

FATIGUE TESTING OF COMPOSITES WITH IN-SITU FULL-FIELD STRAIN MEASUREMENT

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1 Introduction

Light-weight, high stiffness, and high strength are among many properties which make composites advantageous over other materials. However, the presence of defects, or material flaws, in composites and its effect on the material strength is not well understood to date and can be significant [1]. The central aim of this project is to understand how different types of defects may affect the material properties of fibre reinforced composites. As a first initiative, a novel fatigue test method is developed to study defects and failure modes that normally would not have been perceived in a standard fatigue test setup.

2 Materials and defects

Although the novel fatigue test setup developed within this project can be used for any type of material the primary aim of this project is to study fibre reinforced composites with different type of defects. Examples of such material combinations are carbon fibre reinforced epoxy (typically used in aerospace industry) and glass fibre reinforced vinyl-ester (typically used in the wind mill industry). The aerospace industry typically uses non-crimp fabrics and the composite laminates are manufactured through a traditional vacuum infusion process or resin transfer molding (RTM). Different types of defects can be introduced into the material in a controlled way. As an example, one can place small pieces of PTFE foil between the fabric layers in order to mimic areas of delamination in the laminate. Another way is to manipulate the fibres prior to the infusion process, e.g. cutting fibres or introducing areas with very large fibre crimp. Finally, one can introduce voids into the resin, in a controlled way, by manipulating the pressure during the infusion process. These are some examples of different type of manufacturing defects which can affect the fatigue strength of the composite.

3 Loading conditions

The suggested novel test method was developed in order to better understand the progression of failure of composite laminates with different kinds of defects. The fatigue test assembly consisted of a conventional arrangement, an upper fixed crosshead and a lower vertically translatable crosshead, both positioned and aligned against each other at a correct angle. A guidance plate was installed between these two crossheads in order to prevent the lower crosshead from rotating about its centre of axis and to allow for transversal load actuation on the specimen. The upper crosshead was equipped with a force transducer and a linear variable displacement transducer (LVDT). The distance between the crossheads at idle condition that is, zero positioning, was adjusted to cover the full grip length of the specimen.

4 Strain measurement scheme

A high speed camera was placed in front of the specimen for in-situ photographs which later were processed in the digital image correlation (DIC) software, ARAMIS [2], in order to obtain full-field strain measurement, see Fig. 1. Fig. 2 schematically shows how the photograph sampling was done. Each red dot represents a position where a picture was taken. The strain field on the specimen surface can be observed in two different ways. One way is by starting the photograph sampling at zero load (and zero strain) and then progress by recording a picture at a predefined load level in each cycle, for instance at the peak load level as is shown Fig. 2a. This would give the strain field including both strains due to the primary loading and potential strain concentrations due to fatigue of the material. A second way of recording the strain field is by starting the photograph sampling at the same specified load level for every cycle. This is shown in Fig. 2b, where photograph sampling only occurred at the peak load for every load cycle. This method illustrates only changes in strain field due to cyclic

fatigue, that is strains due to primary load are thus not included. The second approach is adopted for producing results presented in this paper.

5 Sampling and Test Procedure

Table 1 specifies the rate at which the test specimens were cycled and the optimum sampling rate that the high speed camera was triggered to obtain a full load envelope, both peak and valley, for every triggered signal. The camera trigger was executed on three conditions: achieved cycle count, amount of sinusoidal load signal, and where on the signal, peak or valley (Fig. 2). The trigger time for the signal was 1ms and the signal accuracy depended on the error for the load signal. This error was adjusted using a proportional-integral-derivative controller, a control-loop, to minimize the discrepancy between the actuated load and the read-off value from the load cell.

Camera alignment in relation to the test specimen was of great essence to rule out the possibility of instrumentation error. The camera was centred in relation to the specimen using a tripod and fine-tuning of this alignment was done by adjusting the camera lens to focus on specimen notch to obtain high quality photographs. An LED light-source was placed on a tripod and directed on the specimen measurement area to provide sufficient illumination for the camera.

6 Test Specimens

6.1 Materials and Manufacturing

Non-crimp fabrics were used and the composite laminates were manufactured through RTM to produce the minimum amount porosity. The sample reinforcement was a UD carbon (HTS40) bindered non-crimp fabric (242.5 g of carbon/m²). Quasi-isotropic lay-up stacks of the reinforcement were prepared for sample production. The laminate stacking sequence was [+45/0/-45/90]_{2s}. The resin used was Hexcel's HexFlow RTM6.

6.2 Method for introducing voids

For the purpose of obtaining high porosity in the material, sample laminates were manufactured with the same materials, but with a "wet-VAP" process developed at Swerea SICOMP. The vacuum assisted process (VAP) is a patented [3] method to infuse a reinforcement using a semi-permeable membrane to provide a vacuum gradient over the entire reinforcement surface as the flow moves in an in-plane direction. The "wet-VAP" process entails pouring the resin onto the mold, then laying the

reinforcement on top, sealing it with a semi-permeable membrane, and applying vacuum across the top of the membrane. Thus, there is no resin inlet, and the main path of resin travel is through the thickness towards the membrane. The mold and resin were pre-heated to 80°C. To induce a high level of porosity, the resin was vigorously stirred for several minutes to aerate it. A vacuum pressure of 60 mbar was applied above the membrane, and then the mould placed into an oven to start a standard RTM6 cure.

