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Effect of Ply-Drop on Stress and Strain Fields in Tapered Thermoplastic Matrix Composites

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Abstract. The analysis of ply-drop in carbon fibre reinforced thermoplastic composite with PPS matrix was carried out using numerical modelling. The results of fatigue tests yielded the ply-drop as a critical point when cyclically loaded in tension. Several delaminations were found in phractography in the area of ply-drop. The finite element model was build using ply-by-ply technique, that enables to evaluate the stress and strain fields in each lamina. The concentrations at the interface of terminated plies and resin rich region were identified. The terminating ply with orientation of 0/90° causes high stress concentrations of shear stress in connection with adjacent plies and high strains in resin rich region. The proper choice of terminated ply location can extend the fatigue behaviour considerably.

Introduction

Woven composites are used in aerospace due to its high strength and stiffness-to-weight ratio. In order to reach this goal, the thickness is reduced in locations of lower loading resulting in terminating of plies (ply-drops), that are generally stress and strain concentrators. Its effect on strength, fatigue characteristics and fracture mechanism has not yet been widely investigated for the modern aerospace-grade composites with thermoplastic matrix.

Several types of thickness variations by ply-drops can be classified according to Ref. [1] as external, internal (longitudinal or transverse), and mid-plane ply-drop constructions. Basically, a ply-drop can be embedded between plies or at the surface. The bonded top plies located at the continued ones can suffer by separation owing to interlaminar cracks emanating from free surface as studied in Ref. [2]. Inserting semipregs to proper structure areas can achieve more uniform stress distribution and lead to the desired thickness change and the inclination to separation of adjacent plies can be suppressed as well.

Modelling the stress and strain field at ply-drop can show the issues of concentrations and help to optimize the design of ply stacking. In present work, the shear stress concentration on ply drops and longitudinal stress on the tapering transition were analysed by modelling. In fatigue loading, these concentrations cause delamination initiated by loading in mode I or II as observed in Ref [3].

Fatigue test. Presented analysis was carried out investigating the delamination occurring during fatigue tests in ply-drops of tailored blank C/PPS thermoplastic composite as shown by fractography in Fig. 1. The delamination raised by fatigue loading typically initiated at the termination of the ply oriented 0/90°. The fabric had a five-harness satin weave, so the crossing of yarns causes the wavy yarn laying. The thickness transition was made from 16 to 11 layers, i.e. the layup before transition was $[0/90, \pm 45]_{4s}$ and after that $[(0/90, \pm 45)_2, \overline{0/90}]_s$. The nominal thicknesses of the sections were 4.96 mm for 16 layers, 3.41 mm for 11 layers and the tapered angle was 6°. During manufacturing of thermoplastic composite, the layers of tailored blanks are positioned, stacked together and cured in the die. Nevertheless, some slip can occur and finally the layers can be displaced in the range of mm. Such slip can be seen in Fig. 1, where layers ±45° and 0/90° should terminate together.

The fatigue test was performed under tension loading with frequencies in the range of 0.5–15 Hz and the load ratio of 0.05. The symmetric tension specimens with thinner part with 11 layers in the centre were tested. The thicker part was clamped on both sides. Mainly two fracture modes were present due to fatigue: Fracture at a ply-drop and fracture away from the ply-drops. The former one was analysed in more detail as described in following section.

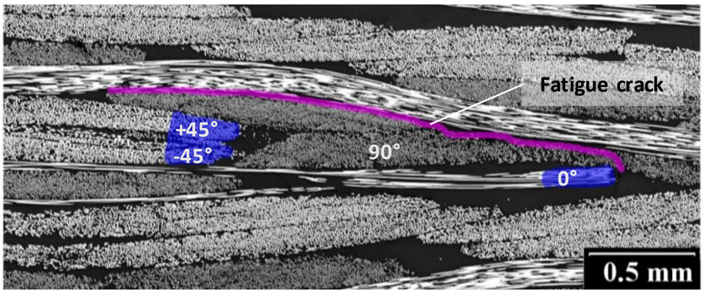

Fig. 1: Laminate cross-section after 34 000 cycles, showing delamination (fatigue crack) initiated from 0/90° ply drop.

Modelling. Woven composites are heterogeneous materials that are not easy to characterize computationally. There are several difficulties owing to hierarchical structure and microstructure. The modelling is being done in the macro (component), meso (fabrics) and micro level (yarn, tows) according to structure detail. The meso-scale analysis requires at least the characterisation of plies and the detailed 2D or 3D model shall be used. Such model can evaluate internal stress, interlaminar stress and can suggest stress risers and delamination.

