EXPERIMENTAL AND NUMERICAL STUDY OF HYBRID EFFECT IN HIGH PERFORMANCE QUASI-ISOTROPIC THIN-PLY CARBON/GLASS COMPOSITES

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ABSTRACT

This work studies the hybrid effect in a high performance Quasi-Isotropic (QI) carbon/glass hybrid composite under tensile loading. The hybrid effect is the enhancement in the strain at failure of the carbon fibres in a hybrid composite compared with a pure carbon composite. Different types of QI lay-ups were tested and analysed to understand the interaction between the layers and the effect of the stiffness of the adjacent sub-laminates. A numerical model using the Finite Element method was proposed to evaluate the strain distribution considering an initial failure of one of the 0° carbon plies. The results show that the stiffness of the layers and the stacking sequence play an important role in the failure strain of the carbon plies; the layups with stiffer adjacent layers showed a higher hybrid effect.

1. INTRODUCTION

Several works have demonstrated the potential in hybrid composites to obtain a more gradual failure and higher strains to final failure of the lower strain materials [1]–[5]. The so-called hybrid effect was first shown by Hayashi et al. in 1972 [6],[7]. In their study on Uni-Directional (UD) glass/carbon hybrid composites, it was reported that the failure strain of the carbon layers was 40% higher than the reference carbon composite. Over recent years, hybrid composites have been used to overcome one of the main problems of composites, which is related to the inherent brittleness and unstable characteristic [8]. In 2013 Czél and Wisnom introduced UD glass/carbon hybrid architectures using combination of thin-ply carbon/epoxy and standard thickness glass/epoxy prepregs [9]. The approach successfully achieved a positive hybrid effect, supressing catastrophic delamination around the first carbon failure and promoting fragmentation of the carbon plies. By combining different types of Low Strain Material (LSM) and High Strain Material (HSM) fibres and selecting an optimal configuration [10], it is possible to obtain a gradual failure in the low strain material and a nonlinear stress–strain response from the composite.

According to Jalalvand et.al, in UD thin-ply hybrid composites the damage modes depend directly on the absolute and relative carbon thicknesses and material properties [10]–[13]. The authors gave evidence of the effect of thicknesses on the stress-strain response of the UD ply-by-ply hybrid composites and proposed damage mode maps for all possible damage modes, demonstrating the importance of the ply thickness to achieve a positive hybrid effect. Most composite structures are subjected to multiple loading orientations, and UD composites are not widely applied in real-life applications because of their poor transverse properties. Unlike UD hybrid composites, just a few works have been conducted on Quasi-Isotropic (QI) hybrid composites to achieve a gradual failure response [14], [15] and there is a lack of numerical and analytical models to understand the hybrid effect in QI laminates. Fotouhi et.al. [16] proposed high performance QI composite layups that show gradual failure and hybrid effects under tension. However, in their work, it was reported that the hybrid effect depends on the stacking sequence, demonstrated by changing the direction of loading, despite the material and the absolute/relative carbon thicknesses remaining constant. This was postulated to be related to the stiffness of the layers adjacent to the fragmenting 0° carbon plies. Taking into account that premise, the current work further studies the early stages of fragmentation, when an initial crack is generated in one of the 0° carbon plies, giving evidence of the interaction between 0° carbon layers and the effect of position and stiffness of adjacent sub-laminates in the hybrid effect. To such an end, numerical modelling and experimental work in QI thin-ply hybrid composites is conducted to demonstrate correlations between the magnitude of the hybrid effect and the stiffness of the adjacent sub-laminates.

2. METHOD

2.1. Materials and specimen design

To understand the interaction between the two 0° carbon layers in the early stage of fragmentation and the effect of the stiffness of the adjacent sub-laminates in the hybrid effect, different layups are proposed and the manufacturing process is described in this section. Fig. 1 gives information about the hybrid specimen types and the sequences that they were laid up in for two different QI configurations, i.e. ±45QI (45/90/-45/0) and ±60QI (60/-60/0). In each configuration, only the positions of the plies are rearranged, keeping constant thickness, material and number of layers.