6.3 Void detection

The volume porosity in the laminates was estimated using C-scan and a calibration curve, produced by measuring several other laminates for porosity with both c-scan and optical microscopy. Results from these 2D scans were displayed as attenuation (expressed in dB) against porosity content (expressed in percentage).

6.4 Specimen preparation

Specimens were cut-out from a larger laminate such that the surface fibres were aligned with the loading direction (from here on defined as 0° fibres). The specimens were prepared according to ASTM D 3039 for tabbing by using Araldite 2015. The specimen notch was machined by hand-drilling using an Ø6mm twist drill bit made of high speed steel which resulted in a reasonably good surface quality when using sticky tape. The tape helped to produce pressure over the surface area under preparation to prevent fibres from flaking close to the notch edges during the drilling. For the purpose of full-field strain analysis, a speckle-pattern consisting of white and black colour was shed on the specimen to trace deformation during loading. The environmental condition for testing was room temperature dry at 24°C.

7 Example of results

7.1 Test parameters for cyclic fatigue tests

Two specimens were tested in static failure to obtain and verify the ultimate tensile strength (F_{QS}^{UTS}), which was averaged to 39kN. This was used to design the fatigue test programme. Three specimens were run each at 70%, 80% and 90% of F_{QS}^{UTS} in fatigue to determine the quality of the strain data from the high speed camera and the test duration (Table 1). Loading at 80% of F_{QS}^{UTS} load case in fatigue fulfilled these conditions mentioned in this section.

7.2 Fatigue tests with in-situ full-field strain measurement

For the purpose of benchmarking this test method, a total of 11 fatigue tests are reported, 5 samples with low porosity content, less than 1%, and 6 samples with high porosity content, between 2-4%. Fractographic observations were conducted on these test samples, and close to the vicinity of the notch along the 90° fibres, to validate the DIC strain plots.

The opposing side of each test specimen on the laminate was polished and studied under the microscope to annotate the initial specimen microstructure in unloaded state. Fatigue testing was then run on the samples, interrupted at certain milestone levels of load cycles for polishing and microscopy. The micro-crack density formation over loading was thus monitored (Fig. 3 and 4).

7.2 Discussion about the fatigue test results

Fig. 3 shows the results for the low porous laminates. A characteristic damage state takes place during the fatigue life. For each of the five tests, the DIC strain plots show formation of strain concentrations around the notch, and these strain sites seem to grow for increased fatigue cycles. Details of the fracture surface confirm increased matrix-dominated fracture surfaces at inferred growth directions, as indicated by the strain plot.

Prior to loss in load carrying capability, it was noticed on the surface layer of the substrate that cracks started to form at the strain sites. These cracks eventually propagated in the load carrying plies, and this material defect of expanding-contracting cracks were depicted as non-visualized patches in the DIC results (Fig. 3 at 111,850 cycles), and this eventually led to overall specimen failure.

Fig. 4 shows the results for the high porous laminates. High strain concentrations start to form in the vicinity of the notch around 1000 cycles and intensify here for continued fatigue cycling, followed by specimen failure in cleavage. Fracture study of the surface shows increased matrix-dominated failure close to the notch that dissipates in surface scans away from the notch.

Transverse sectioning along the 90° fibres of all test specimens revealed no failure in the load-bearing (0°) fibres.

8 Conclusion

The significance of damage and defects and their detection has been presented. A novel fatigue test of composites with in-situ full-field strain measurement has been presented. Strain results show

detection of micro-cracks during fatigue cycling. This was also verified through polishing and micrographs.

9 Acknowledgements

The Swedish national aeronautics and research programme NFFP5 supported the work described in this paper. Thanks to Andrew George of Swerea SICOMP for assistance with manufacturing and providing material for testing.

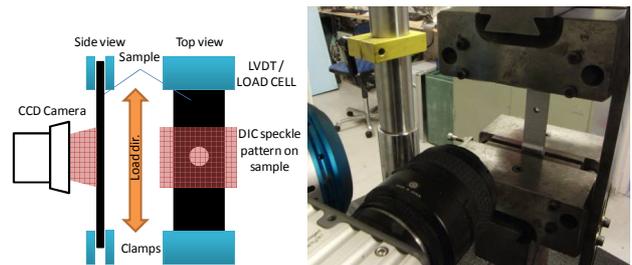


Fig.1 Fatigue test setup with in-situ full field strain measurement.

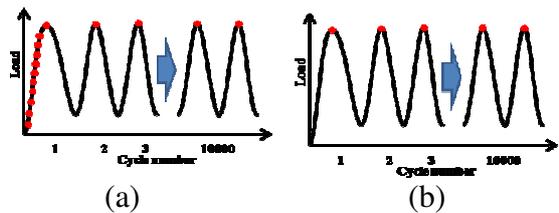


Fig. 2. Example of photograph sampling sequence.