Investigating fatigue cracks the 3D finite-element model of ply-drop was created using ply-by-ply technique, that enables to evaluate the stress and strain fields in each lamina. Some idealisation in the model was necessary to apply. The void volume at the ply transition was filled by resin assuming ends of two adjacent plies ±45° and 0/90° at the same location, but it was not generally true (note remark above). That volume was filled by PPS resin assumed as an isotropic material with Young's modulus of 3800 MPa and Poisson's ratio 0.36. Each ply was represented as 3D continuum with orthotropic material applied. The parameters were used according to Ref. [4] as follows: $E_{11} = E_{22} = 85$ GPa, $E_{33} = 10.5$ GPa, $G_{12} = 4.1$ GPa, $G_{13} = G_{23} = 3.5$ GPa, $\nu_{12} = 0.05$ and $\nu_{13} = \nu_{23} = 0.41$. Only an ideally linearly elastic material model was used in the analysis.

Analysis results. The FE model was loaded by 40 kN in tension. The results show some concentrations in ply-drop region. The highest longitudinal stress peak is located at the interface of the 0/90° ply and the resin rich region. The lower position (straight side of the specimen) is worse. The in-plane stress plot indicates the symmetry of the layup with stress peaks at continuous ply oriented ±45° caused by the termination of the ply oriented 0/90°, but the out-of-plane shear stress plot does not show clear stress symmetry (see Fig. 2) owing to tapered part in the top of the detail. Nevertheless, the peaks at the interface of continuous ±45° ply and the terminated one oriented 0/90° are clear. No severe stress peak is present in the middle at terminated ply oriented 0/90°. The stress plot is shown in Fig. 2 together with direct notation of the stress values in details of ply transitions. The red ellipses mark peak values.

In strain plot shown in Fig. 2, it is obvious that high concentrations are caused by termination of plies with orientation of 0/90° next to resin rich regions.

