PREDICTING LOW VELOCITY IMPACT DAMAGES IN STITCHED COMPOSITE LAMINATE

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Abstract

Stitching has been proved experimentally to be an effective technique for suppressing delamination in composite laminates. A general tool such as finite element simulation is needed to optimize the design of stitched composites. This work is addressed to develop finite element model of stitched composites subjected to quasi-static indentation model that represent low velocity impact loading. Surface based cohesive contact is used to simulate delamination, and spring connector elements are used to represent the stitch threads. Cohesive contact is chosen because it can be applied simultaneously with friction contact which is important in taking into account effect of through thickness compression. The properties of spring connector is obtained using a novel method called interlaminar shear test (IST) that evaluates single stitched laminate under shear loading. As initial study, a quasi-static indentation test on $[90_3/0_3]$s laminate is simulated for both stitched and unstitched laminate. The predicted load displacement curves show good agreement with experimental one and delaminated area of stitched laminate, at 1.8 mm indenter displacement, is smaller than unstitched one.

1. Introduction

Composite laminates, particularly carbon fibers reinforced plastics (CFRP), have a superb strength and stiffness to weight ratio. However, composite laminates are very weak in thickness direction and prone to be delaminated at interlayer. To solve this problem, 3-dimensional reinforcement using stitching, Z pinning, weaving, knitting are attracting many researchers [1]. Stitching is one of potential method that conducted by inserting threads in the thickness direction during preform processing as shown in Fig. 1 (for modified-lock stitching type). Stitching has been proved experimentally that increase mode I and mode II critical energy release rates of CFRP by 900% [2] and 250% [3], respectively. Stitch threads also suppress the delamination area due to low velocity impact [4, 5] which improves the compression after impact (CAI) properties simultaneously [6].

A reliable numerical tool is needed for further application of stitched composites, so that optimum structural design with stitched composite can be obtained. This work is addressed to provide a numerical analysis of delamination on stitched composites subjected to quasi static indentation (QSI). It is well known that QSI can represent low velocity impact test [7, 8].

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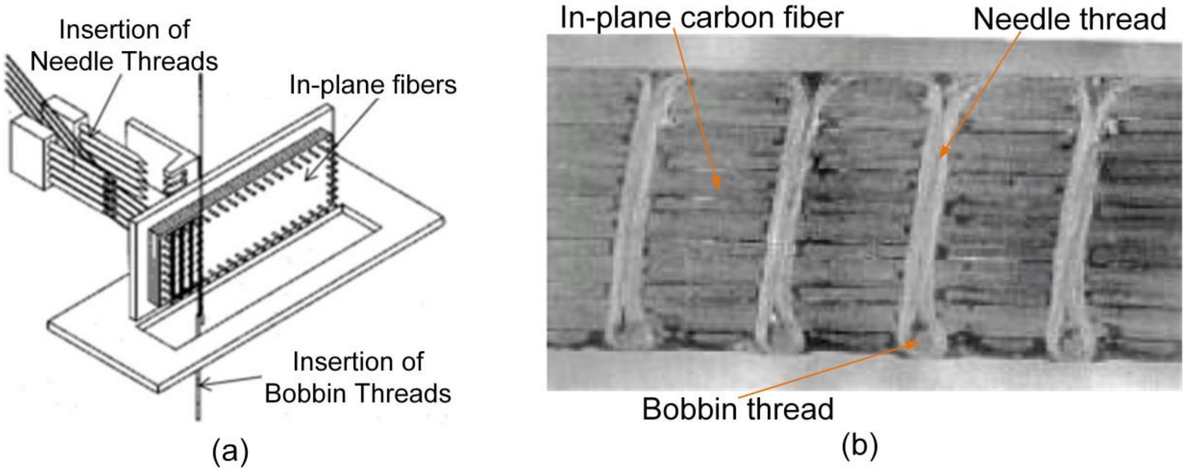

Figure 1. 3D-reinforcement by stitching with modified lock technique (a) Manufacturing process (b) Cross-sectional of stitched laminate

2. Modelling Techniques

2.1. General Techniques

The simulations are conducted step by step, starting from small and simple model of single stitched laminate as shown in Fig.2. These steps are required to verify the most important points in modeling of QSI such as interaction of stitch thread with laminate, delamination propagation, and matrix crack.

