STUDIES ON THE EFFECTS OF THERMAL RESIDUAL STRESSES ON THE STRUCTURAL INTEGRITY OF HYBRID AND COMPOSITE ELEMENTS

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1. INTRODUCTION

The existence of residual stresses during the manufacturing are now well accepted. These stresses can lead to dimensional changes in the final cured components or in the worst-case scenario, completely ruined the part. Residual thermal stresses occur as a consequence of the difference in the coefficients of thermal expansion (CTE) caused by different components and different lay-ups.

The dimensional changes cause by residual stresses have been studied precisely and designers consider them as the design parameters. In addition, there are some tools to predict and prevent them [1–3]. However, the effects of residual stresses on the mechanical performance of composites strength are poorly understood and are mostly benignly neglected by at best assuming a constant value [4, 5]. The thermal residual stresses may initiate and amplify early damage [6]. The presence of residual thermal stresses prior to the application of an external load is often regarded as a defect or inherent flaw in matrix/interfacial adhesive by developing microcracks, delamination, fiber-matrix debonding [7, 8]. Specially on Hybrid specimen when difference in thermal expansion is high, these stresses may significantly lower the mechanical properties.

2. RESIDUAL STRESS IN HYBRID STRUCTURE

The specimen have been designed to suit ASTM D5528 [9] for Double Cantilever Beam (DCB) testing. In this work, Interfaces between layers of hybrid specimen of Ti-6AL-4V titanium alloy and composite pre-pregs with unidirectional AS4 fibres and Hexcel 8552 epoxy matrix, has been studied. The important parameter in designing the hybrid specimen is significant mismatch between material's CTE. This parameter is also the main cause of origin of thermal stress during the manufacturing. The thermal stress that has been produced during the manufacturing must be controlled, otherwise it could cause bending and distortion of whole specimen in the manufacturing phase or after opening the mold and edge treatment. In addition, the residual thermal stress could alter the Energy Release Rate for the crack propagation and change the fracture behavior. for this reason Symmetrically cracked (SC) specimen has been designed to control the built-in thermal residual stress. In other hand two Asymmetrically cracked (AC#1,#2) designed to emphasized the effect of thermal residual stress.

The specimen has been sensorized by FBG sensors carried by optical fibre. Two kind of optical fibre has been used in this activity: Ormocer and Polyacrylate coating. The coating of Polyacrylate has been removed in the position of sensors to increase the detectability of sensors. One additional temperature sensor has been embeded as well, to separate mechanical and thermal strain by subtraction of temperature sensor's wavelength from the wavelength of strain sensors. With the help of embeded FBG sensors, strain evolution during the manufacturing have been assessed. The results indicated that the main strain change happen during the cooling phase of manufacturing from 120 °C to the ambient temperature. After manufacturing the specimen were cut by waterjet to inhibit any possible damages that could be caused during the cut. The specimens have been tested by MTS machine to investigate the effect of thermal residual stress on fracture behaviour of the interface under study.

The amount of material's CTE and remaining strain after manufacturing has been calibrated by FEM simulation with the help of FBG's results. The numerical analysis continued by simulation of DCB loading. In this phase the modelling continued in two paths; one simulation contain the cooling analysis and loading as multistep analysis while the other one just had the loading simulation. comparison of these two numerical analysis with experimental results indicate the possible effect of thermal residual stress.

The difference between the results of numerical analysis with cooling and without cooling indicates the effect of thermal residual stress. By comparison of Numerical and experimental results, the numerical analysis with cooling shows good correlation with experimental results. The SC specimen did not show any significant effect of thermal residual stresses existence; however the effect of thermal residual stress is visible in the AC#1 and AC#2. The numerical-experimental results of strain evolution during opening of specimen AC#1 has been shown in figure 1.

