The effect of ply folds as manufacturing defect on the fatigue life of CFRP materials

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ABSTRACT. Manufacturing defects are inherent to any manufacturing process. However, in composite materials they might be unavoidable, e.g. ply waviness or even folds of plies are present in complex shaped parts during high pressure resin transfer molding of carbon fiber reinforced polymers. In this work, the effect of the ply folds on the fatigue life of the composite material is investigated. Folds along fiber direction (as they commonly appear during manufacturing) were artificially introduced in unidirectional non crimp fabric plies. The target of this study is the prediction of damage initiation due to this particular type of manufacturing defect. The folds locally increase the fiber volume fraction and also introduce resin rich areas. Fatigue tests in fiber direction and transverse to fiber direction are performed at different load ratios under constant amplitude loading. The influence of the defect geometry on damage initiation and progression is investigated at different scales by non-destructive methods before testing, continuous strain measurement and monitoring the damage progression during testing and fractography analysis after final failure. Most of the time, the first damage was observed at the location of the introduced fold for all considered load cases. However, it was also found, that the folds lead to no significant reduction in fatigue life.

KEYWORDS. Manufacturing defects; CFRP; Fatigue damage, Fold.

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INTRODUCTION

The high pressure resin transfer molding (HP-RTM) process shows great potential for efficient manufacturing of automotive composite structures in series production. Unidirectional or woven fiber mats are preformed and positioned in the mold, resin is injected and cures in the closed mold in less than 10 min. However, manufacturing defects as in-plane or out-of-plane waviness as well as ply folding along or transverse to fiber direction cannot be avoided, when complex parts are manufactured by HP-RTM. These defects can cause a reduction in static strength or fatigue life. This influence has to be known in order to define if a composite part featuring manufacturing imperfections can be accepted or not. In previous research work the effect of out-of-plane ply waviness in the same material was studied and a reduction in compressive static and fatigue properties was found depending on a defect severity parameter [1]. In this work the influence of ply folding along fiber direction on the fatigue life of a unidirectional laminate is investigated. A ply folding along fiber direction causes a local increase in fiber volume fraction and by this a local increase in the stiffness in fiber direction.

Effects of local stiffness changes due to gaps and overlaps were already studied in CFRP laminates manufactured through automated fiber placement. A meshing tool for numerical investigation of the effect of defects and their interaction has been developed [2]. However the model has not been validated by test data. An experimental study on the same topic was performed in [3] by static testing of unidirectional and multidirectional material with introduced gaps and overlaps along fiber direction. The conclusion was that ultimate static strength is reduced less than 5% at the lamina level, while at the laminate level the reduction is up to 13 %. This is mainly due to ply waviness induced into the plies surrounding the defect ply.

A study on the effect of thickness and fiber volume fraction variations on strain field inhomogeneity under transverse load was done in [4]. In this study it was found that a strain inhomogeneity of up to 10 % is possible for fiber volume fraction variations in a flat part. This is expected to be important for reliability and fatigue behavior.

In this work, the effect of ply folding on the fatigue performance of unidirectional CFRP laminates is experimentally assessed. The fold is induced along fiber direction into the extreme top and bottom plies of the laminate, as this is the most common case encountered during manufacturing. The specimens are loaded axially under constant amplitude loading. Progressive damage and failure due to the defect are investigated. The results are assessed using SN curves. Additionally, the stress states leading to failure for selected load cases are numerically modelled. A defect metric is defined in order to assess the influence of the detailed defect geometry.

EXPERIMENTAL METHODS

Material and specimen configuration

Test specimens provided by the industry partner were water jet cut out of $[0]_6$ carbon/epoxy plates with a constant thickness of $t = 2.23$ mm. The specimens feature artificially introduced manufacturing defects. The composite material is manufactured out of a unidirectional automotive non-crimp fabric (NCF) with an areal weight of one ply of $m_A = 300$ g/m². The matrix constituent is Epoxy and the manufacturing method is HP-RTM. For production reasons the unidirectional NCF is assembled using transverse glass fiber tows with a spacing of about 2 mm. The average fiber volume fraction of the material without defect is $V_{f,n=6} = 0.45$, which is calculated using the formula:

$$V_{f,n} = (n\, m_A) / (\varrho_f\ t) \qquad (1)$$

where $n = 6$ is the number of plies and $\varrho_f = 1.8$ g/mm³ is the density of the carbon fibers.