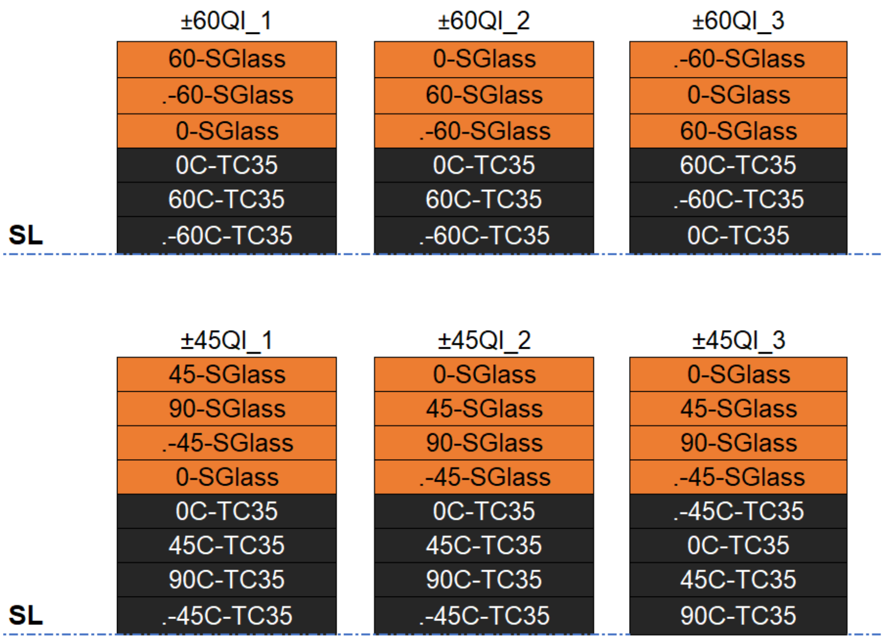


Fig. 1 QI layups proposed to understand the interaction between the layers (SL: Symmetric Line).

The LSM is a SkyFlex USN020 spread tow CFRP thin prepreg from SK Chemicals, which has TC35 carbon fibres and K50 epoxy matrix. The HSM is a standard thickness UD S-glass/913 Epoxy prepreg supplied by Hexcel. Basic properties of the applied fibres and prepreg systems can be found in Table 1 and Table 2

Fibre type	Elastic Modulus [GPa]	Failure Strain [%]	Tensile Strength [GPa]	Density [g/cm^3]
TC35 Carbon	240	1.67	4.0	1.80
S-Glass	88	5.50	4.8	2.45

Table 1. Fibre properties of the applied UD prepregs [17].

Prepreg Material	Elastic Modulus [GPa]	Volume Fraction [%]	Cured ply thickness [mm]	Fibre mass [g/m^2]
TC35/Epoxy	114.3	46.9	0.027	20
S-Glass/Epoxy	45.7	50	0.155	190

Table 2. Cured ply properties of the applied UD prepregs [17], [18].

2.2. Test procedure

Testing of the specimens was executed under uniaxial tensile loading and displacement control at a crosshead speed of 2 mm/min on a computer controlled Instron 8801 type 100 kN rated universal hydraulic test machine with a regularly calibrated 25 kN load cell and wedge type hydraulic grips. Strain values were measured using an Imetrum video gauge system, tracking the points applied on the specimen face over a gauge length of 150mm, see Fig. 2.

Fig. 2 Fixture and mounting arrangement for the uniaxial tensile tests.

2.3. Modelling approach

The numerical model of this paper studies the interaction between two 0° carbon layers in a hybrid composite. If there is effective interaction between the layers, when one of the 0° carbon layers fails by fragmentation, an increment in strain and stress is produced in the undamaged 0° carbon ply causing it to fail straight away. This interaction between the 0° carbon layers makes them behave like a thicker single ply rather than two single layers failing individually.