Utilised Hardware	Parameters of Interest
Specimen, Notched coupons (wxhxt) (25x175x4.1)mm with w/d(4.2)	<ul style="list-style-type: none"> To show local strain gradients in the vicinity of the notch To show the effects porosity may have on the specimen fatigue life
Static tester, Instron 4505	<ul style="list-style-type: none"> Obtain ultimate tensile load for specimens, and use these results to design a fatigue test programme
Low and high cycle fatigue tester, Schenk Hydropuls equipped with a 100kN load cell (Dynamic range 80% full scale, accuracy <0.5%) and an LVDT (Range ±50mm, accuracy<0.5%)	<ul style="list-style-type: none"> Low cycle fatigue at 7Hz, Tension-Tension, load ratio at 0.1 Triggering with high speed camera Sampling rate Load cell and LVDT 50Hz
High speed camera, DantecDynamics NanoSense MKIII with a 60mm lens / Data sampling on stand-alone PC with Windows 7	<ul style="list-style-type: none"> Frames per second 1000Hz Trigger mode set to Circular Triggering with TTL-low edge Images pre-triggered 25 Images post-triggered 25
Light source, IDT 19LED cluster	<ul style="list-style-type: none"> Cool light system for homogenous illumination over region of interest
PC for DIC, ARAMIS optical deformation analysis	<ul style="list-style-type: none"> Post-processing of 2D images from the HSC to obtain surface strain values for tested specimen

Table1 List of equipment.

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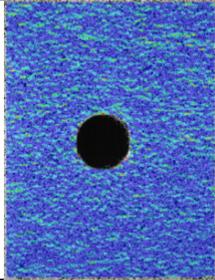
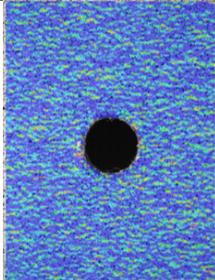
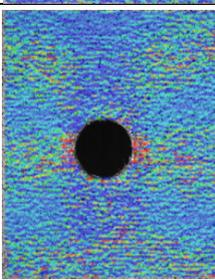
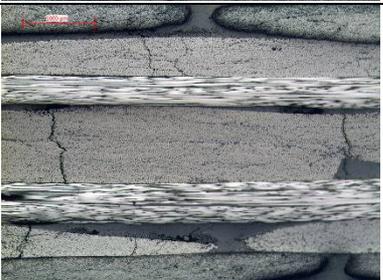
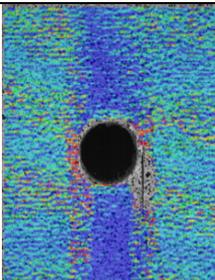
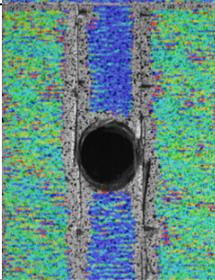
Achieved number of cycles	Full-field strain plots (ϵ_y)	Legend	Polishing of cross-section
0	Not applicable		
100			
1,000			
10,000			
100,000			
111,850 (Complete loss of load carrying capability)			Not applicable

Fig.3 Test results for laminates with low porosity.

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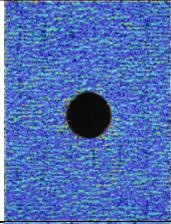
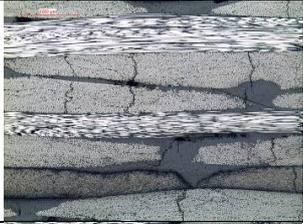
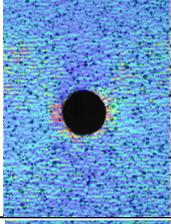
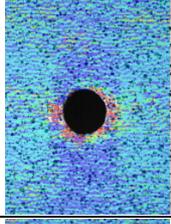
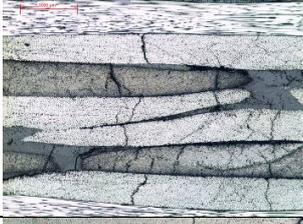
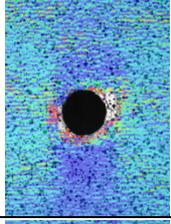
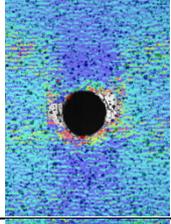
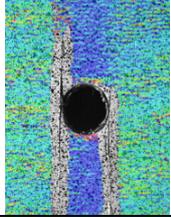
Achieved number of cycles	Full-field strain plots (ϵ_y)	Legend	Polishing of cross-section
0	Not applicable		
100			
1,000			
10,000			
20,000			
30,000			
39,850 (Complete loss of load carrying capability)			Not applicable

Fig.4 Test results for laminates with high porosity.

10 References

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