Tensile and compressive specimens were cut out of the plates along and transverse to fiber direction and aluminum end tabs were bonded on each specimen. The specimen geometries are based on DIN EN ISO 527-4 for pure tensile and ASTM D 3410 for static compression loading; the same specimen configurations are also used for the fatigue load cases [5, 6]. The specimen configurations including the fold position (the black strips) are shown in Fig. 1.

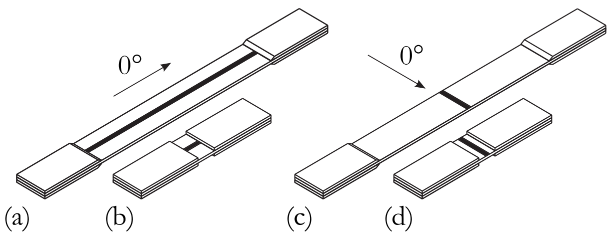

Figure 1: Specimen configuration for different loading cases: (a) longitudinal tension; (b) longitudinal compression; (c) transverse tension; (d) transverse compression.

Defect Configuration

The microstructure of the introduced fold defect was investigated by computer tomography of some specimens and optical microscopy of each specimen. The edge of a typical specimen with fold is shown in Fig. 2.

The computer tomography scan gives the distribution of each ply through the thickness (Fig. 2a). The glass fibers between plies used for NCF production give indication of the exact position of each ply, of the fold location and configuration, and of the perturbation induced by the presence of the fold into the neighboring plies, i.e. the modified thickness and the induced waviness of the plies. Based on this observation a detailed sketch of the defect configuration is possible (Fig. 2b), which is further used for understanding the correlation between the defect geometry and the material strength, and for building the finite element (FE) models of the specimens featuring defects.

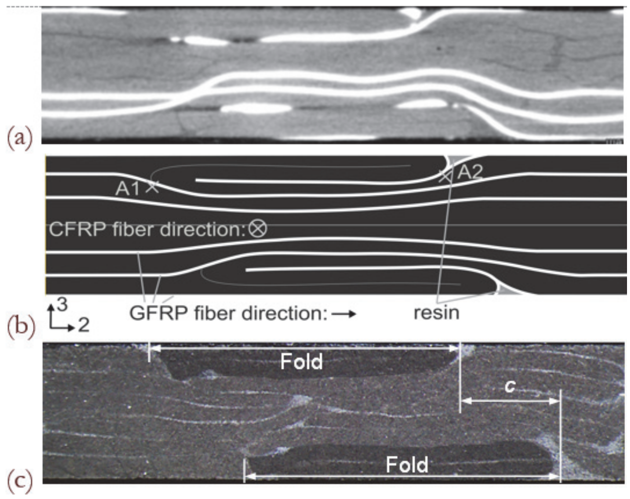

Figure 2: Defect configuration of folds; (a) computed tomography scan; (b) schematic sketch; (c) microscopy image of edge.

Because of the fold presence, there is a local increase in fiber volume fraction at the defect location. Two additional plies are added over the laminate thickness within each fold. Thus, the average local fiber volume fraction in the folded area can be calculated to $V_{f,n=10} = 0.75$.

Additionally to the local increase in fiber volume fraction, resin pockets in the turning points can be distinguished. The distance *c* between the two folds is measured using the optical microscopy images of the edges (Fig. 2c) for each specimen, such that a possible influence of this parameter on the test results can be identified after the tests.

Since the folds are introduced along fiber direction in a unidirectional material no fiber waviness is introduced into the composite material, which is a comparable configuration to the laminate configuration in [3]. However, while in [3] the fold in plies located mid-thickness of the laminate, in the present study the folds are located into the surface plies, which is according to the most often encountered situation by our commercial partner, according to their manufacturing process.

Experimental setup

Static tension and compression tests, as well as constant amplitude fatigue tests with different load ratios ($R = 0.01$, $R = -1$, $R = 100$) at a frequency of 10 Hz are performed. At least ten specimens are tested at each load ratio and defect orientation. The specimens are clamped with hydraulic wedge grips on the aluminum tabs. An in-house designed alignment device is used for all tests in order to guarantee an axial load introduction. Strain gauges are applied at the defect location for local strain measurement and an extensometer is used for the tensile specimens, for global strain measurement.

