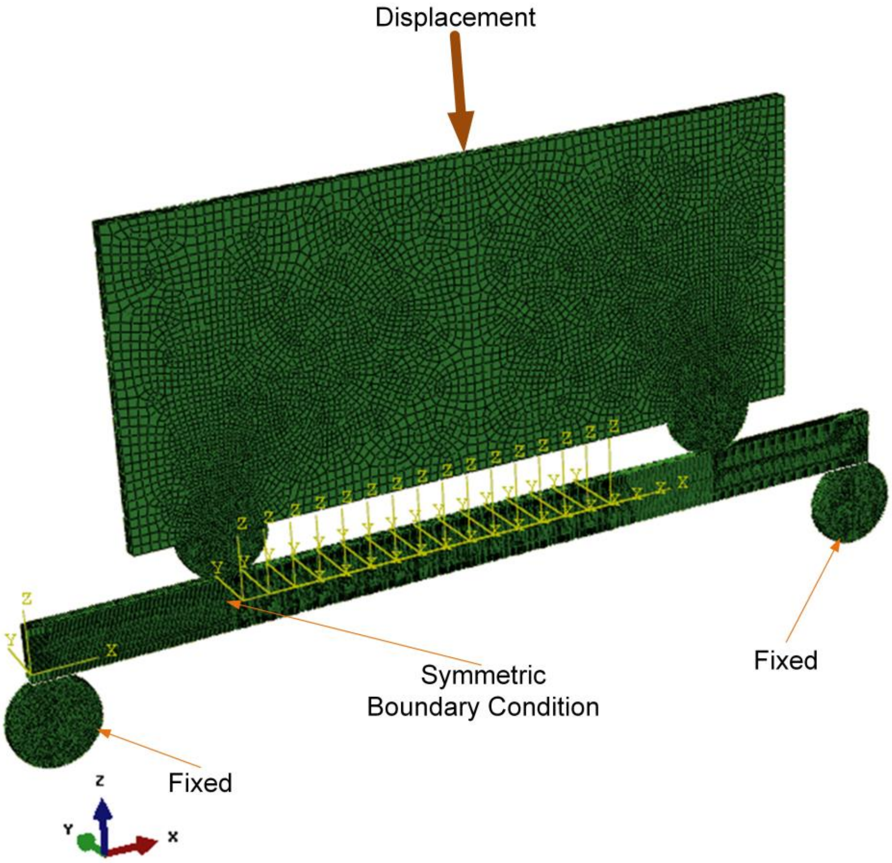


Figure 2. Finite element model of tabbed 4ENF test of stitched laminate.

2.2. Modeling of stitch threads

The stitch threads are modeled by spring connector elements. Mechanical properties of spring connector are defined using inter-laminar shear tested (IST) of single stitched laminate (figure 3) [8]. All nodes in stitch thread areas at interlaminar surface of upper and lower laminate are constraint by multi point constraints (MPCs) as shown in figure 4. The diagonals of MPCs area are measured from actual specimens. Furthermore spring connector element connects the center node of MPC area. Figure 5 presents a typical result of single stitched laminate of previous work [8] that adopted in modeling 4ENF test.

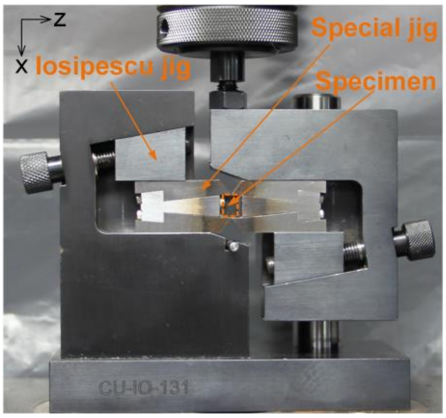


Figure 3. Single stitched laminate under pure shear testing.