To study this interaction, an ABAQUS 2-D finite element model with 8-node quadratic plane strain quadrilateral elements with linear elastic material properties was used. The numerical model consists of a unit cell of 10 mm of a section along the laminate and evaluates the early stage of fragmentation of the 0° carbon layers considering an initial failure of the fibres of one of the 0° carbon plies. The model studies the induced strain on the undamaged 0° carbon layer from the crack in the top 0° carbon ply and the effect of the position and stiffness adjacent sub-laminates in the hybrid effect.

The initial failure of the fibres in the top 0° carbon ply is modelled as a discontinuity in the boundary conditions. Between the plies, cohesive elements are used to model potential local delamination and a displacement of 0.2mm (2% maximum strain) is applied, which is slightly higher than the failure strain of the TC35 fibres. Fig. 3 shows a schematic of the numerical model. FE results will be explained in the next sections.

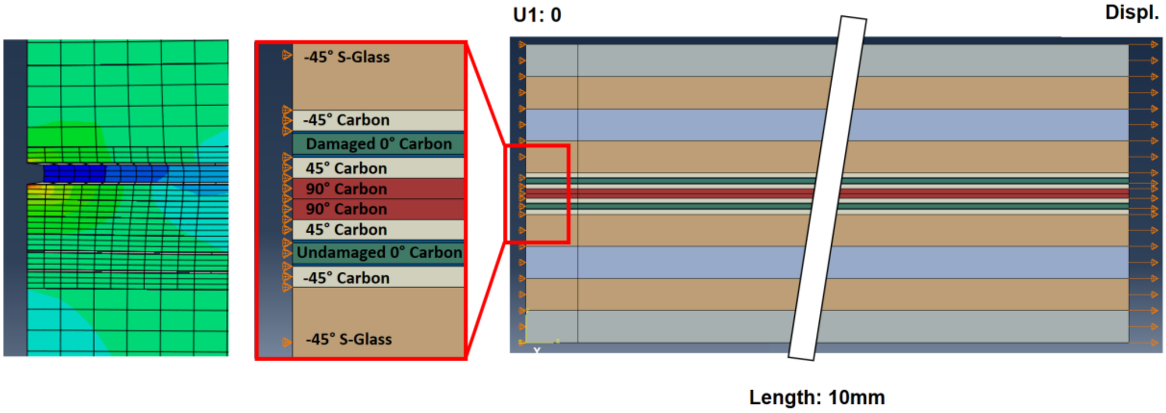


Fig. 3 Applied numerical model using ABAQUS, layup ±45QI_3 .

3. RESULTS AND DISCUSSION.

3.1. Experimental results.

Results obtained from the tensile tests for the investigated configurations, illustrated in Figs. 4 and 5, show a desired non-catastrophic response with a positive hybrid effect, reaching higher strain to failure for the carbon plies compared with the fibre failure strain reported in Table 1. The knee point on the stress-strain curves in Fig. 4 and Fig. 5, indicates the strain and the stress levels at which fragmentation is established in the 0° carbon layers. The stress and strain at the knee point are called ‘‘pseudo-yield stress’’σ_{py} and ‘‘pseudo-yield strain’’ ε_{py}, respectively. Different ε_{py} values and therefore different hybrid effects were found in the investigated specimens, despite the thickness and material used being the same. Fragmentation is a progressive mechanism characterized by the nucleation and growth of small cracks in the 0° carbon plies, the cracks affect locally the loading capacity of the layers producing strain and stress increments in the adjacent plies, this mechanism is completed when cracks reach a saturation point and the carbon plies are not able to carry load any more.