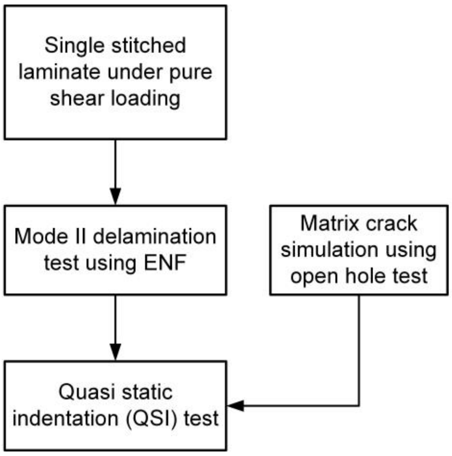

Figure 2. Simulation steps.

2.2. Modelling of stitch thread and delamination propagation

In order to understand the interaction between stitch thread and laminate, interlaminar shear test (IST) of single stitched laminate using a modified Iosipescu fixture was conducted in the previous work [9]. Based on this experimental result, finite element model of single stitched laminate was developed and spring connector element was used to represent the stitch thread.

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The elements at stitch thread area are constraint using multiple points constrains (MPCs) as described in Fig.3.

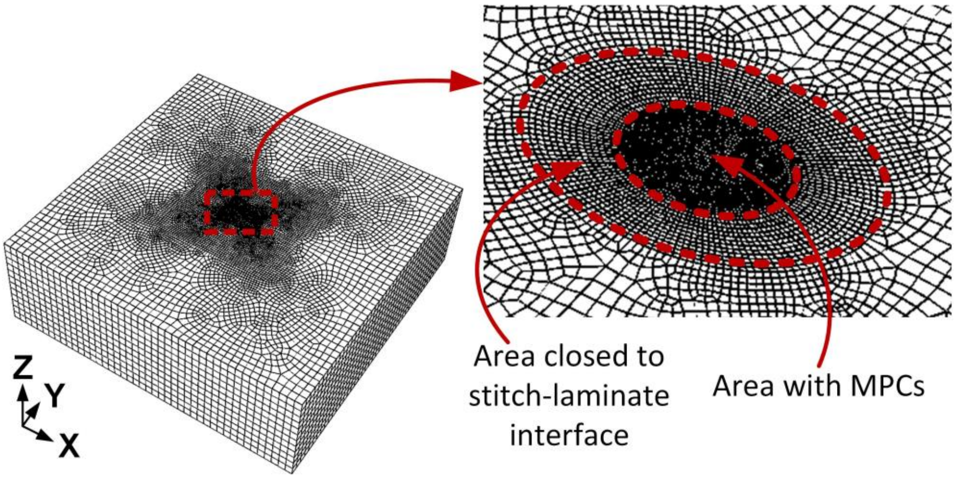

Figure 3. FE model of single stitched laminate.

Modeling technique of single stitched laminate is then adopted in modeling mode II delamination test using tabbed end notched flexural (TENF) test. To simulate delamination propagation, cohesive zone model (CZM) is applied at interlaminar where the delamination occurred. Detailed of the first two steps in Fig.2 have been discussed in the previous work [9].

2.3. Simulating matrix crack

Matrix crack is prohibited to be occurred during mode II delamination test, therefore do not consider in related finite element simulation in the previous work. In case of quasi static indentation, matrix crack has to be modelled as another type of damage beside delamination. To simulate matrix crack in this work, Hashin`s criterion (Eq. 1) for matrix tension crack initiation is applied to the model.

$$\left\{\frac{\sigma_{yy}}{Y_T}\right\}^2 + \left\{\frac{\sigma_{xy}}{S_{xy}}\right\}^2 + \left\{\frac{\sigma_{yz}}{S_{yz}}\right\}^2 \geq 1 \tag{1}$$

where σ_{yy} is normal stress perpendicular to fiber direction at each layer. σ_{xy} and σ_{yz} is in-plane and out of-plane shear stress, respectively. Y_T is matrix tensile strength, meanwhile S_{xy}, and S_{yz} is matrix shear strength in-plane and out of-plane direction, respectively. In this study, the matrix tensile strength is 30 MPa, and matrix shear strength is 80 MPa.