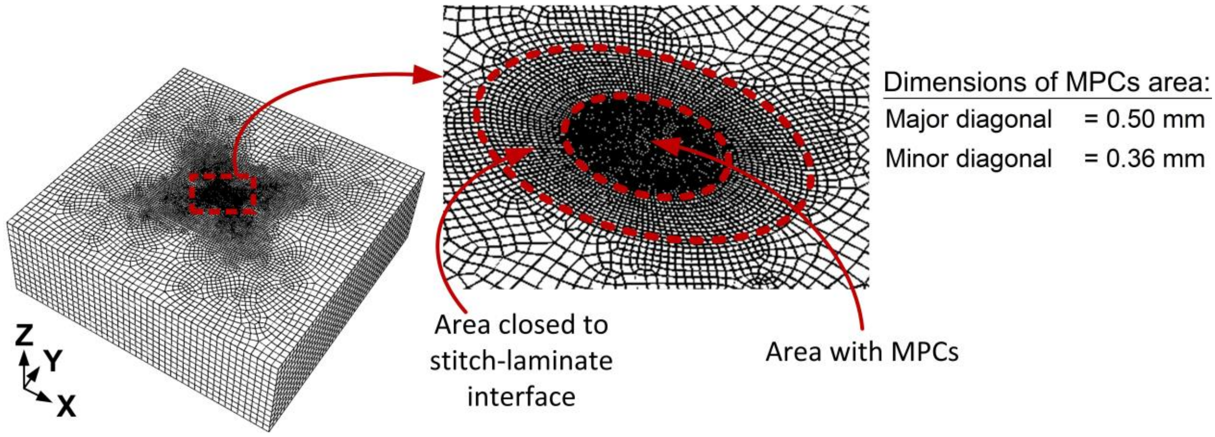


Figure 4. Modelling of single stitched laminate[8].

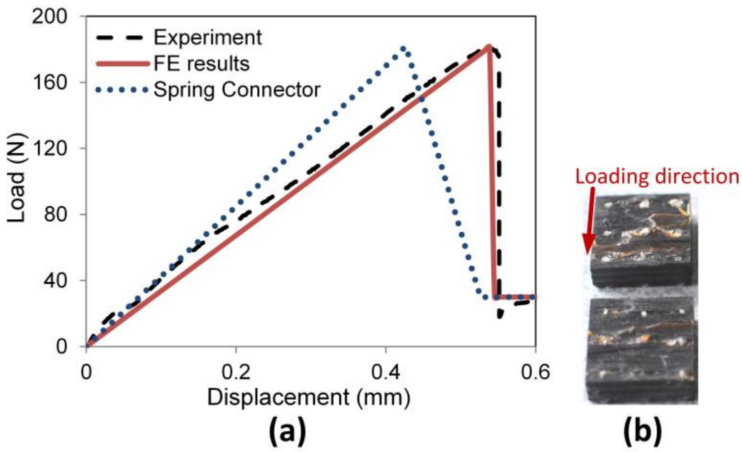


Figure 5. Single stitched laminate under pure shear testing.

2.3. Delamination criterion

In order to simulate delamination propagation, cohesive zone elements are used and inserted at mid-layer (figure 6). Initial delamination happened whenever a quadratic stress failure criterion (equation (1)) is satisfied.

$$\left\{\frac{(\sigma_I)}{\sigma_I^o}\right\}^2 + \left\{\frac{\sigma_{II}}{\sigma_{II}^o}\right\}^2 + \left\{\frac{\sigma_{III}}{\sigma_{III}^o}\right\}^2 = 1 \tag{1}$$

where $\sigma_{I,\ II,\ III}$ are stress component under pure mode I, II, and III, meanwhile $\sigma^0_{I,\ II,III}$ are critical interfacial strength for each kind of loading mode.

Furthermore, damage (delamination) growth is controlled by mixed mode fracture energy criterion (equation (2)) with exponential softening fracture-based method. Mode I and mode II energy release rates are obtained from experiment while mode III is assumed to be the same with mode II. The cohesive zone parameters are listed in table 2 which are obtained from previous work [8].

$$\left\{\frac{G_I}{G_I^c}\right\}^\alpha + \left\{\frac{G_{II}}{G_{II}^c}\right\}^\alpha + \left\{\frac{G_{III}}{G_{III}^n}\right\}^\alpha = 1 \tag{2}$$