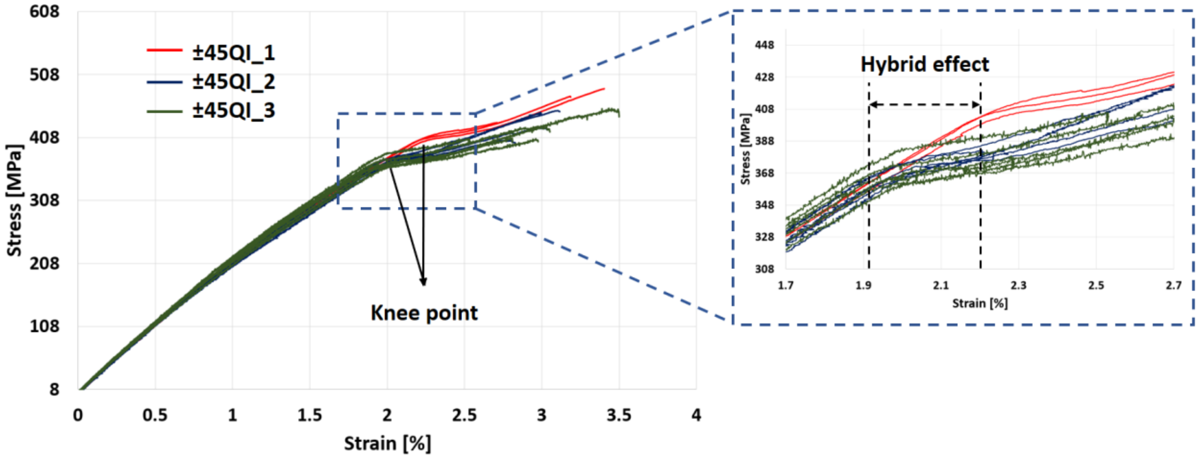


Fig. 4 Results of the tensile tests for the ±45QI specimens.

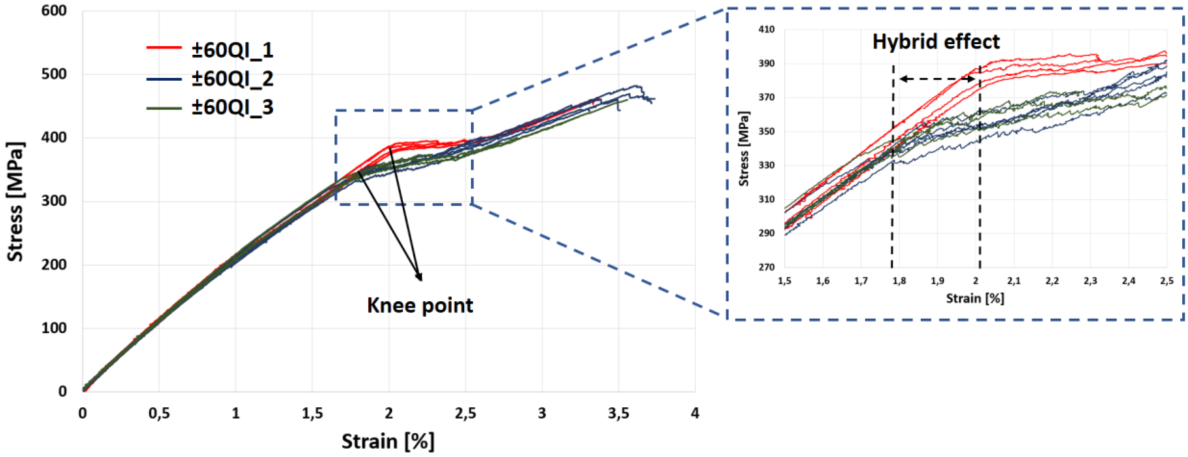
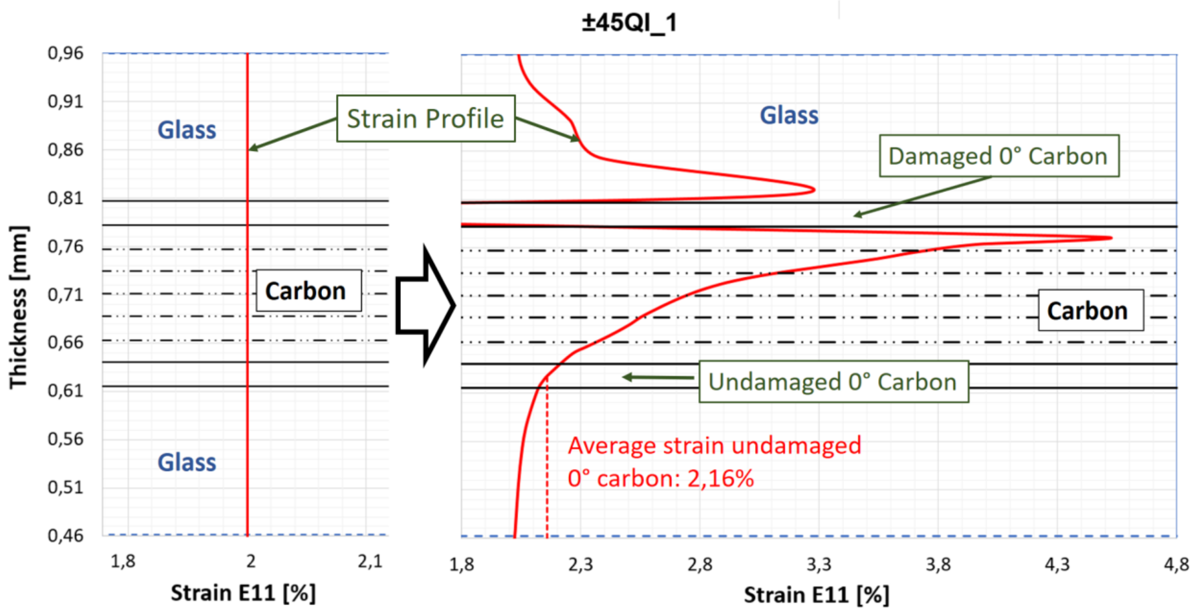


