Evaluation of a Bond Joint in the Carbon Weave Reinforced Thermoplastic Manufactured by Stacked Tailored Blanks

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Abstract: The bond joint in carbon weave reinforced thermoplastic is evaluated from the point of view of delamination under static loading. The un-precracked tensile specimens with reinforcing layer made by stacked tailored blanks are analysed in detail in the area of the bond joint. Experimental investigation is supported by finite element (FE) analysis together with cohesive zone model (CZM) for interlaminar behaviour. FE models created using shell or solid elements are examined. The simple lap bond joint and tapered bond joint are compared with each other based on the FE results considering the influence of the bond joint shape on the delamination.

Keywords: Bond Joint; CFRP; FEM; PPS.

1 Introduction

The composites are used in aerospace industry over decades. In recent years thermoplastic composites are more and more common over their relatively high costs of the raw material and the lack of familiarity among engineers. The advantages in possibility of high production rate and improvements in particular the mechanical properties can balance the disadvantages.

The carbon fabric reinforced polyphenylene sulfine (CF/PPS) is mostly supplied in the form of pre-consolidated sheets. A layer can be prepared to the specified size and orientation – tailored blank and then combined to final shape with desired stacking sequence. Joining of layers is made by several techniques e.g. by thermoforming. Thermoplastic prepregs are heated at a temperature which is over the melting temperature of thermoplastic resin and then is material moved into a forming mould and pressed together to consolidate the composite material. The use of matched metal dies ensures dimension precision and good surface quality on both surfaces of the part. Replacing one rigid metal die with a flexible rubber block produces a homogenous pressure distribution, the thickness variability is allowed, but the surface is not smooth.

The bond joint of stacked layers in the area of thickness change is the critical point. The deformation of the edge of reinforcing layer occurs as a product of forming technology, which leads to the tapered bond joint. Delamination difficulties appear under loading and so the bond joint is subjected to the analysis.

2 Testing of the specimens

The tensile specimens were made from stacked tailored blanks by thermoforming. The specimens were tested using one-axis servo-hydraulic test maschine INSTRON 10 kN. Loading was applied in the form of constant displacement rate of 0.5 mm/min. The specimens were 25 mm wide and 275 mm long with reinforcing stacked layer located at the centre. Base layer with the thickness of 3.5 mm included 11 laminas with stacking sequence $[[(0.90)/(\pm 45)]_5/(0.90)]$. The additive 6 reinforcing layers had stacking sequence $[(0.90)/(\pm 45)/(0.90)]_s$ and total thickness of the specimen was 5.5 mm in this part. The composition of laminas was carbon fabric with area mass of 285 g/m^2 and polyphenylene sulfide (PPS) matrix with weight content of 43 %.

The specimens were loaded in tension and a delamination at the bond joint was monitored. Only one side of the specimen was recorded by video camera during loading. The delamination was observed in all specimens. Initial stable delamination growth was followed by rapid delamination advance and final failure in the vicinity of the bond joint almost in all specimens. The typical fracture is shown in Fig. 2.

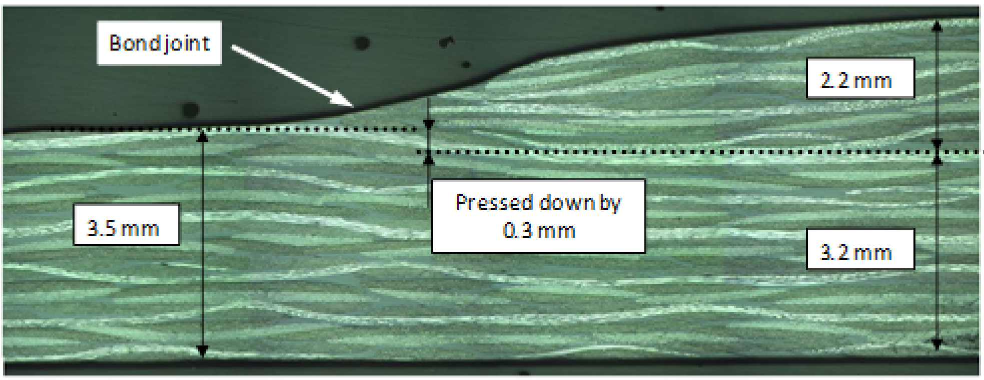


Fig. 1: Detail image of layer stacking in the vicinity of the bond joint.