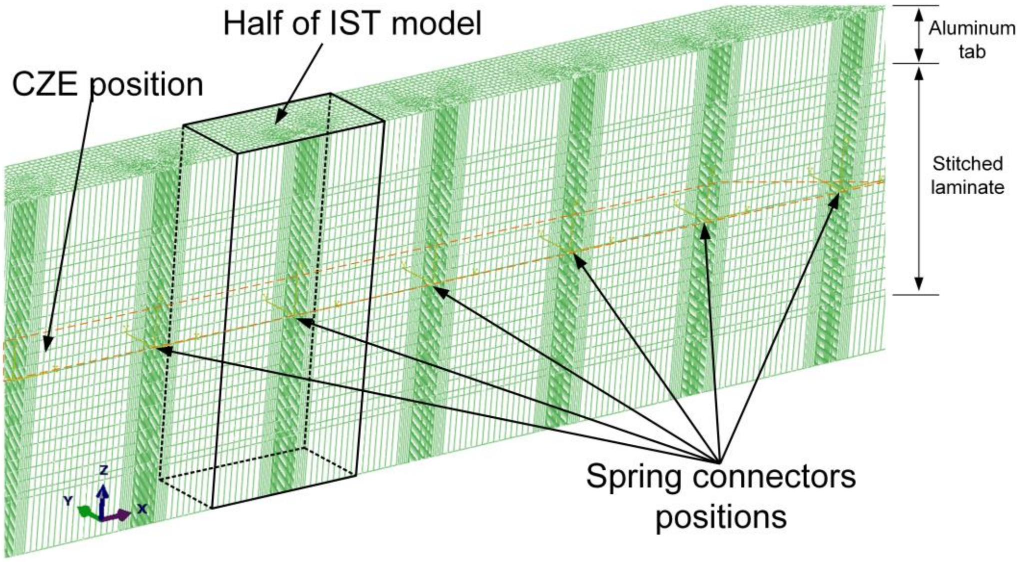


Figure 6. Tabbed 4ENF meshing technique.

Table 2. Cohesive zone parameters

K_0 (N/m^3)	σ_I^o (MPa)	σ_{II}^o (MPa)	σ_{III}^o (MPa)	G_I^c (J/m^2)	G_{II}^c (J/m^2)	α
4.25 x 10^{14}	40	70	70	450	800	1

2.4. Energy release rates prediction
Energy release rate is calculated from the simulation results based on compliance calibration method following equation (3):

$$G_{IIC} = \frac{mP^2}{2B} \quad (3)$$

where m is the slope of compliance vs. crack length, P is a certain load where delamination start to propagate, and B is the width of the specimen. To obtain the value of m, the compliance of the model are simulated at the crack length of 35, 38, 41, and 44mm. Noted that these crack length involved 1, 2, 3, or 4 active stitch threads at the delaminated area, respectively.

3. Results and discussion

3.1. Load displacement curve
Load-displacement curve of unstitched laminate models for unidirectional and multidirectional laminate are plotted in figure 7 and 8. The load-displacement curve of unidirectional laminate model showed higher stiffness compared to multidirectional one and need shorter deflection for crack tip to reach the centre of loading span. This could be happened because the delamination occurred at the same interface (0°/0°) and the mode II energy release rate (area under the curve) should be the same.

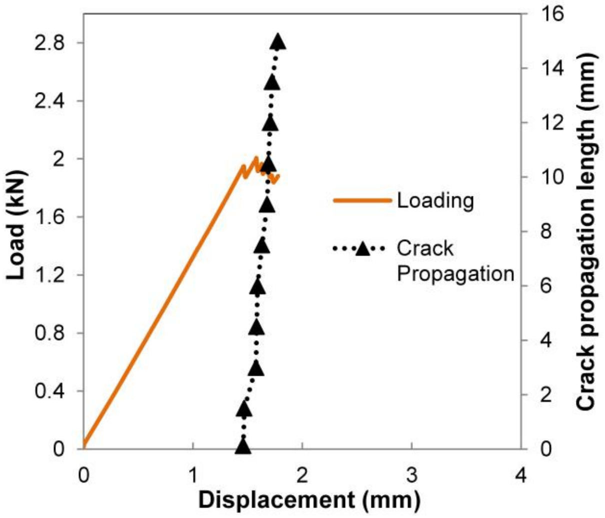


Figure 7. Load-displacement curve of unstitched unidirectional laminate.