Fig. 5 Results of the tensile tests for the ±60QI specimens.

3.2. Numerical results.

Fig. 6 shows the strain profile through the thickness of layup ±45QI_1 with and without fragmentation of the top 0° carbon ply at the final iteration step corresponding to 0.2mm of displacement (2% strain). Before fragmentation the strain profile is constant, however, when a crack occurs in the top 0° carbon ply, the strain becomes zero in the damage zone and maximum in the adjacent layers. This condition generates an increment in the strain of the undamaged 0° carbon ply. The average strain on the undamaged 0° carbon ply is obtained using a path calculation in Abaqus and in the case of the layup ±45QI_1, it corresponds to 2.16% (red dashed line in Fig. 6), this means that there is an increment of 0.16% in the strain of the undamaged 0° carbon ply because the local failure of the top °0 carbon layer by fragmentation.



a) b)

Fig. 6 Strain distribution through the thickness of layup ±45QI_1 at 2% of strain, a) Strain profile without fragmentation of 0° carbon plies, b) Strain profile with fragmentation of top 0° carbon ply.

The interaction between the two 0° carbon plies and the adjacent layers has an effect in the hybrid response of the layups. Using the same methodology proposed above for the layup ±45QI_1, the average strain was calculated in the undamaged 0° carbon ply for all configurations, taking into account an initial crack in the top 0° carbon ply. Fig. 7 shows the correlations between the average strain in the undamaged 0° carbon ply and the pseudo-yield strain from the experimental tests. In the specimens with a lower increment in the average strain of the undamaged 0° carbon ply, a higher pseudo-yield strain is observed, which means an increased hybrid effect. However, the difference in the strain in the undamaged 0° carbon plies between the specimens is related to the stiffness of the adjacent plies. Changing the stacking sequence results in variation of the strain distribution. Fig. 8 shows a correlation between the average strain in the undamaged carbon ply and the total stiffness of the adjacent layers. As expected, when the adjacent layers are stiffer, lower strain values are observed in the undamaged 0° carbon ply and therefore a higher hybrid effect response is achieved.

The stiffness of the adjacent plies was calculated based on the engineering modulus of the plies in the loading direction multiplied by their thickness. According to Fig. 6, the increment in the strain distribution take place in plies below and above the fragmented top 0° carbon ply. The total stiffness of the adjacent layers is obtained by adding the stiffness of all plies between the 0° carbon layers and the outer ply adjacent to the fragmented top 0° carbon ply, see Fig. 9.