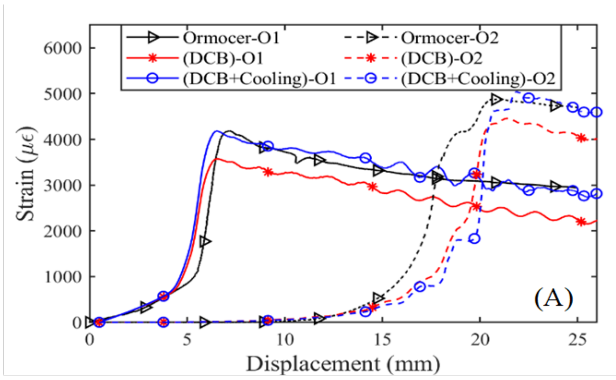

Figure 1: Numerical and experimental results for AC#1

3. DAMAGE IN CURVED LAMINATES WITH DIFFERENT LAY-UPS

Curve specimens have been designed inspired by ASTM standard D6415 [10]. Two lamination sequences of Zero $[0]_{48}$ and Crossply $[0/0/90/90]_{4s}$ have been chosen for this study. The main failure mode in Zero specimen is delamination while in Crossply specimen the main mode of failure could not recognize but Gaussian distribution of 3D Hashin damage criteria shows interaction of matrix cracking and delamination.

The specimens have been produced with flexible counter-mold and metal mold by the technique of vacuum bag in the autoclave. The cured specimens showed significant amount of spring in after manufacturing, specially this deformation is more significant in the Crossply specimen.

After manufacturing each laminate has been cut to three specimens and they had been tested by MTS machine to experience opening loading. Zero specimens had catastrophic failure by multiple cracks spread through the thickness and one long crack which went in the legs.

The build-in thermal residual stress during manufacturing has been studied by the help of numerical analysis. In this simulation the specimen has been cooled down from curing temperature 180 °C to the ambient temperature 20 °C. As has been expected the Zero specimen has negligible amount of built-in stresses, however for the Crossply specimen, in-plane stress reach to 35 MPa which is very high for AS4/8552 unidirectional material, since the ultimate shear strength is just 64 MPa. The numerical analysis continued by simulation of the opening loading. As the same for Hybrid simulation, to understand the effect of thermal residual stresses two analysis of loading with cooling and without cooling have been performed.

The maximum load that specimen has been experienced during the test have been applied in the simulation and the maximum amount of stress have been read in the failure point. The Zero results were in agreement by Gaussian results that the main failure mode is delamination. But in the Crossply, the in-plane stresses indicate that transverse matrix cracking appear before delamination and cause premature failure in the specimen.

The study continued with the non-linear modeling of specimen to investigate the damage behaviour of specimen in more detail. The FE model of this activity developed with the cohesive modelling approach based on the different roles that are actually played by the in-plane and the out-of-plane stress components. Hence, the area of the lamina cross-section is considered lumped at the lamina mid-plane and represented by a bi-dimensional element, such as a membrane or a shell element and are connected by brick elements as interface elements. The bi-dimensional elements just carrying the out-of-plane stress components; however, conventional brick elements with a constitutive behaviour characterised by a null in-plane response could be adopted as interface elements [11].

With the help of this modeling technique, the damage behaviour of Zero and Crossply specimens have been studied. The Crossply specimen results indicate that intralaminar damage cause degradation of tensile strength in the damaged elements which leaded to the premature delamination. Figure 2 shows the comparison of numerical and experimental results of load versus displacement for Crossply specimen.

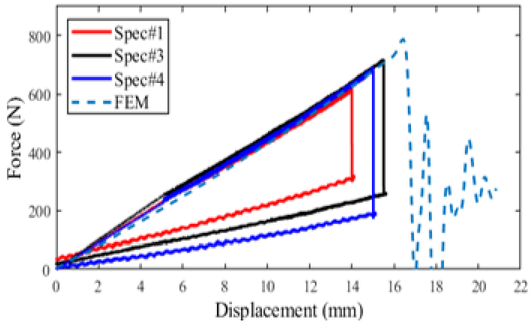

Figure 2: Numerical and experimental results for AC#1

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