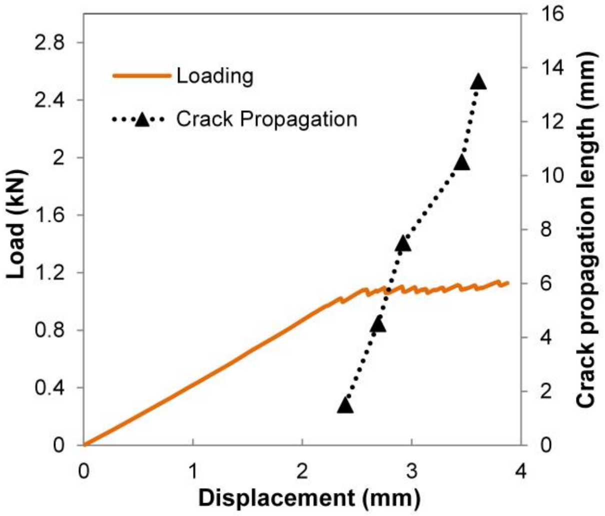


Figure 8. Load-displacement curve of unstitched multi-directional laminate.

Load-displacement curve of stitched laminate using 4ENF and T4ENF are plotted in figure 9 and 10. Both stitched laminate models are multidirectional laminate. On the other hand, stitched unidirectional laminate is not considered in this study because stitching process usually requires multidirectional in-plane fibre orientation, thus the preform can be stretched in many directions to minimize fibre waviness. Aluminium tabs at T4ENF specimen increased the stiffness but decreased the deflection/displacement needed to propagate the crack till mid of span. Both curves also showed that the load still increased during crack propagation which indicate that the more active stitch threads at delaminated area, the more load could be absorbed by the stitch threads.

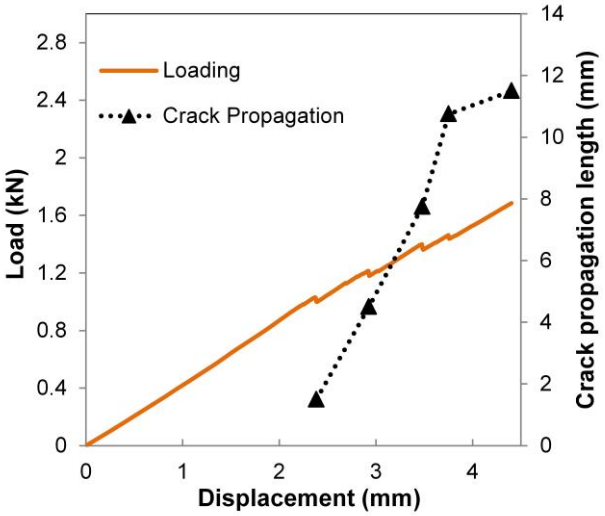


Figure 9. Load-displacement curve of stitched multidirectional laminate under 4ENF test.

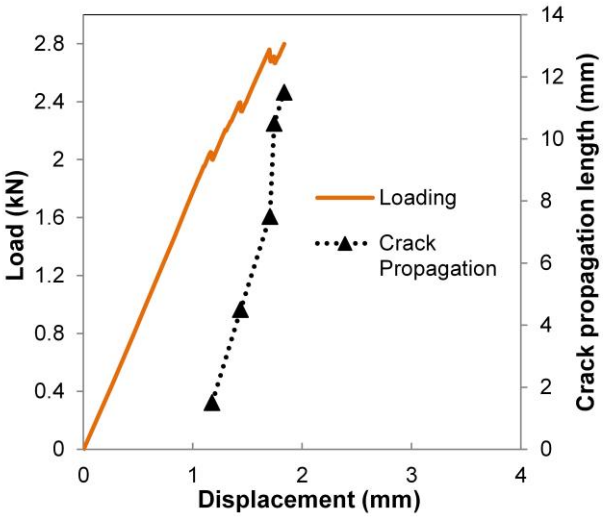


Figure 10. Load-displacement curve of stitched multidirectional laminate under Tabbed 4ENF test.