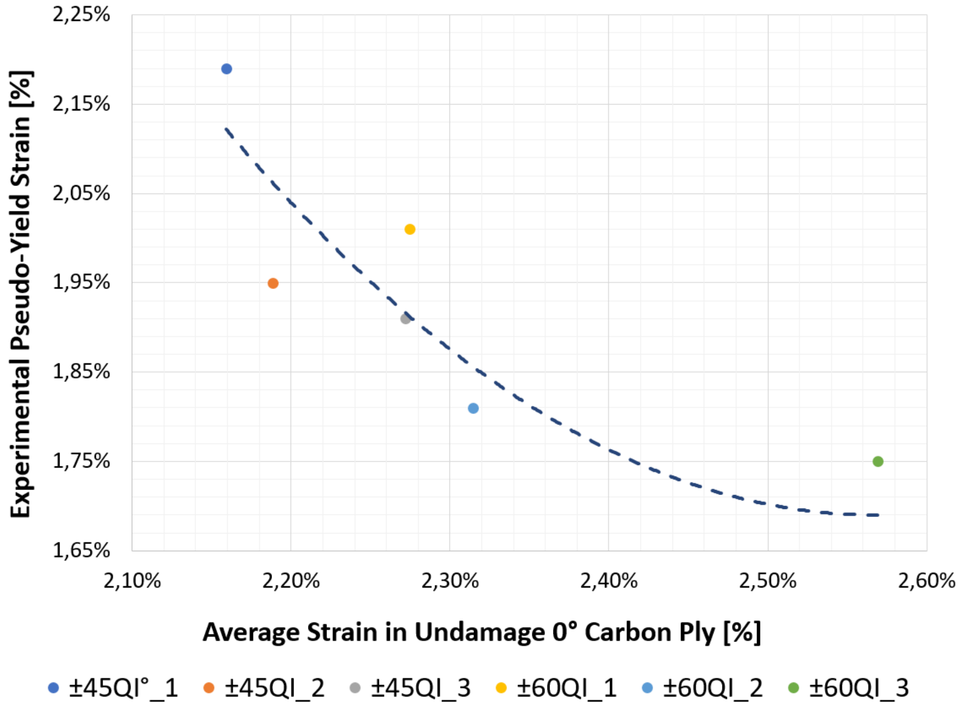


Fig. 7 Correlation between average strain in the undamaged 0° carbon ply at 2% applied strain and experimental results for the pseudo-yield strain.

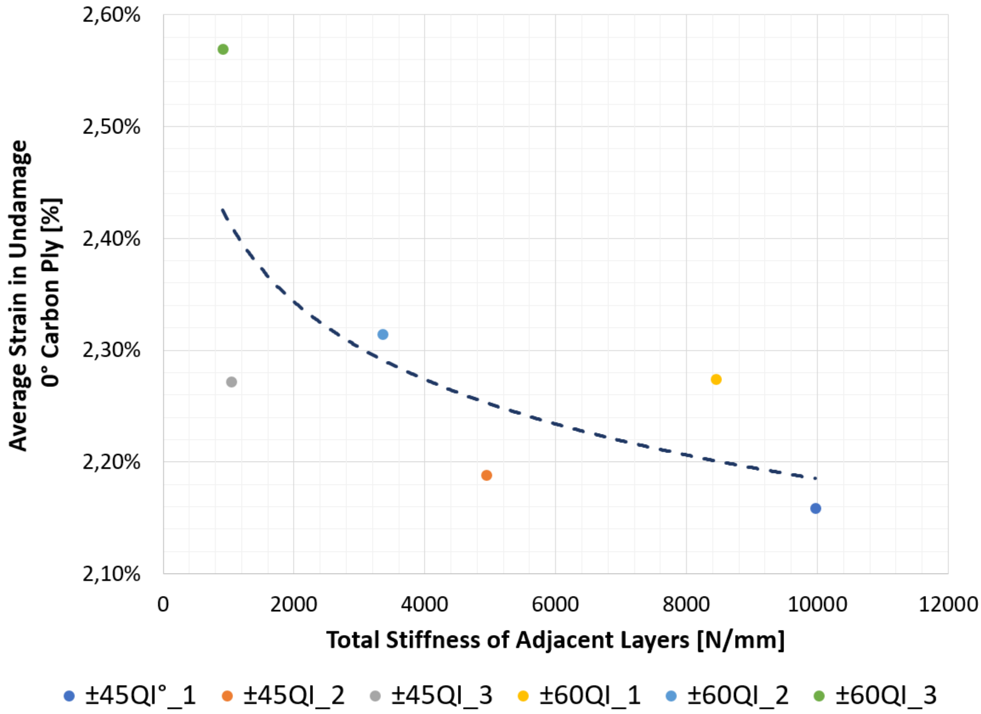


Fig. 8 Correlation between total stiffness of the adjacent layers and average strain in the undamaged 0° carbon ply at 2% applied strain.