RESULTS AND DISCUSSION

The results of the different load cases are presented in this section. First the results of tests in fiber direction are given (i.e., the influence of the defect on fiber failure), and then results of tests in transverse to fibers direction are presented (i.e., the influence of the defect on inter fiber failure).

Fiber Direction

Various damage mechanisms could be observed and monitored through the use of a camera (resolution = 5 MPx, frame rate = 0.2 fps) during the fatigue loading, and through fractography analysis (optical microscope with magnification factor of max. 63x) after testing: breakage of the longitudinal tows inside of the folds, longitudinal splitting along the folds turning lines (corresponding to the A1 and A2 turning points in Fig. 2b), and delamination of the folds along the fold lamination longitudinal plane (corresponding to the fold junction line A1A2 in Fig. 2b). All these separate damage mechanisms are initiated at the location of the fold; they are concurrent and coupled (influence each other); they are initiated at approximately the same moment (number of cycles) during the fatigue loading. Each of them is a progressive damage mechanism, i.e. longitudinal splitting propagates along longitudinal and through-thickness direction, delamination propagates along longitudinal direction, and more individual tows will break during cyclic loading. To be noted that the same progressive damage mechanisms appear in the material without the fold defect; however, in this case, the damage initiation location can be anywhere along the width of the specimen, while in the case of defect material the onset takes place always at the fold location. By finite element analysis it was found that the increased stiffness within the fold does not lead to a stress concentration by itself. A multiaxial stress state is introduced within the fold by clamping effects and this leads to damage initiation of the folded region nearby the tabs.
The longitudinal tows breakage will bring a corresponding stiffness drop, which can be recorded by the strain measurements. What is reported in the present manuscript is the initial stiffness drop, corresponding to the damage onset of the progressive damage events. There will of cause be load carrying capacity after damage onset (which is defined here as the initial longitudinal stiffness drop, found to be around 2 – 8 % of the initial stiffness of the material featuring the fold manufacturing defect before damage initiation. The recorded data for the final failure of the material (defined as the total loss of the load carrying capacity) needs further analysis and understanding, and it will be presented in further reports.
In Fig. 3, damage onset points of the material with defect are compared to the corresponding onset SN curves of the material without defect. The tension-tension (T-T) results are normalized on the ultimate tensile strength; the tension-compression (T-C) and compression-compression (C-C) results are normalized on the ultimate compressive strength. The static ultimate strengths for specimens with folds are also included. For the C-C load case no data without defect is available at this moment, further testing is needed for this case. Yet, the results of the material without defect under T-C loading (the gray lines in Fig. 3c) can be used for preliminary comparison.