3.2. Stress distribution along the thickness direction

Figure 11-12 exhibit normal stresses (S_{11}) distribution of 4ENF and T4ENF simulation results at the end of simulation in Figure 9-10. It is important to be noted that actually the highest stress area is around stitch region at delaminated area, but it is excluded from the figures because the energy dissipated by damages around stitch threads are taken into account in G_{IIC} calculation. However, damage occurred in another region (except at interlaminar area) is prohibited during mode II delamination test.

In order to investigate the possibility of damage at each layer, the maximum normal stresses at the middle of loading span region are plotted in figure 13. It is clearly shown that aluminum tabs significantly reduced maximum normal stresses at each layer to become about one third of those in laminate without tabs. Additionally, since the yield strength of aluminium alloy 7075 T6 is about 450-500 MPa, it could also be ensured that there is no plastic deformation at aluminium tab until the end of simulation. Therefore, T4ENF specimen is recommended for mode II delamination testing of stitched composites.

The use of standard 4ENF specimen seems still acceptable for limited purpose such as measuring G_{IIC} at initial crack length of 35 mm. To understand the maximum condition where standard 4ENF can be used, further study is required to investigate matrix crack during the test simulation which strongly depend on matrix properties.

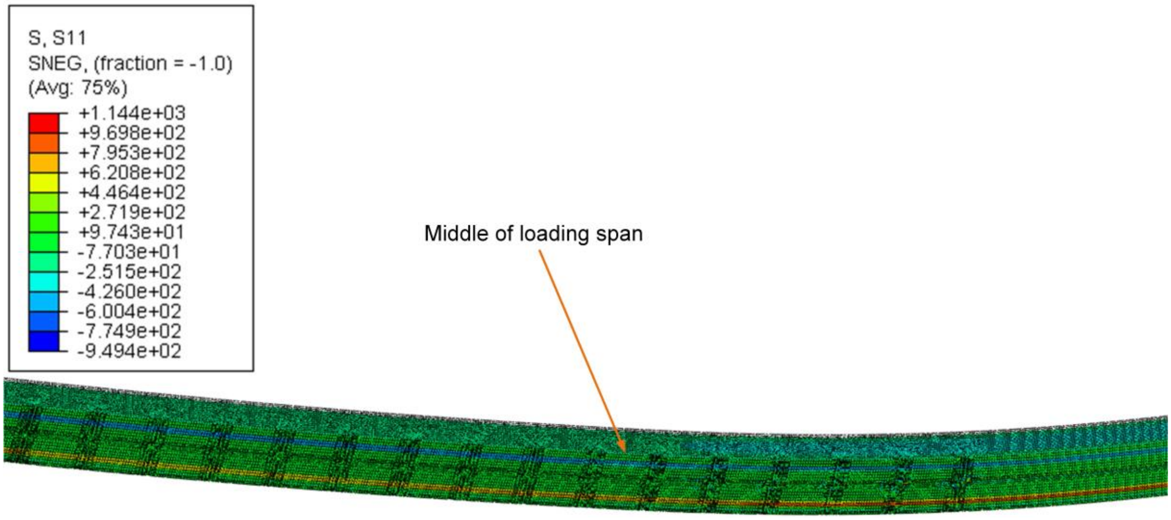


Figure 11. Stress distribution (S_{11}) in 4ENF simulation.