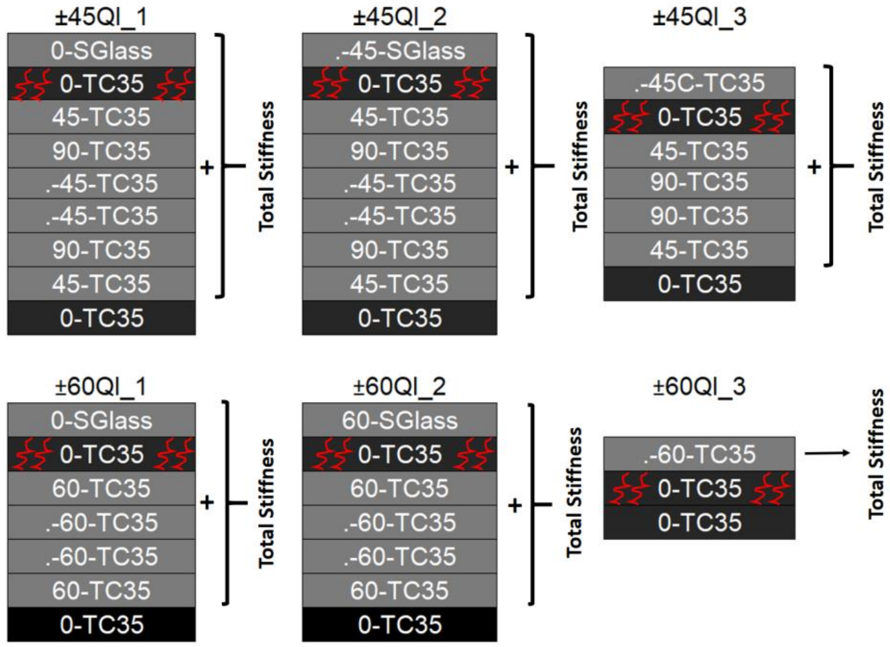


Fig. 9 Total stiffness calculation taking into account layers between the two 0° carbon plies and the layers just above the fragmented top 0° carbon ply.

4. CONCLUSIONS

According to the experiments, different carbon failure strains are recorded in the QI specimens when the stacking sequence is changed. For the layups with stiff layers next to the fragmented 0° carbon plies, the hybrid effect is higher than those with lower stiffness layers with high off-axis angles.

The numerical model showed that the interaction between the two 0° carbon layers and the stiffness of the adjacent plies has an effect on the strain concentrations following first ply failure which may affect the hybrid response of the layups. At an early stage of fragmentation when a crack is produced in one of the 0° carbon plies, an increment in the strain is reported locally in the undamaged 0° carbon ply. This increment in the average strain depends directly on the stiffness of the adjacent sub-laminates, therefore layups with stiffer adjacent plies have a higher hybrid effect. The work demonstrated that for QI hybrid composites not only the thickness of the layers is important but also the interaction between the plies and the position of the stiffer layers.

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5. REFERENCES

[1] Y. Swolfs, L. Gorbatikh, and I. Verpoest, "Fibre hybridisation in polymer composites: A review," *Compos. Part A Appl. Sci. Manuf.*, vol. 67, pp. 181–200, 2014.

[2] G. Czél, M. Jalalvand, and M. R. Wisnom, "Design and characterisation of advanced pseudo-ductile unidirectional thin-ply carbon/epoxy-glass/epoxy hybrid composites," *Compos. Struct.*, vol. 143, pp. 362–370, 2016.