Once matrix crack occurred, the laminate properties are degraded to become 20 % of its original value for E_{22}, G_{xy}, and G_{yz}, refers to parametric studied by Tserpes et.al [10]. Both of matrix crack initiation and materials degradation rules are simulated using user subroutine USDFLD in Abaqus package. To verify the user subroutine, a simple open-hole tension test of four layers unidirectional laminate is simulated as described in Fig. 4. Two types of unidirectional laminate are modelled which are 0° and 90°.

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Figure 4. FE model of open hole test.

2.4. Quasi static indentation model

The experimental work reported by Aymerich et al. [11] on low velocity impact is simulated in this study. The laminate consist of 12 ply with orientation $[0_3/90_3]s$ and manufactured from Seal-prepreg graphite/epoxy HS160/REM. Mechanical properties of laminate are listed in Table 1. The specimen size was 65 x 87.5 mm with average thickness of 2 mm. Low velocity impact test was conducted on a drop-weight impact testing machine using a hemispherical nose steel impactor of 12.5 mm diameter. The samples were simply supported on a steel plate with a 45 x 67.5 mm rectangular opening.

Table 1. Mechanical properties of laminate.

Elastic Modulus (GPa)		Shear Modulus (GPa)	Poisson`s Ratio
E_{11}	$E_{22} = E_{33}$	$G_{12} = G_{13} = G_{23}$	$\upsilon_{12} = \upsilon_{13} = \upsilon_{23}$
125	7.45	3.97	0.261

The finite element model is developed using the commercial software ABAQUS package. To reduce computational time, only a quarter of specimen is modelled with symmetric boundary condition. The size of laminate model is 38.75 x 22.5 x 2 mm as shown in Fig. 5. Each layer is modelled by one element in thickness direction. Solid elements (C3D8) are used with element size of 0.23 x 0.27 mm [11]. At stitch threads region, much smaller element size is used (0.05 x 0.05 mm). Moreover, the impactor is model as a rigid body so that do not include in the analysis. Surface based cohesive contact is used to simulate delamination instead of using cohesive zone element. Cohesive contact is selected considering its capability to be used simultaneously with contact friction at the interlaminar. Moreover, cohesive contact surface reduce computational calculation because it does not need additional element. The parameters of cohesive contact are listed in Table 2. Once delamination occurred, the delaminated surfaces still in contact each other with contact friction coefficient of 0.6 which refers to parametric study conducted by Zhang and Zhang [12].

Table 2. Cohesive contact parameters.

Stiffness (MPa/mm)		Strength (MPa)		ERR (J/mm^3)	
K_I	$K_{II} = K_{III}$	σ_I^o	$\sigma_{II}^o = \sigma_{III}^o$	G_n^c	$G_s^c = G_t^c$
120,000	43,000	30	80	0.52	0.97

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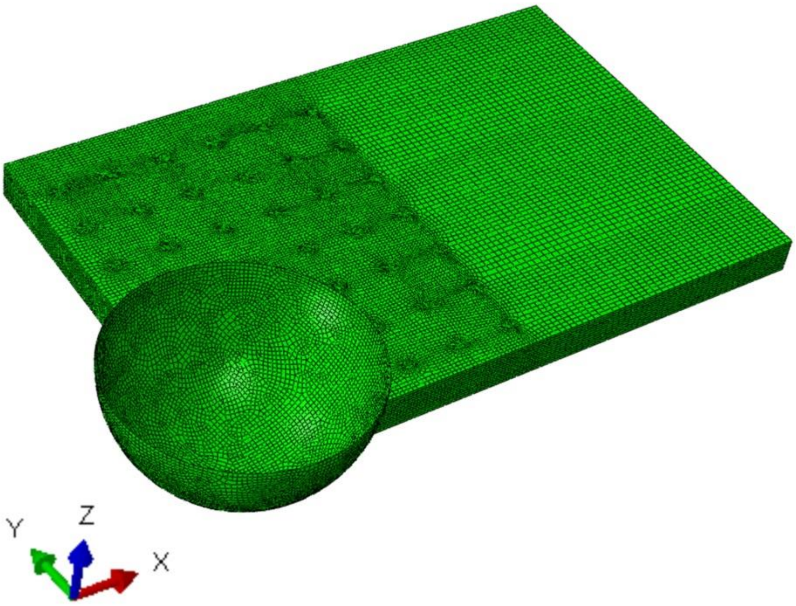

Figure 5. FE model of stitched laminate under QSI.