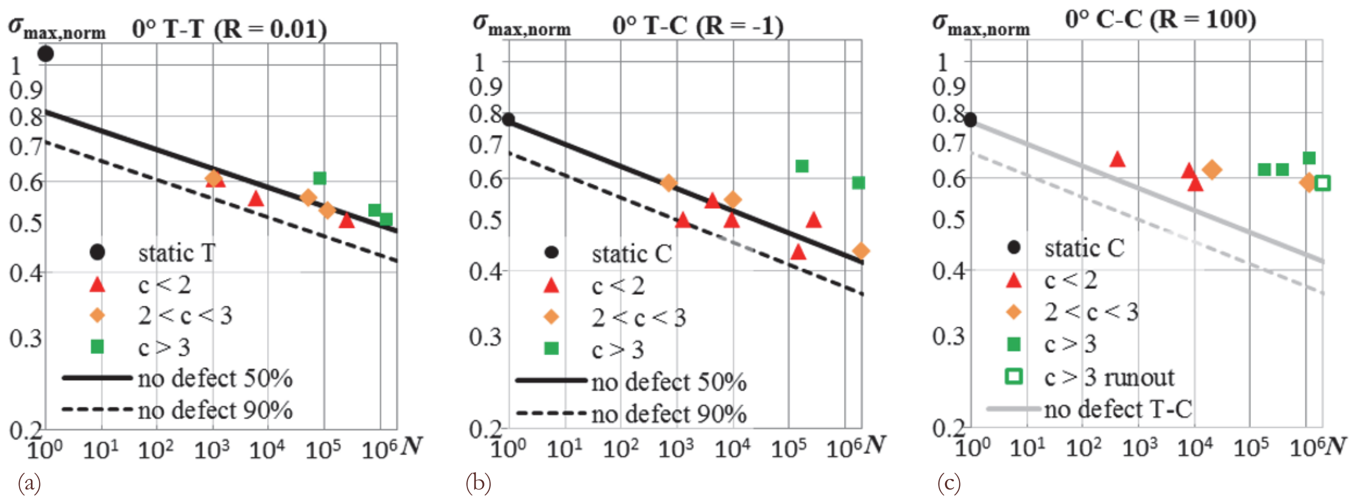

Figure 3: Fiber direction loading SN curves, normalized on the static strength.

Regarding the static results, it can be inferred from Fig. 3a that the tensile strength is slightly increased by the presence of the fold, compared to the strength without defect; this is because the additional fibers act as reinforcement for this loading case. The compressive strength with defect is reduced to 80 % of the strength without defect, see Fig. 3b,c; the cause of this has to be further investigated and understood. In fiber direction the fold is a local reinforcement, since locally more fibers are present; the reinforcing effect can be noted under tension loading, but not under compression. The distance c did not have a measurable influence on the static results; the same fracture load was measured for different c values.

For the fatigue results, the moment of damage initiation was found to be dependent on the distance *c* (Fig. 2c). Thus, three ranges of the distance *c* were defined in order to study its influence on the test results; for folds with a smaller distance *c* damage initiated earlier for all considered load cases and load ratios. However, for T-T as well as T-C at small *c* values, failure occurred within the scatter band of the tests without defect. For T-C with $c > 3$ mm the fatigue life is increased, compared to the material without defect.

Transverse to Fibers Direction

In the transverse to fibers direction the damage mechanism is inter fiber fracture. In the unidirectional laminate the specimens fail within one load cycle due to fracture through the whole thickness of the laminate; no progressive damage takes place. Two different damage mechanisms were observed for the transverse load cases. One is tension failure, corresponding to static tension and fatigue T-T and T-C (the transverse static tension strength is only 30 % of the static compression strength). The transverse tension failure is due to matrix cracking or interfacial debonding between matrix and fibers with a fracture plane perpendicular to the load direction. This fracture plane in most of the cases was located at the turning point of the fold in the resin rich area.

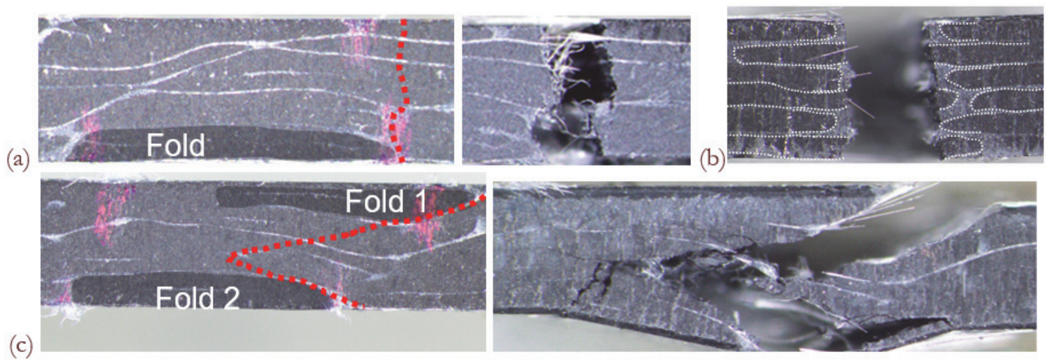

Figure 4: Transverse fracture: (a) at the fold turning point, T-T loading (before and after test); (b) at resin rich area away from fold, T-T loading; (c) at both outer turning points, C-C loading (before and after test).

Fig. 4a shows the edge of a T-T specimen before and after fracture at the inner turning point of a fold. The two additional plies in the folded area are displayed darker and the crack is indicated by the dashed line. However, for two of the T-T specimens fracture was observed not at the fold area, but within the gauge section away from the fold, where at least three gaps between tows occurred aligned along the same vertical line, see Fig. 4b. It follows that in transverse tension additional weak resin rich areas between additional tows at the fold have a higher influence on the static and fatigue strength than the local increase in fiber volume fraction.