[3] G. Czél, M. Jalalvand, M. R. Wisnom, and T. Czigány, "Design and characterisation of high performance, pseudo-ductile all-carbon/epoxy unidirectional hybrid composites," *Compos. Part B Eng.*, vol. 111, pp. 348–356, 2017.

[4] P. Suwarta, M. Fotouhi, G. Czel, and M. R. Wisnom, "Fatigue Behaviour of Pseudo-Ductile Thin Ply Hybrid Composites," in *Iccm21*, 2017, no. August, pp. 20–25.

[5] Y. Swolfs, I. Verpoest, and L. Gorbatikh, "Recent advances in fibre-hybrid composites: materials selection, opportunities and applications," *Int. Mater. Rev.*, vol. 64, no. 4, pp. 181–215, 2019.

[6] T. Hayashi, K. Koyama, A. Yamazaki, and M. Kihira, "Development of new material properties by hybrid composition. 1st report.," 1972.

[7] T. Hayashi, "On the improvement of mechanical properties of composites by hybrid composition," in *8th International Reinforced Plastics Conference, Brighton, UK*, 1972, pp. 149–152.

[8] M. E. Launey and R. O. Ritchie, "On the fracture toughness of advanced materials," *Adv. Mater.*, vol. 21, no. 20, pp. 2103–2110, 2009.

[9] G. Czél and M. R. Wisnom, "Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg," *Compos. Part A Appl. Sci. Manuf.*, vol. 52, pp. 23–30, 2013.

[10] M. Jalalvand, G. Czél, and M. R. Wisnom, "Parametric study of failure mechanisms and optimal configurations of pseudo-ductile thin-ply UD hybrid composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 74, pp. 123–131, 2015.

[11] M. Jalalvand, G. Czél, and M. R. Wisnom, "Numerical modelling of the damage modes in UD thin carbon/glass hybrid laminates," *Compos. Sci. Technol.*, vol. 94, pp. 39–47, 2014.

[12] M. Jalalvand, G. Czél, and M. R. Wisnom, "Damage analysis of pseudo-ductile thin-ply UD hybrid composites - A new analytical method," *Compos. Part A Appl. Sci. Manuf.*, vol. 69, pp. 83–93, 2015.

[13] M. R. Wisnom, G. Czél, Y. Swolfs, M. Jalalvand, L. Gorbatikh, and I. Verpoest, "Hybrid effects in thin ply carbon/glass unidirectional laminates: Accurate experimental determination and prediction," *Compos. Part A Appl. Sci. Manuf.*, vol. 88, pp. 131–139, 2016.

[14] M. Jalalvand, M. Fotouhi, and M. R. Wisnom, "Orientation-dispersed pseudo-ductile hybrid composite laminates – A new lay-up concept to avoid free-edge delamination," *Compos. Sci. Technol.*, vol. 153, pp. 232–240, 2017.

[15] M. Fotouhi, M. Jalalvand, and M. R. Wisnom, "Notch insensitive orientation-dispersed pseudo-ductile thin-ply carbon/glass hybrid laminates," *Compos. Part A Appl. Sci. Manuf.*, vol. 110, no. April, pp. 29–44, 2018.

[16] M. Fotouhi, M. Jalalvand, and M. R. Wisnom, "High performance quasi-isotropic thin-ply carbon/glass hybrid composites with pseudo-ductile behaviour in all fibre orientations," *Compos. Sci. Technol.*, vol. 152, pp. 101–110, 2017.

[17] G. Czél, M. Bugár-mészáros, and M. R. Wisnom, "the Effect of Test Temperature on the Pseudo- Ductility of Thin-Ply Hybrid Composites," *ECCM18 - 18th Eur. Conf. Compos. Mater.*, no. June, pp. 24–28, 2018.

[18] G. Czél, M. Jalalvand, and M. R. Wisnom, "Demonstration of pseudo-ductility in

unidirectional hybrid composites made of discontinuous carbon/epoxy and continuous glass/epoxy plies," *Compos. Part A Appl. Sci. Manuf.*, vol. 72, pp. 75–84, 2015.