3. Results and discussion

Verification of user subroutine that used to model matrix crack is shown in Fig. 6. The red elements indicate the place where matrix crack happened for both unidirectional laminate. It is confirmed that the matrix cracks occurred parallel to fiber direction. Both simulations results (Fig. 6) are captured at the end of load-displacement curve shown in Fig. 7.

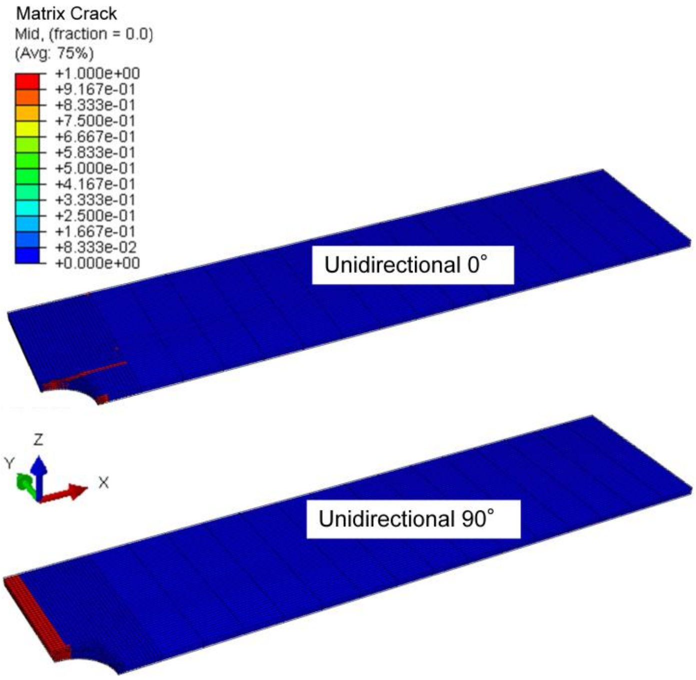

Figure 6. FE results of open hole simulation.

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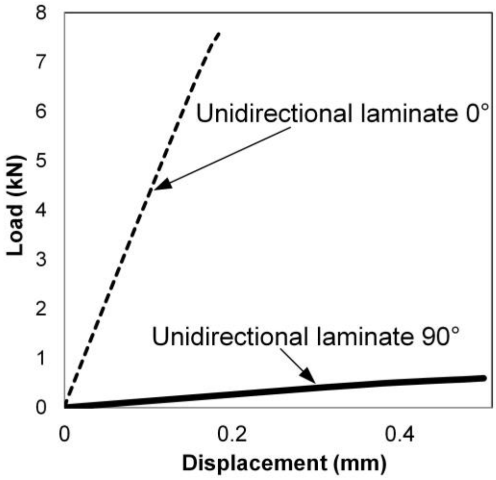

Figure 7. Load-displacement curves obtained by open-hole test simulation.

Results of QSI simulation are plotted in Fig. 8 and 9. The predicted load-displacement curves for unstitched and stitched laminate are close to experimental one. However, the predicted slopes change earlier. To understand the reason of earlier change of the slopes, the effect of matrix tensile strength is investigated as shown in Fig. 9. The matrix tensile strength showed negligible effect on load displacement curve. The point where the slope change is still cannot be captured exactly, therefore further study still required such as on the effect of cohesive contact properties, materials degradation rule, etc.