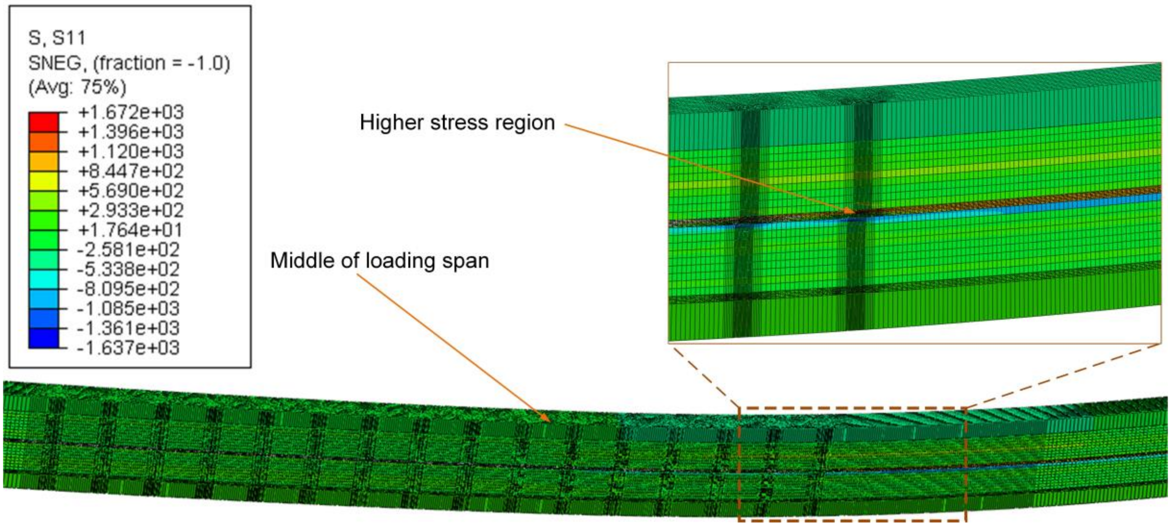
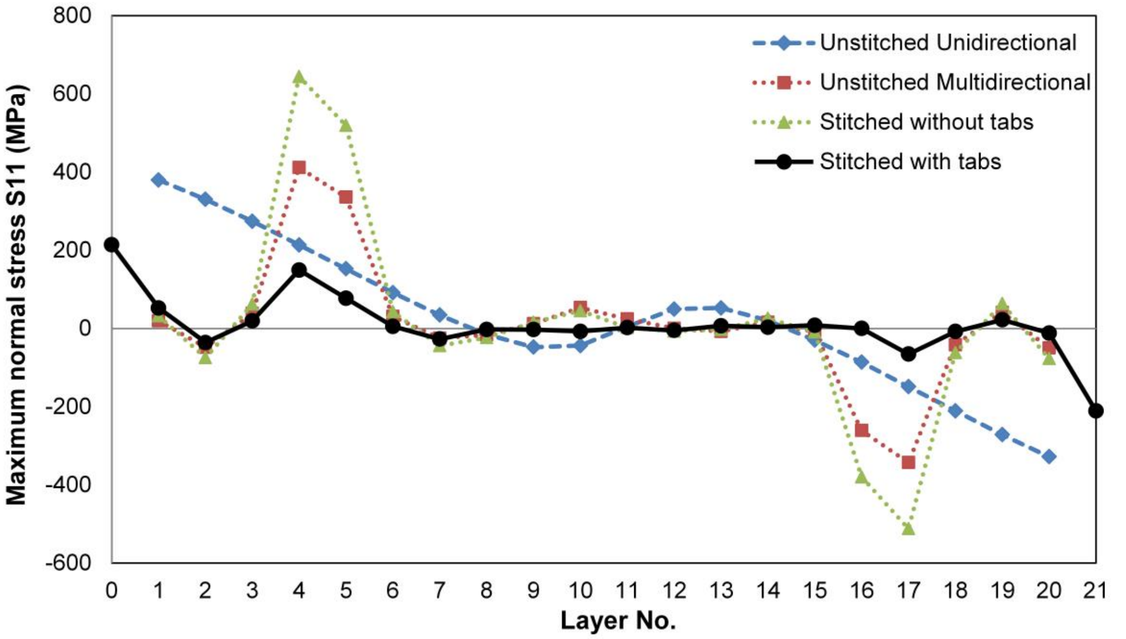


Figure 12. Stress distribution (S_{11}) in tabbed 4ENF simulation.