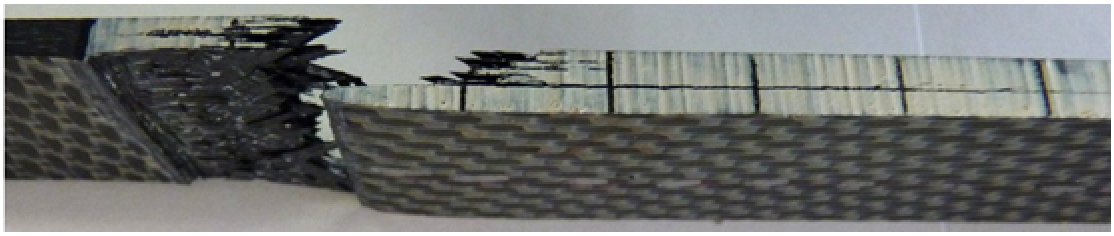
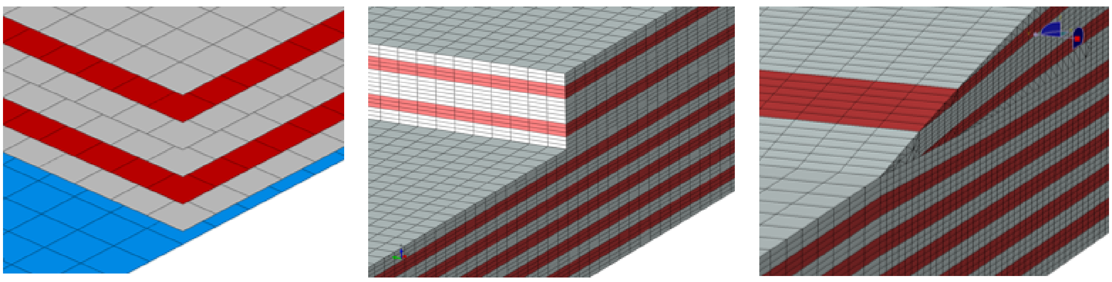


Fig. 2: Typical fracture of the tension specimen.

3 Finite element analysis of the bond joint

The test procedure was simulated by finite element (FE) method using software ABAQUS 6.13.2 [1]. The analysis of the bond joint and delamination properties was the main scope. Two types of the bond joint shape were evaluated using different approaches of FE modelling. The problems were solved by implicit solver. The delamination properties were analysed on the simple lap bond joint and the tapered bond joint, which is the result of the manufacturing process. The shell element and solid element models with symmetry plane perpendicular to the loading axis were created. The model simulating tapered bond joint utilized solid elements, but from the reason of results comparability, the simple lap bond joint model using solid elements was also created. The FE models are shown in detail in Fig. 3. Shell element model contains 85 000 elements with characteristic element length of 0.5 mm and solid element models contains 560 000 elements of C3D8R type mainly and C3D6R type in a rest of volume. The mesh in the vicinity of the bond joint is in the model of tapered bond joint refined to characteristic element length of 0.2 mm.



a) simple lap bond joint – shell elements | b) simple lap bond joint – solid elements | c) tapered bond joint –solid elements

Fig. 3: FE models of tension specimens – detail.

The material constants of laminas are related to orthotropic material model and are used according to Ref. [2, 3] for dry conditions and temperature of 23 °C.

The cohesive zone model (CZM) was used in FE analysis in order to cover the interlaminar behavior and to allow the delamination of layers. The models are build layer-by-layer and cohesive surfaces bonds layers together. Linear cohesive behaviour prior to failure and linear softening cohesive behaviour after damage initiation (linear elastic – linear softening) is used in CZM. Initial stiffnesses K_i, strengths at delamination

Tab. 1: Parameters of CZM.

Parameter	Kn [N/mm^3]	Ks [N/mm^3]	Kt [N/mm^3]	τ_n^0 [N/mm^2]	τ_s^0 [N/mm^2]	τ_t^0 [N/mm^2]
Value	3800	1400	1400	10	15	15
Parameter	G_{IC} [kJ/m^2]	G_{IIC} [kJ/m^2]	G_{IIIC} [kJ/m^2]	η [-]		
Value	1.4	2.8	2.8	2		

initiation ${\tau_i}^0$, fracture toughness in separate modes of loading G_{iC} and relations governing the mix-mode loading needs to be employed.