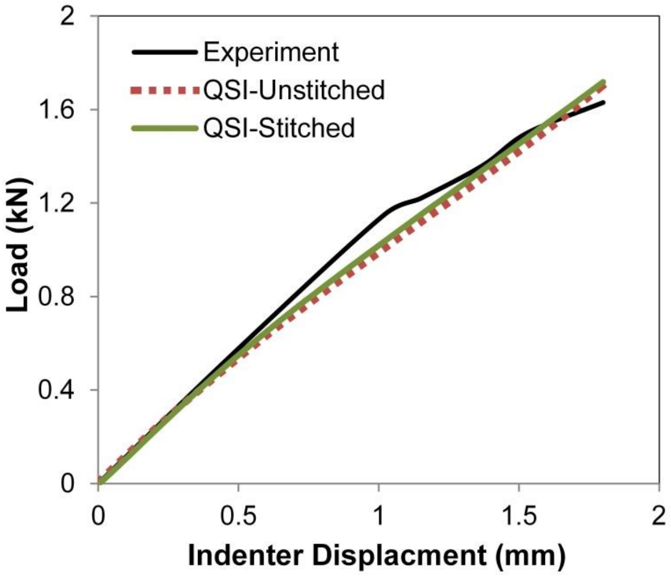

Figure 8. Predicted load displacement curves of QSI in comparison to experimental results [9].

Furthermore, the size of predicted delamination areas is exhibited in Fig. 10. Although it is difficult to distinguish exactly the value of delamination area, it can be understood that the delamination area of stitched laminate is smaller than experimental one which shows the delamination suppression by stitch threads. The difference could be clearer at higher level of load or indenter displacement.

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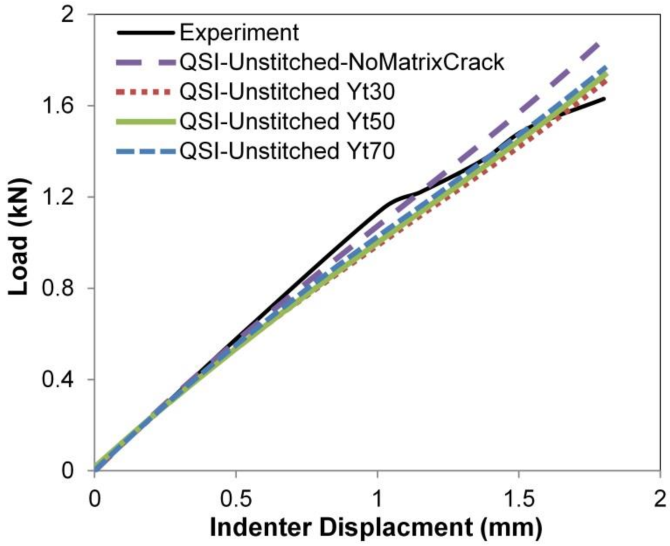

Figure 9. Effect of matrix tensile strength on QSI results

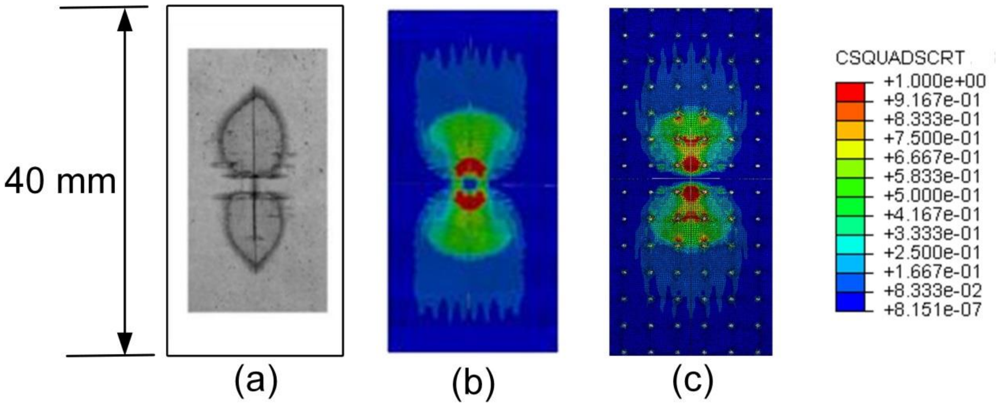

Figure 10. Predicted delamination of unstitched and stitched laminate in comparison to experimental result [11].

4. Conclusions

Quasi static indentation simulation has developed step by step. The predicted load displacement curves are closed to the experimental one. The slope of simulation results change earlier and the reason is not perfectly addressed. Future studies are required to understand the reason of this earlier change such as on degradation rules, cohesive contact properties, etc. The predicted delamination area of stitched laminate is smaller than unstitched one which confirmed the delamination suppression by stitch threads.

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