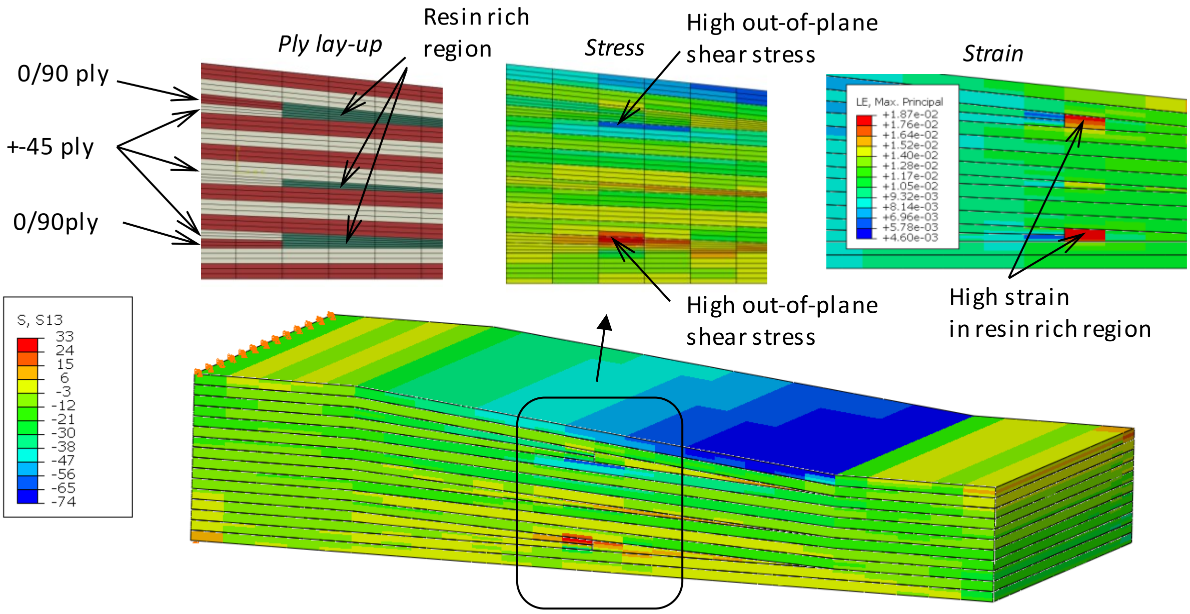

Fig. 2: FE half-model of the ply-drop; results at the load of 40 kN

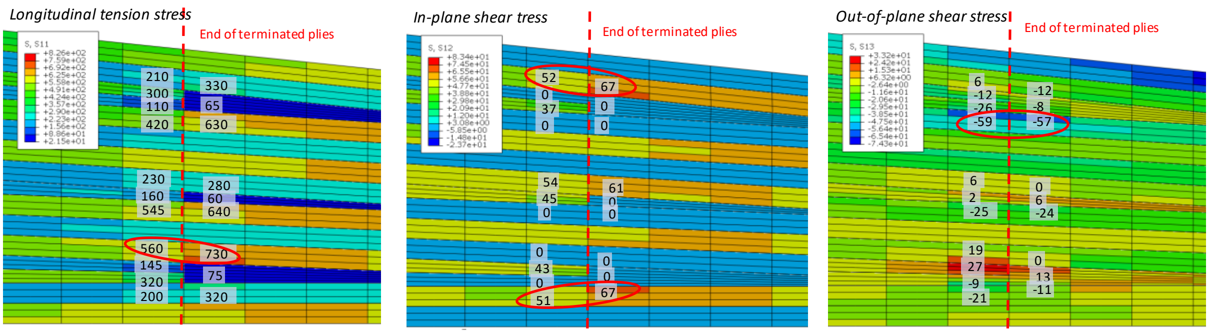

Fig. 3: Stress results in detail at the load of 40 kN; red ellipses marks peak values.

Discussion

From the point of view of crack initiation, the surface phenomenon should be considered. The fatigue crack initiates at the surface [5], therefore the interface of the resin and the fibre is critical. The difference in longitudinal stress between the 0/90° play and the resin region is 330 MPa, that is considerably high compared to 93 MPa of strength of pure PPS resin according to Ref. [6]. It suggests, that during loading, plastic deformation occurs. The results show linear strains in resin of 1.9 %, but due to high interface tension stress, the resin will be apparently plastically deformed and decrease the stress peak.

The FE results are consistent with experimental observations. Some fatigue cracks appeared at the termination point of the ply oriented 0/90° adjacent to the continuous one oriented ±45° (see Fig.1) and their growth continued along the ply oriented 0°. The growth is evidently driven by high shear stress. The other interesting finding was the indispensable heating during the fatigue test described in Ref. [3]. The heating of the specimen was greater together with increasing frequency of the cyclic loading. In addition to heating due to material damping, it could be caused by dissipation of the energy during plastic deformation and after the delamination, by friction between plies.

Conclusions

The FE analysis of the ply-drop in woven composite with thermoplastic matrix indicated several difficulties with the terminating plies. Less stress peak was determined in the middle of the specimen.

Without doubts, it can be said that the ply-drop is critical point with impact on fatigue behaviour. In analysed design, the ply-drop configuration is not the favourable solution owing to termination of two layers together. This approach enlarges the void filled by the resin and during fatigue loading the delamination occurs primarily in this location. The proper choice of terminated ply location can extend the fatigue behaviour considerably, e.g. to end the 0/90° plies in the thicker section, and the +-45° plies in the thinner section where the stress is higher.

Acknowledgements

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References

[1] K. He, S., Hoa, R. Ganesan, The study of tapered laminated composite structures: a review, Compos. Sci. Technol. 60 (2000) 2643–2657. doi:10.1016/S0266-3538(00)00138-X.

[2] J. Šedek, R. Hron, M. Kadlec, Bond Joint Analysis of Thermoplastic Composite Made from Stacked Tailored Blanks. Applied Mechanics and Materials, Vol. 827, 2015. pp.161-168, ISSN 1662-7482. DOI: 10.4028/www.scientific.net/AMM.827.161.

[3] R. Růžek, M. Kadlec, L. Petrusová, Effect of fatigue loading rate on lifespan and temperature of tailored blank C/PPS thermoplastic composite, International Journal of Fatigue 113 (2018) 253–263

[4] B. Vieille, V. M. Casado, C. Bouvet, 2014. Influence of matrix toughness and ductility on the compression-after-impact behavior of woven-ply thermoplastic- and thermosetting-composites: A comparative study. Compos. Struct. 110, 207–218.

[5] J. Schijve, Fatigue of Structures and Materials, 2. issue, Springer, 2010, 621 pages, ISBN-13: 978-1-4020-6807-2

[6] Mitsubishi Chemical Advanced Materials, Techtron 1000, product data sheet, available at: <http://qepp.matweb.com/search/DataSheet.aspx?Bassnum=P1SM37>