The quadratic failure criterion according to Ref. [1] was used for estimation of damage initiation. The components of interlaminar strengths τ_i^0 and actual interlaminar tractions τ_i are combined in the relationship (1). The damage is not initiated under purely compressive stress.

$$f = \left\{ \frac{\langle \tau_n \rangle}{\tau_n^0} \right\}^2 + \left\{ \frac{\tau_s}{\tau_s^0} \right\}^2 + \left\{ \frac{\tau_t}{\tau_t^0} \right\}^2 \tag{1}$$

The variation of fracture toughness G in relation to mode ratio in the mix-mode loading is used according to Ref. [4]. The criterion (2) is expressed as a function of the mode I and II fracture toughnesses and a parameter η determined from mixed mode bending (MMB) tests at different mode ratios. G_T is the energy release rate under mixed-mode loading exhibiting no mode III loading and G_{II} is substituted by energy release rate for shear loading G_{shear}, if tearing appears.

$$G_{TC} = GI_C + (GII_C - GI_C)(G_{II}/G_T)^\eta \tag{2}$$

Used parameters of CZM are listed in Tab. 1.

The normal interlaminar stress reaches its maximum value at the edge of the bond joint in the centre of the width and is greater in the simple lap bond joint. Simple lap bond joint contains non-loaded material at the top part of the edge, which does not contribute to the load transfer and "constraints" the lower part, which results in higher interlaminar stresses. The delamination occurs only within the bond joint between base layer and externally reinforcing layer as was experimentally confirmed. The load at the delamination onset is approximately the same for all configurations of the analysed models. The damage initiation and advance can be determined according to damage parameter CSDMG used in ABAQUS. CSDMG equals 0 when the interfacial strength is not exceeded and equals 1 when cohesive surfaces are not in connection (for more information see Ref. [1]). Assuming CSDMG = 0.94 the delamination of simple lap bond joint models corresponds to experimentally observed one or assuming CSDMG = 0.95 for tapered joint models respectively. The tapered model shows faster delamination growth (see Fig. 4), but the thinner base layer in the thicker part of the specimen is more likely the reason than the influence of the bond joint shape.

4 Conclusion

The bond joint of the thermoplastic composite manufactured by stacking layers of tailored blanks was analyse using FE method and supported by experiment. Shell elements were proven to be sufficient in analyses of delamination onset and growth. The solid element modelling offers superior characterisation of shape details, but no significant differences in delamination growth were observed. Nevertheless the tapered bond joint is preferable because of lower interlaminar stresses and so the tapered shape caused naturally by the manufacturing technology does not behave as an imperfection. However, the thinning of the base layer in the vicinity of the bond joint caused by pressing should be avoided.

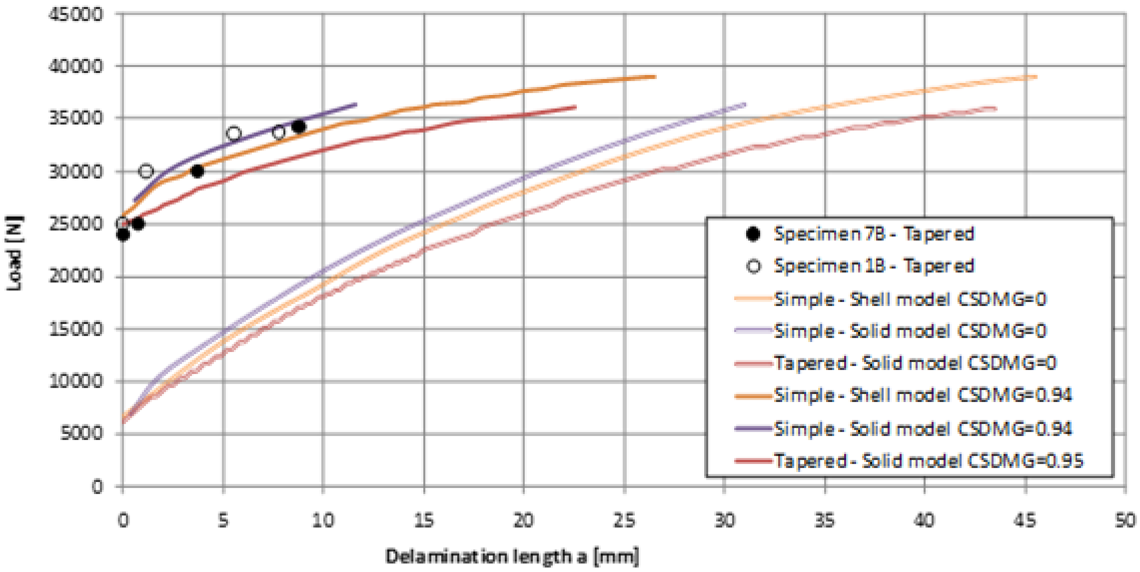


Fig. 4: Delamination growth; tapered and simple lap bond joint FE models, experiment.

Acknowledgement

This work was funded by the support for research organization development provided by the Ministry of Industry and Trade of the Czech Republic.

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