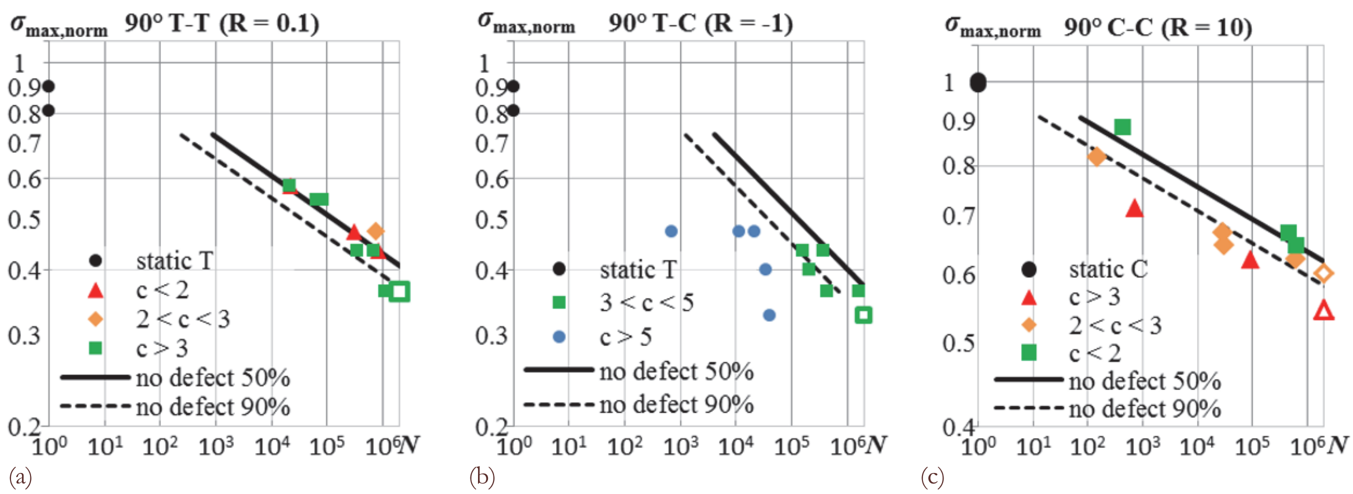

Figure 5: Transverse to fiber direction SN curves, normalized on the static strength.

The results for the T-C fatigue loading are presented in Fig. 5b. Here, it can be noted that the specimens with lower *c* values still fall into the scatter band of the specimens without defect, but a reduced fatigue life is recorded for the specimens with a higher distance *c*. This is because of the fact that the T-C specimens have to be short (in order to avoid compression buckling) and for high *c* values the folds are located into the tabs effects area of the specimens. An interaction of stress concentrations at fold and tabs occurs, which reduces the fatigue life of specimens.

The second damage mechanism is compression failure, corresponding to static compression and fatigue C-C. In transverse compression the fracture surface is inclined, forming a wedge. By optical microscopy it was observed that, for the material with defect, compression fracture always happened through the triangular resin pockets at the fold, as shown in Fig. 4c. In a linear static FE analysis the influence of the fold was modelled by stiffness variation in resin and folded volume, which showed a local increase of the von Mises stress in the plies near the resin pockets, and orientation of the higher stress areas corresponding to the fracture lines in experiments. An influence of the distance *c* could also be observed for C-C fatigue loading (Fig. 5c): for smaller distance *c* the material withstands a reduced fatigue life.

CONCLUSIONS

A unidirectional carbon fiber reinforced polymer material featuring folds as manufacturing defect has been studied by means of experimental tests and simple numerical FE simulations. The influence on the fatigue life has been investigated under constant amplitude fatigue loading. In fiber direction a dependency on the distance *c* between the folds was found, where smaller distances lead to higher stress concentrations and lower fatigue life, while in transverse to fibers direction failure usually occurred in resin rich areas nearby the fold without an influence of *c*. All in all, the studied folds had a minor influence on the fatigue performance and are considered to be allowable in structural parts.

However, for multidirectional laminates, waviness might be introduced by the folds in the off-axis plies, which lead to a strength and fatigue life reduction of about 50 % in compression, as was found in a previous study [1]. A combination of these two defects could have a higher influence on the fatigue life, and should be investigated in future work.

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