3.3. Predicting of energy release rate

A typical compliance vs. crack length curve is plotted in figure 14. The slope (m) can be calculated from the curve as shown in the same figure. Furthermore energy release rates were calculated using equation 2 and plotted in figure 15. Figure 15 exhibited energy release rate of stitched laminate is twice the unstitched one (0.88kJ/m^2). However, G_{II} values are still increasing continuously and saturated value could not be achieved. The more crack propagate, the more active stitch thread at delaminated region. Saturated region could be achieved if the stitch thread starts to be broken. From displacement data of each spring connector, the maximum displacement is about 0.2 mm which is much longer to be broken. Increasing deflection of specimen, until stitch thread broken, has to be done carefully considering matrix crack and fiber rupture. The thickness of the aluminum tabs could be increased as well, but one has to check shear stress at the interface of aluminum and laminate. Thicker tab create higher shear stress at the tabs-laminate interfaces that prone to be de-bonding.



Layer No	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Orientation	LowerTab	45	90	-45	0	0	45	90	90	-45	0	0	-45	90	90	45	0	0	-45	90	45	UpperTab

Figure 13. Maximum normal stress distribution across the thickness.

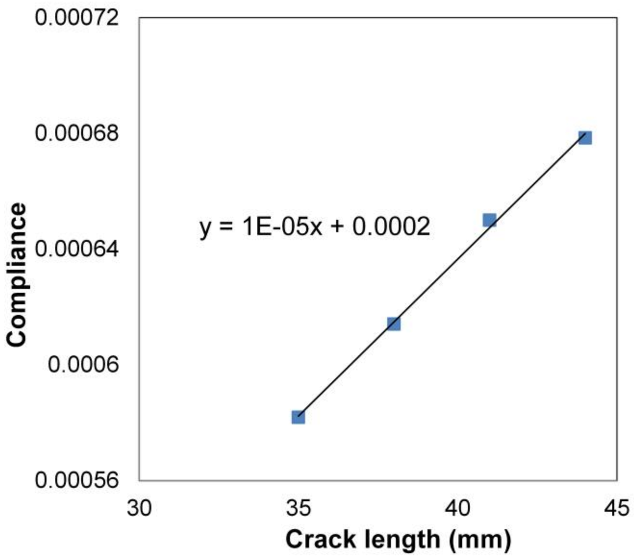


Figure 14. Compliance vs crack length.

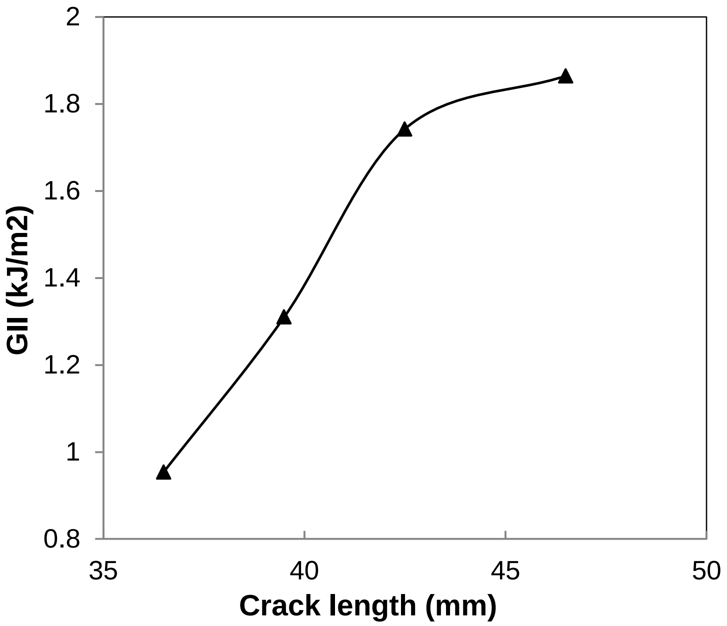


Figure 15. Energy release rate vs. crack length (R-curve).

4. Conclusion

A finite element analysis of 4ENF and T4ENF test has been conducted. In order to obtain energy release rates vs crack length (R-curve), T4ENF has to be used to avoid matrix crack. Predicted energy release rates of stitched laminate are twice the value of unstitched one. Higher energy release of stitched laminate could be achieved with longer crack length, but one has to ensure that there is no matrix crack occurred. It is also possible to increase thickness of aluminium tab to reduce more normal stress (S11) in each layer of laminate. In case of increasing the thickness of aluminium tab, the shear stress between tabs and laminate should be carefully controlled to be not more than the critical interfacial stress.

Acknowledgments

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